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APPLICATION OF THE DUAL-COMPONENT MODEL OF WORKING MEMORY TO ADHD

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Attention deficit/hyperactivity disorder (ADHD) has been associated with a deficit in working memory across both verbal and spatial domains, but the precise nature of this deficit is poorly understood. The dual-component model postulates that working memory capacity consists of two dissociable components: maintenance in primary memory (PM) and recall from secondary memory (SM). Participants diagnosed with ADHD (n = 32) and age-matched controls (n = 31) performed both verbal and spatial free-recall tasks, and subsets of these two samples were selected for further comparison based on their use of a "recency" order-of-report strategy. The primary results showed that maintenance in PM appears to be largely intact whereas recall from SM appears to be deficient in ADHD relative to age-matched controls. Similar outcomes were observed across both task domains. Implications for understanding both the underlying pathology and treatment of ADHD are discussed.

Keywords: ***ADHD; Dual-component model; Working memory.***

The constellation of behavioral symptoms comprising attention deficit/hyperactivity disorder (ADHD) has been hypothesized to arise from a deficit in executive functioning that is generally thought to consist of a network of higher order cognitive control processes that support and enable goal-directed behavior across time (Barkley, 1997; see also Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). One of the largest and most robust differences to be observed between children with ADHD and age-matched controls is in the domain of working memory (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt et al., 2005). Generally speaking, working memory is critical to everyday functioning because it allows individuals to maintain and retrieve task-relevant information in the presence of irrelevant distraction (Kane & Engle, 2002; Unsworth & Engle, 2007). In this way, individuals may organize and execute complex goal-directed activities across time without succumbing to more habitual, automatized, or prepotent responses.

With respect to ADHD, existing evidence has been interpreted to suggest that ADHD is associated with a weakness in the active maintenance and manipulation of

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information and, furthermore, that these mechanisms are more impaired in the spatial domain than in the verbal domain (Martinussen et al., 2005). However, although there appears to be strong evidence that ADHD is associated with a weakness in the maintenance and manipulation of both verbal and spatial information (Martinussen et al.), this conclusion has been based primarily on models of working memory that have not emphasized other, potentially important, components of working memory involving the strategic retrieval of information that has been lost from working memory (due to failures in active maintenance). For instance, Unsworth and Engle's (2007) recent dual-component model specifies two basic functions of working memory: (a) the active maintenance of a limited amount of novel information in primary memory (PM), particularly in the presence of internal and external distraction; and (b) the retrieval of goal-relevant information from secondary memory (SM), after that information has been lost from PM (due to failures of active maintenance and/or storage limitations).

If Unsworth and Engle's (2007) model of working memory is plausible, then accurate interpretation of group differences in working memory capacity must consider the possibility that information can be recalled from both PM (via active maintenance) and SM (via the encoding and retrieval of information that is lost from PM); otherwise, the effects of one process on task performance may be confused with the effects of the other. Recently, Unsworth and Engle used a verbal free-recall task to assess individual differences within the context of the dual-component model. According to Unsworth and Engle, free-recall tasks are valid measures of working memory capacity. In their reanalysis of Engle, Tuholski, Laughlin, and Conway's (1999) structural equation model of the relation between working memory capacity, fluid intelligence, and scholastic aptitude, Unsworth and Engle showed that performance on a verbal free-recall task loaded just as highly (0.77) on the latent construct of working memory capacity as performance on three more traditional complex span tasks did: operation span (0.77), reading span (0.58), and counting span (0.62).

More importantly, free-recall tasks may be better suited for assessing recall from PM and SM than complex or simple span tasks because free-recall tasks can provide separate measures of each component, once certain assumptions concerning the order in which list items are reported are met (see below for further details), whereas complex and simple span tasks typically provide a single measure that reflects contributions from both components. In particular, performance on free-recall tasks can be divided into recency and pre-recency portions: typically, individuals are better at recalling the last few presented (recency) items than they are at recalling the earlier presented (pre-recency) items because the recency items can be actively maintained and then simply unloaded from PM whereas the pre-recency items need to be encoded and then retrieved by means of a probabilistic search through SM.

Using a variety of different measures, Unsworth and Engle (2007) found that individuals with low capacity performed worse than individuals with high capacity on the recency and pre-recency components of their verbal free-recall task, suggesting weaknesses in their ability to recall information from both PM and SM, respectively. Based on this evidence, Unsworth and Engle concluded that low capacity individuals were less likely to maintain task-relevant information in PM than high-capacity individuals and they were also less proficient at using internally generated, contextual (i.e., time- and list-specific) cues to retrieve relevant information from SM. As a result, low-capacity individuals were more likely to retrieve irrelevant information from previous trials than high-capacity individuals.

Likewise, there appears to be ample evidence that individuals with ADHD have lower working memory capacity than individuals without ADHD (Martinussen et al., 2005; Willcutt et al., 2005). However, it is currently unknown whether this performance difference reflects a difference in the ability to recall information from PM (as is typically inferred), the ability to recall information from SM, or both. Note that, although Unsworth and Engle (2007) found differences in the ability to recall information from both PM and SM in their study of high- and low-capacity adults, their analysis suggested that these two components could, in principle, be dissociated. Hence, one question of particular theoretical interest concerns the possibility that previously reported differences in working memory capacity observed between children with and without ADHD may actually reflect a deficit in the ability to recall information from SM, not the ability to maintain information in PM.

The present study focused on adolescents within a relatively narrow age range (11–14 years) to improve chances of observing a significant group difference in recall from SM, should such a group difference exist. More specifically, abundant developmental research has shown that pre-recency items are typically recalled less accurately by younger children (e.g., 7 years) than by older adolescents (e.g., 11 years) during free recall; whereas, recency items are typically recalled equally well across a wide range of age groups and more accurately overall than pre-recency list items (see Ornstein & Naus, 1978; and Pressley & Schneider, 1997, for reviews). Such age differences have been attributed to the development of a variety of rehearsal strategies (e.g., cumulative rehearsal) that selectively aid in the encoding and retrieval of pre-recency items. Hence, the accuracy of recall for pre-recency items (but not recency items) may be near the bottom of the scale for younger children, making it difficult to observe further deficiencies as a function of group on these items.

Consistent with this concern, Douglas and Benezra (1990) measured performance on a verbal free-recall task in a sample of relatively young ADHD and non-ADHD individuals (7–12 years of age) but failed to find a significant group difference in overall accuracy (note that their data were only reported averaged over serial position and could not be examined as a function of recency and pre-recency items). In addition, Westerberg, Hirvikoski, Forssberg, and Klingberg (2004) measured performance on a spatial serial-recall task in both ADHD and non-ADHD individuals as a function of age (which ranged from 8 to 15 years). They found that fewer spatial locations were recalled overall by the ADHD group than by the control group, and, more importantly, they found that the group difference increased as a function of age, which may be attributed, at least in part, to developmental differences in the ability to recall information from SM (though their measure of performance conflated PM and SM). We therefore considered it prudent to focus the present investigation on an older age group whose performance on the pre-recency items was expected to be well above the floor.

In addition, we also considered it prudent to evaluate the "order-of-report" strategy that participants used in the present study because the theoretically driven inference from the recency and pre-recency portions of performance to the PM and SM components of working memory, respectively, requires that (a) participants attempt to maintain the recency items in PM in which case they should tend to report these items first (i.e., the probability of first recall should be relatively high for these items; see Howard & Kahana, 1999); and (b) participants attempt to retrieve the pre-recency items from SM in which case they should tend to report these items after all maintained items have been unloaded from PM (i.e., the probability of first recall should be near zero for these items; see

Unsworth & Engle, 2007). Unsworth and Engle did not conduct an individual-by-individual analysis of order-of-report strategy; however, they provided empirical evidence that their adult participants used a "report-recency-items-first" strategy as a group by showing that the average probability of first recall was relatively high for the recency items and it was relatively low for the pre-recency items in both the high-capacity and low-capacity groups.

Given the apparent spontaneous usage of the "report-recency-items-first" strategy in Unsworth and Engle's (2007) study, we assumed that explicit order-of-report instructions would be unnecessary in the present study. However, given the importance of this assumption for interpreting performance, we conducted a more formal analysis of recall strategy to determine whether individual adolescents in the present study would consistently use the same "report-recency-items-first" strategy as the group of adults in Unsworth and Engle's study appeared to use. Likewise, we also investigated whether the adolescents in the ADHD group were capable of spontaneously using the same order-of-report strategies as the adolescents in the control group. Failure of the adolescents to use such a strategy would jeopardize the mapping from the recency and pre-recency portions of performance to the PM and SM components of working memory, respectively. For instance, items from the pre-recency portion of the list that are maintained during list presentation and reported first likely have dual representation in both PM and SM, making it difficult to interpret performance on these items (see also, Watkins, 1974). Consequently, the main comparisons of interest between the ADHD and control groups were based only on those participants who used the "report-recency-items-first" strategy.

In summary, the present study applied the dual-component model of working memory to a group of ADHD and non-ADHD individuals to determine whether individuals with ADHD are deficient in their ability to recall information from PM, their ability to recall information from SM, or both. In addition, working memory performance was assessed using both verbal and spatial free-recall tasks to investigate whether group differences in either component of working memory would be consistently observed across the two task domains (Martinussen et al., 2005).

METHOD

Participants

Participants were 63 adolescents, aged 11–14 years, classified as either ADHD (n = 32) or control (n = 31). The participants were recruited from two middle schools (Grades 6 to 8) in a mid-Western public school district. The total population of the two schools was 1,938 adolescents. Initial contact letters briefly describing the study were sent to the parents of the two groups separately. Letters intended for the ADHD group emphasized the researchers' interest in understanding working memory in children diagnosed with ADHD; these letters were provided to school officials who then mailed the letters to the parents of all adolescents in the district who were known to have a diagnosis of ADHD based on medical information provided to the school by the parents (n = 115). Letters intended for the non-ADHD group emphasized the researchers' interest in understanding the development of working memory in adolescents of all abilities so that researchers could better understand working memory problems in clinical populations such as ADHD; these letters were mailed to the parents of all the remaining adolescents (n = 1823).

Initial Screening

Interested parents in both groups responded by calling the researchers whereupon the primary caregiver and adolescent provided informed consent and assent, respectively, before participating in an initial screening phase. During this initial screening phase, the number and severity of ADHD symptoms were obtained for each adolescent by administering the parent and teacher versions of the Vanderbilt ADHD Diagnostic Scale (Wolraich, Feurer, Hannah, Baumgaertel, & Pinnock, 1998; Wolraich, Lambert, Doffing, Bickman, Simmons, & Worley, 2003) to the adolescent's primary caregiver and one of the adolescent's teachers, respectively. The total number of *Diagnostic and Statistical Manual of Mental Disorders*, fourth edition (*DSM-IV*; American Psychiatric Association, 1994) symptoms receiving scores greater or equal to 2 (indicating severity) was then summed across the parent and teacher ratings (using the "or" algorithm, Lahey et al., 1994) within each of the inattentive and hyperactive/impulsive dimensions. In other words, a symptom was counted if either the parent or teacher indicated a score of 2 or greater for each symptom. For the sake of comparison, average scores based on "parent-only" and "teacher-only" reports are also provided in Table 1. Adolescents were screened into the ADHD group if they obtained a score of 6 or greater on the inattentive dimension (ADHD-PI); or, if they obtained a score of 6 or greater on both the inattentive and hyper-active/impulsive dimensions (ADHD-C). Note, however, that the researchers made no specific predictions based on ADHD subtype, and so the distinction between ADHD-PI and ADHD-C was ignored in the analyses reported below. All 32 of the respondents in the ADHD group met one of these two criteria. Adolescents were screened into the control group if they obtained a score less than 5 on both dimensions. Six of the 37 respondents in the control group obtained a score of 5 on at least one of the two dimensions and were excluded from the study, leaving a total of 31 participants in this group.

Table 1 Average Characteristics of the ADHD and Control Groups Regardless of Recall Strategy (Standard Deviation).

	Control (n = 31)	ADHD (n = 32)
# attention symptoms		
Parent or teacher	0.81 (1.30)	8.03 (1.33)
Parent only	0.52 (0.96)	7.72 (1.98)
Teacher only	0.37 (0.89)	3.73 (3.14)
# hyperactive/impulsive symptoms		
Parent or teacher	0.48 (0.96)	5.09 (2.64)
Parent only	0.32 (0.70)	4.83 (2.87)
Teacher only	0.17 (0.75)	1.47 (2.19)
Full-Scale IQ	109.90 (13.14)	99.19 (16.73)
Verbal IQ	106.39 (15.49)	98.03 (16.12)
Performance IQ	111.58 (13.01)	100.47 (18.07)
Age in years	12.93 (0.95)	12.69 (0.93)
Boys: girls	18:13	22:10
Comorbidities		
Anxiety	1	1
Depression	0	1
ODD	1	15

Note. ODD = Oppositional-Defiant Disorder.

Structured Interview

Following initial screening, the primary caregiver and adolescent were invited to attend a two-hour laboratory session. During this session, the primary caregiver participated in a structured interview using the Computerized Diagnostic Interview Schedule for Children Version 4 (C-DISC-IV; Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000) to verify the presence of the number, age of onset, associated impairment, and cross-situational pervasiveness of the ADHD symptoms in the ADHD group and the absence of these *DSM-IV* criteria in the control group. In addition, a variety of other, potentially comorbid, psychiatric conditions (such as anxiety, depression, and Oppositional Defiant Disorder [ODD]) were also examined in both groups. The results of the structured interview were consistent with group assignment based on initial screening.

Cognitive testing. Each adolescent performed three cognitive tasks; the order of which was counterbalanced across participants. Note that most of the adolescents in the ADHD group were being treated with stimulant medication; however, this medication was withheld for at least 24 hours prior to any cognitive testing. The Wechsler Abbreviated Scale of Intelligence (WASI; The Psychological Corporation, 1999) was administered to each of the adolescents to obtain a general measure of cognitive functioning. A full-scale IQ greater or equal to 70 was required for inclusion in the study.

In addition, each child also performed both a verbal and spatial version of the free-recall task. The verbal task was based on the free-recall task used by Unsworth and Engle (2007). Participants were presented with 15 lists of 12 unique high-frequency words that were randomly combined. The words were printed in 20-point font, and all words appeared white against the black background of a standard CRT monitor. Each word was presented consecutively for one second in the middle of the computer screen. Following the presentation of a single list, question marks appeared in the center of the screen prompting a response by the participant. At this point, participants were asked to verbally recall, in any order, as many words as possible. Participants reported their answers into a microphone that was connected to a standard cassette recorder. In addition, following Unsworth and Engle, the experimenter also recorded the response time of each verbal response by pressing a response key for each response that was uttered. Participants were given as much time as necessary to recall the word lists. Three practice trials using letter stimuli (instead of words) preceded the test trials. The word lists were presented in the same random order to all subjects.

The spatial free-recall task was adapted from the spatial serial-recall task used by Westerberg et al. (2004). Participants were presented with 15 lists of 12 different locations that were marked by white squares. Squares appeared at any one of $15 \times 12 = 180$ unique screen locations. Each location was cued only once across the 15 different lists. Locations were cued by temporarily changing the color of the square from white to red. Each of the 12 locations in a list was cued in consecutive order for one second. At the conclusion of the list, participants were prompted to use the computer mouse to recall, in any order, as many locations as possible by clicking on the relevant locations. Participants were given as much time as necessary to recall the spatial lists. For each response, the computer recorded the location of the mouse click, the order of the mouse click, and the time of each mouse click. Note that pilot testing revealed that the spatial task was too difficult when all 180 locations appeared at once. Therefore, in order to make the task more manageable, only 36 of the possible 180 squares appeared at any one time. These 36 trials remained visible for three consecutive trials (3 trials × 12 cued locations = 36 possible 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.

Data analyses and predictions. The order and number of correct and incorrect recall responses were recorded for each participant on both the verbal and spatial tasks separately. A response was scored correct if it matched one of the list items. In the verbal free-recall 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).

Order-of-report strategies were formally assessed in two ways in the present study. First, probability-of-first-recall functions were generated for each participant and then evaluated separately in order to group participants into one of three order-of-report groups. 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. Participants were placed in the “recency” group if probability of first recall was higher for the last four items than for the first four items across the 15 lists. In contrast, participants were placed in the “pre-recency” group if probability of first recall was higher for the first four items than for the last four items across the 15 lists. Finally, participants were placed in the “combined” group if probability of first recall was equal across the recency and pre-recency portions of the list.

Second, previous research has suggested that probability correct as a function of serial position varies as a function of order-of-report strategy (Madigan, 1971). Serial position curves with relatively strong recency effects and relatively weak primacy effects are produced when participants are explicitly instructed to use a recency strategy; whereas, curves with relatively strong primacy effects and relatively weak recency effects are produced when participants are instructed to use a pre-recency strategy. If the use of probability-of-first-response functions is an appropriate method for classifying individuals into different order-of-report groups, then each group should produce a distinctive serial position curve consistent with this previous research (Madigan). In other words, when probability correct is measured as a function of serial position, a significant interaction between serial position and order-of-report group should be obtained.

Following this formal analysis of recall strategy, two different dependent measures were calculated from the recall data generated by those participants who used the “report-recency-items-first” strategy in order to compare recall from PM and SM across the ADHD and control groups.

1. Probability correct as a function of serial position was used as a measure of recall from both PM (recency portion of the curve) and SM (pre-recency portion of the curve). If the ADHD group is deficient in recall from PM, then this group should be less accurate when the last several items in the list are considered. If the ADHD group is deficient in recall from SM, then this group should be less accurate when the first several items in the list are considered.
2. Tulving and Colotla’s (1970) method was also used to provide estimates of the number of items that can be recalled from PM and SM (see also Watkins, 1974 and Waugh & Norman, 1965). 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 recall of an item, the more likely the item was recalled from SM as

opposed to PM. Following Tulving and Colotla, the number of words between a given word's presentation and recall will be tallied. If there are seven or fewer words intervening between presentation and recall of a given word, the word was considered to be recalled from PM. If more than seven words intervened between presentation and recall, the word was considered to be recalled from SM. Other researchers (Craik & Birtwistle, 1971; Unsworth & Engle, 2007) have validated these estimates by showing that recall from SM is affected by the buildup of proactive interference whereas recall from PM is not. Moreover, Unsworth and Engle have used this method to show that low-capacity individuals recall fewer items from both PM and SM than high-capacity individuals. If the ADHD group is deficient in recall from PM, then this group should recall fewer items from PM. If the ADHD group is deficient in recall from SM, then this group should recall fewer items from SM.

RESULTS

Table 1 describes the characteristics of the two diagnostic groups. As expected, the ADHD group had significantly more inattentive and hyperactive/impulsive symptoms than the control group, $t(61) = 21.77$, $p < .0001$, $d = 5.49$, and $t(61) = 9.14$, $p < .001$, $d = 2.32$, respectively. Also as expected, the ADHD and control groups were equal in age, $t(61) = 1.04$, $p > .30$, $d = 0.26$. Note that the adolescents in the ADHD group had significantly lower IQ scores than the adolescents in the control group ($M = 99.19$ and $M = 109.90$, respectively), $t(61) = 2.82$, $p < .01$, $d = 0.71$. Although such IQ differences are commonly found in the ADHD literature, the proper interpretation of these differences has generated extensive debate (see Nigg, 2006, for a fuller discussion of this issue). For instance, there are a variety of sound theoretical reasons to expect that IQ should vary as a function of diagnostic status in the present study. For instance, previous research has shown that individual differences in working memory capacity are moderately and positively related to intelligence (Cowan et al., 2005; Kane & Engle, 2002; Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth & Engle, 2006). By hypothesis, ADHD is associated with a weakness in working memory relative to the control group that in turn might cause the observed difference in IQ. However, at issue is whether diagnostic status might also be confounded with a difference in IQ due to potential selection bias arising from nonrandom assignment into the ADHD and control groups that in turn might cause a difference in working memory. As is standard in this literature, we will address whether any observed differences in working memory might arise from this potential confound by treating IQ as a statistical covariate in the critical analyses reported below.

Verbal Free Recall

Order-of-report strategies. Examination of the probability-of-first-recall functions revealed that 34/63 (53.97%) of the participants fell into the recency group, 17/63 (26.98%) of the participants fell into the pre-recency group, and 12/63 (19.05%) of the participants fell into the combined group. Figure 1 (upper panel) shows probability of first recall as a function of serial position averaged over participants and trials in each of the three order-of-report groups. As can be seen, the probability of first recall was highest for the 12th list item in the recency group whereas the probability of first recall was highest for the first list item in the pre-recency group. Performance in the combined group fell in between these two extremes.

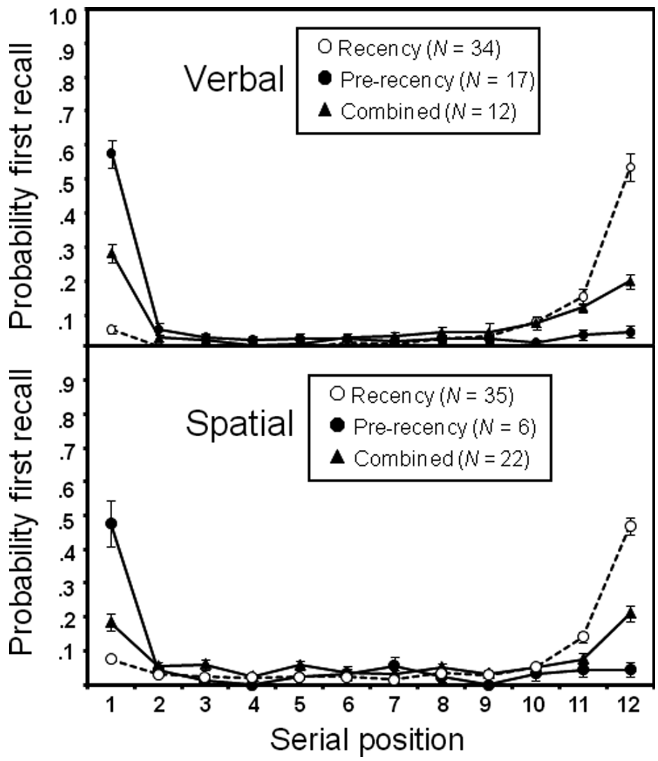

Figure 1 Probability-of-first-recall functions for each of the three order-of-report groups in both the verbal (upper panel) and spatial (lower panel) free-recall tasks. Error bars represent standard error.

The serial position curves associated with each of the recency, pre-recency, and combined groups are shown in Figure 2 (upper panel). The results were consistent with expectations: The recency group produced a serial position curve with a predominant recency effect; the pre-recency group produced a serial position curve with a predominant primacy effect; and the combined group produced a serial position curve that was intermediate between the two extremes. These different patterns were confirmed with 2 × 3 mixed Analysis of Variance (ANOVA) with serial position as the within-subjects variable and recall strategy group as the between-subjects variable. The results revealed a significant serial position × recall strategy group interaction, $F(22, 660) = 29.25$, $p < .0001$, $\eta_p^2 = .494$.

Given that the adolescents in the present study appeared to use a variety of different order-of-report strategies, it is also important to consider whether the use of particular strategies varied as a function of diagnostic group. Indeed, performance on free-recall tasks can be construed as a form of learning and it is possible that individuals in the ADHD group attempted to learn the word lists differently than the control group. However, examination of individual probability-of-first-recall functions revealed that approximately equal numbers of participants from the two diagnostic groups fell into each of the three recall groups: 18 ADHD participants and 16 control participants used the recency strategy; 7 ADHD participants and 10 control participants used the pre-recency strategy; and 7 ADHD participants and 5 control participants used the combined strategy.

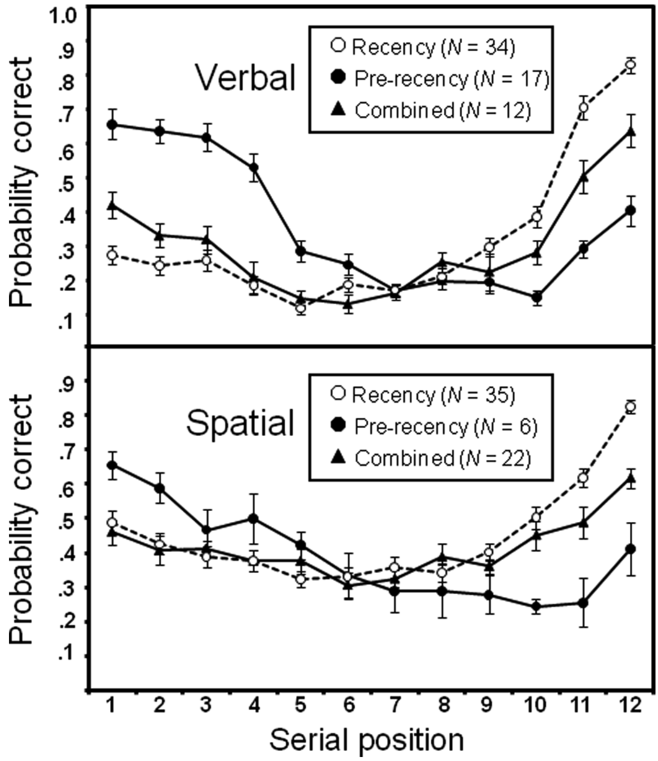

Figure 2 Probability correct recall as a function of serial position for each of the three order-of-report groups in both the verbal (upper panel) and spatial (lower panel) free-recall tasks. Error bars represent standard error.

Hence, the use of different recall strategies appeared to be independent of diagnostic group, $\chi^2(2) = 0.97$, $p > .50$, suggesting that the two groups reported the order of the list items in very similar ways.

In order to determine whether participants in the three order-of-report groups varied in age, full-scale IQ, verbal IQ, performance IQ, the number of inattentive symptoms, or the number of hyperactive/impulsive symptoms, separate 3 × 2 Analyses of Variance (ANOVAs) were conducted on each of these six dependent variables with recall strategy and diagnostic group as the two between-groups variables. Apart from the significant main effects of diagnostic group noted above, the only significant effect to be observed was a significant main effect of recall strategy when the number of hyperactive/impulsive symptoms served as the dependent measure, $F(2, 63) = 3.47$, $p < .05$, $\eta_p^2 = .109$, indicating that participants in the combined strategy group had more of these symptoms ($M = 4.07$) than participants in either the recency ($M = 2.50$) or pre-recency ($M = 2.36$) strategy groups.

In summary, these preliminary findings are important because they suggest that adolescents may use a variety of different order-of-report strategies when simply instructed to freely recall as many words as possible. Such findings might be surprising when considered in relation to Unsworth and Engle’s (2007) study that appeared to suggest that both high- and low-capacity adult participants routinely used only the recency strategy during verbal free recall; though it should also be noted that Unsworth and Engle

Table 2 Average Characteristics of the ADHD and Control Groups Including Only Those Participants who Used the Recency Strategy in the Verbal Free-Recall Task (Standard Deviation).

	Control (*n* = 16)	ADHD (*n* = 18)
# attention symptoms		
Teacher or parent	0.94 (1.44)	7.94 (1.51)
Parent only	0.63 (1.15)	7.40 (2.53)
Teacher only	0.33 (0.62)	4.18 (3.30)
# hyperactive/impulsive symptoms		
Teacher or parent	0.44 (1.03)	4.56 (2.41)
Parent only	0.13 (0.34)	4.40 (2.75)
Teacher only	0.33 (1.05)	0.94 (1.44)
Full-Scale IQ	110.75 (15.91)	98.33 (18.49)
Verbal IQ	106.88 (17.70)	96.94 (18.11)
Performance IQ	112.25 (12.92)	100.11 (19.59)
Age in years	13.08 (0.98)	12.52 (1.07)
Boys: girls	10:6	12:6
Comorbidities		
Anxiety	0	1
Depression	0	1
ODD	0	9

Note. ODD = Oppositional Defiant Disorder.

did not provide a formal analysis of order-of-report strategies in their study.[1] Table 2 describes the characteristics of the two diagnostic groups when only those participants who used the recency strategy were included in the sample. Overall, the characteristics of the two diagnostic groups when only the "recency strategy" participants were included were very similar to the characteristics of the two diagnostic groups when all the participants were included (see Table 1). In order to determine whether the ADHD and control groups differed in either the PM or SM components of working memory, the two groups were compared on the two measures of PM and SM using only those participants who utilized the recency strategy.

Serial position effects. The probability of correct recall is shown in Figure 3 (upper panel) as a function of serial position for both the ADHD ($n = 18$) and control ($n = 16$) groups. A 12×2 mixed ANOVA with serial position as the within-subjects factor and group as the between-subjects factor was performed on the accuracy data. This analysis revealed significant main effects of serial position, $F(11, 352) = 97.05$, $p < .0001$, $\eta_p^2 = .752$, and group, $F(1, 32) = 4.78$, $p < .05$, $\eta_p^2 = .130$. As expected, accuracy was higher for the last several items in the list (the recency portion) than for the first several items (the pre-recency portion). In addition, the ADHD group was significantly less accurate overall

[1]In addition, it is also interesting to note that despite four decades of intensive study into the development of recall strategies across childhood, there has been relatively little investigation of order-of-report strategies, as opposed to other strategies (Bjorklund, 1987; Lehmann & Hasselhorn, 2007; Orstein & Naus, 1978; and Pressley & Schneider, 1997). These findings suggest that the development of order-of-report strategies may be an interesting topic of study in its own right; though this issue was not intended to be the primary focus of the present study. Rather, the present study was primarily concerned with those participants who used the recency strategy so that inferences about PM and SM could be drawn from recall performance.

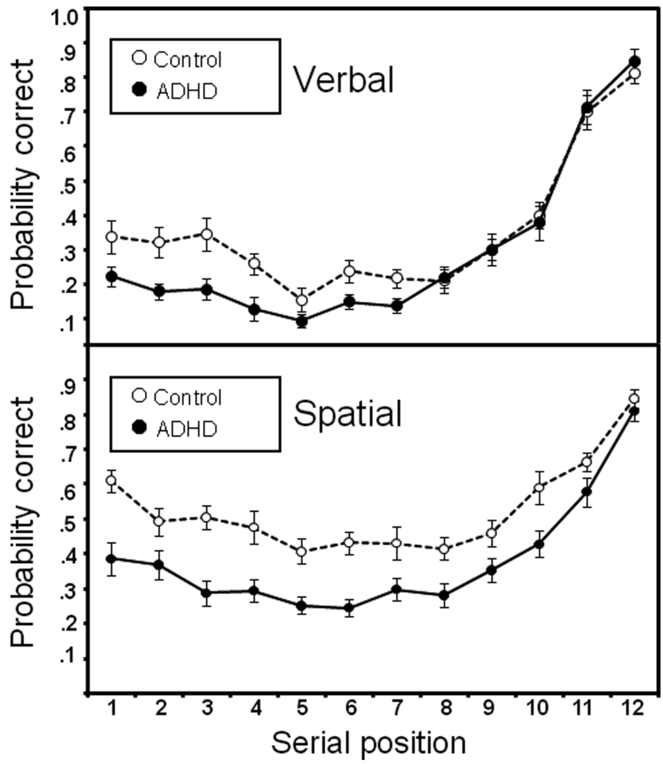

Figure 3 Probability of correct recall as function of serial position for both the ADHD and control groups in both the verbal (upper panel) and spatial (lower panel) free-recall tasks. Error bars represent standard error.

than the control group. Most importantly, however, there was a significant serial position × group interaction, $F(11, 352) = 2.36$, $p < .01$, $\eta_p^2 = .069$, indicating that the ADHD group was less accurate than the control group, but only when the ADHD group tried to recall the items from the pre-recency portion of the list. Subsequent analyses confirmed that the ADHD group was significantly less accurate than the control group recalling items from positions 1, 2, 3, 4, 6, and 7 (all *p*s < .05; *d*s ranged from 0.72 to 0.99), but equally accurate recalling items from positions 5, 8, 9, 10, 11, and 12 (all *p*s > .10; *d*s ranged from 0.00 to 0.54). Based on the dual-component model of working memory (Unsworth & Engle, 2007), these findings suggest that the ADHD group recalled less verbal information from SM, but equal verbal information from PM, relative to the control group.

In addition, we also examined these effects using IQ and "degree of recency strategy" as covariates. The degree of recency strategy was computed by averaging the probability of first recall across the last four items. This analysis confirmed that the present pattern of results cannot be attributed to a potential confound in IQ or degree of recency strategy between the two groups, as the serial position x group interaction remained significant even after these variables were entered as a covariates in the analysis, $F(11, 330) = 3.56$, $p < .001$, $\eta_p^2 = .106$.

Estimates of primary and secondary memory. The present study suggests that the ADHD group recalled less verbal information from SM, but not PM, relative to the control group. If this interpretation is correct, then estimates of the number of words successfully recalled from PM should be similar across the two groups whereas estimates of the number of words successfully recalled from SM should be different. This issue was addressed by estimating the capacity of PM and SM using Tulving and Colotla's (1970) method. A 2 × 2 mixed ANOVA with memory type as the within-subjects factor and group as the between-subjects factor was performed on the capacity estimates. Consistent with expectation, a significant memory type × group interaction, $F(1, 32) = 5.97$, $p < .025$, $\eta_p^2 = .157$, indicated that the ADHD and control groups both recalled an equal number of items from PM ($M = 2.48$ vs. $M = 2.54$, respectively, $t(32) = 0.30$, $p > .75$, $d = 0.10$), but a different number of items from SM ($M = 1.02$ vs. $M = 1.76$, respectively, $t(32) = 3.14$, $p < .005$, $d = 1.06$).

In addition, note that the present pattern of results cannot be attributed to a potential confound in IQ or degree of recency strategy between the two groups, as the critical memory type x group interaction remained significant even after these two variables were entered as a covariates in the analysis, $F(1, 30) = 5.64$, $p < .025$, $\eta_p^2 = .158$.

Spatial Free Recall

Order-of-report strategies. Examination of the probability-of-first-recall functions revealed that 35/63 (55.56%) of the participants fell into the recency group, 6/63 (9.52%) of the participants fell into the pre-recency group, and 22/63 (34.92%) of the participants fell into the combined group. Figure 1 (lower panel) shows probability of first recall as a function of serial position averaged over participants and trials in each of the three order-of-report groups. As can be seen, the probability of first recall was highest for the 12th list item in the recency group whereas the probability of first recall was highest for the first list item in the pre-recency group. Performance in the combined group fell in between these two extremes.[2]

The serial position curves associated with each of the recency, pre-recency, and combined groups are shown in Figure 2 (lower panel). The results were consistent with expectations and very similar to the results obtained on the verbal recall task: The recency group produced a serial position curve with a predominant recency effect; the pre-recency group produced a serial position curve with a predominant primacy effect; and the combined group produced a serial position curve that was intermediate between the two extremes, especially on the recency portion of the curve. These different patterns were confirmed with 2 × 3 mixed Analysis of Variance (ANOVA) with serial position as the within-subjects variable and recall strategy group as the between-subjects variable. The

[2]Overall, the number of participants who used the recency strategy on the spatial task ($n = 35$) was very similar to the number who used this strategy on the verbal task ($n = 34$); however, the number of participants who used the pre-recency and combined strategies varied more widely across the two tasks. In particular, 24 participants used the recency strategy across both tasks; 11 participants used the recency strategy in the spatial task, but not in the verbal task; 10 participants used the recency strategy in the verbal task, but not in the spatial task; and 18 participants did not use the recency strategy on either task. The consistency with which participants used a particular order-of-report strategy across the two tasks was estimated via the φ coefficient, which can be interpreted similar to Pearson's r. There was a significant correlation between the order-of-report strategies used across the two tasks, $\varphi(63) = .40$, $p < .05$, indicating that participants were moderately consistent in their use of order-of-report strategies across the two tasks. Nevertheless, because there was not perfect consistency in strategy usage across the two tasks, we will refrain from conducting a direct statistical comparison of the two task domains.

results revealed a significant serial position × recall strategy group interaction, $F(22, 660) = 7.24$, $p < .001$, $\eta_p^2 = .194$.

Examination of individual probability-of-first-recall functions also revealed that approximately equal numbers of participants from the two diagnostic groups fell into each of the three recall groups: 19 ADHD participants and 16 control participants used the recency strategy; 3 ADHD participants and 3 control participants used the pre-recency strategy; and 10 ADHD participants and 12 control participants used the combined strategy. Hence, the use of different recall strategies appeared to be independent of diagnostic group, $\chi^2(2) = 0.42$, $p > .70$, once again suggesting that the two groups reported the order of the list items in very similar ways.

In order to determine whether participants in the three order-of-report groups varied in age, full-scale IQ, verbal IQ, performance IQ, the number of inattentive symptoms, or the number of hyperactive/impulsive symptoms, separate 3 × 2 ANOVAs were conducted on each of these six dependent variables with recall strategy and diagnostic group as the two between-groups variables. There were no significant main effects or interactions involving recall strategy (all *p*s > .05).

In summary, as in the verbal task, the majority of adolescents (56%) used the recency strategy to perform the spatial recall task; and the number of adolescents who used the recency strategy in the ADHD group ($n = 19$) was approximately equal to the number of adolescents who used the recency strategy in the control group ($n = 16$). Table 3 describes the characteristics of the two diagnostic groups when only those participants who used the recency strategy were included in the sample. Overall, the characteristics of the two diagnostic groups when only the "recency strategy" participants were included were very similar to the characteristics of the two diagnostic groups when all the participants were included (see Table 1). Once again, we will assess whether the ADHD and

Table 3 Average Characteristics of the ADHD and Control Groups Including Only Those Participants who Used the Recency Strategy in the Spatial Free-Recall Task (Standard Deviation).

	Control ($n = 16$)	ADHD ($n = 19$)
# attention symptoms		
Parent or teacher	0.69 (1.25)	8.26 (1.10)
Parent only	0.19 (0.75)	8.12 (1.22)
Teacher only	0.50 (1.10)	4.18 (3.34)
# hyperactive/impulsive symptoms		
Parent or teacher	0.62 (1.20)	5.37 (2.91)
Parent only	0.31 (0.79)	5.18 (3.13)
Teacher only	0.31 (1.01)	1.18 (1.98)
Full-Scale IQ	113.75 (13.89)	97.16 (17.76)
Verbal IQ	112.56 (14.17)	95.63 (16.49)
Performance IQ	111.94 (15.65)	99.42 (20.79)
Age in years	13.07 (0.94)	12.66 (0.93)
Boys: girls	9:7	11:8
Comorbidities		
Anxiety	0	1
Depression	0	0
ODD	1	8

Note. ODD = Oppositional Defiant Disorder.

control groups differed in either the PM or SM components of working memory by comparing the two groups on the two measures of PM and SM using only those participants who utilized the recency strategy.

Serial position effects. The probability of correct recall is shown in Figure 3 (lower panel) as a function of serial position for both the ADHD (n = 19) and control (n = 16) groups. A 12 × 2 mixed ANOVA with serial position as the within-subjects factor and group as the between-subjects factor was performed on the accuracy data. This analysis revealed significant main effects of serial position, $F(11, 363) = 50.33$, $p < .0001$, $\eta_p^2 = .604$, and group, $F(1, 33) = 18.42$, $p < .0001$, $\eta_p^2 = .358$. As expected, accuracy was higher for the recency portion of the list than for the pre-recency portion; and, the ADHD group was significantly less accurate overall than the control group. There was also a marginally significant serial position × group interaction, $F(11, 363) = 1.79$, $p = .054$, $\eta_p^2 = .051$. As can be seen in Figure 3, the ADHD group was less accurate than the control group on all but the last two items. Subsequent analyses confirmed that the ADHD group was significantly less accurate than the control group recalling items from positions 1 to 10 (all ps < .05; ds ranged from 0.71 to 1.51), but equally accurate recalling items from positions 11 and 12 (both ps > .10; ds were 0.57 and 0.31, respectively).

Note, however, that the marginally significant serial position × group interaction should be interpreted cautiously as it was no longer found to be significant when IQ was entered as a covariate in the analysis, $F(11, 341) = 0.72$, $p > .70$, $\eta_p^2 = .023$. Instead, this analysis revealed only a significant main effect of group, $F(1, 31) = 7.33$, $p < .02$, $\eta_p^2 = .191$. In summary, analysis of serial position effects revealed that the ADHD group was consistently less accurate than the control group on the spatial recall task, and this difference appeared to extend further into the recency portion of the list when spatial items were presented than when verbal items were presented. Such findings provide relatively strong evidence that the ADHD group is deficient in the recall of spatial information from SM, relative to the control group; in addition, the present findings also provide some (albeit weaker) evidence that the ADHD group is also deficient in the active maintenance of spatial information in PM, relative to the control group. Converging evidence for these conclusions was sought in the subsequent analysis.

Estimates of primary and secondary memory. A 2 × 2 mixed ANOVA with memory type as the within-subjects factor and group as the between-subjects factor was performed on the capacity estimates. Consistent with expectation, a significant memory type × group interaction, $F(1, 33) = 9.90$, $p < .005$, $\eta_p^2 = .231$, indicated that the capacity difference observed between the ADHD and control groups was smaller for PM (M = 2.26 vs. M = 2.58, respectively) than it was for SM (M = 2.31 vs. M = 3.75, respectively). However, subsequent analyses revealed that the capacity difference observed between the ADHD and control groups was significant for both PM, $t(33) = 2.25$, $p < .05$, $d = 0.77$, and SM, $t(33) = 4.10$, $p < .001$, $d = 1.39$.

In addition, the memory type x group interaction remained marginally significant after IQ and degree of recency strategy were entered as covariates in the analysis, $F(1, 31) = 3.18$, $p = .08$, $\eta_p^2 = .093$. However, although subsequent analyses confirmed that the ADHD group recalled fewer locations from SM than the control group, $F(1, 31) = 6.40$, $p < .02$, $\eta_p^2 = .171$, the previous group difference observed for PM was no longer significant, $F(1, 31) = 2.16$, $p > .15$, $\eta_p^2 = .065$. These findings corroborate the previous findings by showing that the ADHD group has a relatively strong deficiency recalling spatial information from SM, but only a relatively weak deficiency in maintaining spatial information in PM, relative to the control group.

GENERAL DISCUSSION

The present study has applied the dual-component model of working memory to performance on verbal and spatial free-recall tasks in an effort to shed light on the nature of the working memory deficit that is typically observed in individuals with ADHD relative to age-matched controls. The present study has provided important new evidence that the maintenance of information in PM appears to be largely intact whereas recall of information from SM appears to be deficient in ADHD relative to age-matched controls. Moreover, this dissociation was consistently observed across both verbal and spatial task domains, and it was observed even when preexisting differences in IQ and strategy usage were statistically controlled. The observed dissociation thus provides a clearer understanding of the deficient neurocognitive mechanisms that underlie ADHD. As such, the present findings add to a growing body of research that demonstrates the theoretical utility of the dual-component model for understanding various group differences in working memory capacity (Unsworth, 2007; Unsworth & Engle, 2007).

In arriving at this conclusion, we should point out two potential limitations of the present study. First, the observed pattern of results was based exclusively on those individuals who used the recency order-of-report strategy in the present study. For this reason, the sample size in each of the ADHD and non-ADHD groups was reduced by approximately half. Thus, a major priority for future studies is to replicate the main findings reported in this article using larger samples. Note that future investigations of the dual-component model may reduce variation due to different order-of-report strategies without sacrificing sample size by providing explicit instructions to utilize a recency strategy (see also, Craik & Birtwistle, 1971).

The second limitation was that reading ability was not formally assessed in the present study, which may have affected performance in the verbal free-recall task. Note, however, that it is unlikely that the observed dissociation between PM and SM can be attributed to a potential confound in reading ability between the two groups because such a difference would be expected to lead to deficits in both components of working memory (see also, Douglas & Benezra, 1990). In addition, it should also be noted that a similar dissociation was observed on both verbal and spatial tasks, which also mitigates this concern.

The present conclusion suggesting that recall from PM is intact in ADHD may once again lead some researchers to question whether free recall is a valid measure of the active maintenance component of working memory, perhaps because this task did not include serial-recall instructions or adequate interference as in complex span tasks. However, the mere use of serial-recall instructions does not preclude the joint operation of both PM and SM components of working memory, and the use of interference may actually make performance more dependent on SM mechanisms, if the interference effectively causes information to be lost from PM (Unsworth & Engle, 2006). Thus, it may be difficult to design recall tasks that can measure PM independent of SM; though recall tasks do exist that can measure SM independent of PM (e.g., the delayed free-recall task, the continuous distractor paradigm; Unsworth, 2007). If this analysis is correct, then the best solution to measuring PM is to devise recall tasks that can provide separate estimates of both PM and SM components, as was accomplished in the present study.

Of course, if the active maintenance component of working memory can be aligned with other mechanisms such as executive attention (Kane & Engle, 2002) or the focus of attention (Cowan, 2001), and if these attentional mechanisms can mediate performance on other tasks that do not require recall, then it may be possible to devise tasks capable of isolating these more basic mechanisms without implicating the SM-component. Indeed, there is a large body of research that has examined the relative integrity of executive attention and focus of attention across samples of ADHD and non-ADHD children using a variety of visual orienting and visual selection tasks (see Huang-Pollack & Nigg, 2003, for a review; see also Huang-Pollack, Nigg, & Carr, 2005). However, consistent with the present results, this evidence suggests that the operation of these attentional mechanisms is largely intact in ADHD.

The present findings provided strong evidence that the working memory deficit associated with ADHD represents a SM deficit, not a PM deficit. But why did this SM deficit occur? In general, retrieval from SM involves a probabilistic search through a memory set that contains both target and nontarget items. Due to the small sample size of the present study, we did not attempt to provide a more detailed examination of the contents and dynamics of this search process. However, future studies could provide a more detailed examination of this search process by examining additional measures of recall performance such as intrusion errors and interresponse times (Rohrer & Wixted, 1994; Unsworth & Engle, 2007; Wixted & Rohrer, 1994). If the ADHD group has deficient recall from SM, then this deficiency may arise because their search set contains more irrelevant information. Consequently, the ADHD group may commit more recall errors than the control group. Likewise, interresponse times that measure the latency between recall responses may increase more steeply in the ADHD group than in the control group because the search sets in the ADHD group contain more information (relevant items + irrelevant items).

In addition, although group comparisons of PM and SM controlled for order-of-report strategy in the present study, it is interesting to speculate that the observed SM deficit may have arisen because individuals in the ADHD group did not utilize one or more of the various other rehearsal strategies (e.g., cumulative rehearsal) that appear to be available to this age group during free-recall tasks (Lehmann & Hasselhorn, 2007; Orstein & Naus, 1978; and Pressley & Schneider, 1997). Indeed, other research has demonstrated that individuals with ADHD are deficient in their implementation of organizational memory strategies that may be used with semantically related verbal information, though not in their metacognitive knowledge of such strategies (Cornoldi, Marzocchi, Belotti, Caroli, De Meo, & Braga, 2001; see also Douglas & Benezra, 1990). Thus, the present findings warrant an expanded investigation of the use of memory strategies such as cumulative rehearsal across ADHD and non-ADHD groups.

The observed dissociation between PM and SM in ADHD also has potential clinical implications and may help clarify other recent findings suggesting that systematic training of working memory can significantly enhance working memory and fluid IQ while also reducing the expression of ADHD symptoms (Klingberg et al., 2005). In this intervention, children practiced verbal and spatial working memory “storage” tasks in which lists of verbal items or arrays of lights were presented on each trial and participants were required to try to recall as many items as possible. In the treatment condition, the number of items to be remembered on each trial was adjusted to match the span of the individual on a trial-by-trial basis; whereas, in the control condition, the number of items to be remembered on each trial was kept low.

According to the present account, the exposure to increasingly greater amounts of information in Klingberg et al.'s (2007) treatment condition likely overwhelms the capacity of PM, thereby providing trainees with the opportunity to recall information from SM. In this view, training may not improve the ability to maintain information in PM so much as it improves the ability to efficiently encode and retrieve task-relevant information from SM after it has been lost from PM. As the present study has shown, such enhancement may alleviate ADHD symptoms because this mechanism is deficient in ADHD. Moreover, such enhancement may also improve fluid IQ because individuals with higher capacity to recall information from SM tend to have higher fluid IQs (Mogle et al., 2008; Unsworth & Engle, 2006).

In conclusion, the present study has applied the dual-component model of working memory to performance on verbal and spatial free-recall tasks in an effort to shed light on the nature of the working memory deficit that is typically observed in individuals with ADHD relative to age-matched controls. The primary results showed that the maintenance of information in PM appears to be largely intact whereas recall of information from SM appears to be deficient in ADHD relative to age-matched controls. Moreover, similar outcomes were observed across both verbal and spatial task domains. The present findings therefore provide a clearer understanding of the deficient neurocognitive mechanisms that underlie ADHD and as such may also lead to the design of more potent cognitive interventions involving the intensive training of working memory.

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