

CE Component analysis of verbal versus spatial working memory training in adolescents with ADHD: A randomized, controlled trial

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Adaptive training of working memory (WM) using the Cogmed-RM intervention has recently shown some efficacy as an alternative treatment for ADHD, but this intervention may not be optimally designed. A recent component analysis of WM has suggested that maintenance in primary memory (PM) appears to be largely intact whereas recall from secondary memory (SM) appears to be deficient in ADHD relative to age-matched controls. However, extrapolating from basic research, there is reason to believe that Cogmed-RM may target the PM component more than the SM component; though training with spatial exercises may target the SM component more than training with verbal exercises. To investigate, participants diagnosed with ADHD were randomly assigned to either a verbal training condition ($n = 24$) or a spatial training condition ($n = 23$) using a randomized, controlled design, and both groups were instructed to complete at least 20 days of training. The PM and SM components of WM were assessed immediately before and after training using both verbal and spatial free recall tasks. The main findings showed that both versions of the intervention enhanced the maintenance of information in PM regardless of test modality, but not the recall of information from SM. Therefore, the component of WM that is improved by Cogmed-RM is not the same component of WM that is deficient in ADHD.

Keywords: Adaptive working memory training; ADHD; Working memory; Intervention; Component analysis.

Successful treatment of attention deficit/hyperactivity disorder (ADHD) requires a thorough scientific understanding of the deficient neurocognitive mechanisms thought to underlie behavioral symptoms and impaired functioning (Nigg, 2006). The constellation of behavioral symptoms comprising ADHD has been hypothesized to arise, at least in part, from deficits in executive processes that support and enable goal-directed behavior across time (Barkley, 1997; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). One of the largest and most robust differences observed between children with ADHD and age-matched controls is in the domain of working memory (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010; Kofler, Rapport, Bolden, Sarver, & Raiker, 2010; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Rapport et al., 2009; Willcutt et al., 2005).

Generally speaking, working memory (WM) is critical to everyday functioning because it allows individuals to maintain and retrieve task-relevant information in the

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presence of irrelevant distraction (Unsworth & Engle, 2007a). 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, a meta-analysis of existing evidence has been interpreted to suggest that ADHD is associated with a weakness in the active maintenance and manipulation of information and, furthermore, that these mechanisms are more impaired in the spatial domain than in the verbal domain (Martinussen et al., 2005).

At the same time that neurocognitive impairments in WM have been consistently documented in the ADHD literature, other research has begun to establish that verbal and spatial WM capacity is plastic and may be enhanced via adaptive training (Holmes, Gathercole, & Dunning, 2009; Jaeggi, Buschkuhl, Jonides, & Perrig, 2008; Olesen, Westerberg, & Klingberg, 2004; see Klingberg, 2010, for a review). Given that the symptoms associated with ADHD arise, at least in part, from weaknesses in WM, Klingberg et al. (2005) recently examined whether adaptive WM training might serve as an effective intervention for ADHD (see also, Klingberg, Forssberg, & Westerberg, 2002). Specifically, this study investigated whether 25 adaptive training sessions using a mixture of verbal and spatial WM exercises would improve verbal and spatial WM and would reduce ADHD symptoms in a sample of unmedicated children with ADHD using a randomized, controlled design. Two similar versions of the computerized WM training program were compared. In the treatment condition, children performed verbal and spatial WM exercises in which the number of items to be remembered on each trial was adaptively adjusted to match the capacity of the individual subject. The beneficial effects of training were hypothesized to be strongest under these conditions. In the control condition, the same training tasks were used, but the number of items to be remembered on each trial was kept low. Consequently, the beneficial effects of training were expected to be much weaker under these conditions. Both WM capacity and ADHD symptoms were rated before, immediately after, and three months after the intervention.

With respect to WM capacity, the critical results showed significant improvements in the treatment group relative to the control group immediately after the intervention on all measures: spatial WM (forward and backward span board), verbal WM (forward and backward digit span), active goal maintenance (Stroop RT and accuracy), and fluid IQ (Raven's Progressive Matrices). These significant improvements were also retained in the 3-month follow-up on all measures of cognitive functioning except number correct on Stroop and Raven's progressive matrices, which were both subject to a ceiling effect. In addition, the results also showed significant reductions in parent-rated inattentive and hyperactive/impulsive symptoms in the treatment group relative to the control group both immediately after and 3 months after intervention. However, although teacher-rated symptoms showed a similar trend as the parent-rated symptoms along both dimensions, these findings did not attain significance at either time point following intervention.

The findings reported by Klingberg et al. (2005) provide preliminary evidence that WM training can enhance WM and reduce the symptoms of inattention, hyperactivity, and impulsivity that are associated with ADHD. As such, this intervention, which has come to be called "Cogmed-RM," signals the possibility of a new wave of cognitive-based treatments for ADHD that are specifically focused on enhancing the basic neurocognitive processes that are thought to be impaired in ADHD.

The present research further examined the efficacy of Cogmed-RM by conducting a more rigorous "component analysis" of WM. A central assumption underlying the Cogmed-RM intervention is that ADHD symptoms arise, at least in part, because WM

mechanisms are impaired, and the intervention alleviates these symptoms by enhancing at least some of these deficient mechanisms. However, there has been no attempt to determine whether the components of WM that are enhanced following adaptive training are the same components that are deficient before training.

Furthermore, with respect to the deficient components, although there appears to be strong behavioral evidence that ADHD is associated with a weakness in the active maintenance and manipulation of both verbal and spatial information (Martinussen et al., 2005), this conclusion has been based primarily on models of WM that have not emphasized other, potentially important, components of WM involving the strategic retrieval of information that has been lost from WM (due to failures in active maintenance). For instance, Unsworth and Engle's (2007a) dual-component model specifies two basic functions of WM: (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).

According to the dual-component model, accurate interpretation of group differences in WM 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 conflated with the effects of the other. Unfortunately, the studies reviewed in previous meta-analyses of ADHD and non-ADHD individuals (Martinussen et al., 2005; Willcutt et al., 2005) did not consider this possibility and therefore cannot differentiate whether the observed difference in WM capacity reflects a difference in the ability to recall information from PM (as was inferred), the ability to recall information from SM, or both.

In order to address this gap in knowledge, Gibson, Gondoli, Flies, Dobrzanski, and Unsworth (2010) recently applied the dual-component model of WM to ADHD (Combined and Primarily Inattentive subtypes) using both verbal and spatial immediate free recall (IFR) tasks. Unsworth and Engle (2007a) demonstrated that performance on a verbal IFR task loaded just as highly on a latent WM construct as did performance on other, more traditional, measures of WM (such as operation span). However, unlike these more traditional measures, IFR allows separate estimates of PM and SM to be derived so long as participants use a "recency" order-of-report strategy in which they report items from the end of the list before they report items from the beginning of the list. In particular, performance on IFR tasks can be divided into recency and pre-recency portions; and, 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.

Based on only those participants who utilized the recency order-of-report strategy, Gibson et al. (2010) provided important new evidence that the maintenance of information in PM was largely intact whereas the retrieval of information from SM was deficient in adolescents with ADHD relative to age-matched adolescents without ADHD. For instance, probability correct as a function of serial position was used as a measure of recall from PM (recency portion of the curve) and SM (pre-recency portion of the curve). Within the verbal domain, Gibson et al. found that the ADHD and non-ADHD groups were equally accurate recalling items from the recency portion of the list (Items 8 to 12), whereas the ADHD group was less accurate than the non-ADHD group recalling items from the pre-recency portion of the list (Items 1 to 7). Similar findings were obtained in the spatial domain except

that the group difference extended from the first item to the tenth item, corroborating the impairment in the SM component and also suggesting increasing impairment in the PM component as well.

In addition to examining serial position effects, Gibson et al. (2010) also used Tulving and Colotla's (1970) method to provide estimates of the number of items that can be recalled from PM and SM (see also, Unsworth & Engle, 2007a). 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 its recall were tallied. An item was considered to be recalled from PM when there were seven or fewer items intervening between that item's presentation and its recall. In contrast, an item was considered to be recalled from SM when there were more than seven items intervening between that item's presentation and its recall. Other researchers (Craik & Birtwistle, 1971; Unsworth & Engle, 2007a) have validated these estimates by showing that recall from SM was affected by the buildup of proactive interference whereas recall from PM was not.

In the verbal domain, estimates revealed that the ADHD and non-ADHD groups both recalled an equal number of items from PM ($M = 2.48$ vs. $M = 2.54$, respectively), but a significantly different number of items from SM ($M = 1.02$ vs. $M = 1.76$, respectively). In addition, this significant difference was maintained even when IQ and recall strategy were used as covariates. Likewise, in the spatial domain, estimates revealed that the capacity difference observed between the ADHD and non-ADHD groups was significantly smaller for PM ($M = 2.26$ vs. $M = 2.58$, respectively) than it was for SM ($M = 2.31$ vs. $M = 3.75$, respectively), but the capacity difference observed between the ADHD and non-ADHD groups was significant for both PM and SM. However, the group difference observed for PM was no longer significant when IQ and recall strategy were used as covariates whereas the group difference observed for SM remained significant.

The observed dissociation between PM and SM in ADHD thus provides a clearer understanding of the deficient neurocognitive mechanisms that underlie ADHD. If this component analysis is correct, then adaptive WM training interventions for ADHD should target the SM component more than the PM component. However, there is some reason to believe that Cogmed-RM may actually target the PM component more than the SM component. More specifically, tasks that have been designed to measure WM capacity have traditionally been divided into "simple span" and "complex span" tasks. Simple span tasks typically involve the presentation of lists of various lengths that participants attempt to recall in forward serial order immediately following the conclusion of the list. In contrast, complex span tasks typically involve the performance of two tasks on each trial. For instance, in the operation span task (Turner & Engle, 1989), participants must first solve a mathematical operation and then attempt to store a simultaneously (or sequentially) presented list item on each trial. As in simple span tasks, lists of various lengths are presented that participants attempt to recall in forward serial order immediately following the conclusion of the list.

Using confirmatory factor analysis, Unsworth and Engle (2007b) showed that simple span tasks such as forward word span loaded more highly on the PM factor than on the SM factor. In contrast, complex span tasks such as operation span loaded more highly on the SM factor than on the PM factor. According to Unsworth and Engle, complex span tasks provide better measures of SM abilities than PM abilities because the processing task causes all but the last of the to-be-remembered list items to be displaced from PM into SM.

As a result, successful recall in complex span tasks mostly reflects cue-dependent retrieval processes that access information from SM. Simple span tasks provide better measures of PM abilities than SM abilities because the displacement of items from PM into SM only occurs with relatively long list lengths in these tasks (i.e., with list lengths that exceed the storage capacity of PM). As a result, successful recall in simple span tasks mostly reflects the unloading of information that is actively maintained PM, at least when list-length is relatively short. However, successful recall in simple span tasks may increasingly measure SM abilities (as opposed to PM abilities) as list-length increases.

With this distinction in mind, the verbal and spatial exercises contained in Cogmed-RM may be considered to be simple span tasks because lists of verbal items or arrays of lights are presented on each trial and participants are simply required to try to recall as many items as possible in serial order. According to Unsworth and Engle's (2007b) analysis, this intervention should therefore have a stronger effect on PM abilities than SM abilities. If so, then Cogmed-RM may not be optimally designed to treat ADHD. Note, however, that individuals may be exposed to increasingly longer lists of to-be-remembered items as training progresses that may serve to overwhelm the capacity of PM, thereby training recall from SM. Thus, it is possible that this intervention may improve the ability to efficiently encode and to retrieve task-relevant information from SM after it has been lost from PM, at least to some extent. At the present point in time, there has been no systematic investigation of which components of WM are enhanced by Cogmed-RM. Therefore, the primary purpose of the present study was to investigate whether the Cogmed-RM intervention enhances only the PM component of WM, or whether this intervention also enhances the SM component in a sample of medicated adolescents with ADHD.

In addition, recall that the standard Cogmed-RM intervention contains a mixture of both verbal and spatial WM exercises. Other research examining the relation between WM capacity and higher level cognitive abilities such as fluid IQ has suggested that spatial simple span tasks may function more like complex span tasks than verbal simple span tasks (Kane, et al., 2004; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Oberauer, 2005; Shah & Miyake, 1996). Thus, it is possible that adaptive training with spatial simple span exercises may enhance the SM component more than adaptive training with verbal simple span exercises. Accordingly, the Cogmed exercises were divided into two separate training conditions—a verbal training condition and a spatial training condition—to examine whether spatial training might be more effective than verbal training using a randomized, controlled design.

There were two primary outcome measures of interest that were administered immediately before and after training—serial position effects and estimates of the capacity of PM and SM—both of which were derived from performance on verbal and spatial IFR tasks. Note that the use of both verbal and spatial IFR tasks also allowed us to examine whether any observed enhancement of WM would extend beyond the specific domain of training. Evaluation of these two primary outcome measures will allow us to determine whether training with verbal or spatial simple span exercises enhances only the PM component of WM. Because of the exploratory nature of this study, we focused only on the immediate effects of training because we expected these effects to be strongest at this point in time.

In the present study, we considered interventions that enhance only the PM component to be undesirable (or at least nonoptimal), given that ADHD is associated with a greater impairment in the SM component than in the PM component (Gibson et al., 2010); though we acknowledge that such interventions may have some beneficial effects on ADHD symptoms (see, e.g., Klingberg et al., 2005). However, if the present analysis is

correct, then the beneficial effects of these interventions should be interpreted to operate via compensatory pathways: Namely, the enhancement of PM may reduce the burden on deficient SM processes by decreasing the amount of information that is lost from PM thereby decreasing the amount of information that must be recalled from SM. Thus, as a secondary outcome, we also measured ADHD symptoms immediately before and after training using the DuPaul ADHD rating scale (DuPaul, Power, Anastopoulos, & Reid, 1998). Improvements in ADHD symptoms should follow the same pattern of improvements observed in WM following training.

METHOD

Recruitment of Participants

Adolescents, aged 11–16 years, were recruited from three middle schools (Grades 6 to 8) in a Midwestern public school district during the fall of 2008 and 2009. Initial contact letters briefly describing the study 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. Approximately 6% of the total population was contacted. A total of 53 families responded and were scheduled for an initial screening. Target sample size was based on the ability to observe significant enhancement in the PM component, which was expected to reflect a relatively large training effect. A total sample of 31 was required to detect a large effect with 90% power, and a total sample of 23 was required to detect a large effect with 80% power. The protocol for the present study was approved by the institutional review board at the University of Notre Dame.

Initial Screening

The primary caregiver and adolescent 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 primary caregiver provided information about the adolescent's treatment plan during this session. The type, time, and dosage of all medications were documented using a questionnaire. The primary caregiver then 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 *Diagnostic and Statistical Manual of Mental Disorders*, fourth edition (*DSM-IV*; American Psychiatric Association, 1994) ADHD symptoms. Because there were no specific hypotheses regarding the subtypes of ADHD, no attempt was made to differentiate between the primarily inattentive (ADHD-PI) and combined (ADHD-C) subtypes. In addition, a variety of other, potentially comorbid, psychiatric conditions (such as Anxiety, Depression, and Oppositional Defiant Disorder) were also examined. A diagnosis of ADHD was required for inclusion in the study. Five of the 53 respondents failed to meet this diagnostic criterion.

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. Note that the initial phone contact with the primary caregiver revealed that 42 of the 53 adolescents were being treated with medication at the time of the

initial screening (stimulant ADHD medication [dexamethylphenidate, lisdexamfetamine, methylphenidate, and mixed amphetamine salts]: $n = 40$; nonstimulant ADHD medication [atomoxetine, guanfacine]: $n = 3$; and nonstimulant non-ADHD medication [bupropion]: $n = 1$). All stimulant ADHD medication and atomoxetine were withheld for at least 24 hours prior to the WASI; however, the non-ADHD medication and guanfacine were not withheld. A full-scale IQ greater or equal to 70 was required for inclusion in the study. One of the 53 respondents failed to meet this intellectual criterion.

Pretraining Sessions

Immediately before the intervention, the adolescents and their primary caregivers participated in a 2-hour laboratory session at the same location as the initial screening. Primary caregivers were instructed to follow their adolescent's normal medication treatment plan before arriving to the pretraining session based on the information they provided at the initial screening session. The type, time, and dosage of that day's medication were also documented at the pretraining session using the same questionnaire that was used at the initial screening session.

During each session, the adolescent performed a verbal and spatial version of the IFR task. Both of these tasks were administered by a research assistant who was blind to training condition. The verbal task was based on the IFR task used by Unsworth and Engle (2007a) and Gibson et al. (2010). Participants were presented with 15 lists of 12 unique 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 1 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 instructed to verbally recall as many words as possible. Note that Gibson et al. (2010) found that only approximately half of their ADHD and non-ADHD samples spontaneously used the critical recency order-of-report strategy. Thus, in the present study, participants were explicitly instructed to begin recalling words toward the end of the list first (see also, Craik & Birtwistle, 1971). Participants reported their answers into a microphone that was connected to a digital recorder. A response was scored correct if it matched one of the list items, 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). 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 30 seconds to recall the word 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). Three practice trials using letter stimuli (instead of words) preceded the experimental 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, Hirvikoski, Forssberg, and Klingberg (2004). Participants were presented with 15 lists of 12 different locations that were marked by white squares. Squares appeared at any one of 180 unique screen locations (15 lists x 12 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 1 second. At the conclusion of the list, participants were prompted to use the computer mouse to recall as many locations as possible by clicking on the relevant locations. As in the verbal task, 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. For each response, the computer recorded the location of the mouse click, the order of the mouse click, the time of each mouse click, and the number of correct recall responses. A response was scored correct if it matched one of the list items. As in the verbal task, participants were given 30 seconds to recall the spatial lists, and they were required to wait the full 30 seconds before proceeding to the next trial. In order to make the task manageable, only 60 of the possible 180 squares appeared at any one time. These 60 squares were selected randomly from the set of 180 possible locations and they remained visible for five consecutive trials (5 trials x 12 cued locations = 60 locations). At the conclusion of the fifth trial in each set, a new set of 60 locations was randomly selected from the 180 possible locations without replacement. This sequence of 5 trials repeated three times for a total of 15 trials. The three sets of 60 randomly selected squares were determined separately for each participant. As in the verbal task, three practice trials preceded the experimental trials.

The two primary outcome measures were calculated from the IFR tasks: (a) 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), and (b) 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. Recall that an item was considered to be recalled from PM when there were seven or fewer items intervening between that item's presentation and its recall. In contrast, an item was considered to be recalled from SM when there were more than seven items intervening between that item's presentation and its recall.

While the adolescent was completing the two IFR tasks, the primary caregiver completed the home version of the DuPaul ADHD rating scale (DuPaul et al., 1998). In addition, the school version of the DuPaul ADHD rating scale was also sent to one of the adolescent's teachers (identified at the initial screening session) approximately 2 weeks before the pretraining session. All teacher ratings that were returned were returned at most 1 week before the adolescent began training. For each of the 18 *DSM-IV* ADHD symptoms, parents and teachers rated whether "never or rarely (0)," "sometimes (1)," "often (2)," or "very often (3)" described the adolescent's behavior at home or school, respectively. Parent and teacher ratings were tallied separately for the nine inattentive symptoms and for the nine hyperactive/impulsive symptoms. 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 adequate as demonstrated by good internal reliability coefficients, high test-retest reliability, and effective discriminatory power (DuPaul et al., 1998). Note that two teachers failed to return their ratings for the pretraining session and were unresponsive to repeated attempts to collect these data; the two associated adolescents were excluded from the final analysis of the teacher-rated secondary outcome.

Primary caregivers and adolescents were paid \$20.00 each for participating in the pretraining session. Teachers were paid \$5.00 regardless of whether they completed the rating scale or not.

Working Memory Training

The 47 adolescents who met the diagnostic and intellectual inclusion criteria were randomly assigned to one of the two WM training groups. A programmer employed by Cogmed generated the random allocation sequence and then assigned participants to one of the two conditions in a consecutive fashion according to their ID number. Twenty-four adolescents were randomly assigned to the verbal WM training group and 23 adolescents were randomly assigned to the spatial WM training group. Participants were informed that they would be randomly assigned to one of two training conditions, but the nature of these two training conditions was not described further. Both the participants and the research assistants assessing outcomes were blind to training condition. Note that the primary caregiver was asked to maintain their adolescent's normal treatment plan during the training phase of the study based on information provided at the pretraining session.

Each of the two training conditions was composed of a total of six exercises: Five exercises were unique to each training condition and one exercise was common to both training conditions. Nine of the 11 exercises were extracted directly from the standard Cogmed-RM intervention; the two remaining exercises were modified versions of the standard exercises.

The five unique exercises in the verbal training group were: Corrector, Decoder, Input Module with Lid (forward version), Stabilizer (standard version), and Stabilizer (random version). These five simple span exercises involved remembering lists of letters or digits that were typically recalled in the forward serial order. Note that in the two stabilizer exercises, dots of light appeared either in an ordered sequence (standard version) or in a random sequence (random version) along with each of the to-be-remembered letters. At the completion of the list, one of the letters from the list was presented and participants had to click on the dot that had been associated with the letter. Thus, some of the verbal tasks may have contained a spatial component (see the "General Discussion" section for further discussion of this issue).

The five unique exercises in the spatial training group were: Asteroids, Data Room, Rotating Dots, and Visual Data Link (stationary version) and Visual Data Link (rotating version). These five simple span exercises involved remembering the positions of dots in two- or three-dimensional grids that translated, rotated, or remained stable. All the exercises required participants to remember the lists in the forward serial order.

The one common exercise (Space Whack) was included to help maintain blindness to training condition in the event that two participants happened to discuss their training experience with each other (though this did not occur). In addition, the common exercise was also included to break the monotony of the five unique exercises as this exercise resembled the popular "whack-a-mole" arcade game (albeit involving space aliens that emerged from craters) and it was judged to be the most "game-like" by the researchers.

For each of the exercises, the length of the list was automatically adjusted, on a trial-by-trial basis, to match the WM span of the participant on that particular exercise. Both WM training groups completed their exercises at home on a personal computer that was connected to the Internet. Participants were allowed to complete the exercises in any order. All recall responses were reported by clicking a cursor on the display using a computer mouse. Positive feedback was provided verbally by the program after most successful trials; in addition, participants also received "energy" on all successful trials that they could

use in a video game involving racing robots at the end of each day of training. Participants completed a total of 120 trials per day (20 trials x 6 exercises) before they were allowed to progress to the next day of training. By comparison, trainees complete a total of 115 trials per day in the standard Cogmed-RM regimen. Performance on the training exercises was automatically uploaded to a secure Web site that was monitored for compliance by the authors. All the authors were certified by Cogmed to administer the intervention, and they made weekly phone calls to the adolescents to provide feedback and to answer questions about the training in accordance with this certification.

Both WM training groups were instructed to complete a maximum of 25 days of training, and a minimum of 20 days was required for inclusion in the study. Seven of the 47 adolescents (14.89%) failed to meet this minimum training criterion ($n = 3$ in the verbal group and $n = 4$ in the spatial group); these individuals were not included in the final analysis of primary and secondary outcomes. Note that Cogmed has documented a total of 15,000 completed trainings worldwide, 4000 of which have been completed in North America. In addition, 75% of the users in North America are children (under 18 years of age), and compliance by these North American children has been documented to be 90% (personal communication from Jonas Jendi, Cogmed CEO). Thus, the compliance rate observed in the present sample (approximately 85%) was similar to the compliance rate observed in the population of North American children who have attempted Cogmed-RM. Of the 21 adolescents who completed the verbal training, 17 completed 25 days of training, 2 completed 24 days of training, and 2 completed 23 days of training. Of the 19 adolescents who completed the spatial training, 16 completed 25 days of training, 2 completed 24 days of training, and 1 completed 20 days of training.

Posttraining Assessment

Within one week of completing the intervention, the primary caregiver and adolescent returned to the laboratory for a 2-hour laboratory session at the same location as the pretraining session. During scheduling of the posttraining session, the primary caregiver was reminded to medicate their adolescent at the same time and with the same dosage based on the information they provided at the pretraining session. The posttraining session was also scheduled at the same time of day as the pretraining session. Note that two of the adolescents (both from the spatial training condition) changed their medication between the pretraining and posttraining sessions: One adolescent changed from lisdexamfetamine (Vyvanse) to sertraline (Zoloft) and the other changed from methylphenidate (Concerta) to guanfacine (Intuniv); however, these two individuals were retained in the final analysis of primary and secondary outcomes. Note also that two of the adolescents (one from each of the two training conditions) who completed all 25 days of training failed to report for the posttraining session and were unresponsive to repeated attempts to schedule their posttraining visit; these two individuals could not be included in the final analysis of primary and secondary outcomes.

The same primary and secondary outcome measures that were administered at the pretraining session were readministered at the posttraining session, and all participants were compensated at the same rate. Note that the spatial data for one of the adolescents was lost at the posttraining session due to a computer error; this individual was not included in the final analysis of primary outcomes but was included in the final analysis of secondary outcomes. All participants completed the study during the spring semester.

RESULTS

Figure 1 summarizes the flow of participants through the trial and Table 1 describes the characteristics of the 47 adolescents who met the initial diagnostic and intellectual inclusion criterion. As expected, there were no significant differences between the two training groups in age, $t(45) = -1.52, p > .10$; full-scale IQ, $t(45) = -1.48, p > .10$; verbal IQ, $t(45) = -0.76, p > .45$; or performance IQ, $t(45) = -1.20, p > .20$. In addition, the ratio of boys to girls and the presence of comorbidities were also similar between the two groups.

Analysis of Working Memory Training

Figure 2 shows how the average span length, averaged again over the six training exercises, changed across the 20 mandatory days of training in each of the two training groups. The effect of training duration on average span length was evaluated using a two-way mixed Analysis of Variance (ANOVA) with training duration (Day 1 to Day 20) as the sole within-subjects factor and training group (verbal vs. spatial) as the sole between-subjects factor. As expected, average span length rose sharply over the first few days in

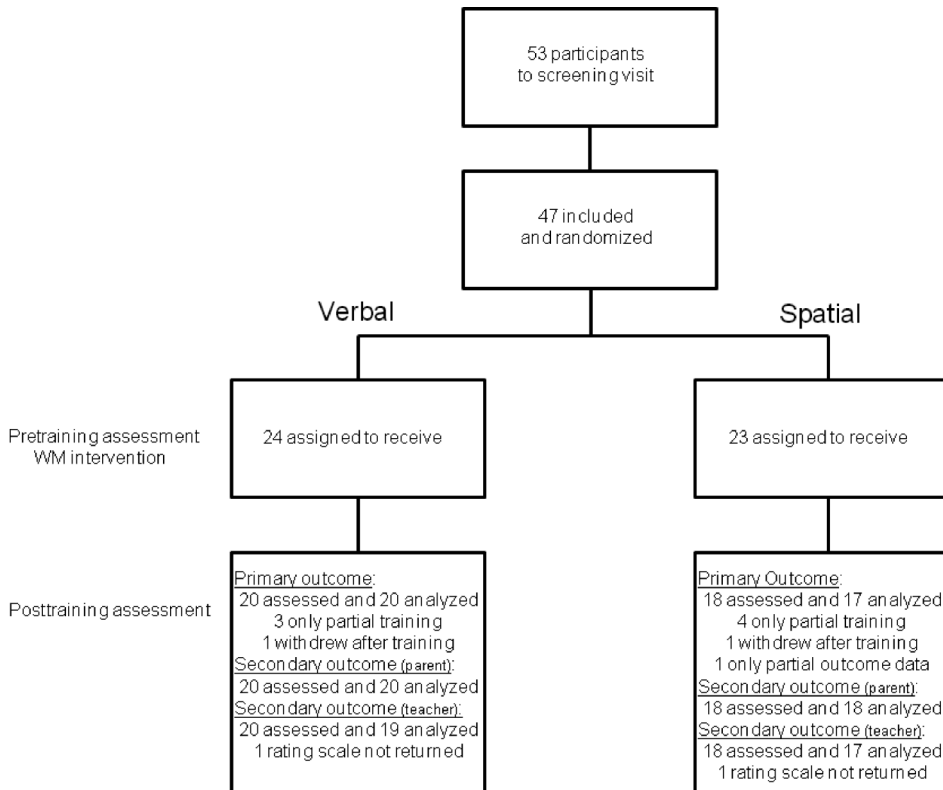


Figure 1 Flow of participants through the study.

Table 1 Average Characteristics of the Verbal and Spatial Training Groups (Standard Deviation).

| | Verbal (<i>n</i> = 24) | Spatial (<i>n</i> = 23) |
|----------------|-------------------------|--------------------------|
| Full-Scale IQ | 94.83 (11.89) | 100.57 (14.52) |
| Verbal IQ | 94.33 (12.19) | 97.13(12.96) |
| Performance IQ | 97.88 (16.23) | 103.61 (16.46) |
| Age in years | 12.33 (1.17) | 12.87 (1.25) |
| Boys:Girls | 19:5 | 18:5 |
| Comorbidities | | |
| Anxiety | 2 | 2 |
| Depression | 1 | 0 |
| ODD | 11 | 7 |

Note. ODD = Oppositional Defiant Disorder.

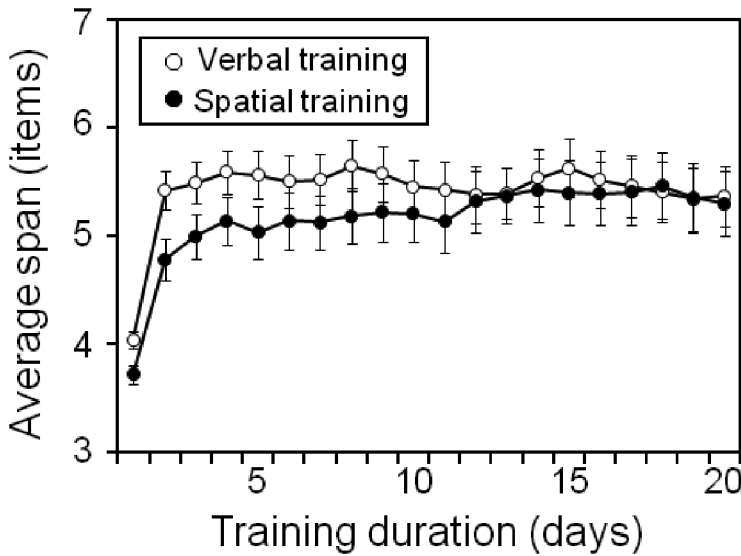


Figure 2 Average span length as a function of training duration in each of the two training groups. Error bars represent standard errors.

both training groups and then remained relatively stable over the remainder of the training period, as indicated by a significant main effect of training duration, $F(19, 665) = 14.37, p < .001, \eta_p^2 = .29$. None of the other main effects or interactions approached significance (all $ps > .20$).

Primary Outcome: Serial Position Effects

The probability of correct recall is shown in Figure 3 as a function of serial position, test modality, and time for both the verbal (*n* = 20) and spatial (*n* = 17) training groups. A four-way mixed ANOVA with serial position (Position 1 to 12), test modality (verbal IFR vs. spatial IFR), and time (pretraining vs. posttraining) as the three within-subjects factors and training group (verbal vs. spatial) as the sole between-subjects factor was performed on

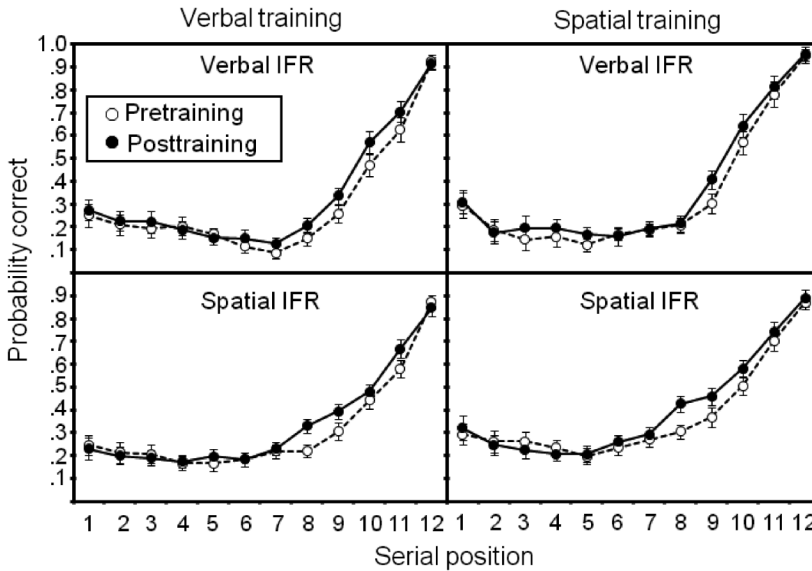


Figure 3 Probability of correct recall shown as a function of serial position, test modality, and time in each of the verbal and spatial training groups. Error bars represent standard errors.

the probability of correct recall. The primary purpose of the present study was to investigate whether Cogmed-RM only enhances the PM component of WM. Consistent with this expectation, there was a significant Serial Position \times Time Interaction, $F(11, 385) = 2.65$, $p < .005$, $\eta_p^2 = .07$, indicating that accuracy was significantly higher following training, but only for the recency portion of the list. Subsequent analyses confirmed that the adolescents were significantly more accurate recalling items in the posttraining condition than in the pretraining condition from Positions 8, 9, 10, and 11 (all $ps < .05$; ds ranged from 0.39 to 0.62), but equally accurate recalling items across time from Positions 1, 2, 3, 4, 5, 6, and 7 (all $ps > .30$; ds ranged from 0.01 to 0.21). Based on the dual-component model of working memory (Unsworth & Engle, 2007a), these findings suggest that Cogmed-RM only enhances the PM component of working memory.

As can be seen in Figure 3, the pattern of enhancement observed following spatial training was nearly identical to the pattern of enhancement observed following verbal training; accordingly, the Serial Position \times Time \times Training Condition interaction did not approach significance, $F(11, 385) < 1$. Consequently, there was no evidence that spatial training was more effective than verbal training. In addition, Figure 3 also shows that the pattern of enhancement observed when the test modality matched the training modality was nearly identical to the pattern of enhancement observed when the test modality mismatched the training modality; accordingly, the Test Modality \times Time \times Training Condition interaction did not approach significance, $F(1, 35) < 1$. Consequently, there was no evidence that WM enhancement was confined to the domain of training.

Primary Outcome: Capacity of PM

If Cogmed-RM enhances the PM component of WM, then estimates of the number of items successfully recalled from PM using Tulving and Colotla's (1970) method

should also show significant improvement following training. A three-way mixed ANOVA with test modality (verbal IFR vs. spatial IFR) and time (pretraining vs. posttraining) as the two within-subjects factors and training group as the sole between-subjects factor was performed on the estimates of PM. Consistent with expectation, there was a significant main effect of time, $F(1, 35) = 19.50, p < .0001, \eta_p^2 = .36$, indicating that the adolescents recalled fewer items from PM before training than after training ($M = 2.54$ vs. $M = 2.77$, respectively, $d = 0.52$). Also consistent with expectation, neither the Time x Training Condition interaction, nor the Test Modality x Training Condition interaction approached significance (both F s < 1).

Primary Outcome: Capacity of SM

If Cogmed-RM only enhances the PM component of WM, then estimates of the number of items successfully recalled from SM using Tulving and Colotla's (1970) method should not show a significant improvement following training. A three-way mixed ANOVA with test modality (verbal IFR vs. spatial IFR) and time (pretraining vs. posttraining) as the two within-subjects factors and training group as the sole between-subjects factor was performed on the estimates of SM. Consistent with expectation, there was a nonsignificant main effect of time, $F(1, 35) = 1.50, p > .20, \eta_p^2 = .04$, indicating that the adolescents recalled the same number of items from SM both before and after training ($M = 1.48$ vs. $M = 1.61$, respectively, $d = 0.15$). Likewise, neither the Time x Training Condition interaction, nor the Test Modality x Training Condition interaction approached significance (both p s $> .20$).

Secondary Outcome: Parent-Rated ADHD Symptoms

Two-way mixed ANOVAs with time (pretraining vs. posttraining) as the within-subjects factor and training group (verbal training vs. spatial training) as the between-subject factor were performed on the ratings of inattentive symptoms and hyperactive/impulsive symptoms separately. For the analyses' parent ratings, there were $n = 20$ in the verbal training group and $n = 18$ in the spatial training group. With respect to inattentive symptoms, there was a significant main effect of time, $F(1, 36) = 22.11, p < .0001, \eta_p^2 = .38$, indicating that there were significantly more of these symptoms before training than after training ($M = 19.05$ vs. $M = 15.89$, respectively, $d = 0.49$). Neither the main effect of training group, nor the Time x Training Group interaction approached significance, $F(1, 36) = 1.85, p > .15, \eta_p^2 = .05$; and, $F(1, 36) < 1$, respectively.

With respect to hyperactive/impulsive symptoms, there was also a main effect of time, $F(1, 36) = 5.01, p < .05, \eta_p^2 = .12$, again indicating that there were significantly more of these symptoms before training than after training ($M = 11.26$ vs. $M = 9.60$, respectively, $d = 0.28$). In addition, there was also a Significant Time x Training Group interaction, $F(1, 36) = 5.84, p < .05, \eta_p^2 = .14$, indicating that there was greater improvement in the verbal training condition than in the spatial training condition. Surprisingly, however, further analyses revealed that adolescents in the verbal training group had significantly more hyperactive/impulsive symptoms than adolescents in the spatial training group before the training began ($M = 14.30$ symptoms vs. 7.89 symptoms, respectively), $t(36) = 3.78, p < .002$. An Analysis of Covariance (ANCOVA) was therefore performed with training group as the group factor, posttraining symptoms as the dependent variable, and pretraining symptoms as the covariate. When the number of hyperactive/impulsive

symptoms was equated at pretraining, the verbal training group no longer showed greater improvement than the spatial training group, $F(1, 35) = 1.51$, $p > .20$, $\eta_p^2 = .04$. Hence, only the significant main effect of time will be interpreted.

Secondary Outcome: Teacher-Rated ADHD Symptoms

For these analyses, $n = 19$ in the verbal training group and $n = 17$ in the spatial training group. With respect to inattentive symptoms, there was a significant main effect of time, $F(1, 34) = 6.97$, $p < .02$, $\eta_p^2 = .17$, indicating that there were significantly more of these symptoms before training than after training ($M = 12.44$ vs. $M = 10.75$, respectively, $d = 0.22$). Neither the main effect of training group, nor the Time x Training Group interaction approached significance, $F(1, 34) = 3.13$, $p > .05$, $\eta_p^2 = .08$, and, $F(1, 36) < 1$, respectively. There were no significant effects observed when hyperactive/impulsive symptoms were analyzed (all $ps > .15$).

GENERAL DISCUSSION

The present study utilized the dual-component model of WM to examine which components of WM are enhanced by the Cogmed-RM adaptive training intervention in a sample of adolescents with ADHD. Based on this model, the present study has provided important new evidence that Cogmed-RM mainly enhances the maintenance of information in PM but appears to have little beneficial effect on the recall of information from SM. In addition, the same pattern of enhancement was observed regardless of the modality of the intervention and regardless of whether the modality of the intervention matched the modality of the WM outcome measures. These latter two findings suggest that the verbal and spatial exercises contained in Cogmed-RM are equally potent and that the beneficial effects of adaptive training can transfer to untrained tasks (see below for further discussion about the nature of these beneficial effects).

The present findings are important because they suggest that the component of WM that is most improved following adaptive training with Cogmed-RM (i.e., the PM component) is not the same component that is most impaired in ADHD (i.e., the SM component; see Gibson et al., 2010 for details). Hence, the present findings should motivate the design of more potent interventions for ADHD that target the SM component more than the PM component. According to Unsworth and Engle's (2007b) analysis, this modification could be accomplished by changing the exercises from a simple span format to a complex span format because inserting an additional processing task between to-be-remembered list items should increase the probability that these items are lost from PM. Therefore, adaptive training with complex span tasks may involve recall from SM more than adaptive training with simple span tasks. We are currently conducting a preliminary randomized, controlled trial to determine whether the SM component is more enhanced following adaptive training with a mixture of both verbal and spatial complex span exercises relative to adaptive training with a mixture of both verbal and spatial simple span exercises.

Although there appears to be a discrepancy between the component of WM that is most enhanced following training and the component of WM that is most impaired in ADHD, the present study did nevertheless observe significant improvements in both parent-rated and teacher-rated inattentive symptoms regardless of training group and in parent-rated hyperactive/impulsive symptoms regardless of training group. According to the present view, the improvement in ADHD symptoms that resulted from the enhancement

of PM occurred in a compensatory fashion, by taking some of the burden off the deficient SM component. In other words, Cogmed-RM may improve ADHD symptoms by decreasing the probability that information will be lost from PM. If this account is correct, then interventions that target the SM component should also have a stronger effect on ADHD symptoms than interventions that target only the PM component.

One purpose of the present study was to investigate whether training with spatial simple span exercises might improve SM abilities more than training with verbal simple span exercises. However, as reported above, the same pattern of enhancement was observed across both the verbal and spatial training conditions. This null effect of training condition in turn raises two potential concerns that may diminish the primary conclusion of the present study—namely, that Cogmed-RM enhances only the PM component of WM.

First, one may argue that the null effect of training condition does not allow us to distinguish whether the observed improvement in PM was due to training-related enhancement or to the mere effects of practice given that no other baseline condition was included in the present study. In response to this concern, we would first like to remind the reader that previous research (e.g., Holmes et al., 2009; Klingberg et al., 2005) has already demonstrated significant training-related (as opposed to practice-related) enhancement of WM following Cogmed-RM, which we would now retrospectively attribute to the enhancement of PM. Second, it is also unlikely that the mere effects of practice would selectively benefit only the PM component in the present study. Third, and most importantly, the conclusion that only the PM component was significantly enhanced ultimately deflates the need to differentiate between these two possible effects of time, at least for the purposes of the present study. This is because, for practical purposes, we are seeking an intervention for ADHD that enhances the SM component, not the PM component. Thus, just as it would be imprudent to invest additional resources in order to further validate an intervention that appeared to *decrease* WM capacity, we believe it is also imprudent to invest additional resources to further validate an intervention that appears to target only the PM component of WM. Rather, for present purposes, we believe a more prudent strategy is to focus resources on the development of alternative interventions that are capable of targeting the critical SM component.

Second, one may also argue that the null effect of training condition was obtained because the two training conditions were not sufficiently different, which in turn may lead one to wonder whether the training condition that was expected to be more potent was in fact weaker than expected due to the design of the intervention. In considering this possibility, it is indeed likely that some of the exercises in the verbal training condition included a spatial component; in contrast, none of the exercises in the spatial training condition included a verbal component. Recall, however, that training modality was manipulated in the present study because there was some reason to believe that the spatial modality might have a stronger influence on the SM component than the verbal modality (Kane et al., 2004; Miyake et al., 2001; Oberauer, 2005; Shah & Miyake, 1996). Thus, although the verbal training condition may have been similar to the spatial training condition, the basis of this similarity would have led to the expectation of greater enhancement of SM in the verbal training condition (due to the presence of spatial components) as opposed to less enhancement of SM in the spatial training condition. Thus, the null effect of training condition does not undermine the conclusion that Cogmed-RM enhances only the PM component.

In conclusion, the present study utilized the dual-component model of WM to examine which components of WM are enhanced by the Cogmed-RM adaptive WM

intervention. The present findings showed clearly that the Cogmed-RM adaptive training intervention appears to target the maintenance of information in PM, but not the recall of information from SM. As such, there appears to be a mismatch between the components of WM that are improved by Cogmed-RM and the components of WM that are deficient in ADHD (Gibson et al., 2010). In order to address this discrepancy, future efforts should be focused on the development of alternative interventions for ADHD that are capable of targeting the SM component of WM.

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