Published in final edited form as:
J Appl Res Mem Cogn. 2012 September 1; 1(3): 179–184. doi:10.1016/j.jarmac.2012.06.005.

Component Analysis of Simple Span vs. Complex Span Adaptive Working Memory Exercises: A Randomized, Controlled Trial

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Abstract

There has been growing interest in using adaptive training interventions such as Cogmed-RM to increase the capacity of working memory (WM), but this intervention may not be optimally designed. For instance, Cogmed-RM can target the primary memory (PM) component of WM capacity, but not the secondary memory (SM) component. The present study hypothesized that Cogmed-RM does not target SM capacity because the simple span exercises it uses may not cause a sufficient amount of information to be lost from PM during training. To investigate, we randomly assigned participants to either a standard (simple span; $N = 31$) or a modified (complex span; $N = 30$) training condition. The main findings showed that SM capacity did not improve, even in the modified training condition. Hence, the potency of span-based WM interventions cannot be increased simply by converting simple span exercises into complex span exercises.

Keywords

Working memory capacity; working memory training; dual-component model of working memory

Working memory (WM) is a limited-capacity process that allows individuals to maintain and retrieve goal-relevant information in the presence of irrelevant distraction (Kane & Engle, 2002; Unsworth & Engle, 2007a). In this way, individuals may organize and execute complex goal-directed activities across time without succumbing to more habitual, automatized, or pre-potent responses. The importance of WM capacity for higher-level cognitive abilities and adaptive functioning has been demonstrated on numerous fronts. For instance, lower amounts of WM capacity have been associated with lower fluid intelligence scores (Conway, Getz, Macnamara, & Engel de Abreu, 2011), poorer academic outcomes (Alloway, Gathercole, Kirkwood, & Elliott, 2009), and a greater number of inattentive, hyperactive, and impulsive symptoms (ADHD; Gibson, Gondoli, Flies, Dobrzenski, & Unsworth, 2010).

Given that WM capacity constrains a wide range of important outcomes, it is not surprising that researchers have attempted to improve these individual outcomes by expanding the

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capacity of WM. Indeed, a debate has erupted over the past decade about whether adaptive WM training interventions can enhance higher-order cognitive abilities and adaptive functioning (see Buschkuehl & Jaeggi, 2010; Diamond & Lee, 2011; Klingberg, 2010; Morrison & Chein, 2011; and, Shipstead, Redick, & Engle, 2010, 2012 for recent reviews). On the one hand, several empirical studies have been interpreted to suggest that training-induced increases in WM capacity can be accompanied by improvements in fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Klingberg et al., 2005), reading comprehension (Chein & Morrison, 2010; Dahlin, 2010), math competence (Holmes, Gathercole, & Dunning, 2009), and ADHD symptoms (Gibson, Gondoli, Johnson, Steeger, & Morrissey, 2011; Holmes, Gathercole, Place, Dunning, Hilton, & Elliott, 2010; Klingberg et al., 2005). On the other hand, others have questioned the soundness of this empirical evidence based on a variety of concerns about the measurement of these outcomes, the theoretical conception of WM, the use of appropriate control groups, and whether the benefits of adaptive training can actually be attributed to changes in WM capacity (Shipstead et al., 2012; see also, Shipstead, Hicks, & Engle, in press).

In the present study, we acknowledge the importance of this debate, and contend that the full potential of WM training is not likely to be realized unless these efforts are brought into closer alignment with current theories of WM. For instance, Unsworth and his colleagues (Unsworth & Engle, 2007a; Unsworth & Spillers, 2010) have recently proposed a “dual-component model” which contends that WM capacity is composed of at least two dissociable components: (1) the active maintenance of a limited amount of information in primary memory (PM) and (2) 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).

The dual-component model has practical implications for the design of WM interventions because component analyses of WM have suggested that SM capacity is just as important as PM capacity, if not more so, for explaining individual differences in overall WM capacity (Unsworth & Engle, 2007a; Unsworth & Spillers, 2010), fluid intelligence (Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth, Brewer, & Spillers, 2009; Unsworth & Engle, 2007b; Unsworth & Spillers, 2010) and ADHD symptoms (Gibson et al., 2010). Based on these findings, there is good reason to believe that the most potent WM training interventions would be those that can target both PM and SM capacity.

Recently, Gibson et al. (2011) investigated whether the PM, SM, or both components of WM could be enhanced by one well-known and widely used adaptive WM intervention known as “Cogmed-RM,” which contains a mixture of both verbal and visual-spatial exercises. Because spatial tasks may be more potent than verbal tasks (Kane et al., 2004; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Oberauer, 2005; Shah & Miyake, 1996), the Cogmed exercises were divided into two separate training conditions in Gibson et al.'s (2011) study—a verbal training condition ($N = 20$) and a spatial training condition ($N = 17$)—to examine whether spatial training might engage the SM component more than verbal training. Following Unsworth and Engle (2007a), serial position effects and estimates of PM and SM capacity were derived from performance on verbal and spatial immediate free recall (IFR) tasks. The main findings showed that Cogmed-RM selectively improved the PM component of WM capacity ($d = 0.52$), but not the SM component of WM capacity ($d = 0.15$). Hence, the potential benefits of Cogmed-RM for higher-level cognitive functioning are not as potent as they could be.

The primary purpose of the present study was to investigate whether modifying the exercises included in the standard version of Cogmed-RM from simple span to complex span exercises would better target SM capacity. Chein and Morrison (2010) recently created an adaptive training intervention that consisted solely of one verbal and one spatial complex span exercise, but they did not measure the PM and SM components of WM capacity. Consequently, they did not provide any evidence that their intervention targeted the SM component of WM capacity.

According to Unsworth and Engle (2007b), complex span tasks that require dual-task performance (e.g., operation span) 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 the retrieval of information from SM. In contrast, 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 in 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 beyond the capacity of PM (see also Unsworth & Engle, 2006). Thus, it may be possible to engage the SM component more fully during training by using complex span exercises instead of simple span exercises.

In order to test whether complex span exercises might target SM capacity better than simple span exercises the present experiment compared two versions of Cogmed-RM: a standard-exercise version of Cogmed-RM and a modified-exercise version of Cogmed-RM. According to Unsworth and Engle's (2007b) analysis, inserting an additional processing task between to-be-remembered items (as in complex-span tasks) should cause distraction and increase the probability that list items are lost from PM, regardless of list length. If so, then the average span achieved during training in the modified-exercise condition should be consistently lower than the average span achieved during training in the standard-exercise condition.

Furthermore, if inserting an additional processing task increases the probability that list items are lost from PM, then training with adaptive complex span exercises should target the SM component of WM capacity more than training with adaptive simple span exercises. If so, then the SM component of WM capacity should be enhanced to a greater extent following training in the modified-exercise condition than in the standard-exercise condition. For this reason, the modified-exercise condition was construed as the treatment condition in the present study whereas the standard-exercise condition was construed as the control condition. Construing the standard-exercise condition as a control condition may seem unusual given that it is typically used as an active training intervention. However, the standard-exercise condition is arguably the most optimal control condition for present purposes because the active component of this intervention should induce the same motivation and expectations as the modified-exercise condition while also having no effect on the SM component.

Although the standard-exercise condition could be construed as a control condition with respect to SM capacity, it could not be construed as a control condition with respect to PM capacity because the PM component of WM capacity was expected to be enhanced more or less equally across the two training conditions. Nevertheless, no further attempt was made to clarify the nature of the changes observed in the PM component of WM capacity because the main purpose of this study was to determine if Cogmed-RM could be modified to target the SM component of WM capacity.

Method

Participants

Seventy-four adolescents (mean = 13.05 years; SD = 2.07; range = 9-16 years) were recruited from the local community and randomly assigned to either the standard-exercise ($N = 36$) or the modified-exercise ($N = 38$) training condition. The participants were paid a total of $140.00 for their participation (pre-training assessment, 5-week intervention, and post-training assessment). Target sample size was based on the ability to observe significant enhancement in the SM component of WM capacity. In particular, the researchers sought to develop an intervention that could produce relatively large training effects because such an intervention should have the greatest practical impact on higher-level cognitive abilities and adaptive functioning. Thus, power estimates were based on the rationale that small to medium training effects would be relatively unimportant from a practical standpoint. A total sample of 32 in each training condition was required to detect a large effect with 90% power; and, a total sample of 23 was required in each training condition 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.

Pre-training and post-training assessments

One verbal and one spatial immediate free recall (IFR) task was administered immediately before (pre-training) and within one week of finishing the intervention (post-training). Justification for using IFR tasks to measure PM and SM capacity has been provided by Unsworth and Engle (2007a); furthermore, the two IFR tasks were identical to those used by Gibson et al. (2010) and Gibson et al. (2011). In these tasks, 15 lists of 12 unique high-frequency words or spatial locations were presented. The spatial locations were randomly selected from a 15 × 15 matrix. Each item was presented consecutively for one second. Following the presentation of a single list, question marks appeared in the center of the screen prompting a response by the participant. Participants were given 30 seconds to recall as many of the words or spatial locations from the current trial as possible in any order they wished. Words were reported orally and recorded digitally, whereas spatial locations were reported by clicking a mouse at the appropriate locations and stored by the computer. Following Gibson et al. (2011), participants were instructed explicitly to begin recalling words toward the end of the list first to control for order-of-report strategies, though strict serial ordering was not required (see also, Craik & Birtwistle, 1971). For each task, three practice trials preceded the experimental trials.

Two primary outcome measures were calculated from the IFR tasks: (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); and, (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 (Gibson et al., 2010; Gibson et al., 2011; Unsworth & Engle, 2007a). With respect to the latter outcome, 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, and it was considered to be recalled from SM when there were more than seven items intervening between that item's presentation and its recall. Both outcomes were calculated separately in the verbal and spatial IFR tasks and then averaged for analysis because modality did not interact with any of the other experimental factors in the analyses reported below.

WM training interventions

The participants in both training conditions were instructed to complete 25 days of WM training within five weeks. Participants were required to complete at least 20 days of WM training within this five-week period to be included in the final analyses. The participants completed the computerized WM training at home via the internet. Daily training performance (maximum span, minimum span, and average span) on each exercise was logged to a secure website, and monitored on a daily basis to ensure compliance. Both training conditions included a combination of verbal and spatial span exercises. The five verbal exercises involved remembering the correct forward serial order of letters and digits, whereas the five spatial exercises involved remembering the correct forward serial order of locations in a two- or three-dimensional grid. A new list of items was presented on each trial, and only eight of the 10 possible exercises were presented on each day. Trainees completed all eight exercises each day; total time spent training each day was set at 30 minutes (not including breaks).

Four of the exercises (two from each modality) that were presented each day were designated as “common exercises,” and they were selected from a total set of six exercises. In this way, trainees were introduced to different common exercises throughout the course of the training (every five days) to break monotony. The common exercises were simple span tasks, and the six common exercises used in the standard-exercise training condition were identical to those used in the modified-exercise training condition. These exercises were included to provide a common basis for comparison across the two training conditions.

The remaining four exercises (two verbal and two spatial) were designated as “critical exercises,” and these same four exercises were presented every day. The four critical exercises used in the standard-exercise training condition were identical to those used in the modified-exercise training condition except that the exercises used in the standard condition were simple span tasks whereas those used in the modified condition were complex span tasks. This was accomplished for the two critical verbal exercises by inserting basic mathematical operations (e.g., (2+2)/4 = 3) between list items as in the operation span task. These operations were considered to be of intermediate and optimal difficulty by Turner and Engle (1989; see also, Unsworth et al., 2005). Both the interim and final solution to the operation was always a whole number between 0 and 9. Participants used the computer mouse to respond whether the operation was “true” or “false” before the next list item was presented. Likewise, this was accomplished for the two critical spatial tasks by inserting random-dot spatial patterns between list items as in the symmetry span task (Kane et al., 2004). Participants used the computer mouse to respond whether the pattern was “symmetrical” or “asymmetrical” before the next list item was presented. Participants were required to maintain 100% accuracy on the processing tasks before list length would adjust to ensure that they did not ignore the processing tasks. The two processing tasks used in the modified-exercise condition (mathematical operations and symmetry) were also included as *separate* exercises (not interleaved between list items) in the standard-exercise condition to control for training time and simple exposure to this information.

The number of list items presented on each trial was adjusted automatically, on a trial-by-trial basis, to match the WM span of the participant on each task, and the same adaptive algorithm was used in both training conditions. In particular, the number of items presented on each trial increased by one item after participants successfully recalled the correct forward serial order of 100% of the items at a given length three times in row; in contrast, the number of items decreased by one item after participants failed to recall the correct forward serial order of 100% of the items at a given length three times in a row.

Results and Discussion

Of the 74 participants who completed the pre-training assessment, 67 continued on to the WM training phase of the study ($N = 33$ in the standard-exercise training condition and $N =$

34 in the modified-exercise training condition). Of these 67 participants, two participants in the standard-exercise training condition and three participants in the modified-exercise training condition were excluded from the final analyses because they failed to follow instructions when completing the verbal or spatial IFR tasks (either at the pre-training or the post-training assessment; see Gibson et al., 2010; 2011; Unsworth, Brewer, & Spillers, 2011). In addition, one of the participants in the modified-exercise training condition was excluded from the final analyses because his post-training, verbal IFR data were lost due to a computer error.

WM Training

The average span achieved during training is shown in Figure 1 as a function of duration for both the standard-exercise ($N = 31$) and modified-exercise ($N = 30$) training conditions. The average span achieved on the four critical exercises is shown in the upper panel of Figure 1 whereas the average span achieved on the four common exercises is shown in the bottom panel of Figure 1. The average span achieved on each of the critical and common exercises was analyzed separately 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 condition (standard-exercise vs. modified-exercise) as the sole between-subjects factor.

For the critical exercises, as expected, average span length increased over time in both training conditions, as indicated by a significant main effect of training duration, $F(19,1121) = 78.42$, $p < .0001$, $\eta_p^2 = .57$. According to Unsworth and Engle (2007b), inserting an additional processing task between the to-be-remembered items causes distraction and increases the probability that each list item, except the last, will be lost from PM; therefore, it is reasonable to expect that the average span level should be lower in the modified-exercise training condition than in the standard-exercise training condition. Consistent with this expectation, there was also a significant main effect of training condition, $F(1,59) = 29.60$, $p < .0001$, $\eta_p^2 = .33$. Although the difference between the two training conditions decreased over time, $F(19,1121) = 3.05$, $p < .001$, $\eta_p^2 = .05$, this difference remained substantial (1.06 items) on the 20th day of training.

For the common exercises, as expected, there was also a significant main effect of training duration, $F(19,1121) = 110.23$, $p < .0001$, $\eta_p^2 = .65$, but neither the main effect of training condition, nor the training duration X training condition interaction approached significance (both Fs < 1). The average spans achieved on the four common exercises were equal across the two training conditions, which suggests that the participants in the two training conditions could achieve the same level of training when the difficulty of the exercises was equated. Altogether, these findings suggested that the modified exercise training condition appeared to operate as intended.

Serial position effects

The probability of correct recall is shown in Figure 2 as a function of serial position and time for both the standard-exercise and modified-exercise training conditions. A three-way, mixed ANOVA with serial position (position 1 to 12) and time (pre-training vs. post-training) as the two within-subjects factors and training condition (standard-exercise vs. modified-exercise) as the sole between-subjects factor was performed on the probability of correct recall.

As expected, there was a significant main effect of time, $F(1,59) = 11.67$, $p < .001$, $\eta_p^2 = .16$, indicating that accuracy was significantly higher in the post-training condition than in the pre-training condition,. However, most importantly, the results indicated that the significant increase in accuracy was confined to the recency portion of the serial position curve for both training conditions. Consequently, there was a significant serial position X time interaction, $F(11,649) = 4.26$, $p < .001$, $\eta_p^2 = .07$, but none of the effects involving training condition approached significance (all *F*s < 1). Subsequent analyses confirmed that accuracy was significantly higher in the post-training condition than in the pre-training condition when items were recalled from positions 8, 9, 10, and 11 (all *p*s < .05; *d*s ranged from 0.29 to 0.46), but accuracy was equally high when items were recalled from positions 1, 2, 3, 4, 5, 6, and 7 (all *p*s > .40; *d*s ranged from -0.15 to 0.07). Hence, these findings suggest that neither training condition influenced the SM component of working memory.

PM and SM capacity

The number of items correctly recalled from PM and SM is shown in Table 1 as a function of time for both the standard-exercise and modified-exercise training conditions. A three-way, mixed ANOVA with memory type (PM vs. SM) and time as the two within-subjects factors and training condition as the sole between-subjects factor was performed on these capacity estimates. As expected, there was a significant main effect of time, $F(1,59) = 10.93$, $p < .005$, $\eta_p^2 = .16$, indicating that more items were recalled in the post-training condition ($M = 2.43$) than in the pre-training condition ($M = 2.30$). In addition, there was also a significant main effect of memory type, $F(1,59) = 28.26$, $p < .0001$, $\eta_p^2 = .32$, indicating that more items were recalled from PM ($M = 2.64$) than from SM ($M = 2.09$). Consistent with the serial position data, there was also a significant memory type X time interaction, $F(1,59) = 4.91$, $p < .05$, $\eta_p^2 = .08$, indicating that the significant effect of time was confined to estimates of PM capacity, and none of the effects involving training condition approached significance (all *F*s < 1). Subsequent analyses confirmed that PM capacity was greater in the post-training condition ($M = 2.75$) than in the pre-training condition ($M = 2.52$), $t(60) = 4.99$, $p < .0001$, $d = 0.41$. In contrast, SM capacity did not differ significantly across the post-training and pre-training conditions ($M = 2.11$ and $M = 2.08$, respectively), $t(60) = 0.43$, $p > .65$, $d = 0.03$. Subsequent analyses also confirmed that the same pattern was observed for those participants whose training gains fell above the median (see Jaeggi et al., 2011).

General Discussion

The dual-component theory of WM suggests that the most potent WM interventions are those that can target both the PM and SM components of WM capacity. However, existing interventions such as Cogmed-RM appear to target only the PM component (Gibson et al., 2011). The present study examined whether the SM component of WM capacity could be targeted and enhanced more following training with complex span exercises than following training with simple span exercises. Although the analysis of the training data confirmed that the complex span exercises used in the modified-exercise training condition were in fact more distracting than the simple span exercises used in the standard-exercise training condition, the analyses of serial position effects and capacity estimates suggested that exercise type was not sufficient to influence the SM component of WM capacity. Hence, the present findings corroborate the findings obtained by Gibson et al. (2011) using a more heterogeneous sample of adolescents (Gibson et al., 2011, used a sample of adolescents who were diagnosed with ADHD) and a wider range of training conditions.

The present study attempted to target the SM component of WM capacity by modifying the nature of the exercises used during training under the theoretical assumption that to-be-remembered information must first be lost from PM, either as a result of distraction or because the capacity of PM has been overwhelmed, before the SM component can be targeted (Unsworth & Engle, 2007b). However, although it may be necessary for training interventions to satisfy this criterion in order to target the SM component of WM capacity, the present findings suggest that it may also be necessary to satisfy other criteria as well.

For instance, although the use of complex span tasks may increase the probability that any given item will be lost from PM during training, satisfying this criterion alone may not guarantee that trainees are given adequate opportunities to practice retrieving this information from SM. Rather, providing adequate opportunities to practice retrieving information from SM may require further consideration of how the span length of the adaptive exercises is adjusted on a trial-by-trial basis to match the capacity of the trainee. In particular, the span length of the adaptive exercises is typically adjusted based on a 100% recall accuracy threshold, which may result in training spans that are too short to fully engage the SM component. We are currently investigating whether decreasing the recall accuracy threshold used during training may better target the SM component.

In addition, it is also worth considering whether the failure to observe significant change in the SM component of WM capacity might be due to the manner in which PM and SM capacity was defined in the present study. Indeed, the present study attempted to differentiate between PM and SM capacity within the same IFR tasks using Tulving and Colotla's (1970) method, which may have overestimated the capacity of PM and underestimated the capacity of SM. Clearly, examination of the serial position curves shown in Figure 2 indicates that significant enhancement of the SM component of WM capacity would be more likely to be observed (regardless of training condition) if this component included a greater portion of recency items.

Still, the fact remains that the training-induced improvements in performance observed in the present study were confined to a relatively small portion of the serial position curve, and these improvements are unlikely to reflect robust changes in SM capacity. For instance, Unsworth and Engle (2007a) compared the performance of high- and low-capacity individuals (as defined by the operation span task) on a 12-item verbal IFR task and found significant differences across all but the last serial position. These findings suggest that it ought to be possible to increase performance across both the recency and pre-recency portions of the serial position curve if WM training is truly able to increase both PM and SM capacity.

Finally, Unsworth (2009) has also suggested that retrieval from SM involves at least three components: the size of the search set (latency), the recovery of potential targets from this set (accuracy), and error monitoring (intrusions). Within this context, the conclusions of the present study pertain mostly to the recovery component. However, comprehensive examination of the other two components will require using outcome measures other than IFR tasks that can eliminate contributions from the PM component.

Practical Application

There is great potential to use adaptive WM interventions to improve intellectual, academic, and adaptive functioning. However, current theoretical understanding suggests that the ability to reach this potential may have been limited in the past by the development of relatively impotent interventions, leading to inconsistent empirical findings, critical scientific reviews, and public mistrust. The goal of the present study has been to address this concern by attempting to translate the dual-component theory of WM into a more potent intervention. Although the present findings suggest that this goal cannot be attained simply by converting simple span exercises into complex span exercises, such efforts have not been exhausted and should continue along the lines suggested above. Fair assessment of the full potential of WM training therefore awaits the development of these theoretically-inspired interventions.

Acknowledgments

The present study was funded by the Indiana Clinical and Translational Sciences Institute, which is funded in part by Grant # RR025761 from the National Institutes of Health, National Center for Research Resources, Clinical and Translational Sciences Award. The authors would like to thank Alisha Baker, Liz Davis, Laura Maxey, Erica Miller, and Elise Smith for their help with data collection.

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Highlights

Cogmed-RM targets primary memory (PM) but not secondary memory (SM).

The most potent interventions should target both PM and SM.

Including complex span exercises is not sufficient to target SM in adolescents.

Future modifications should focus on increasing span length during training.

The promise of WM training awaits the development of more potent interventions.

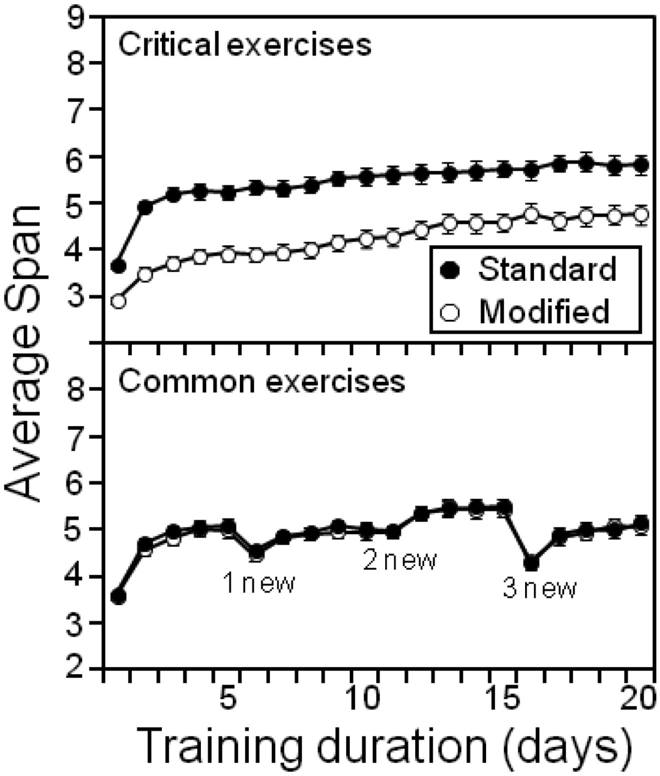

Figure 1.
Average span length achieved during training as a function of training duration and training condition for each of the critical exercises (top panel) and common exercises (bottom panel). Error bars represent standard errors.

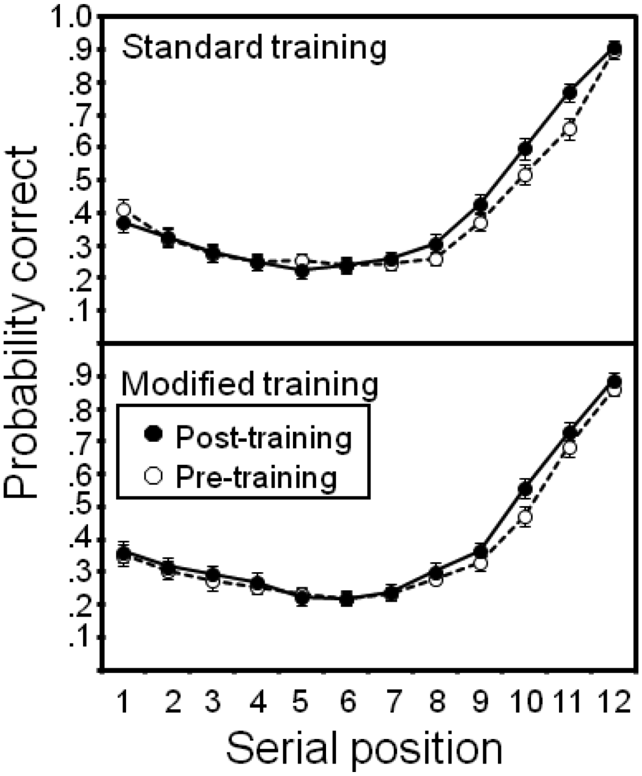

Figure 2.
Probability of correct recall shown as a function of serial position and time in each of the standard-exercise (top panel) and modified-exercise (bottom panel) training conditions. Error bars represent standard errors.

Table 1

Mean estimates of PM capacity and SM capacity as a function of time in each of the two training conditions (standard errors appear in parentheses).

	Time	
	Pre-training	**Post-training**
Standard training		
PM capacity	2.60 (0.10)	2.82 (0.10)
SM capacity	2.10 (0.14)	2.13 (0.18)
Modified training		
PM capacity	2.45 (0.10)	2.69 (0.15)
SM capacity	2.06 (0.15)	2.08 (0.18)