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ORIGINAL RESEARCH

Working Memory Capacity and ADHD Symptoms in Boys: Examining the Heterogeneity of Working Memory Functioning Using Latent Profile Analysis

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Abstract
Recent studies demonstrate that working memory (WM) is integral to etiological models of ADHD; however, significant questions persist regarding the relation between WM performance across tasks with varying cognitive demands and ADHD symptoms. The current study incorporates an individual differences approach to WM heterogeneity (i.e., latent profile analysis) to (a) identify differential profiles of WM across the phonological and visuospatial WM subsystems; and (b) characterize differences in symptom presentation among WM profiles. Parent and teacher ratings of child behavior, obtained for boys with ($n = 51$) and without ($n = 38$) a diagnosis of ADHD, were compared across latent classes of visuospatial and phonological WM performance. Latent profile analysis identified three classes of WM functioning: Low WM, Moderate WM, and High WM. Membership in the Low and Moderate WM classes was associated with greater levels of parent- and teacher-rated inattentive and hyperactive symptoms. While 84% of the ADHD group were assigned to the Low and Moderate WM classes, more than a quarter of children without ADHD exhibited Moderate WM limitations. Collectively, these findings extend prior work suggesting that there is substantial heterogeneity in WM functioning in children with and without ADHD and that these differences contribute to the expression of symptoms of inattention and hyperactivity.

Keywords ADHD · Working memory · Latent profile analysis · Children · Executive functioning

Attention-Deficit/Hyperactivity Disorder (ADHD) affects approximately 5% of children worldwide (Polanczyk et al. 2014) and is characterized by persistent and impairing difficulties with inattention, hyperactivity, and impulsivity (American Psychiatric Association 2013). Moreover, the disorder is associated with a number of adverse outcomes including social difficulties (e.g., Bunford et al. 2015; Wehmeier et al. 2010), academic underachievement (e.g., Daley and Birchwood 2010), and functional impairments at home (e.g., Barkley 2014) that persist into adolescence and young adulthood (Barbaresi et al. 2013; Molina et al. 2009; Sibley et al. 2017). Further, the disorder is associated with substantial individual (Altszuler et al. 2016) and societal (Pelham et al. 2007) financial burden. Despite well-documented cross-domain functional outcomes, significant questions remain regarding the underlying mechanisms contributing to symptom presentation.

The last two decades have given rise to substantial interest in understanding how executive functions contribute to the core symptoms and poor functional outcomes experienced by individuals with ADHD (Bunford et al. 2015; Burgess et al. 2010; Castellanos and Tannock 2002; Nigg 2003). Multiple studies have indicated that not all children with ADHD experience similar levels of impairment in cognition (Chhabildas et al. 2001; Fair et al. 2012; Kasper et al. 2012; Willcutt et al. 2005). When multiple executive functioning

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constructs are included, almost 90% of children with ADHD exhibit impaired performance on at least one executive function with significant variability in the specific construct and degree of impairment, as well as the extent of concurrent impairment across multiple executive functions (Kofler et al. 2019). Specifically, meta-analytic studies suggest that up to 80% of children with ADHD may have a working memory (WM) deficit (Kasper et al. 2012) whereas approximately 50% may exhibit poor inhibitory control (Nigg et al. 2005; Willcutt et al. 2005). Collectively, this work indicates that rather than experiencing similar executive function deficits, the disorder may be better characterized by heterogeneity with respect to cognitive dysfunction. Further, these differences in specific neurocognitive impairments in children with ADHD may aid in our understanding of their contribution to heterogeneity in functional impairments (Kofler et al. 2017) as well as symptom remission (Karalunas et al. 2017).

Previous studies have attempted to leverage the consistent heterogeneity of neuropsychological impairments in ADHD (Nigg et al. 2005) into potential endophenotypes for ADHD (Biederman et al. 2004; Lambek et al. 2010; Nigg et al. 2004). Specifically, varying cognitive profiles and associations with behavioral symptoms and clinical outcomes in ADHD have given rise to theoretical models to explain the heterogeneity of cognitive abilities in ADHD (see Luo et al. 2019). The models differ in the perceived role of executive functions and motivational processes in the emergence of ADHD and their differential association with symptom domains. For example, the dual-pathway model (Lambek et al. 2018; Sonuga-Barke 2002) posits that cognitive and motivational processes differentiate symptom domains such that inattention is closely associated with executive dysfunction while motivational deficits are more strongly associated with hyperactive symptoms. In contrast, the cognitive-energetic (Sergeant 2000) and neurodevelopmental models (Halperin and Schulz 2006) propose that the interplay between neurocognitive abilities results in the emergence of behavioral difficulties, which would indicate that executive functions and motivational processes have associations with both inattentive and hyperactive symptom domains. Despite these theoretical models, evidence for an association between ADHD subtype and executive function performance remains scant (Lockwood et al. 2001). Notably, studies investigating subtype and executive function performance only include group comparisons between the inattentive and combined presentations of ADHD and typically developing children leading to a limited understanding of the relationship between cognitive performance and specific symptom domains (i.e., inattention and hyperactivity; Sonuga-Barke et al. 2008). Consequently, dimensional approaches towards investigating symptom severity associated with specific executive dysfunctions may be more appropriate for addressing specificity of the two ADHD symptom domains.

Many researchers have postulated that WM difficulties represent a core impairment in ADHD (Castellanos and Tannock 2002; Rapport et al. 2001; Martinussen et al. 2005) leading to behavioral difficulties; however, little is known about the association between WM and ADHD symptoms independent of diagnosis. Working memory is a limited capacity cognitive function essential for attending to relevant stimuli through the temporary storage, rehearsal, updating, and manipulation of internally-held modality-specific information (Martinussen et al. 2005). One particular model of WM that has been examined extensively in children with ADHD is the Baddeley (2007) WM model that conceptualizes WM as being primarily comprised of four subcomponents — two limited capacity domain short term memory storage/rehearsal systems (i.e., phonological and visuospatial) working in tandem with a domain-general central executive to store and maintain information in WM for the purpose of task execution. The episodic buffer has been proposed as a fourth limited capacity subsystem which binds and temporarily stores information from the two modality specific subsystems thereby forming a unitary episodic representation for information. However, among the handful of studies examining the episodic buffer in elementary school-aged children, with and without ADHD (Alderson et al. 2015; Gray et al. 2017; Kofler et al. 2018), the studies suggest that there are no between-group differences in this component in youth with the disorder relative to those without the disorder. As a result, the current study focuses on the components of the model that have consistently been implicated as deficient in children with ADHD (i.e., phonological storage/rehearsal, visuospatial storage/rehearsal, and central executive).

While WM deficits among children and adults with ADHD are well documented in both meta-analytic and experimental work (Brocki et al. 2008; Martinussen et al. 2005; Rapport et al. 2008; Willcutt et al. 2005), examinations of these deficits and their association with symptoms of the disorder are mixed. Some (Brocki et al. 2010; Gathercole et al. 2008; Lui and Tannock 2007) but not all studies (Gallego-Martinez et al. 2018; Sonuga-Barke et al. 2002) find substantial relations between ratings of inattentive symptoms and poor performance on assessments of WM performance. Furthermore, few studies have demonstrated an association between composite WM performance, representing simultaneous utilization of multiple WM subsystems for successful task execution (e.g., phonological working memory plus central executive), and parent and teacher rated symptoms of hyperactivity (Kofler et al. 2017; Kuntsi et al. 2001).

Investigations providing a more granular analysis of the WM subsystems have found visuospatial and phonological storage/rehearsal to be related to a diagnosis of ADHD (Alloway 2011; Rapport et al. 2008) as well as to subjective evaluations of inattention but not hyperactivity/impulsivity (Thorell 2007; Tillman et al. 2011). When inattention and hyperactivity/impulsivity were evaluated using objective measures, both symptom domains of ADHD have been found to be differentially associated with the WM subsystems. Specifically, Kofler et al. (2010) found that increasing cognitive load in both phonological and visuospatial WM tasks was associated with decreased orientation towards the task, indicating increased inattention. Studies utilizing actigraphy have found hyperactivity to be associated with visuospatial (Kofler et al. 2015; Patros et al. 2017), phonological (Rapport et al. 2009), and central executive processes (Kofler et al. 2015). Similarly, impulsivity, measured using computerized paradigms, was found to be associated also with visuospatial (Patros et al. 2015), phonological, and central executive processes (Raiker et al. 2012). The current study seeks to examine whether heterogeneity in cognitive performance in ADHD extends to modality-specific performance and whether this heterogeneity is associated with differences in severity of symptom presentation as rated by parents and teachers.

The well-established heterogeneity found in symptom presentation as well as neurocognitive deficits necessitates novel person-centered approaches to examining the relationship between cognition and symptoms of the disorder. This approach has the potential to isolate meaningful differences within groups to identify homogenous groups of individuals that share similar characteristics not detected by traditional analytic approaches. To date, only one study has adopted this approach to understanding relationships between WM performance and ADHD. Specifically, Gomez et al. (2014) utilized latent profile analysis (LPA) to identify distinct ADHD subgroups of varying WM impairment (severely impaired, moderately impaired, and not impaired). The three ADHD groups were not significantly different from each other on inattentive symptoms and exhibited greater inattentive symptoms relative to a typically developing (TD) group. While this study by Gomez et al. (2014) represents a critical step in better understanding the heterogeneity in WM dysfunction in ADHD, the separate examination of these profiles in children with ADHD and typically developing children limits the conclusions that can be drawn. Specifically, recent evidence suggests that heterogeneity in executive functioning is likely nested (or overlapping) within similar variability observed in the TD population (Fair et al. 2012; Mella et al. 2016; Mostert et al. 2015). Furthermore, WM ability has also been found to be associated with age (Gathercole et al. 2004) and racial/ethnic background (Lawson et al. 2014) necessitating a need to consider demographic variables as potential contributors to the observed heterogeneous WM ability within samples of children with ADHD.

The current study utilized latent profile analysis to characterize variation in WM through the examination of subgroups across children with and without ADHD to capture the natural variation of WM in the broader population. Additionally, the current study is the first to evaluate whether WM ability varies across modalities and cognitive load demands (i.e., manipulation of an increasingly greater number of stimuli) leading to latent profiles characterized by decrements in performance in one modality with intact performance in the other at varying levels of cognitive load. The association between children's WM profiles and specific symptoms of ADHD are examined. Consistent with past findings, we anticipate the detection of multiple WM subgroups reflecting between group differences in WM as cognitive demand increases. Furthermore, it is hypothesized that more pervasive impairment in WM will be associated with higher parent/teacher-rated inattentive and hyperactive symptom severity. Finally, we hypothesize that each WM subgroup will be comprised of both individuals with and without ADHD consistent with previous work (Fair et al. 2012) demonstrating nested cognitive heterogeneity among groups, with the poorest performing groups being primarily comprised of individuals with ADHD.

Method

Participants

The sample[1] was comprised of eighty-nine English-speaking boys with and without ADHD aged 7 to 12 years old (M = 9.71 years, SD = 1.25 years) recruited or referred to a university-based Children's Learning Clinic (CLC) through community resources (e.g., referrals from primary care physicians, community mental health clinics, self-referral) and whose parents agreed to have them participate in developmental/clinical research studies. Children meeting diagnostic criteria for ADHD or not meeting criteria for any disorder in the *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; American Psychiatric Association 2013) were considered for inclusion. A psychoeducational evaluation was provided pro bono to parents of all participants. Typically developing (TD) children (those without a suspected psychological disorder) generally were self-referred families interested in learning about their child's cognitive and academic profile. The racial and ethnic make-up of the sample was consistent with the surrounding population: 69.7% Caucasian non-Hispanic, 18% Hispanic, 5.6% African-American, and 6.7% multi-racial or other race or ethnicity. All parents and children provided their informed consent/assent to participate in the study, and the university's

[1] A subset of these children were included in previous studies (Alderson et al. 2010; Bolden 2012; Calub et al. 2019; Kofler et al. 2014; Raiker et al. 2012; Rapport et al. 2008; Rapport et al. 2009; Sarver et al. 2015) to examine conceptually distinct hypotheses. Notably, this sample has never been included in a study utilizing latent profile analysis or examining the association between the experimental laboratory-based tasks and the rating scales used in the current study.

Institutional Review Board approved the study prior to the onset of data collection.

Procedures

Parents and children participated in a detailed, semi-structured clinical interview including all screening questions of the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS; Kaufman et al. 1997) with supplemental questions for parent-indicated elevated symptoms. The K-SADS assesses for current and past episodes of psychopathology as reflected by symptoms and their associated onset, course, duration, severity, and degree of impairment based on criteria from the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition* (DSM-IV; American Psychiatric Association 2013).[2] Clinical interviews were supplemented with parent and teacher versions of symptoms ratings from the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), Teacher Report Form (TRF; Achenbach and Rescorla 2001), and Child Symptom Inventory (CSI-4: Gadow et al. 2004). Children were excluded from the study if they presented with a history of seizures, psychosis, or received a Full Scale IQ score less than 85. Children with gross neurological, sensory, or motor impairment were excluded as well. Full Scale IQ scores in the ADHD group ($M = 105.57$, $SD = 11.45$) and TD group ($M = 109.53$, $SD = 10.78$), were not significantly different from each other, $t(87) = 1.65$, $p = .10$.

Fifty-one children were diagnosed with ADHD and met the following criteria: (1) an independent diagnosis of any presentation of ADHD by the directing clinical psychologist based on the results of the K-SADS; (2) A score at least two standard deviations above the mean on the Attention Problems clinical syndrome scale of the CBCL or exceeding the ADHD criterion for inattentive, hyperactive, or combined subscale score for the parent version of the CSI-4; and (3) A score of at least two standard deviations above the mean on the Attention Problems clinical syndrome scale of the TRF or exceeding the ADHD criterion for inattentive, hyperactive, or combined subscale score for the teacher version of the CSI-4. Nearly the entire sample diagnosed with ADHD was formally diagnosed with combined subtype/presentation ($n = 44$). The remaining children met criteria for inattentive subtype/presentation ($n = 4$), hyperactive subtype/presentation ($n = 1$), or not otherwise specified ($n = 2$). A subset of these children additionally met diagnoses for Oppositional Defiant Disorder ($n = 8$), a Learning Disorder ($n = 6$), or an Anxiety disorder ($n = 6$). A majority of the children in the ADHD group (60%) did not meet criteria for any comorbid disorders. Aside from stimulant medication ($n = 15$), families did not report any additional prescribed psychiatric medication.

Thirty-eight children were included in the TD group based on the following criteria: (1) K-SADS clinical interview reviewed by the directing clinical psychologist did not reveal evidence of clinically elevated levels of any clinical disorder; (2) typical developmental history as reported by a parent with no indication of potential developmental delays or history of clinically elevated DSM-IV symptoms; (3) ratings below 1.5 standard deviations on the externalizing clinical syndrome scales of the CBCL and TRF; and (4) ratings below the ADHD criterion on the CSI-4 subscales.

Parents of children in the group of children with ADHD were asked to withhold medication for a minimum of 24 h prior to testing for children currently prescribed psychostimulants. The WM tasks described below were counterbalanced and administered as part of a larger battery of neurocognitive tasks requiring the child's presence for approximately 2.5 h during a single session (children attended four sessions scheduled approximately one week apart). To minimize fatigue, children received brief breaks (2–3 min) following each task and longer breaks (10–15 min) following the completion of multiple tasks. All tasks were programmed using SuperLab Pro (Version 2;2002) and administered to the child on a computer.

ADHD Symptoms

The CSI-4 (Gadow et al. 2004) is a 97-item behavior rating scale completed by both the parent and teacher that assesses a variety of emotional and behavioral disorders in childhood. Parents and teachers rate whether symptoms occur never (0), sometimes (1), often (2), or very often (3), providing a severity score for each item. The CSI-4 has shown high test-retest reliability (.75 to .84) and internal consistency (.86 and .88; Sprafkin et al. 2002). In the current study, the inattention, hyperactivity, and combined inattention and hyperactivity severity scores subscales were used as dependent variables reflecting the sum of the severity scores across items.

The CBCL and TRF (Achenbach and Rescorla 2001) are broadband measures of behaviors associated with childhood psychopathology completed by parents and teachers, respectively. Parents and teachers rate the child's behavior across 113-items within the past six months. The items contribute to subscales that assess problem behaviors and functioning across multiple domains (e.g., withdrawn/depressed, somatic complaints, attention problems; Syndrome Scales) as well as subscales consistent with DSM diagnoses (i.e., DSM Oriented Scales). These scales have well-established psychometric properties including test-retest reliability (.63 to .97) and internal consistency (.66 to .92; Achenbach and Rescorla 2001). T-scores from the ADHD related subscales of the CBCL and

[2] All participants within the ADHD group also met criteria for ADHD based on the Diagnostic and Statistical Manual of Mental Disorders, 5th edition (DSM-5; American Psychiatric Association 2013), as determined by the KSADS (2013 update), which was published during the collection of this data.

TRF (Attention Problems, Inattention, Hyperactive/Impulsive, DSM-Oriented ADHD, DSM-Oriented Inattention, and DSM-Oriented Hyperactivity) were used in the analyses.

Phonological (PH) Working Memory Task

The phonological (PH) working memory task used in this study is similar to the Letter-Number Sequencing subtest of the WISC-IV (Wechsler 2003) and is identical to the task described in Rapport et al. (2008). Specifically, the stimuli consisted of a capital letter and a series of numbers (approximately 4 cm in height) which appeared on a computer monitor for approximately 800 ms with a 200 ms interstimulus interval. The stimuli were presented in a jumbled order (e.g., 3 F 1 6) and children were instructed to verbally recall the sequence presented in numerical order, from smallest to largest, and state the letter last (e.g., 1 3 6 F). Participants were required to achieve 80% accuracy on five practice trials to ensure understanding of the task demands prior to advancing to the full task. The serial position of the letter was counterbalanced across trials and never appeared first or last in a series of letters and numbers to minimize recency and primacy effects. Four different set sizes (3, 4, 5, and 6 stimuli), each with 24 unique trials, were administered to evaluate performance across varying set size conditions. Requiring participants to remember the letter presented while maintaining presented numbers and reordering them sequentially places demands on attentional shifting abilities, mental manipulation of stimuli and modality-specific storage and rehearsal processes. Therefore, the task can be considered to tap central executive and storage rehearsal processes simultaneously. Two trained research assistants, blind to diagnosis and seated outside of the room, recorded children's verbal responses independently of one another. Children's responses were scored correct if the numbers were stated in the correct serial position (i.e., lowest to highest) and the letter recalled as the final stimulus in the presented list. The primary dependent variable for each set size was average stimuli correct per trial as recommended by Conway et al. (2005).

Visuospatial (VS) Working Memory Task

The visuospatial (VS) working memory task is identical to the one described in Rapport et al. (2008). Specifically, a series of black dots and one red dot (approximately 2.5 cm in diameter) appeared one at a time in one of nine squares arranged in three offset vertical columns (to prevent phonological encoding) with no two dots appearing in the same square on any given trial. Children were instructed to recall the order in which the dots were presented then indicate the position of the red dot last (regardless of when it was presented) on a modified keyboard number pad that corresponded to the three offset vertical columns presented on the screen. The serial position of the red dot was counterbalanced across trials and never appeared first or last in the series to minimize recency and primacy effects. All participants achieved 80% accuracy on five practice trials to ensure understanding before progressing to the full task. Four different set sizes (3, 4, 5, and 6 stimuli) of 24 trials each were administered to evaluate children's performance across varying cognitive demand. Similar to the PH working memory task, the task places demands on attentional shifting abilities between new (i.e., black dots appearing after the red dot) and old information (i.e., black dots appearing after the red dot). Further participants have to mentally manipulate stimuli to meet task demands and rehearse VS information until all stimuli are presented. Therefore, the task can be considered to tap central executive and storage rehearsal processes simultaneously. Each button press corresponding with the order and location of the presented dots, regardless of the preceding and ensuing stimuli, was scored as correct. This included correctly identifying the red dot's location as the last response emitted. The primary dependent variable for each set size was the average stimuli correct per trial as recommended by Conway et al. (2005).

Data Analytic Plan

Performance data, or the average stimuli correct per trial distinguished by set size and modality, for participants in both diagnostic groups was submitted to a latent profile analysis (LPA) in Mplus Version 8.2 (Muthén and Muthén 2017). Latent profile analyses detect latent subgroups within a population without sacrificing statistical power due to unequal subgroup size (Lanza et al. 2013). Additionally, the use of finite mixture models, such as LPA, as opposed to more traditional group-based approaches, reduces the risk of Type I errors by reducing the overall number of comparisons that must be conducted in a single analysis (Lanza and Rhoades 2013). Because guidelines concerning the necessary sample size for LPA are unavailable, emerging literature in this area demonstrates that factors reflecting significant strengths of the current study (e.g., strong indicators of the construct, increased number of indicators, degree of class separation) are critical determinants of adequate power to detect subgroups in LPA and may attenuate limitations introduced by smaller samples (Muthén and Muthén 2002; Tein et al. 2013; Wurpts and Geiser 2014). Additionally, a recent simulation study conducted by Dziak et al. (2014), indicated that a sample size of 100 is sufficient to detect a medium effect size. Given prior evidence of large magnitude effect size differences on these WM tasks (PH: 1.89, VS: 2.31; Rapport et al. 2008) this study was sufficiently powered to recover the latent profiles in this sample ($n = 89$). Performance on the phonological and visuospatial WM tasks across the four set sizes (i.e., 3, 4, 5, and 6 stimuli load) were used as class indicators to identify latent classes based exclusively on WM performance.

Analyses used robust maximum likelihood estimation with 150 random starting values to avoid convergence on a local maximum (Asparouhov and Muthén 2014). The number of latent classes was determined by evaluating fit for a one class solution and then adding additional classes in sequence until optimal model fit was accomplished. Selection criteria were as follows: (1) low Bayesian Information Criteria (BIC) and sample-size adjusted BIC (ABIC) which indicate the amount of unexplained variance remaining in the model with lower numbers indicating less unexplained variance; (2) significant bootstrap likelihood ratio test (BLRT) which reflects whether the difference in fit between *K* classes compared to *K-1* classes is statistically significant ($\alpha < 0.05$); and (3) high entropy values which reflect how accurate *K* classes are at predicting individual class membership. For the latter index, values closer to 1 indicate fewer classification errors (i.e., greater number of individuals classified correctly).

Following the selection of the optimal class model, mean scores across ratings of ADHD symptom domains (dimensional) and diagnostic status (categorical), were evaluated across set sizes as distal outcomes. Differences in class symptom profiles were modeled using the BCH method (Bakk and Vermunt 2016) in which equality of means in distal outcomes are multiply imputed utilizing posterior probabilities. Following estimation of means, a chi-square distribution, rather than an F-distribution, is used to compare the classes on the distal outcomes (continuous and categorical). Diagnostic status was categorized based on whether the participant belonged to the ADHD group or the typically developing group and included in the analysis utilizing the DCAT method (Asparouhov and Muthén 2014).

Results

Model Fit

To estimate the optimal number of classes, we evaluated the fit of models reflecting 1 to 5 classes. The best log-likelihood values were replicated with starting values of 100, 500, and 1000. Table 1 provides the BIC, ABIC, BLRT, and entropy values for the models. Unexplained variance (BIC, ABIC) was the lowest for the 3-, 4-, and 5-class models. Closer examination of these models revealed that the ABIC differences between the 5- and 4-class models (ΔABIC = 37.94) and the 4- and 3-class models (ΔABIC = 42.83) were negligible relative to the difference between the 3- and 2-class models (ΔABIC = 80.84). As expected, the BLRT was significant across all class models indicating better fit as the number of latent classes increased. All models generated entropy values ranging between .92 and .93—a finding that indicates a desirable level of class separation (average posterior probability at or above .90) with good classification accuracy across all models. Finally, examination of the number of participants classified across the latent classes indicated that one of the classes in the 5-class model contained only 7 participants (i.e., 8% of the sample). Due to this small class size, the additional class was judged as not providing significantly greater information relative to the 4-class model. Due to the similarity in fit between the 4- and 3-class models, we examined linear plots to determine which model was more interpretable as recommended by Bauer and Curran (2003). The linear plots indicated that the 4-class model produced two classes that were very similar to one another in terms of WM performance. Collectively, consideration of the indices and model parsimony supported a 3-class model as the optimal solution. As a result, the three classes were compared to one another in subsequent analyses.

Prior to conducting the LPA, bivariate correlations and one-way ANOVAs were conducted to investigate whether demographic variables (i.e., age and race) were significantly associated with any of the indicator variables. Results of the one-way ANOVA indicated that race was not significantly associated with PH or VS working memory performance, $F(4, 84) = .54–1.69$, $p\text{s} = .16–.71$. Pearson correlations indicated age was significantly associated with PH and VS working memory performance $r\text{s}(89) = .24–.43$, $p\text{s} < .05$. When the LPA was repeated with the inclusion of age as a covariate, the pattern of results remained unchanged, indicating that assignment to latent classes was independent of this variable. As a result, the simple three-class model with no covariates is reported below to facilitate interpretation.

WM across Latent Class

Examination of performance across set sizes revealed that the classes were representative of a pattern of differential WM performance. Overall, the difference in WM performance among classes did not differ in terms of modality (i.e. PH and VS). As such, performance is described in terms of WM performance across set sizes, regardless of modality, in which the average stimuli correctly recalled is expected to increase as the number of available stimuli (i.e., set size) increases until cognitive load capacity is exceeded for an individual. The first class consisted of a Low WM class with overall poor recall ability across all set sizes with gradual decrements in performance at higher set sizes. Specifically, performance in this group reflected the ability to recall, on average, two stimuli per trial across both modalities ($M = 1.80$, $SD = .46$) even on trials with larger set sizes. Class two demonstrated stable or decreasing recall ability at moderate set sizes (i.e., four and/or five stimuli) indicating that they were able to recall, on average, three stimuli accurately ($M = 2.61$, $SD = .61$), reflecting a Moderate WM class. The third class demonstrated High WM

Table 1 Fit statistics of the latent profile analysis models

Model	BIC	Adjusted BIC	BLRT *p* value	Entropy	N assigned to each Profile (P)
1-class	1769.25	1718.76	–	–	P1 = 89
2-class	1499.76	1420.86	$p < .01$	.93	P1 = 42; P2 = 47
3-class	1447.32	1340.02	$p < .01$	.92	P1 = 19; P2 = 35; P3 = 35
4-class	1432.89	1297.19	$p < .01$	.93	P1 = 30; P2 = 12; P3 = 9; P4 = 38
5-class	1423.35	1259.25	$p < .01$	.92	P1 = 9; P2 = 7; P3 = 25; P4 = 32; P5 = 16

BIC Bayesian Information Criteria, *BLRT* Bootstrap likelihood ratio test

based on a pattern of stable performance across set sizes without a decrement in performance at higher set sizes. Specifically, those in the High WM class evinced accurate recall of, on average, four stimuli ($M = 3.57$, $SD = .61$). As illustrated in Fig. 1, the three WM classes were significantly different from each other with respect to number of stimuli accurately recalled across all set sizes and across both modalities (visuospatial and phonological). For all set sizes the Low WM class had the lowest scores, followed by the Moderate WM class with the High WM class obtaining the highest scores across both modalities (see Table 2).

Comparison of Inattentive and Hyperactive Symptoms across Classes

Parent Ratings. WM performance for all of the children, regardless of diagnostic status, were submitted to the latent profile analysis. As such, comparisons between WM class and ADHD symptoms are independent of diagnostic status (see Table 2). Comparison of the inattentive and hyperactive symptom raw scores for the parent CSI-4 and subscale T-scores for the CBCL revealed significant class differences, all $\chi^2 s$ (2) > 41.01, *p*s < .001. Specifically, the High WM class was rated as exhibiting significantly fewer symptoms ($p<.05$) across the ADHD domains relative to the Low and Moderate WM classes. Effect sizes fell within the large range ($d = 0.90$–1.17; Cohen 1992), for all symptom domains when comparing the High WM class and the Moderate WM class. Effect sizes were greatest ($d = 1.24$–1.53) when comparing the High WM and Low WM classes, indicating that parents' perceptions of inattentive and hyperactive symptoms differed to a greater degree between the High and Low WM classes than between the High and Moderate WM classes. In contrast, the Moderate WM class was not significantly different ($p > .05$) from the Low WM class for the parent rating subscales (*p*s > .07), with one exception (i.e., CBCL Attention Problems subscale). Specifically, the Moderate WM class had a significantly lower T-score on the CBCL Attention Problems relative to the Low WM class, χ^2 (2) = 5.96, $p < .05$, Cohen's $d = .65$.

Teacher ratings. As reported in Table 2, a similar pattern was observed for teacher reported symptoms across the subscale T-scores for the CSI-4 and the TRF with significant differences emerging across all subscales (all χ^2s (2) > 6.10, *p*s < .05). Examination of between class differences revealed that membership in the High WM class was associated with significantly lower ratings relative to the Moderate WM class on all CSI-4 and TRF subscales (all *p*-values $\leq .05$; Cohen's *d* ranged from 0.55 to 0.87). Relative to the Low WM class, the

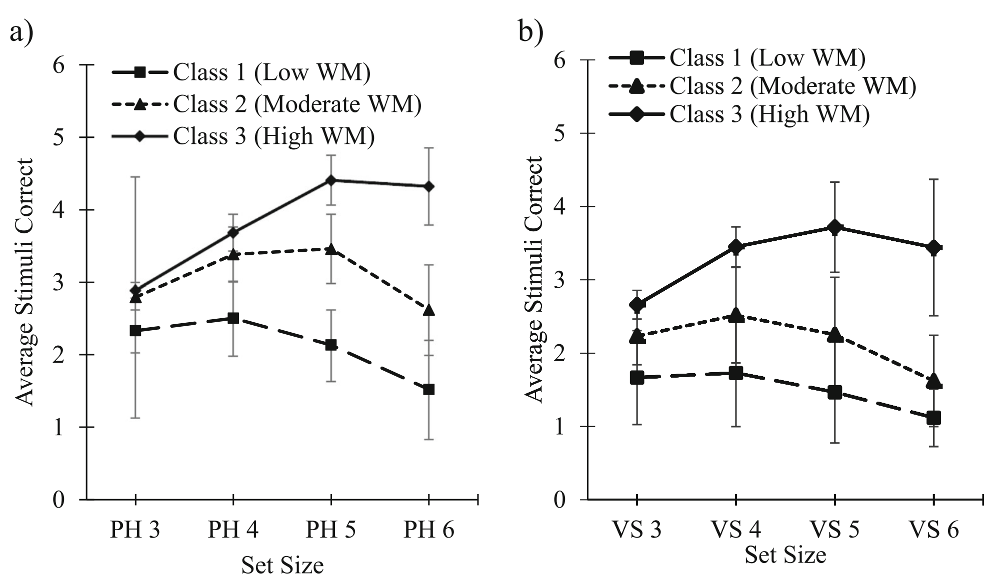

Fig. 1 Mean (and standard deviation) of average total stimuli correct per trial across set sizes for the (**a**) phonological working memory task, and (**b**) visuospatial working memory task. PH=Phonological, VS=Visuospatial, WM = Working Memory

Table 2 Contrasts of measures across the three latent classes

	1. Low WM $n = 19$	2.Moderate WM $n = 35$	3. High WM $n = 35$	X^2 ($df = 2$)	Group Contrasts
Phonological WM					
Set Size 3	2.23 (.30)	2.79 (.17)	2.89 (.11)	90.64***	3 > 2 > 1
Set Size 4	2.50 (.51)	3.39 (.38)	3.69 (.25)	93.48***	3 > 2 > 1
Set Size 5	2.13 (.49)	3.46 (.48)	4.41 (.34)	343.58***	3 > 2 > 1
Set Size 6	1.52 (.68)	2.62 (.62)	4.33 (.53)	299.67***	3 > 2 > 1
Visuospatial WM					
Set Size 3	1.67 (.64)	2.23 (.39)	2.66 (.20)	70.71***	3 > 2 > 1
Set Size 4	1.73 (.73)	2.52 (.65)	3.45 (.27)	144.59***	3 > 2 > 1
Set Size 5	1.47 (.69)	2.25 (.78)	3.72 (.62)	165.54***	3 > 2 > 1
Set Size 6	1.12 (.39)	1.62 (.62)	3.44 (.93)	164.17***	3 > 2 > 1
CSI-4 Parent					
Inattentive	75.50 (10.91)	69.42 (13.36)	55.03 (13.99)	38.13***	1 = 2 > 3
Hyperactivity	70.52 (15.32)	66.45 (16.38)	49.11 (12.07)	41.01***	1 = 2 > 3
Combined	74.39 (13.27)	69.90 (14.77)	52.48 (13.35)	43.23***	1 = 2 > 3
CSI-4 Teacher					
Inattentive	65.67 (9.87)	61.52 (11.45)	54.27 (11.37)	15.78***	1 = 2 > 3
Hyperactivity	60.68 (13.52)	62.12 (13.81)	51.16 (9.86)	17.58***	1 = 2 > 3
Combined	64.83 (12.14)	63.07 (12.55)	53.31 11.24)	17.03***	1 = 2 > 3
CBCL					
Attention Problems	75.94 (11.26)	67.93 (11.96)	57.93 (9.09)	40.69***	1 > 2 > 3
DSM-Oriented ADHD	68.98 (9.69)	67.96 (10.13)	56.47 (9.33)	32.67***	1 = 2 > 3
TRF					
Attention Problems	63.55 (9.88)	62.92 (9.80)	56.65 (7.35)	12.70**	1 = 2 > 3
Inattention	84.95 (14.57)	77.27 (18.39)	66.08 (19.49)	16.401***	1 = 2 > 3
Hyperactive/Impulsive	81.68 (17.61)	79.74 (18.91)	66.92 (18.90)	11.31**	1 = 2 > 3
DSM-Oriented ADHD	64.42 (9.18)	63.34 (9.32)	57.32 (7.68)	12.71**	1 = 2 > 3
DSM-Oriented Inattention	87.80 (13.29)	80.25 (17.84)	67.47 (18.31)	22.34***	1 = 2 > 3
DSM-Oriented Hyperactivity	82.43 (17.49)	81.42 (18.22)	66.77 (18.59)	14.29**	1 = 2 > 3

*** $p < .001$, **$p < 0.01$, *$p < 0.05$

WM Working Memory, *CSI-4* Child Symptom Inventory, *CBCL* Child Behavior Checklist, *TRF* Teacher Report Form, *DSM* Diagnostic and Statistical Manual of Mental Disorders

High WM class was associated with significantly lower ratings (all p-values < .05) across all CSI-4 and TRF Teacher subscales. Differences among latent classes across all subscales of the TRF and CSI were associated with large effect sizes (ds = 0.80–1.71), with the exception of the Hyperactive/Impulsive subscale of the TRF ($d = 0.74$) which was associated with a medium to large magnitude effect size (Cohen 1992). Similar to the parent ratings, no significant differences emerged (all p-values > .05) between the Low and Moderate WM classes on the CSI-4 Subscales and the TRF subscales (ds = 0.06–0.44). In essence, there were significant medium to large magnitude differences in parent and teacher perceptions of inattentive and hyperactive behavior between individuals in the Low and High WM classes as well as between the Moderate and High WM classes across multiple rating scales. There were small to medium differences in teachers' perceptions between the Low and Moderate WM classes with respect to the inattentive subscales of the TRF and CSI; however, no significant teacher rated differences for the hyperactivity subscales emerged for the two worse performing WM classes. In contrast, there were small nonsignificant differences in parent perceptions between the Low and Moderate WM classes for the hyperactivity and combined subscales of the CSI.

Distribution of Diagnostic Status across Latent Classes

The distribution of individuals comprising the two diagnostic groups (ADHD and TD) across varying levels of WM was also examined. Overall, the contingency tables indicated that assignment to WM class was related to diagnosis, $\chi^2(2) = 58.05$, $p < .001$, wherein 94.8% and 5.2% of the Low WM class was comprised of individuals from the ADHD and TD groups, respectively. In contrast, 71.5% and 28.5% of the Moderate WM class was comprised of children from the ADHD and TD groups, respectively. Finally, the High WM class was comprised primarily of TD children (78.6%) relative to the ADHD (21.4%) group. Collectively, the results reveal that the majority of children (84%) with ADHD exhibited low (35%) or moderate (49%) WM performance while nearly all children in the TD group (98%) exhibited moderate (26%) or high (72%) WM performance.

Discussion

Heterogeneity in WM performance of children with ADHD likely reflects the contribution of multiple neuropsychological pathways to the disorder (Castellanos and Tannock 2002; Nigg and Casey 2005; Sonuga-Barke 2002). Consistent evidence for heterogeneity in WM functioning in ADHD (Fair et al. 2012; Kofler et al. 2019; Willcutt et al. 2005) highlights the need to adopt novel analytic approaches such as latent profile analysis to account for individual differences in neurocognitive functioning and clarify the role of children's WM abilities in parent- and teacher-rated symptoms of the disorder (i.e., inattention, hyperactivity, and impulsivity) as well as diagnostic status. The current study demonstrates that WM performance in children with and without ADHD is more nuanced than traditionally thought (e.g., impaired versus not impaired). Specifically, the ability to manipulate, store, rehearse, and recall increasingly greater numbers of stimuli until capacity limitations are reached, at which point performance stabilized or decreases (Cowan 2001), may exhibit greater variability than previously suspected in clinical and nonclinical populations. As such, further investigation into these varying levels of WM performance (e.g., low, moderate, high) is warranted and is likely to significantly advance this domain of inquiry. The High WM class, on average, did not evince decrements in accuracy to recall rearranged stimuli. In contrast, the Moderate WM class evinced worse performance relative to the High WM class across both phonological and visuospatial WM tasks for all set sizes. Children in the Low WM class displayed consistently worse performance relative to the two other classes, regardless of the cognitive burden across both phonological and visuospatial tasks. Therefore, the Low and Moderate WM classes exhibited poorer performance relative to the High WM class with the Low WM class demonstrating the worse performance relative to the other two groups.

The current study is the first to utilize latent profile analysis to examine subgroups of WM across distinct WM domains in children with and without ADHD, and to elucidate the association between WM and parent and teacher-rated ADHD symptoms regardless of diagnoses. Consistent with Gomez and colleagues (2014), this study replicated three classes of WM—High, Moderate, and Low, with similar distributions of children with ADHD within the Low and Moderate WM classes. The finding that poor WM performance was not exclusive to children diagnosed with ADHD were consistent with previous studies that have found impaired WM in typically developing populations (Cowan 2014; Fair et al. 2012). Further, despite the overlap in WM performance between the ADHD and TD groups, the poorest performing WM group consisted nearly exclusively of children with a diagnosis of ADHD. Twenty-nine percent of the Moderate WM class was comprised of TD children, which is consistent with past evidence of nested heterogeneity in cognitive performance in children with and without ADHD. The class groupings revealed a subset of children without ADHD that evince poor WM performance; however, children with ADHD exhibited, overall, the weakest WM performance. Such groupings support the notion that WM occurs on a spectrum such that WM in typically developing children and children with ADHD represent extremes along the same continuum with some overlap.

The best fitting model did not indicate a difference in change in performance across set sizes between modalities, indicating that capacity limitations were not specific to modality (e.g., visual, phonological). These findings suggest that poor performance in one modality may be closely associated with poor performance in the other modality. Specifically, ADHD may be characterized by difficulty in both visuospatial and phonological storage/rehearsal processes. Alternatively, given that both tasks involve central executive processes, it is also plausible that poor functioning of the central executive may be contributing to poor performance across both tasks. An overall WM deficiency linked to central executive dysfunction is consistent with investigations that suggest that poor WM performance is associated with a central executive deficit (Alderson et al. 2013a, 2013b; Dovis et al. 2013; Raiker et al. 2012; Rapport et al. 2008).

A second purpose of the current investigation was to examine the relationship between latent profiles of WM and symptoms of ADHD. Consistent with past findings (Alloway et al. 2009; Brocki et al. 2010; Gathercole et al. 2008), the current study found that children with deficits in WM were characterized by elevated parent/teacher-rated symptoms of inattention and hyperactivity/impulsivity. The Low and Moderate WM were not significantly different from each other in terms of symptom T-scores for all subscales except for the Attention Problems of the CBCL, for which the Low WM class had significantly higher ratings. Across all of the subscales, the Low and Moderate WM classes had significantly higher ratings of inattention and hyperactivity relative to the High WM class. Collectively, these findings suggest that any impairment in WM is associated with greater perceived levels of inattentive and hyperactive behavior by parent and teachers relative to no WM impairment (Friedman and Miyake 2004; Kofler et al. 2010; Poole and Kane 2009; Unsworth and Engle 2007). Moreover, there was no difference in behavioral ratings between the WM classes comprised of children exhibiting the poorest performance, indicating that, while WM may be dimensional in nature, there may not be an absolute correspondence between WM and severity of behavioral symptoms. Specifically, children with moderate WM may exhibit similar behavioral symptoms as those with low WM, but there are additional factors that determine whether a child with moderate WM will meet criteria for a diagnosis of ADHD.

The higher parent- and teacher-rated symptoms of hyperactivity in the classes with worse WM performance is consistent with prior studies demonstrating a robust relation between WM and objectively measured impulsivity (Raiker et al. 2012) and hyperactivity (Kofler et al. 2016; Rapport et al. 2009; Sarver et al. 2015). While any degree of WM difficulties was associated with greater hyperactive and inattentive symptoms, the greatest level of WM difficulties, as reflected by membership in the Low WM class, was associated with even greater levels of inattentive behavior. This finding is consistent with prior work demonstrating a stronger association of WM with inattentive symptoms than with hyperactive symptoms (Brocki et al. 2010), yet only one of the inattentive subscales across both parent and teaching ratings was significantly different between the groups, indicating that this association may be highly dependent on the rating scale utilized.

A novelty of the current study is the examination of WM distributions across individuals meeting diagnostic criteria for ADHD and TD children who do not meet criteria for ADHD simultaneously to inform understanding of potential nested heterogeneity (Fair et al. 2012). Results revealed that the ADHD group exhibited mostly low to moderate WM (84%) performance. In contrast, more than a quarter (29%) of children in the TD group exhibited low to moderate WM performance. This finding replicates previous work highlighting heterogeneity in neurocognitive dysfunction across typically developing samples (e.g., Costa Dias et al. 2015; Fair et al. 2012) and indicates that children with the most severe impairment in WM may be more readily identifiable and at greater risk for meeting diagnostic criteria for ADHD (Kane et al. 2001). The current findings are consistent with studies that have identified heterogeneity in WM performance (e.g., Bunford et al. 2015) as well as studies demonstrating that both inattentive and hyperactive symptoms are associated with working memory performance (Kofler et al. 2010; Kofler et al. 2015; Patros et al. 2017). Specifically, WM performance was associated with both inattentive and hyperactive domains such that severity of symptoms was associated with latent WM class membership. The finding that children assigned to the Moderate and Low WM classes exhibited similar levels of ADHD symptoms suggests that it may be more difficult to differentiate among children with low to moderate WM based solely on parent/teacher symptom ratings consistent with the nonpathognomonic nature of symptoms of ADHD (e.g., inattention; Wanmaker et al. 2014).

Despite the use of a well-characterized sample, a novel analytic approach (i.e., latent profile analysis), and cognitive tasks derived from a well-established theoretical model of WM, the current study findings should be interpreted with caution. The study utilized a relatively modest sample size; however, the incorporation of multiple indicators (i.e., eight) with strong psychometric properties and construct validity as well as the identification of multiple classes with well-defined separation suggests the study was adequately powered to detect subgroups (Dziak et al. 2014; Muthén and Muthén 2002; Wurpts and Geiser 2014). Additionally, given that the tasks utilized in the current study did not require cross-modality binding of information, the current study did not address the potential role of the episodic buffer. Future work may benefit from the inclusion of an older sample as well as WM tasks that require the use of the episodic buffer. In terms of sample composition, the current study excluded children with diagnoses other than ADHD (e.g. anxiety, autism, and depression) without comorbid ADHD yet included children that met diagnoses for ADHD as well as additional diagnoses. Considering that symptoms of inattention and hyperactivity are nonpathognomonic to ADHD and are often reported in individuals with other clinical disorders (e.g., anxiety, autism spectrum disorder; Dawson et al. 2002; Griffith et al. 1999;

Wanmaker et al. 2014), dimensional approaches to the evaluation of WM performance across muliple disorders may help elucidate further the relationship between WM and ADHD symptoms. Such an approach is consistent with the research-based framework outlined by the Research Domain Criteria (RDoC; Insel et al. 2010). Further, given that the average IQ score of the ADHD group did not differ significantly from that of the typically developing group, the current ADHD sample may represent a group of children with higher than average IQ compared to ADHD samples used in prior studies (Frazier et al. 2004). As a result, considering the high correlation between IQ and WM (Kane et al. 2005), the sample may have limited the number of children with severely impaired WM. Finally, given the low proportion of children with ADHD in the current sample who also met criteria for a comorbid disorder, future studies employing more representative samples are necessary to examine the extent to which the current findings generalize to complex cases of ADHD.

Collectively, the current findings extend prior literature on WM deficits in ADHD (Gomez et al. 2014; Martinussen et al. 2005; Pennington and Ozonoff 1996; Willcutt et al. 2005) by examining the heterogeneity of WM dysfunction across varying cognitive load and its association with parent/teacher rated behavioral ADHD symptoms. The results demonstrate that parent/teacher rated ADHD symptoms are more easily detectable when comparing children with strong WM ability to children with poor WM ability; however, more nuanced consideration may be necessary when considering children with more moderate WM abilities. Notably, these findings indicate that poor WM performance is not unique to ADHD but are also observed in children without the disorder, consistent with evidence that ADHD reflects a quantitative rather than qualitative developmental difference in brain maturation over the course of development (Shaw et al. 2007). Future work should evaluate the extent to which intact functioning in specific WM domains (i.e., phonological storage/rehearsal, visuospatial storage/rehearsal, and central executive) exerts a protective effect with respect to symptom presentation or across other areas of functional impairment (e.g., social functioning, academic performance). Additionally, employing similar approaches with other neurocognitive functions, as well as objective assessments, is also recommended to provide a better understanding of the relation between executive functioning and ADHD symptoms. Finally, the field may benefit significantly from studies examining the development of executive functions in tandem with fluctuations of ADHD symptoms across development. Such studies would elucidate the correspondence between changes in WM subcomponents and ADHD symptoms, as well as the utility of the integration of WM assessment into the examination of secondary deficits associated with ADHD such as impaired social, occupational, and academic functioning.

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Compliance with Ethical Standards

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Ethical Approval This research was approved by the Institution's Ethics Board. 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 parental consent and child assent (for children under age 18 years) was obtained from all individual participants included in the study.

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