Expanding the mind's workspace: Training and transfer effects with a complex working memory span task

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In the present study, a novel working memory (WM) training paradigm was used to test the malleability of WM capacity and to determine the extent to which the benefits of this training could be transferred to other cognitive skills. Training involved verbal and spatial versions of a complex WM span task designed to emphasize simultaneous storage and processing requirements. Participants who completed 4 weeks of WM training demonstrated significant improvements on measures of temporary memory. These WM training benefits generalized to performance on the Stroop task and, in a novel finding, promoted significant increases in reading comprehension. The results are discussed in relation to the hypothesis that WM training affects domain-general attention control mechanisms and can thereby elicit far-reaching cognitive benefits. Implications include the use of WM training as a general tool for enhancing important cognitive skills.

Practice can yield remarkable levels of achievement but little generalization. For example, Ericsson and Chase (1982) reported the illustrative case of a college student who, following many hours of practice on a digit-span task (an often used measure of short-term memory [STM]), could successfully recall over 80 randomly ordered digits. However, the individual was limited to a typical STM span of about seven items for other, even closely related, memoranda. The specificity of the improvements observed in that and other classical studies of skill acquisition and expertise have led many to conclude that the benefits of practice on a given task do not generally extend into other realms of performance (Chase & Simon, 1973; Engle & Bukstel, 1978). By this account, although individuals may exhibit innate differences in certain domain-general capacities, training strategies seeking to promote superior performance through influence on these general capacities would be destined to fail.

Several recent studies, however, have invigorated an interest in the plausibility of using repetitive mental exercise to enhance one domain-general ability-working memory (WM)-and, in so doing, to concurrently improve performance in other cognitive skills (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Klingberg et al., 2005; Persson & Reuter-Lorenz, 2008). Training regimens used in these and other recent efforts appear to have targeted domain-general processes that individuals utilize to broadly support complex cognition. For example, in a study by Verhaeghen, Cerella, and Basak (2004), WM training was shown to influence recall from WM by expanding the capacity of attention. Likewise, others have demonstrated that WM training can impact domain- general cognitive control mechanisms (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002), interference resolution processes (Persson & Reuter-Lorenz, 2008), WM updating processes (Dahlin, Neely, Larsson, B�ckman, & Nyberg, 2008), and even general fluid intelligence (Jaeggi et al., 2008).

Although it provides a very promising foundation, the small corpus of existing WM training studies is limited in two important ways. First, prior demonstrations of transfer included measures closely related to those used to estimate WM itself, rather than to more distant tasks. To address this limitation, we sought to examine a broader battery of measures with the expectation that other tasks known to correlate with individual differences in WM capacity might also benefit from WM training. Second, previous studies utilized training tasks that are not commonly employed in the basic behavioral or psychometric literatures (e.g., atypical variants of the n-back task in Verhaeghen et al. [2004] and Jaeggi et al. [2008]; a battery of video-gamelike tasks, such as that used in Klingberg et al., 2005). Thus, previous findings are somewhat disjointed from the larger behavioral literature and offer only limited insights into the specific WM mechanisms influenced by training (e.g., encoding, strategic processing, updating, etc.).

Encouraged by findings regarding the malleability of WM, in the present study, we test a novel approach to increasing WM capacity through repeated practice with an adaptive complex WM (CWM) span task and examine the generalizability of the resulting WM improvements into the broader landscape of cognitive ability. By training participants using a CWM span task, we hoped to bridge the WM training literature to the wider body of empirical work that implicates WM in complex cognition. This variety of WM task has served as the cornerstone of the psychometric (individual differences) literature on WM for over 30 years and is arguably the most reliable and widely studied predictor of complex cognition (Conway et al., 2005). The hallmark characteristic of CWM tasks is the interweaving of storage (of the test items) and processing (the secondary decision-making task) components, which places a premium on the participant's ability to coordinate maintenance in the face of a concurrent distraction.

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We anticipated that, because CWM tasks place a strong demand on mechanisms linked to domain-general attention control (Engle & Kane, 2004), a training paradigm built around this task would result in both increases of WM span and more far-reaching benefits. Accordingly, the aims of the present study were twofold. First, we sought to examine the impact of a novel training paradigm, an adaptive version of a CWM span task. Second, we sought to expand the known boundaries of generalization by administering a battery of cognitive skills assessments.

METHOD

Participants

Forty-two Temple University undergraduates (25 female) completed the study and were compensated monetarily. Trained participants had a mean age of 20.1 years, and control participants had a mean age of 20.6 years. All participants were native English speakers with no prior events or illnesses that we expected to have an impact on WM performance.

Cognitive Assessments

A battery of computerized and handwritten tests assessed participants' cognitive skill levels before and after WM training. The battery of measures was chosen for its previously documented relationship to individual differences in WM ability (see, e.g., Kane et al., 2004). Temporary memory measures included verbal and spatial STM and verbal and spatial CWM span. The verbal and spatial STM tasks assessed immediate short-term recall of serially presented (1-sec stimulus, 1-sec intertask interval) letters and locations, respectively. A schematic of each CWM measure is shown in Figure 1. The verbal CWM task also involved recall of letters, but each to-be-remembered letter was preceded by 4 sec of repeated, participant-paced, lexical decisions. The spatial CWM task used the same timing parameters but tested memory for locations presented with interleaved symmetry decisions. Participants were given unlimited time to attempt recall, and, after each trial, participants received feedback indicating both the number of correctly recalled items and the overall accuracy of decision making on the intervening distractor task. For each temporary memory measure, participants were first asked to attempt recall of three test items. Following two successful trials at a given length, the number of test items was increased by one. The number of test items increased until participants failed to correctly recall two successive trials at a given list length. A participant's span was then defined as the maximum list length for which all items were recalled in the correct serial order.

A logical reasoning assessment included two tests of verbal reasoning (ETS's Inference and Nonsense Syllogisms tests) and two tests of spatial reasoning (ETS's Surface Development and Paper Folding tests). Cognitive control was measured using the Stroop Color-Word Interference Test (3 blocks of 60 trials each, 50% incongruent). General fluid intelligence was measured with Raven's Advanced Progressive Matrices (APM), using only the odd- or even-numbered problems for a given test session (counterbalanced across participants) and allotting 45 min for test administration.1 Finally, reading comprehension was measured with the Nelson- Denny Reading Test (Forms G and H used in counterbalanced fashion across sessions), using standard test procedures and allowing 20 min for test completion.

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Training Paradigm

WM training utilized the verbal and spatial CWM measures used for pre- and posttraining cognitive assessment, modified only in that the training tasks were adaptive to the participant's performance level (i.e., increased or decreased the number of test items on the basis of participant performance). Participants began each session of training with a list length of four test items (letters or locations); if all four items were correctly recalled for 2 trials in a row and at least 75% of the lexicality or symmetry decisions were made correctly on these trials, the list length was increased to five items. This process of increasing the stimulus count by one following 2 correct trials continued throughout the training session. Likewise, 2 successive incorrect trials caused the list length to be reduced by one item. Each training session lasted between 30 and 45 min and included 16 trials of the verbal CWM task and 16 trials of the spatial CWM task. The overall length of the session was variable, because trial onsets were participant paced and average trial length varied according to participant performance (trials with a larger number of test items took longer to complete).

Procedure

At the onset of the study, all participants completed a battery of standard cognitive tests in a laboratory located on the Temple University campus. Following the initial assessment, half of the participants were randomly selected to participate in the subsequent 4-week WM training regimen; the other half were assigned to an untrained control condition. Training required participants to complete the WM training exercises on 5 days of each week over the duration of 4 weeks. Training sessions were carried out using software that participants downloaded onto their personal computers (1 participant had difficulty downloading the training software and was switched to the untrained group), and trained participants were required to log and submit their daily training results electronically. The activities of untrained participants were not regulated during the 4-week interval. Participants in both groups returned 4-5 weeks after their initial assessment for a second assessment, which included alternate versions of the tests used in the first assessment.

RESULTS

A first step in analysis was to track participants' CWM span improvements over the 20 training sessions. Mean session-to-session performance over the 20 sessions indicated a steady rate of improvement across the 4 weeks of training for both verbal and spatial CWM, as shown in Figure 2.

Analyses next focused on comparisons of participants' cognitive skill levels before and after the training interval for the following measures: temporary memory (verbal CWM, spatial CWM, verbal STM, spatial STM), ETS reasoning tasks (inference, nonsense syllogisms, paper folding, surface development), cognitive control (Stroop), general fluid intelligence (Raven's APM), and reading comprehension (Nelson-Denny). Through these comparisons, we sought to answer two central questions about the impact of WM training: (1) Does WM training lead to an increase in the capacity of temporary memory? and (2) Do the benefits of WM training transfer to specific untrained tasks?

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Since the temporary memory and ETS reasoning assessments each included performance on multiple tests, we created composite scores for each participant. The composite was calculated by normalizing the first and second assessment scores relative to first assessment performance and then averaging the normalized scores for each of the tasks in the composite. For all assessed measures, paired-samples t tests were used to compare first and second assessment scores within trained and control groups, and an independent-samples t test was used to evaluate the difference in the improvements attained by trained versus untrained participants (Table 1). We entered the study with the directional hypothesis that training would improve test scores; thus, all t tests were one-tailed.

For the temporary-memory composite, both control and trained participants showed significant test-retest improvements (i.e., significantly increased performance on the second assessment). It is important to note that the magnitude of the improvement was significantly larger among trained participants, as confirmed by an independent- samples t test contrasting the size of the training effect (i.e., difference in performance from first to second assessment) for trained versus control participants (Table 1). A repeated measures ANOVA was used to further establish the strong influence of training on temporary memory capacity and revealed a highly significant interaction between assessment day and training group [$F(1,40) = 7.483$, p 4.64, p

Having found a significant impact of training on WM, we next examined transfer from training to measures that assessed more disparate cognitive abilities. Since generalization presupposes improvement on the trained tasks, we considered generalization effects both in the entire group of 20 trained participants and in the subgroup of 15 "successfully" trained participants, who demonstrated improved performance on spatial CWM, the more stringent of the two WM measures.

On our measure of fluid intelligence (Raven's APM), no significant improvement was recorded in either the trained group (pretraining, $M = 12.2$, $SE = 0.66$; posttraining, $M = 12.2$, $SE = 0.65$) or the control group (pretraining, $M = 12.4$, $SE = 0.72$; posttraining, $M = 12.2$, $SE = 0.57$) (see Table 1). Examining only the subgroup of successfully trained participants, we similarly found no improvement in Raven's APM performance (pretraining, $M = 13.4$, $SE = 0.51$; posttraining, $M = 13.2$, $SE = 0.55$). Thus, training does not appear to have affected performance on this measure.

Results for the ETS reasoning composite are also included in Table 1. Trained participants exhibited small, but statistically significant, improvements (pretraining, $M = 20.19$, $SE = 0.12$; posttraining, $M = 0.20$, $SE = 0.13$). However, control participants' test-retest improvements (pretraining, $M = 0.17$, $SE = 0.14$; posttraining, $M = 0.37$, $SE = 0.15$) were also statistically significant. Despite slightly larger gains among trained participants, an independent-samples t test directly contrasting improvements for the trained versus control groups was nonsignificant. Gains observed on these reasoning measures may, thus, reflect only test-retest improvements and not a true effect of transfer from training. This interpretation is further supported by the finding that ETS reasoning improvements were no larger for the subset of successfully trained participants (pretraining, $M = 20.18$, $SE = 0.15$; posttraining, $M = 0.16$, $SE = 0.16$).