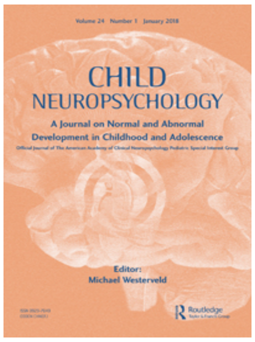

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Application of the dual-component model of working memory to ADHD:Greater secondary memory deficit despite confounded cognitive differences

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ABSTRACT

The dual-component model postulates that working memory capacity consists of two dissociable components: maintenance in primary memory (PM) and retrieval from secondary memory (SM). Recent application of this model to attention-deficit/hyperactivity disorder (ADHD) has revealed that the SM component is more deficient than the PM component across both verbal and spatial modalities. The present study attempts to strengthen this conclusion by addressing two weaknesses in the previous study. First, the present study shows that the SM component continues to be more deficient than the PM component across both modalities under conditions in which (1) all participants were instructed to use the same recall strategy (resulting in the exclusion of fewer participants); and, (2) individual differences in this strategy were controlled. Second, the present study also documents a group difference in word reading efficiency that is confounded with diagnostic status and that might have influenced estimates of PM and SM capacities in the verbal modality. However, although the SM component is more deficient than the PM component in the ADHD group, the magnitude of this interaction does not vary as a function task modality. These findings are interpreted to suggest that the pattern of WM deficiencies observed are part of a causal pathway that can lead to the symptoms of ADHD, as well as to impairments in reading (and intelligence) due to overlapping cue-dependent retrieval mechanisms. These findings provide additional support for the notion that the SM component of WM is an important and neglected target for treatment.

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Attention-deficit/hyperactivity disorder (ADHD) is a prevalent neurodevelopmental disorder that begins in childhood and often persists into adulthood (Barkley, 2015). A common research strategy used to reveal dysfunctional mental processes in ADHD is to compare performance on a challenge task between groups of individuals who either have or have not satisfied diagnostic criteria for ADHD (for a review, see Nigg, 2006). When group differences are detected, they often reveal deficient performance in the ADHD group relative to the control group. Furthermore, when the challenge task probes a basic cognitive process, group differences are often interpreted as reflecting

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a neurocognitive dysfunction that mediates the pathway between initial causes and the core symptoms of ADHD.

Identifying these neurocognitive dysfunctions is important because front-line treatments are often developed to target these deficient mechanisms (Cortese et al., 2015). For instance, contemporary models of ADHD consider working memory (WM) to be a core neurocognitive mechanism that mediates at least one major pathway between the initial causes and core symptoms of ADHD (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010; Raiker, Rapport, Kofler, & Sarver, 2012; Rapport et al., 2008, 2009; for meta-analytic reviews, see Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Accordingly, there has been great interest in the possibility that WM may serve as a therapeutic target for ADHD. Of particular interest is the possibility that adaptive WM training may serve as a non-pharmacological treatment for the core symptoms of ADHD. Unfortunately, several recent meta-analyses have tempered enthusiasm for this approach by concluding that adaptive WM training appears to have very little positive impact on the core symptoms of ADHD (Cortese et al., 2015; Rapport, Orban, Kofler, & Friedman, 2013; Shipstead, Hicks, & Engle, 2012; Sonuga-Barke et al., 2013).

One mitigating issue that may explain the relatively weak efficacy of existing WM training regimens is that the aspects of WM that are deficient in ADHD may not be the same mechanisms that are targeted by adaptive WM training regimens. Indeed, Gibson and his colleagues came to precisely this conclusion when they utilized the dual-component theory of WM to analyze the components of WM that are deficient in ADHD and enhanced by adaptive WM training (Gibson et al., 2011; Gibson, Gondoli, Flies, Dobrzenski, & Unsworth, 2010). The dual-component model specifies two basic functions of WM (Unsworth, Brewer, & Spillers, 2009; Unsworth & Engle, 2007a, 2007b; Unsworth & Spillers, 2010; Unsworth, Spillers, & Brewer, 2010): (1) the active maintenance of a limited amount of novel information in primary memory (PM), particularly in the presence of internal and external distraction; and (2) the retrieval of goal-relevant information from episodic long-term memory—or secondary memory (SM)—after that information has been lost from PM due to failures of active maintenance and/or storage limitations (for further developments of this model, see Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014).

With respect to ADHD, Gibson et al. (2010) showed that the maintenance of information in PM appeared to be largely intact whereas the retrieval of information from SM appeared to be deficient in middle-school children with ADHD relative to age-matched children without ADHD. For instance, in the verbal modality, estimates revealed that the ADHD and non-ADHD groups both recalled an equal number of items from PM, but a different number of items from SM. Likewise, in the spatial modality, estimates revealed that the capacity difference observed between the ADHD and non-ADHD groups was significantly smaller for PM than it was for SM, but the capacity difference observed between the ADHD and non-ADHD groups was significant for both PM and SM. These significant component type × group interactions are interpreted as suggesting that ADHD symptoms arise primarily because middle-school children with ADHD are less likely to retrieve goal-relevant information from SM after it has been lost from PM. Furthermore, by providing a clearer understanding of the WM mechanisms that are deficient in ADHD, these findings also identify a potentially novel target for WM training.

With respect to WM training, Gibson et al. (2011) next examined the extent to which the PM and SM components of WM can be enhanced by the well-known and widely-used adaptive training regimen known as Cogmed-RM. Surprisingly, the main findings showed that Cogmed-RM significantly enhanced the maintenance of information in PM in both verbal and spatial modalities, but did not have a significant effect on the recall of information from SM. These findings are therefore interpreted as suggesting that Cogmed-RM is not optimally designed for the treatment of ADHD because the component of WM that is deficient in ADHD (i.e., the SM component) is different from the component of WM that is targeted by Cogmed-RM (i.e., the PM component).

The discovery of a mismatch between the component of WM that is deficient in ADHD and the one that is enhanced by Cogmed-RM is potentially important because it may help explain the relatively weak efficacy of existing WM training regimens. In addition, these findings have also guided the development of a novel training regimen that is capable of targeting and enhancing the SM component of WM as well as the PM component (Gibson et al., 2012, 2013), though the extent to which this modified training regimen can improve the core symptoms of ADHD has not yet been tested. However, Gibson et al. (2010) identified two weaknesses in their initial group difference study that should be addressed before extensive resources are invested in a training study.

The first weakness concerns the relatively high exclusion rate (approximately 50%) that Gibson et al. (2010) experienced based on an evaluation of the "recall initiation strategies" that were used during the performance of verbal and spatial immediate free recall (IFR) tasks. Recall-initiation strategies reflect the extent to which an individual tends to begin recall from the end or the beginning of the memory list, thereby reflecting either a "recency" or "primacy" recall strategy, respectively. Controlling for these different recall strategies is important because they can influence the relative number of items that an individual recalls from PM and SM (Unsworth, Brewer, & Spillers, 2011). Of particular concern is the use of a primacy recall strategy because it can cause estimates of SM capacity to be inflated and estimates of PM capacity to be deflated to zero (see the method section for details on how estimates of PM and SM are derived). Because the corresponding estimates of PM and SM may be more sensible when recall is based on a recency recall strategy (Unsworth & Engle, 2007a), Gibson et al. based their analyses on only those participants who used this strategy.

Although the discarded participants in Gibson et al.'s (2010) study were equally distributed across the ADHD and control groups, confidence in their results could be strengthened by showing that the same pattern of group differences can be obtained when fewer participants are excluded based on their recall strategy. Accordingly, use of the proper recency recall strategy was experimentally controlled by explicit instructions in the present study (see below for further detail). It was expected that if the findings reported by Gibson et al. could be replicated under these conditions, larger group differences would be found in SM capacity than in PM capacity in the present study.

The second weakness of Gibson et al.'s (2010) study concerns the possibility that the component type × group interaction—signifying a greater deficit in SM capacity than PM capacity—was influenced by other group differences that were confounded with diagnostic status (ADHD vs. control). Of particular concern is the possibility that undocumented reading deficiencies in the ADHD group may have impacted on the participants' memory for words in the verbal IFR task, and perhaps even their memory for spatial locations in the spatial IFR task. Indeed, studies have documented higher than chance rates of comorbidity of reading disability and ADHD ranging from 20% to 50%, suggesting that these two disorders may share common mechanisms (Fawcett & Nicolson, 2001; Fletcher, Shaywitz, & Shaywitz, 1999; Willcutt, Pennington, & DeFries, 2000). Moreover, individuals with ADHD often have difficulty reading words efficiently regardless of whether they have a formal diagnosis of reading disability or not (Ghelani, Sidhu, Jain, & Tannock, 2004). Accordingly, the present study includes measures of phonemic decoding efficiency and sight reading efficiency to assess the magnitude of these potential group differences. Word reading efficiency is emphasized over reading comprehension in the present study because the verbal IFR task requires participants to encode a list of unrelated words, at a rate of one word per second, but does not require them to understand the meaning of the words.

The proper treatment of group differences in cognitive abilities such as word reading efficiency or IQ that may be confounded with diagnostic status is a vexing issue in psychopathology research because there is no easy way to eliminate these differences from the interpretation of the observed effects. For instance, these confounded differences cannot be eliminated experimentally because individuals cannot be assigned to different diagnostic groups randomly; furthermore, matching participants on the basis of the confounded cognitive abilities often leads to non-representative groups of ADHD and non-ADHD individuals. Perhaps more importantly for present purposes, these confounded differences cannot be eliminated statistically because there is no statistical method that can address the question of whether ADHD and control groups that differ in word reading efficiency and/or IQ would differ in PM capacity and/or SM capacity if they did not differ in word reading efficiency and/or IQ (Miller & Chapman, 2001; see also Dennis et al., 2009). Although this latter solution is often attempted, it is simply not appropriate: removing the covariance of the confounded differences from the dependent variable when the covariates are also related to diagnostic status results in a biased adjustment "because some effects attributed to the treatment [i.e., diagnostic status] are eliminated from the dependent variable" (Wildt & Ahtola, 1978, p. 15; see also, Dennis et al., 2009; Miller & Chapman, 2001). For these reasons, although the potential group differences in word reading efficiency and IQ are measured in the present study, no attempt was made to remove the covariance associated with these cognitive abilities from the estimates of PM capacity and SM capacity.

Instead, the opposite track was chosen; that is, the goal was to measure the extent to which confounded differences in word reading efficiency might have inflated (or altered) the observed interaction between diagnostic status and the components of WM capacity. More specifically, it is reasonable to expect that individual differences in word reading efficiency might be more highly related to estimates of WM in the verbal modality than in the spatial modality (Swanson, Zheng, & Jerman, 2009). Such a finding would be potentially important because it would suggest that the confounded group differences are stronger in the verbal modality than in the spatial modality, which in turn could alter the shape of the critical component type × group interaction across the two modalities. Conversely, if the shape of the critical component type × group interaction remains similar across the two modalities then one can be more confident that the observed pattern of findings is correctly attributed to diagnostic status rather than being an effect of word reading efficiency.

As mentioned above, Gibson et al. (2010) observed similar component type × group interactions across both verbal and spatial modalities, although they could not directly compare the extent to which these interactions differed as a function of modality because only a small subset of participants used the appropriate recency recall strategy across both the verbal and spatial IFR tasks (for details, see Gibson et al., 2010, footnote 2). Although it was also expected that some participants would use the recency recall strategy in only one IFR task in the present study, it was also expected that more participants would use the appropriate strategy across both IFR tasks, thus enabling a direct evaluation of the task modality × component type × group interaction.

In summary, the present study was conducted to address two weaknesses of Gibson et al.'s (2010) study. First, the present study examines the extent to which the findings reported by Gibson et al. can be replicated when the recall initiation strategy is tightly controlled and fewer participants are excluded based on this criterion. Second, the present study also examines the extent to which the pattern of group differences are dependent on other group differences in word reading efficiency.

Method

Recruitment of Participants

Following the procedure used by Gibson et al. (2010), children between the ages of 11 and 15 years were recruited from three middle schools (grades 6 to 8) in a mid-western public school district. Initial contact letters briefly describing the study were provided to school officials, who then mailed the letters to the caregivers of all the schoolchildren in the district (approximately 2500 households). The letter emphasized the researchers' interest in understanding WM in children diagnosed with ADHD but also pointed out that this understanding can only be adequately achieved by studying the development of WM in children of all abilities. A total of 109 families responded to this initial contact letter; the primary caregiver was then scheduled for a structured interview and their child was scheduled for cognitive testing. The structured interview and the cognitive testing occurred during the same 2-hour appointment. The primary caregiver and his or her child began this 2-hour session by providing informed consent and assent, respectively, in a laboratory located in the Psychology Department at the University of Notre Dame. The protocol for the present study was approved by the institutional review board at the University of Notre Dame.

ADHD Measures

Following Gibson et al.'s (2010) study, primary caregivers were interviewed using the National Institute of Mental Health Computerized Diagnostic Interview Schedule for Children, Version 4 (NIMH C-DISC-IV; Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000). The NIMH C-DISC-IV is an automated, standardized interview that is designed to be used in research settings and does not require a clinical license or advanced degree to administer. In the present study, the interview was administered by MA- or PhD-level researchers, all of whom had at least 24 hours of experience prior to this study. The NIMH C-DISC-IV was used to verify the presence vs. absence of *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-IV*; American Psychiatric Association, 1994) criteria in each child, and the routine scoring algorithms were used to generate a discrete diagnosis of ADHD, as well as the number of behavioral symptoms and the amount of impairment. The discrete diagnosis is used as an indicator of diagnostic group status in the main analyses; however, as discussed in the results below, a continuous variable called the "CDISC" based on the numerical symptom and impairment scores was also created. The CDISC is a composite variable that reflects the average of the standardized symptom and impairment scores. Shaffer et al. (2000) have reported that the test–retest reliability of the NIMH-C-DISC-IV for ADHD is .79 within a clinical sample. In addition, a variety of other, potentially comorbid, psychiatric conditions including anxiety, depression, and oppositional defiant disorder (ODD) were also examined. If relevant, the primary caregiver provided details about their child's treatment plan during this session. The type, time and dosage of all medications were documented using a questionnaire.

In addition, two other measures of ADHD symptoms were obtained to supplement the NIMH-C-DISC-IV. Each caregiver also completed the home version of the DuPaul ADHD Rating Scale (DuPaul, Power, Anastopoulos, & Reid, 1998), and the school version of the DuPaul ADHD rating scale was sent via mail to one of the child's teachers (identified during the initial phone contact). Caregivers and teachers described the child's behavior at home and school, respectively, by rating each of the 18 *DSM-IV* ADHD symptoms on a scale from 0 to 3, where 0 = *never or rarely*, 1 = *sometimes*, 2 = *often*, and 3 = *very often*. Caregiver and teacher ratings were tallied across the inattentive and hyperactive/impulsive symptom domains. Both of these rating scales have been widely used to measure the number and severity of ADHD symptoms, and the psychometric properties of this measure appear to be adequate, as demonstrated by good internal reliability coefficients, high test–retest reliability, and effective discriminatory power (DuPaul et al., 1998). The total symptom scores ranged from 0 to 54 on each version.

Cognitive Measures

Each participant was administered the Wechsler Abbreviated Scale of Intelligence (WASI; The Psychological Corporation, 1999), a spatial IFR task, a verbal IFR task, and the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). The order of these tasks was counterbalanced across participants. The verbal and spatial IFR tasks were the primary outcome measures in the present study, while the WASI and the TOWRE were used to measure other important cognitive abilities that might be confounded with diagnostic status. Note that caregivers were instructed to withhold any ADHD medication (simulant or non-stimulant) for at least 24 hours prior to any cognitive testing (see the results section for a more detailed description of the types of medication that were withheld).

PM and SM capacities were estimated using the same spatial and verbal IFR tasks as used by Gibson et al. (2010). In the spatial IFR task, participants were presented with 15 trials consisting of 12 different locations marked by white squares that were presented against the black background of a standard cathode ray tube (CRT) monitor. The locations were cued by temporarily changing the color of a square from white to red. Each of the 12 locations in each trial was cued in consecutive order for 1 second, with a 1-second delay in between locations. The squares appeared in any one of 180 (15 trials × 12 locations) unique screen locations. Each location was cued only once across the 15 different trials. To make the task manageable, only 36 of the possible 180 squares appeared at any one time. These 36 squares were selected randomly from the set of 180 possible locations and they remained visible for three consecutive trials (3 trials × 12 cued locations = 36 locations). At the conclusion of the third trial in each set, a new set of 36 locations was randomly selected from the 180 possible locations without replacement. This sequence of 3 trials repeated five times for a total of 15 trials. The five sets of 36 randomly-selected squares were determined separately for each participant. The experimental trials were preceded by 3 practice trials. Each trial was initiated by the administrator after the participant signaled his or her readiness.

At the conclusion of each trial, participants were prompted to use the computer mouse to recall as many locations as possible by clicking on the relevant locations. Because PM capacity and SM capacity can be influenced by participants' order-of-report strategy, participants were told that they could recall the locations in any order, with the sole constraint that they should begin recalling locations from the end of the list first (see Gibson et al., 2011). These instructions tend to induce a recency strategy, which is optimal for estimating the two capacities, and for ensuring that the estimates are based on the same strategy across participants (Craik & Birtwistle, 1971; and see below for details about how this strategy was verified). Participants were given 30 seconds to recall the lists and they were required to wait the full 30 seconds before proceeding to the next trial. This mandatory 30-second recall period ensured that participants could not prematurely terminate their recall in the event that they found the delay imposed by the recall period aversive (Sonuga-Barke, 2003).

In the verbal task, participants were presented with 15 lists of 12 unique high-frequency words that were randomly combined. All words were printed in a 20-point font and appeared white against the black background of a standard CRT monitor. Each word was presented consecutively for 1 second in the middle of the computer screen with a 1-second delay in between words. Following the presentation of a single list, question marks appeared in the center of the screen, prompting a response from the participant. As in the spatial IFR task, participants were told that they could recall the words in any order, with the sole constraint that they should begin recalling words from the end of the list first. In addition, participants were given 30 seconds to recall the lists, and they were required to wait the full 30 seconds before proceeding to the next trial. Participants reported their answers into a microphone, which was connected to a standard cassette recorder. As with the spatial task, 3 practice trials using letter stimuli (instead of words) preceded the test trials. The word lists were presented in the same random order to all participants.

The order and number of correct and incorrect recall responses were recorded for each participant on both the verbal and spatial IFR tasks separately. A response was scored correct if it matched one of the list items. In the verbal IFR task, a response was also scored as correct if it was a plural version of a singular list item ("boards" instead of "board" or vice versa), or if it was a past-tense version of a present-tense list item ("shot" instead of "shoot" or vice versa).

The extent to which participants used the recency order-of-report strategy was formally assessed within each IFR task separately. Two criteria were used to assess strategy (Unsworth et al., 2011), and participants were only included if they met at least one of the two criteria. First, probability-of-first-recall functions were generated for each participant from each of the verbal and spatial IFR tasks and then evaluated separately. Probability of first recall refers to the number of times the item presented at each serial position was reported *first* divided by the total number of trials. Probability-of-first-recall responses were averaged across the first three serial positions (i.e., the primacy positions) and across the last three serial positions (i.e., the recency positions). Participants were classified as having used a recency strategy if the difference between the average recency and primacy responses was .10 or greater (Unsworth et al., 2011, footnote 1). Second, serial position functions, reflecting probability correct responses at each of the 12 serial positions, were also generated for each participant from each of the verbal and spatial IFR tasks and then evaluated separately. Probability correct responses were averaged across the first three serial positions and the last three serial positions. Participants were classified as having used a recency strategy if the difference between the average recency and primacy responses was .10 or greater (Unsworth et al., 2011, footnote 1).

Following Gibson et al. (2010), Tulving and Colotla's (1970) method was used to provide estimates of the number of items that can be recalled from PM and SM. According to Tulving and Colotla, estimates of PM and SM must take into consideration both input and output interference; the greater the amount of interference preceding the recall of an item, the more likely it is that the item was recalled from SM as opposed to PM. Following this method, the number of items between a given item's presentation and its recall were tallied. If 7 or fewer items intervened between the presentation and recall of a given item, the item was considered to have been recalled from PM. If more than 7 items intervened between presentation and recall, the item was considered to have been recalled from SM.

For instance, suppose a participant receives a 12-item list of A, B, C, D, E, F, G, H, I, J, K, and L. Furthermore, suppose this participant then recalls L, K, I, G, D, and H in that order. In this example, three items were recalled from PM: L (0 items intervened between input and output), K (2 items intervened), and I (5 items intervened), while the remaining three items were recalled from SM: G (8 items intervened between input and output), D (12 items intervened), and H (9 items intervened). The number of items recalled from PM and SM was then averaged across the 15 lists. Although the threshold for PM was set at 7 intervening items, this method tends to produce estimates of PM capacity that are less than 4 items because input and output interference are given equal weight, thus making it consistent with modern estimates of PM capacity (Cowan, 2001; Shipstead et al., 2014). Prior work has suggested that this method provides reliable and valid estimates of PM and SM (Craik & Birtwistle, 1971; Unsworth & Engle, 2007a; Unsworth et al., 2010; Watkins, 1974).

The WASI was administered to obtain a general measure of cognitive functioning and consists of two verbal subtests (Vocabulary and Similarities) and the two performance subtests (Block Design and Matrix Reasoning). Using the same inclusion criteria as Gibson et al. (2010), a full-scale IQ (FSIQ) of 70 of above was required for inclusion in the study.

The TOWRE was administered to assess word reading efficiency (Torgesen et al., 1999). The TOWRE consists of two subtests. The first is the Sight Word Efficiency (SWE) subtest, which measures the number of real words that can be read by sight in 45 seconds. The second is the Phonemic Decoding Efficiency (PDE) subtest, which measures the number of non-words that can be correctly pronounced in 45 seconds. As per the instruction manual, the SWE subtest was administered before the PDE subtest, and each participant performed the two versions of the first subtest in consecutive fashion before performing the two versions of the second subtest. The SWE and PDE scores consist of the number of items correctly read or pronounced on each subtest in the allotted time, which are then averaged across both versions of each subtest. Because the SWE and PDE are highly correlated in the present study (r = .85), a composite "Word Reading Efficiency" (WRE) variable was created by averaging the standardized SWE and PDE scores.

Results

Of the 109 participants who responded to the initial contact letter, one participant was excluded because of an FSIQ of less than 70 (a total of 3 participants in the ADHD group had FSIQs less than 80), and 8 participants who were currently taking ADHD medication were excluded because they failed to meet the formal diagnostic criteria for ADHD. Of the remaining 100 participants, 48 had confirmed diagnoses of ADHD and 52 did not. In addition, 19 children in the ADHD group had a diagnosis of ODD compared to only 1 child in the control group; the relatively high incidence of comorbid ODD in the ADHD group is consistent with previous estimates (Barkley, 2015). The incidences of comorbid anxiety (n = 2 vs. n = 1, respectively) and major depression (n = 1 vs. n = 0, respectively) were low and approximately equal across the two groups.

A total of 32 of the 48 participants in the ADHD group were being treated with stimulant ADHD medication at the time of the study (dexmethylphenidate, lisdexamfetamine, methylphenidate, and/or mixed amphetamine salts), while 5 were being treated with non-stimulant ADHD medication (atomoxetine, guanfacine) and 1 was being treated with non-ADHD medication (bupropion). All ADHD medication was withheld for at least 24 hours prior to testing. The remaining 10 participants in the ADHD group and all of the participants in the control group reported no current medication use.

Of these 100 participants, the verbal recall responses from 8 participants (6 from the ADHD group) could not be recovered from the tape recorders; consequently, these participants were excluded from the final analyses. The vast majority of the remaining 92 participants were able to follow the instructions to use a recency recall strategy. In fact, only 5 participants (3 from the ADHD group) were unable to comply with these instructions across both IFR tasks. There were 9 other participants who were able to comply with these instructions for one task but not the other: 4 participants (2 from the ADHD group) were able to use a recency recall strategy in the spatial IFR task but not in the verbal IFR task, and 5 participants (4 from the ADHD group) were able to use a recency recall strategy in the verbal IFR task but not in the spatial IFR task. Altogether, 9 participants in the ADHD group (21%) 5 participants in the control group (10%) were unable to fully comply with the instructions to use a recency recall strategy across both IFR tasks. Finally, 1 participant in the ADHD group who met all the inclusion criteria was eliminated from the final analyses because her spatial SM score was 3 *SD*s above the overall mean.

Thus, included in the analyses are a total of 32 participants in the ADHD group (42 minus the 10 excluded; 24 males) and 45 participants in the control group (50 minus the 5 excluded; 15 males). The number of males and females is significantly different across the two diagnostic groups, $\chi^2(1) = 11.82$, $p < .001$; however, this difference is ignored because the preliminary analyses revealed no significant main effect or interactions when gender was included as an additional between-groups factor.

Group Characteristics

The group characteristics of the 77 participants are listed in Table 1, including *t*-tests for group differences. As expected, there was no significant group difference in age. Also as expected, the scores on the CDISC, as well as on the home and school versions of the ADHD rating scales, are significantly higher in the ADHD group compared to the control group. The FSIQ and WRE scores are also significantly lower in the ADHD group. These differences are therefore confounded with the group difference in diagnostic status.

Preliminary Adjustment of PM and SM Based on Individual Differences in Modality-Specific Recency Recall Strategies

Inclusion in the present study required the use of an experimentally-induced recency recall strategy during performance of both IFR tasks. Despite this requirement, it was

Table 1. Descriptive Statistics for the Participants Who Met All Inclusion Criteria.

	ADHD (n = 32)		Control (n = 45)		*t*		
	M	*SE*	*M*	*SE*	*t*	*p*	*d*
Age	12.50	0.19	12.58	0.13	−0.35	.730	0.08
CDISC	1.04	0.07	−0.74	0.06	19.13	.000	4.47
HRS	27.56	1.86	4.13	1.09	11.52	.000	2.58
SRS*	17.48	2.10	3.56	0.80	6.81	.000	1.54
FSIQ	97.25	2.43	108.27	1.76	−3.77	.000	0.86
WRE	−0.57	0.16	0.40	0.12	−5.02	.000	1.14
VSOR	−0.09	0.15	0.07	0.12	−0.83	.410	0.19
SSOR	−0.14	0.16	0.10	0.13	−1.15	.250	0.26
VPM_{adj}	2.49	0.07	2.85	0.06	−4.06	.000	0.38
VSM_{adj}	0.99	0.11	1.79	0.12	−4.77	.000	1.12
SPM_{adj}	2.59	0.07	2.70	0.06	−1.24	.220	0.29
SSM_{adj}	2.30	0.13	2.89	0.13	−3.13	.003	0.73

Note. *Sample size for SRS is n = 31 (ADHD) and n = 41 (control). CDISC = average standardized symptom and impairment scores from the NIMH-C-DISC-IV; FSIQ = full-scale IQ; HRS = home version of the ADHD rating scale; NIMH-C-DISC-IV = National Institute of Mental Health Computerized Diagnostic Interview Schedule for Children, Version 4; SRS = school version of the ADHD rating scale; SPM_{adj} = estimate of spatial PM capacity adjusted by the SSOR; SSM_{adj} = estimate of spatial SM capacity adjusted by the SSOR; SSOR = spatial strength of recency; TOWRE = Test of Word Reading Efficiency; VPM_{adj} = estimate of verbal PM capacity adjusted by the VSOR; VSM_{adj} = estimate of verbal SM capacity adjusted by the VSOR; VSOR = verbal strength of recency; WRE = average standardized phonemic decoding efficiency and sight reading efficiency scores from the TOWRE.

also expected that participants would still differ in the extent to which they utilized this strategy within a modality, which in turn could influence the relative number of items recalled from PM and SM. Accounting for this variation could be beneficial in the group analysis of PM and SM because it could potentially reduce the magnitude of unexplained error variance, thereby increasing the sensitivity of the group difference analysis. In addition, as there was an expectation that the participants in the ADHD group would be more impaired in SM capacity than in PM capacity relative to the control group, it was also important to rule out the possibility that this pattern of group differences could be accounted for by lingering differences in the extent to which the two groups utilized this strategy.

In the present study, the extent to which the recency strategy was utilized by each individual is reflected by the magnitude of the difference between the average recency and primacy responses obtained in the probability of first response and accuracy measures within each task modality. In addition, because the same individual might differ in the extent to which he or she utilizes this strategy across modalities, this variable is derived separately for each modality. A composite "Verbal Strength of Recency" (VSOR) covariate was created by averaging the standardized difference scores obtained from each of the two measures within the verbal modality, and a composite "Spatial Strength of Recency" (SSOR) covariate was created by averaging the standardized difference scores obtained from each of the two measures within the spatial modality. In both cases, higher scores reflect a stronger recency strategy wherein the number of items recalled from PM is relatively high and the number recalled from SM is relatively low, while lower scores reflect a weaker recency strategy wherein the number of items recalled from PM is relatively low and the number recalled from SM is relatively high. As can be seen in Table 1, there are no significant group differences in VSOR or SSOR covariates—hence, their inclusion should increase power primarily by decreasing unexplained variance from the dependent variables.

The estimates of PM and SM capacity were adjusted by their corresponding VSOR and SSOR scores by first conducting two-way, mixed analyses of covariance (ANCOVAs) within each modality separately, with component type (PM vs. SM) as the within-subjects factor, group (ADHD vs. control) as the between-groups factor, and VSOR/SSOR as the covariate. Both the main effect of group and the critical component type × group interactions are significant in these two ANCOVAs. However, the details of these analyses are not reported now because they are redundant with the main analysis reported below, in which task modality is also included.

As expected, VSOR is positively related to verbal PM (r = .58, p < .001) and negatively related to verbal SM (r = −.38, p = .001). Likewise, the SSOR is positively related to spatial PM (r = .67, p < .001) and negatively related to spatial SM (r = −.41, p = .001). The component type × VSOR interaction is significant in the verbal modality, $F(1, 74) = 65.38$, $p < .0001$, $\eta_p^2 = .47$. This interaction reflects a positive relation between verbal PM capacity and VSOR (slope = 0.34 VSOR units) and a negative relation between verbal SM capacity and VSOR (slope = −0.45 VSOR units). Likewise, the component type × SSOR interaction is significant in the spatial modality, $F(1, 74) = 77.02$, $p < .0001$, $\eta_p^2 = .51$. This interaction also reflects a positive relation between spatial PM capacity and SSOR (slope = 0.40 SSOR units) and a negative relation between spatial SM capacity and SSOR (slope = −0.48 SSOR units).

In both cases, this interaction indicates that the number of items recalled from PM tended to exceed the number recalled from SM when a relatively *strong* recency strategy was utilized, whereas the opposite pattern tended to be observed when a relatively *weak* recency strategy was utilized.

The covariance associated with the VSOR and SSOR covariates was removed from corresponding estimates of PM capacity and SM capacity following Kirk (1982, p. 737). For instance, individual estimates of verbal PM capacity were adjusted by:

$$VPM_{adj} = VPM_{ij} - 0.34(VSOR_{ij} - \overline{VSOR}),$$

where VPM_{ij} is the PM capacity estimate for the individual i in group j, 0.34 is the weighted regression slope relating the VSOR covariate to PM capacity, $VSOR_{ij}$ is the VSOR score for the individual i in group j, and $\overline{VSOR}$ is the overall average of the VSOR covariate.

Comparison of the Verbal and Spatial IFR Tasks

A three-way, mixed analysis of variance (ANOVA) was conducted on the adjusted estimates of PM capacity and SM capacity, with task modality (verbal vs. spatial) and component type (PM vs. SM) as the within-subject factors and group (ADHD vs. control) as the between-groups factor. The adjusted mean estimates of PM and SM capacity are shown in Figure 1 as a function of task modality and group.

The mean number of items recalled from PM (M = 2.66, SE = 0.04) is significantly greater than the mean number recalled from SM (M = 1.99, SE = 0.07), $F(1, 75) = 95.81$, $p < .0001$, $\eta_p^2 = .56$, for the main effect of component type. There is also a significant main effect of group, $F(1, 75) = 16.27$, $p < .001$, $\eta_p^2 = .25$, indicating that the ADHD group (M = 2.09, SE = 0.07) recalled fewer items than the control group (M = 2.56, SE = 0.06).

Of greatest importance, the critical component type × group interaction is significant, $F(1, 75) = 11.33$, $p = .001$, $\eta_p^2 = .13$, suggesting that the group difference is larger

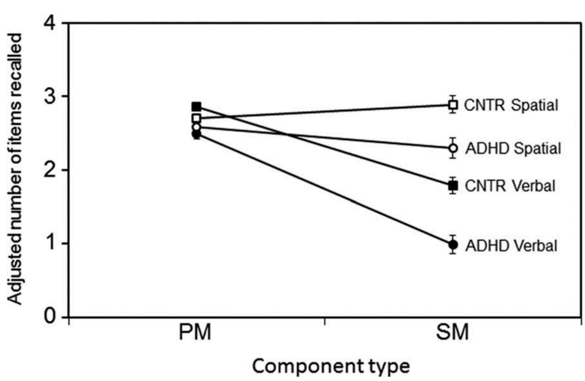

Figure 1. The mean number of items recalled from PM and SM (adjusted by modality-specific strength of recency scores) shown as a function of task modality and group.
Note. CNTR = control group. Error bars reflect standard errors of the mean.

when items are recalled from SM than when items are recalled from PM. However, subsequent analyses revealed that the ADHD group recalled significantly fewer items than the control group from both PM (ADHD: $M = 2.54$, $SE = 0.06$; control: $M = 2.78$, $SE = 0.05$), $F(1, 75) = 16.59$, $p < .001$, $\eta_p^2 = .17$, and SM (ADHD: $M = 1.64$, $SE = 0.10$; control: $M = 2.34$, $SE = 0.09$), $F(1, 75) = 18.33$, $p < .001$, $\eta_p^2 = .19$. As mentioned above, significant component type × group interactions were also obtained when each modality was analyzed separately; the sole deviation from the present conclusion is that the subsequent analyses revealed that the two groups recalled the same number of items from PM in the spatial modality (see Table 1 for specific pairwise comparisons within each modality).

The significant component type × group interaction corroborates the main findings reported by Gibson et al. (2010) and suggests that the SM component is more deficient than the PM component in children with ADHD. In addition, this analysis also shows that the observed differences in PM and SM reflect differences in capacity and cannot be attributed to differences in the extent to which the two groups utilized the recency recall strategy.

If the component type × group interaction reflects the confounded group difference in the WRE scores then the extent of that influence should be stronger in the verbal modality than in the spatial modality, assuming that ADHD and FSIQ influence PM capacity and SM capacity approximately equally across the two modalities. If these assumptions are correct then it would be expected that the correlations between the WRE scores and the two dependent variables are greater in the verbal modality than in the spatial modality; whereas, it was expected that the correlation between the CDISC scores (i.e., the continuous version of diagnostic status) and the two dependent variables, as well as the correlation between FSIQ and the two dependent variables, would be approximately equal across the two task modalities.

As shown in Table 2, the observed correlations are generally consistent with these expectations, though all the correlations tend to be numerically higher in the verbal modality than in the spatial modality. In order to evaluate the relative magnitude of these correlations as a function of task modality, tests of the difference between two dependent correlations were conducted (Steiger, 1980). With respect to the WRE scores, the pattern of correlations is consistent with expectations: the correlation

Table 2. Bivariate Correlations between the Dependent, Diagnostic, and Confounding Variables.

	1	2	3	4	5	6	7
1. VPM_{adj}	–						
2. VSM_{adj}	.47**	–					
3. SPM_{adj}	.45**	.21	–				
4. SSM_{adj}	.26*	.42**	.40**	–			
5. WRE	.51**	.63**	.20	.14	–		
6. CDISC	−.38**	−.45**	−.22	−.30**	−.48**	–	
7. FSIQ	.62**	.54**	.30**	.37**	.47**	−.45**	–

Note. *$p < .05$; **$p < .01$. CDISC = average standardized symptom and impairment scores from the NIMH-C-DISC-IV; FSIQ = full-scale IQ; NIMH-C-DISC-IV = National Institute of Mental Health Computerized Diagnostic Interview Schedule for Children, Version 4; SPM_{adj} = estimate of spatial PM capacity adjusted by the SSOR; SSM_{adj} = estimate of spatial SM capacity adjusted by the SSOR; SSOR = spatial strength of recency; TOWRE = Test of Word Reading Efficiency; VPM_{adj} = estimate of verbal PM capacity adjusted by the VSOR; VSM_{adj} = estimate of verbal SM capacity adjusted by the VSOR; VSOR = verbal strength of recency; WRE = average standardized phonemic decoding efficiency and sight reading efficiency scores from the TOWRE.

between WRE and PM is significantly greater in the verbal modality (r = .51) than in the spatial modality (r = .20), z = 2.83, p = .005; likewise, the correlation between WRE and SM is significantly greater in the verbal modality (r = .63) than in the spatial modality (r = .14), z = 4.68, p < .0001. With respect to the CDISC scores, the pattern of correlations is also consistent with expectations: the correlation between CDISC and PM does not differ across the verbal (r = −.39) and spatial (r = −.22) modalities, z = −1.43, p = .15; likewise, the correlation between CDISC and SM does not differ across the verbal (r = −.45) and spatial (r = −.30) modalities, z = −1.36, p = .18. With respect to the FSIQ, the pattern of correlations is partially consistent with expectations: although the correlation between FSIQ and PM is significantly greater in the verbal modality (r = .62) than in the spatial modality (r = .30), z = 3.18, p = .001, the correlation between FSIQ and SM does not differ across the verbal (r = .54) and spatial (r = .37) modalities, z = 1.61, p = .12. Thus, these findings suggest that the difference in WM capacity between the ADHD and control groups should be larger in the verbal modality than in the spatial modality if the WRE score has a confounding effect on WM.

Returning to the three-way mixed ANOVA, there is some evidence that the difference between the ADHD and control groups is larger in the verbal modality (ADHD: M = 1.74, SE = 0.08; control: M = 2.32, SE = 0.07) than in the spatial modality (ADHD: M = 2.44, SE = 0.09; control: M = 2.80, SE = 0.08); however, the two-way interaction between task modality and group is only marginally significant, $F(1, 75) = 3.18$, p = .08, η_p^2 = .04. Most importantly, the three-way interaction between task modality, component type, and group does not approach significance, $F(1, 75) = 0.02$, p = .88, η_p^2 = .00, suggesting that the shape of the component type × group interaction does not vary as a function of task modality. The only significant interaction involving task modality is the two-way interaction between task modality and component type, $F(1, 75) = 156.37$, p < .0001, η_p^2 = .68. As can be seen in Figure 1, this interaction indicates that task modality has a larger effect on SM capacity than PM capacity, but this finding has no bearing on the conclusion that the WRE score appears to have little influence on the magnitude of the component type × group interaction.

Discussion

Gibson and colleagues have argued that the components of WM that are deficient in ADHD may not be the same components that are targeted by adaptive WM training regimens (Gibson et al., 2010, 2011). With respect to the components of WM that are deficient in ADHD, Gibson et al. (2010) applied the dual-component theory of WM to ADHD and found that the SM component was more deficient than the PM component in a group of middle-school children with ADHD relative to age-matched controls. Accordingly, they interpreted these findings as suggesting that ADHD symptoms arise primarily because individuals with ADHD are less likely to retrieve goal-relevant information from SM after it has been lost from PM. Thus, if these findings are correct, then the SM component of WM may be an important and novel target for front-line treatments of ADHD such as WM training.

The present study seeks to strengthen this conclusion by replicating the findings reported by Gibson et al. (2010) and extending them in two important ways. The first extension involves experimentally controlling the order-of-report strategy used during recall on the verbal and spatial IFR tasks so as to retain a larger proportion of the original sample. This extension is important because Gibson et al. had to discard approximately 50% of their sample (equally distributed across the ADHD and control groups) due to the fact that their participants did not use the proper recency order-of-report strategy during recall. The recency order-of-report strategy was controlled in the present study by explicit instructions to recall the items from the end of the list first. The use of these explicit recall initiation instructions had the intended effect in that the exclusion due to recall strategy was reduced to 18%.

In addition to this experimental control, the extent to which participants utilized the recency recall strategy was further controlled statistically by removing covariance associated with an individual's strength of recency within each modality (VSOR and SSOR) from the corresponding estimates of PM and SM capacity. Despite the fact that all participants included in the analyses met the same objective criteria for using a recency recall strategy, the results show that individual differences in VSOR and SSOR still have a significant influence on the relative magnitude of the number of items recalled from PM and SM, regardless of modality.

With these experimental and statistical controls in place, the pattern of results observed in the present study generally corroborate the results reported by Gibson et al. (2010), albeit with some slight variations. Recall that Gibson et al. consistently found a significant component type × group interaction across both verbal and spatial IFR tasks, suggesting a greater deficiency in SM capacity than in PM capacity. However, although the group difference is consistently larger for SM capacity than for PM capacity, Gibson et al. also found a significant group difference in PM capacity in the spatial IFR task, but not in the verbal IFR task.

Likewise, the present study also consistently found a significant component type × group interaction across both verbal and spatial IFR tasks, suggesting a greater deficiency in SM capacity than in PM capacity. However, although the group difference is consistently larger for SM capacity than for PM capacity, the present study also found a significant group difference in PM capacity in the verbal IFR task, but not in the spatial IFR task (Table 1). Thus, the main difference between the two studies is that the group difference in PM capacity switched from the spatial IFR task in Gibson et al.'s (2010) study to the verbal IFR task in the present study. Nevertheless, the most important result is the successful replication of the component type × group interaction in the present study using a larger sample in which recall strategy was strictly controlled. Thus, the observed dissociation between SM and PM can be confidently attributed to a group difference in capacity as opposed to a group difference in recall strategy.

The second extension of Gibson et al.'s (2010) findings involves the documentation of potential differences in word reading efficiency that may have existed between the ADHD and control groups and that may have influenced the estimates of verbal PM and SM capacities. Consistent with these expectations, the present study shows that the ADHD group scored significantly lower on measures of WRE, a composite variable reflecting both phonemic decoding efficiency and sight reading efficiency.

However, rather than attempting to remove the covariance associated with WRE from the dependent variables—an ill-advised form of statistical control that simply does not accomplish what many researchers believe it accomplishes (Dennis et al., 2009;

Miller & Chapman, 2001)— instead it was predicted that, all else being equal, the difference between the ADHD and control groups should grow larger in the verbal modality than in the spatial modality if WRE has a confounding effect on WM in the present study. Although there is some evidence that the difference between the ADHD and control groups is overall larger in the verbal modality (M_{diff} = 0.58 items) than in the spatial modality (M_{diff} = 0.36 items), this difference is only marginally significant. More importantly, there is no evidence that the magnitude of the component type × group interaction varies as a function of task modality in the present study. Thus, the present study provides little evidence that the confounded group difference in WRE influences the conclusion that SM capacity is more deficient than PM capacity in children ADHD.

On the one hand, the conclusion that WRE has such a small effect on verbal WM in the present study is reassuring; but, on the other hand, this conclusion might raise suspicions given that the words had to be read and encoded before they could be recalled in the verbal IFR task. However, unlike the real- and pseudo-word lists used in the TOWRE, which got progressively harder as the list progressed, the word lists used in the verbal IFR task were composed of high-frequency words that were designed to be easy to read for all participants. Unfortunately, the participants were not asked to read the words as they were presented during the verbal IFR task, in part to avoid introducing another processing requirement, not to mention another potential difference between the verbal and spatial IFR tasks. Consequently, it is not possible to state with any certainty the extent to which the present findings reflect encoding differences or retrieval differences. With that said, given the pattern of correlations shown in Table 2, it is unlikely that the nonsignificant task modality × component type × group interaction occurs because there is a tradeoff between the two modalities. In other words, it is unlikely that this nonsignificant three-way interaction occurs because the effects of the other two documented group differences—diagnostic status and FSIQ—have a relatively smaller effect in the verbal modality than in the spatial modality. In fact, the pattern of correlations suggests the opposite, at least numerically.

A further caution that should be mentioned after considering the relative magnitude of the correlations between the CDISC, WRE, and FSIQ scores, along with the various dependent variables shown in Table 2, is that both the WRE and FSIQ scores appear to be stronger predictors of WM than the CDISC score. In fact, if the estimates of PM and SM capacity within each modality are regressed on CDISC, WRE, and FSIQ, the effects of CDISC are never significant in the context of the other two predictors. Although this finding may seem inconsistent with the present interpretation that SM capacity is more impaired than PM capacity in children with ADHD, it should not be surprising because WRE and FSIQ are both based on cognitive assessments provided by the child, whereas the diagnostic status is based on the primary caregiver's subjective ratings of the child. Thus, the WRE and FSIQ scores are more proximal to the PM and SM scores than diagnostic status.

It is suggested that the most appropriate interpretation of the present findings is that SM capacity is in fact more impaired in ADHD than PM capacity. However, the WRE and FSIQ scores also overlap with diagnostic status, as well as with the two components of WM. Indeed, it is precisely this overlap that makes any attempt to control for WRE or FSIQ ill advised. As mentioned in the introduction, removing the covariance associated with WRE and/or FSIQ from the dependent variables when these covariates are also related to diagnostic status results in a biased adjustment, as some effects attributed to diagnostic status will be eliminated from the dependent variables (Dennis et al., 2009; Miller & Chapman, 2001; Wildt & Ahtola, 1978).

There is abundant evidence suggesting overlap between fluid aspects of IQ and the two components of WM. For instance, numerous studies have been interpreted as suggesting that individual differences in IQ are caused, at least in part, by individual differences in both PM and SM capacities (Cowan et al., 2005; Kane et al., 2004; Mogle, Lovett, Stawski, & Sliwinski, 2008; Shipstead et al., 2014; Unsworth & Engle, 2006; Unsworth et al., 2014). Indeed, on the basis of these studies, IQ is often included as an outcome variable in WM training studies (e.g., Harrison et al., 2013; Klingberg et al., 2005).

There is also abundant evidence suggesting overlap between reading and WM, though most of this research has emphasized the PM component of WM (using Baddeley's model of WM; Baddeley, 1986), and the overlapping role that phonological processes might play across both reading and WM (for a review, see Gathercole & Baddeley, 1993). In contrast, there has been very little emphasis on the SM component of WM, and the overlapping role that cue-dependent retrieval processes might play across both reading and WM.

On the one hand, current theories of WM have clearly stated the importance of cue-dependent retrieval in the description of the SM component of WM (Shipstead et al., 2014; Unsworth & Engle, 2007a, 2007b; Unsworth et al., 2014). Specifically, cue-dependent retrieval from SM has been described as involving three parameters: the size of the cued search set, the recovery of potential targets from this set, and error monitoring (Unsworth, 2007, 2009). Furthermore, empirical studies based on this theory have suggested that the limitation in the SM component of WM capacity is primarily reflected in the size of the search set that is cued from SM (Unsworth, 2007, 2009). That is, individuals with a low SM capacity tend to cue larger search sets containing more irrelevant items during recall tasks than individuals with a high SM capacity.

On the other hand, although current theories of reading acquisition appear to implicate cue-dependent retrieval processes, these processes have typically not been explicitly acknowledged in the acquisition of phonemic decoding or sight word reading abilities (Ehri, 1998; though see Menghini, Carlesimo, Marotta, Finzi, & Vicari, 2010). For instance, efficiently identifying the sound of a letter sequence such as "da" from its written form requires the reader to ignore interference from similarly shaped and spelled letter sequences such as "ba", "do", "de", and "ga". Likewise, efficiently identifying a letter string such as "stick" as a word from its written form requires the reader to ignore interference from similarly shaped and spelled words such as "stink", "slick", "slink", "sting", "sling", "string", "sick", and "sing" (Ehri, 1998). In each of these examples, the written form of the letters serves as a cue that defines the representations that are relevant as well as those that are irrelevant. Any disruptions to these cue-dependent retrieval processes increases the chances that the relevant information may not be immediately accessed, resulting in the inefficient or inaccurate identification of words that do not become properly automatized with practice. In this way, deficiencies in cue-dependent retrieval processes may underlie deficiencies in word reading as well as deficiencies in SM capacity. This possibility is currently being investigated in a longitudinal study by the authors of this paper.

In conclusion, the present study replicates and extends the findings reported by Gibson et al. (2010) on two fronts. First, the present study shows that the SM component continues to be more deficient than the PM component across both modalities under conditions wherein (1) all participants were instructed to use the same recall strategy (resulting in the exclusion of fewer participants), and (2) individual differences in this strategy were controlled. Second, this study also documents a group difference in word reading efficiency that is confounded with diagnostic status and that might have influenced estimates of PM and SM capacities in the verbal modality. However, although the SM component is more deficient than the PM component in the ADHD group, the magnitude of this interaction does not vary as a function of task modality. These findings are interpreted as suggesting that the pattern of WM deficiencies is part of a causal pathway that can lead to the symptoms of ADHD, as well as to impairments in reading (and intelligence) due to overlapping cue-dependent retrieval mechanisms. Altogether, the present findings provide additional support for the notion that the SM component of WM is an important and novel target for front-line treatments of ADHD such as WM training.

Disclosure statement

No potential conflict of interest was reported by the authors.

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