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Strategy training and working memory task performance☆

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Abstract

Three experiments examined how strategy use influences working memory (WM) span performance and the correlation between WM span scores and higher cognitive function, using the operation span measure and the Nelson–Denny assessment of reading ability. Participants completed two versions of the operation span measure in a pre-/post-test design. In each study, half of the participants received strategy instructions prior to post-test. In Study 1, WM span scores increased as result of using a rehearsal strategy. In Study 2, three different strategies (rehearsal, imagery, and semantic) were compared. Low spans, in particular, benefited from using a rehearsal strategy. Also, the relationship between WM span scores and Nelson–Denny reading ability composite scores was enhanced, suggesting that strategy use, unless controlled for, can mask the "true" relationship between WM span and reading ability scores. In Study 3, time spent using the strategies described in Study 2 was controlled. Although no particular span group benefited from using any one strategy, WM span scores obtained while participants used the rehearsal strategy was, again, more predictive of reading ability. The importance of controlling for variation in strategy use during assessments of WM span is discussed.

Keywords: Working memory; Working memory span; Strategy; Reading ability; Operation span

Introduction

Various measures of working memory (WM) capacity reliably predict higher-order cognition, including reading comprehension (Daneman & Carpenter, 1980, 1983), language comprehension (King & Just, 1991; MacDonald, Just, & Carpenter, 1992), reasoning ability (Kyllonen & Cristal, 1990), note taking (Kiewra & Benton, 1988), and following directions (Engle, Carullo, & Collins, 1991). Although the pervasive relationship between WM span scores and higher-order cognition has been documented two questions remain. First, what exactly accounts for individual differences in WM span scores, and second, what accounts for the correlation between WM span scores and measures of higher-level cognition?

Strategies and measures of WM

Measures of WM typically require participants to engage simultaneously in a processing and storage task. For example, the operation span task requires participants to solve math problems, the processing

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component, and remember unrelated words, the storage component (e.g., Engle, Cantor, & Carullo, 1992; Turner & Engle, 1989). Similarly, the reading span task requires participants to read sentences for comprehension, the processing component, and remember the last word of sentences, the storage component (e.g., Budd, Whitney, & Turley, 1995; Daneman & Carpenter, 1980). Other techniques have been used to assess WM capacity (e.g., Baddeley, 1996; Kyllonen & Cristal, 1990; Salthouse, Mitchell, Skovronek, & Babcock, 1989).

In general, WM researchers have assumed that measures of WM assess attentional resources available for both processing and storage (Cantor, Engle, & Hamilton, 1991; Engle et al., 1992; Engle, Nations, & Cantor, 1990; La Pointe & Engle, 1990; Turner & Engle, 1989). Capacity, or the number of items recalled, is thought to reflect the total amount of activation available, once processing demands have been met. Thus, capacity is dependent, in part, upon the nature of the processing. If the processing task is more demanding, then fewer attentional resources will be available for processes related to storage and, consequently, WM span scores will be lower. Conversely, if the processing task is less demanding, then more attentional resources will be available and WM spans scores will be higher. Similarly, individuals who use efficient strategies in the task might recall more items than those who do not.

WM researchers, with the exception of Engle et al. (1992) and McNamara and Scott (2001), have failed to examine how strategies influence measures of WM capacity. We define strategies as techniques intended to facilitate processing and/or storage. The purpose of the present research was to investigate the importance of strategy utilization on measures of WM capacity. More importantly, we were interested in whether individual differences in strategies used during the performance of WM tasks are at the heart of the relationship between measures of WM capacity and such higher-order cognitive tasks as reading ability. In other words, is differential strategy use responsible for the covariation between measures of WM capacity and measures of reading ability?

General capacity hypothesis

Engle et al. (1992) assessed two viable explanations for the WM span–reading comprehension relationship. The first, the general capacity hypothesis, states that individual differences in WM performance reflect a relatively stable individual characteristic that is independent of the specific task being performed. According to this hypothesis, individuals have a fixed amount of general capacity with which to process and temporarily store information in immediate memory. Therefore, the relationship between WM span and reading comprehension is dependent upon *how much* attentional capacity, or WM "space," an individual has available for processing and storage.

In Engle et al. (1992), participants performed the operation span task in which they solved elementary math problems and read aloud words to be remembered. Each math operation-word string was presented serially in seven parts, using a moving window to allow the researchers to measure viewing times for each segment of the operation-word string (Just, Carpenter, & Woolley, 1982). An example of the type of operation-word string used is: "$(12/2) + 3 =$ ____ house." The spaces in this example denote the seven segments of the operation-word string. For example, "(12" was the first portion of the operation-word string presented, followed by "/", and then "2)", and so on. Participants controlled the presentation of the segments of the operation-word strings by pressing a key. Viewing times were recorded for each segment of the operation-word string. After presentation of 2–6 operation-word strings, participants were asked to recall the words presented in the preceding set. The total number of words recalled was positively correlated with an index of reading ability, verbal SAT (VSAT) scores. Engle et al. found that the relationship between WM span and VSAT scores was not reduced when other factors (e.g., time spent processing the math problem, time spent reading the TBR words) were partialled from the relationship. Thus, Engle et al. concluded that general capacity accounted for the relationship between WM span scores and VSAT scores.

Strategic allocation hypothesis

Engle et al. (1992) examined a second plausible explanation for the relationship between WM span and higher-order cognition, the strategic allocation hypothesis. The strategic allocation hypothesis suggests that high spans outperform low spans on WM tasks because they allocate their WM resources more efficiently. Individuals who perform well on measures of WM are commonly referred to as high spans, and individuals who perform poorly on these measures are referred to as low spans. According to Engle et al., if high spans are indeed more strategic, then their viewing patterns for the seven segments of the operation-word strings should differ from that of low spans. However, for the most part, the viewing patterns of high spans and low spans did not differ in their research.

Although Engle et al. failed to provide support for the strategic allocation view, other studies have suggested that high spans and low spans differ in how they perform cognitive demanding tasks, implying that strategies might impact WM performance. For instance, Rosen and Engle (1997) found that high and low spans differed in how information stored in long-term memory was recalled, as measured by a verbal fluency task. High spans were more likely than low spans to use a clustering strategy and suppress previously recalled exemplars during retrieval from long-term memory. Rosen and Engle (1998) reported differences between high and low spans during list learning. High spans produced fewer first-list intrusions during second-list learning than did low spans. Also, Conway, Tuholski, Shisler, and Engle (1999) found that high spans were more susceptible than low spans to negative priming because high spans allocated WM resources to inhibit information previously deemed irrelevant. Finally, Kane and Engle (2000) identified differences between high and low spans in terms of susceptibility to proactive interference. Only low spans experienced proactive interference under no load conditions. Although both high and low spans experienced proactive interference under load, high spans showed greater proactive interference as load increased, suggesting attempts at combating the build-up of proactive interference.

These observed differences between high and low spans could be due to differences in capacity, meaning that those with more capacity have more resources to suppress or inhibit previous information and combat proactive interference. Alternatively, high and low spans might differ in how they opt to allocate the resources they do have. Low spans might have difficulty with these types of tasks not only because they are limited in their WM resources, but also because they do not efficiently allocate the WM resources they do have. Recently, Engle and colleagues (Conway et al., 1999; Kane & Engle, 2000; Rosen & Engle, 1997, 1998) have argued that the observed differences between high and low spans are a product of controlled processing. That is, high spans are more likely to engage in controlled processing than low spans as evidenced by high spans' strategic recall of items from long-term memory, their approach to list learning, and their attempts to combat proactive interference. High spans allocate resources to suppress or inhibit irrelevant information. Low spans do not, and, subsequently, they experience greater interference and more intrusions than high spans. One way that controlled processing might be manifested by high spans is in the form of WM management strategies.

McNamara and Scott (2001) recently examined the impact of strategy training for short-term memory and WM performance. Participants were trained to use a chaining strategy in conjunction with a short-term memory task. Participants read 15 words and were trained, across several sessions, to create a story using these words. WM span scores obtained using the reading span measure improved following training on a short-term memory task. These researchers also found that more strategic participants, prior to training, displayed better WM performance. McNamara and Scott (2001) attributed changes in WM span scores to experience and learning, the knowledge is power hypothesis, rather than changes in the allocation of WM resources as suggested by the strategic allocation hypothesis.

Yet, two questions regarding strategy use and WM performance remain unanswered. First, it is unclear whether high spans are more strategic than low spans when their WM span is being assessed. By more strategic, we mean that high spans are using a strategy and low spans are not and/or high spans are using more efficient strategies than low spans. McNamara and Scott (2001) found that more strategic participants, those that reported using a semantically based strategy on a short-term memory task, performed better on a WM task. Therefore, it is likely that, in general, high spans are more strategic than low spans. Second, and most importantly, it is unclear how strategies impact the relationship between WM span scores and indices of higher cognitive function. There are two ways strategies could influence this correlation. First, strategic differences might account for, or explain, the relationship between WM span and higher cognitive function. Second, differences in strategies on WM tasks might serve as a nuisance or suppressor variable in the relationship between true WM span scores and higher-order cognition. Controlling for strategy use should give us a clearer understanding of the role strategy plays in this relationship.

Present research

The present set of studies was intended to answer three fundamental questions about how strategic processing influences measures of WM capacity. First, how do different WM strategies impact WM span scores? Second, do span groups differentially benefit from different types of strategy instruction? Third, and from our perspective most important, how does strategy instruction impact the relationship between WM span scores and higher cognitive functioning, specifically reading ability? In the present set of studies, we examined the correlations between WM span performance and reading ability while controlling for strategy use. In Study 1, we had some participants complete the WM span measure using a rehearsal strategy. In Study 2, we assessed how using three different strategies (i.e., rehearsal, imagery, and semantic) influenced the relationship WM span and reading ability. Then, in Study 3, we controlled for time spent using an assigned strategy and examined WM span scores and the correlation between WM span and reading ability.

In previous research, it has been argued that WM capacity accounts for individual differences in performance and the said correlation. Alternatively, high spans might be more likely than low spans to use effective strategies when completing a WM task and also be more strategic in doing the reading comprehension task. If this alternative hypothesis is correct, then two predictions are likely to follow. First, low spans should benefit more from strategy training than high spans. If high spans already use effective strategies, then they would be less likely to benefit from strategy training. If low spans are deficient in their use of strategies, then strategy training should increase their WM span scores. Second, if strategy use accounts for the correlation between WM span and reading ability, then the correlation between WM span and reading ability should be reduced significantly when participants use the same strategy. If what we observe instead is an increase in the correlation between WM span and reading ability when strategy use is held constant, then we can conclude that strategies used on the WM span task and separately on the reading test mask or attenuate this relationship. An enhanced correlation under these conditions would suggest that WM span scores obtained without controlling for strategy use underestimate the true-score relationship between individual differences in WM span and reading ability.

Study 1

The first purpose of Study 1 was to determine whether span groups differentially benefit from strategy instruction when performing a test of WM? Because previous research has led us to believe that high spans are, in general, more strategic than low spans, we were especially interested in whether low spans would benefit from using a rehearsal strategy.

The second purpose of this study was to determine what impact strategy instruction has on the correlation between WM span scores and higher cognitive function, in this case reading ability. As we have discussed, if strategy use accounts for the WM span–reading comprehension relationship then the correlation should decrease when strategy use is held constant. On the other hand, if holding strategies constant enhances the correlation, then we can conclude that we have obtained a more accurate assessment of WM span that is more predictive of higher cognitive function and less influenced by differences in strategy use.

In the present study, participants completed two versions of the operation span test (Turner & Engle, 1986). After completing one version of the operation span test, half of the participants were given instructions that contained strategy information to be used during the second operation span test. A rehearsal strategy was selected because in a previous unpublished pilot study (Turley, 1997) some participants, mostly high spans, indicated that they had used a rehearsal strategy while completing the operation span test.[1] More specifically, those participants reported rehearsing the words in a set as many times as possible each time a new word was presented. Therefore, in the present study approximately half of the participants were asked to rehearse the words in a given set each time a to-be-remembered (TBR) word was presented. Participants assigned to the control condition were given no such instructions.

Method

Participants

Participants were 124 undergraduates at Washington State University who were enrolled in introductory psychology courses. Fifty-eight participants were randomly assigned to the control condition and 66 were randomly assigned to the rehearsal training condition. Participation served as a partial fulfillment of a course requirement. All participants were native English speakers.

Materials

Operation span test. To compare original span scores with span scores following rehearsal strategy instruction, two versions of the operation span measure were constructed. As previously described, the operation span test assesses WM span by having participants solve simple math problems while remembering unrelated TBR words that follow each math problem. A pool of 150 operations was constructed to fulfill the same constraints used by Engle et al. (1992; Turner & Engle, 1989). After each math operation, a TBR word was presented for later recall. Two lists of common words, shown in previous research to be recalled equally well (Sorg & Whitney, 1992), served as the TBR words for the pre- and post-WM span measures. TBR words were assigned randomly to math operations used on the pre- and post-test.

Consistent with previous research (e.g., Budd et al., 1995; Daneman & Carpenter, 1980; Just & Carpenter,

[1] In an earlier study, after completing an operation span measure, participants were asked to describe what, if any, strategies they used while performing the operation span measure. Of those who completed this outcome assessment form, 43% reported no specific strategy; rather they paraphrased the instruction provided to them at the start of the session. However, 80% of participants reporting a strategy indicated that rehearsing the TBR words was a part of their strategy. High spans were more likely to report rehearsing the TBR words (69%) than medium (41%) and low spans (24%). Some high spans (25%) also reported using a complex rehearsal strategy that involved the formation of sentences containing all of the TBR words in a given set.

1992; Lee-Sammons & Whitney, 1991; Whitney, Ritchie, & Clark, 1991), operation-word sequences were presented in increasing set size. Participants completed trials with a set size of two, followed by trials of a set size of three, and so forth. All participants were presented with operation-word sequences in sets of 2–6 with three trials of each set size for a total of 15 sets. To ensure that the results were not due to the order in which test stimuli were presented, all stimuli were assigned randomly to two versions of the experimental trials. Participants received a point towards their WM span score if, and only if, they had correctly recalled the TBR word in the appropriate trial, *and* they had correctly solved the corresponding math problem. This scoring procedure was implemented to prevent giving participants credit for recalling words at the expense of solving the math problems incorrectly. Thus, participants could not trade-off processing of the math problems in favor of recalling the TBR words, or vice versa. Both pre- and post-WM span tests were scored in this manner.

Nelson–Denny reading test. After completing the pre- and post-operation span measures, Form G of the standardized Nelson–Denny (1993) test was administered. The Nelson–Denny is composed of two subtests, a vocabulary subtest and a reading comprehension subtest. The vocabulary subtest consists of 80 multiple-choice items, each with 5 answer options. Participants have 15 min to complete this section of the test. The reading comprehension subtest consists of 7 passages and 38 multiple-choice questions, each with 5 answer options. Participants have 20 min to complete this section of the test. Participants were encouraged to limit the amount of time they spent on any one item. They were allowed to return to items and/or passages within a given subtest as needed. Participants' scores were based on the total number of correct responses for each subtest.

Procedures

The pre- and post-operation span tests were administered on computer in accordance with previous research (Engle et al., 1992; Turner & Engle, 1989). The characters were displayed in white on a black background. Participants had 7 s to work through each math operation, solve the math operation, and read an unrelated TBR word. As a result of pilot data collected by our laboratory (Turley, 1997) and previous research (see Cantor & Engle, 1993; Conway & Engle, 1994; Daneman & Carpenter, 1980; Masson & Miller, 1983) suggesting that some form of experimenter-paced presentation of WM span stimuli yields stronger correlations between WM span and measures of reading ability, a 7-s time restriction for completion of each trial was imposed (e.g., Budd et al., 1995; Lee-Sammons & Whitney, 1991).[2] After completion of an operation-word sequence, participants pressed the "Crtl" key, and the next operation-word sequence was immediately presented.

Consistent with Engle et al. (1992), operation-word sequences were presented in seven parts: (a) the left parenthesis and a number, (b) a multiplication or division sign, (c) a number and the right parenthesis, (d) an addition or subtraction sign, and (e) a number from one to nine. (f) The last part of the math operation was followed by " = ____." When this part of the operation was presented, the participant verbally reported an answer to the math operation, and the experimenter recorded the participant's answer. (g) After providing an answer for the math problem, the TBR word was displayed until the participant pressed the "Ctrl" key or ran out of time. If a participant failed to complete an operation-word sequence within the allotted time, the participant was informed that "Time is up," and the next operation-word sequence was presented. Operation-word sequences were presented using a moving window procedure (Just et al., 1982); participants pressed the "Ctrl" key in order to advance to the next portion of the operation-word sequence. The computer recorded viewing times for the seven parts of the operation-word sequences. Like Engle et al., this procedure was employed so that we could measure how long participants spent on various segments of the operation-word sequences. In the present research, we questioned the extent to which strategy instruction changed the amount of time participants devoted to processing the TBR words.

Participants were assigned randomly to one of the two versions of the pre- and post-WM span test and told they had a total of 7 s to work through each operation-

[2] Many of the commonly used WM span measures are experimenter-paced. However, there is variation in terms of what is meant by experimenter-paced. In some studies, the experimenter controls the presentation of the processing component and the TBR information (e.g., Budd et al., 1995; Lee-Sammons & Whitney, 1991; Masson & Miller, 1983: Whitney et al., 1991). In other studies, only presentation of the TBR information is controlled (Cantor & Engle, 1993; Conway & Engle, 1994; Daneman & Carpenter, 1980; Engle et al., 1990; La Pointe & Engle, 1990; Turner & Engle, 1989). In the present research, we used a 7-s time restriction as a means of experimenter control. As we said, we found this to be a reasonable time restriction based upon both pilot work and previous research. Also, based upon figures presented in Engle et al. (1992) high spans spent on average 8.5 s per operation-word sequence and low spans spent on average 7.2 s per operation-word sequence under self-paced conditions. For these reasons, a 7-s time restriction proved to be a reasonable way to control stimulus presentation, yet permit examination of how individuals allocated time to various components of the test stimuli.

Table 1
Reliability indices for WM span measure and Nelson–Denny reading test by condition

	WM span test–retest reliability				Nelson–Denny Cronbach's alpha			
	Control	Rehearsal	Imagery	Semantic	Control	Rehearsal	Imagery	Semantic
Study 1	.772*	.728*			.613	.818		
Study 2	.786*	.602*	.730*	.738*	.824	.739	.715	.774
Study 3	.767*	.692*	.765*	.822*	.737	.706	.760	.525

Note. $^{*}p < .01$.

word sequence. They were encouraged to work as quickly and accurately as possible through the test stimuli. Participants were required to read aloud each part of the operation-word sequence as it appeared on the screen. This included each part of the math problems, the answer to the math problems, and the TBR words. After each set, "Recall Words" appeared on the screen. Then, participants attempted written free recall of the TBR words from the preceding set. Participants were given as much time as necessary to recall words. They also were encouraged to guess when necessary.

Prior to the pre- and post-WM span tests, participants completed 12 practice trials of a set size of two to familiarize them with the task. Participants had to recall correctly both TBR words for three of the last four practice trials in order to continue with the test trials.[3] Each participant was tested individually.

After completing the WM span pre-test, some participants read instructions that contained rehearsal strategy information. Participants receiving rehearsal strategy instruction were told, "Before starting a second version of the computer task you just completed, we ask that you try a particular strategy that may improve your performance on this second version of the task. As before, work as quickly and as accurately as possible on the math operations." Participants in the rehearsal strategy condition were instructed: "When you are presented with a to-be-remembered word, we would like you to rehearse that word aloud as many times as you can before going on to the next math operation. As additional words are added to a set, please rehearse aloud, not only the new word, but also other words presented previously in that set. In other words, each time you are presented with a new to-be-remembered word rehearse that word aloud and any previous to-be-remembered words in that set as many times as you can." To ensure participants were using the described rehearsal strategy, participants were asked to perform the rehearsal task aloud.

Participants assigned to the control condition were given a paraphrased version of the original instructions before completing the post-WM span test. All participants, prior to the administration of the actual post-WM span test, completed 12 additional practice trials. This gave participants assigned to the rehearsal strategy condition the opportunity to practice using the rehearsal strategy. After completion of the pre- and post-operation span measures, participants completed the Nelson–Denny test according to the standardized procedures outlined in the accompanying manual.

Results and discussion

Reliability indices for WM span and reading ability measures

The test–retest reliability for the WM span test and Cronbach's alpha for the Nelson–Denny by condition are reported in Table 1. Cronbach's alpha was calculated based upon *z*-scores for the vocabulary and reading comprehension subtests of the Nelson–Denny for each participant.

Hierarchical regression analyses

Hierarchical regression analyses were conducted to evaluate the main and interactive effects of WM span scores, a continuous variable, and post-test condition, a categorical variable, for each of the criterion variables of interest: post-WM span scores, time spent on the post-WM span TBR words, and reading ability scores. The analysis for post-WM span scores was carried out in two steps. Pre-WM span scores and post-test condition were entered into the first step to evaluate the main effect of each predictor for each of the criterion variables. Cross-product terms representing pre-WM span scores × post-test condition were entered into the second step. The analyses for time spent on the post-WM span TBR words and reading ability scores were carried out in three steps. For time spent on the post-WM span TBR words, time spent on the pre-WM span TBR words were entered into the first step. This procedure allowed us to assess differences from pre to post, and control for the relationship between pre and post TBR word times as we compare time spent on the post-WM span TBR words in the conditions of interest (rehearsal and control, for Study 1). In order to determine if span groups differed in time spent on the TBR words from pre to

[3] Across all three studies described in this manuscript, only four participants were dropped as a result of failure to reach the criterion established for the practice trials.

post, pre-WM span scores were entered in the second step as was condition (rehearsal vs. control, for Study 1). Cross-product terms representing pre-WM span scores × post-test condition were entered into the third step to determine whether span groups differed in the amount of time spent on the post-WM span TBR words as function of condition. For reading ability scores, pre-WM span scores were entered into the first step to control for the relationship between pre-WM span scores and reading ability scores. Post-WM span scores and post-test condition were entered into the second step to evaluate the main effect of each predictor for reading ability. Cross-product terms representing post-WM spans scores × post-test condition were entered into the third step.

For each step, the increment in variance accounted for by variables entered into that step is reported. The squared semipartial correlation (sr^2) for each predictor variable also is reported. The squared semipartial correlation indicates the amount of variance that was uniquely accounted for by a given variable (see Cohen & Cohen, 1983). A significant squared semipartial correlation for a predictor variable in the first step, and in the case of reading ability the second step, indicates a main effect while controlling for other main effects. A significant squared semipartial correlation for a cross-product term indicates a significant two-way interaction while controlling for other two-way interactions (as in Studies 2 and 3) and main effects.

To demonstrate the effect that WM span and strategy training have on the criterion variables of interest, graphs are presented to supplement hierarchical analyses as needed. Although WM span is treated as continuous variable in the hierarchical analyses, for display purposes and when appropriate, the results are presented graphically by span group (categorically; see Aiken & West, 1991). A tertiary split was conducted on WM pretest scores to distinguish between high, medium, and low spans.

Post-WM span scores. To determine the impact of rehearsal strategy instruction on post-WM span scores, pre-WM span scores and codes representing post-test condition (rehearsal vs. control) were entered as predictor variables into the first step of the hierarchical analysis. The cross-product of pre-WM span scores and codes representing post-test condition was entered into the second step along with the predictors for the first step.

The change in WM spans scores from pre-test to post-test as a function of post-test condition and span group are presented in Fig. 1. As indicated in Table 2, pre-WM span scores and post-test condition accounted for 61% [$F(2,121) = 95.193$, $p < .01$] of the variance in post-WM span scores with each variable contributing uniquely (ps $< .05$): pre-WM span scores ($sr^2 = .484$) and the rehearsal condition ($sr^2 = .087$). The two-way interaction was marginally significant, accounting for an addition .9% [$F(1,120) = 2.82$, $p = .10$] of the variance in post-WM span scores.

These data indicate, first, that pre- and post-WM span scores were highly related. Second, there was a difference between the rehearsal condition and the control condition when predicting post-WM span scores while controlling for pre-WM span scores. As shown in Fig. 1, the change in WM span scores from pre- to post-test was greater for those assigned to the rehearsal condition. However, it was unclear from these data whether certain individuals benefited more from rehearsal strategy instruction. The marginally significant interaction between pre-WM span scores and the

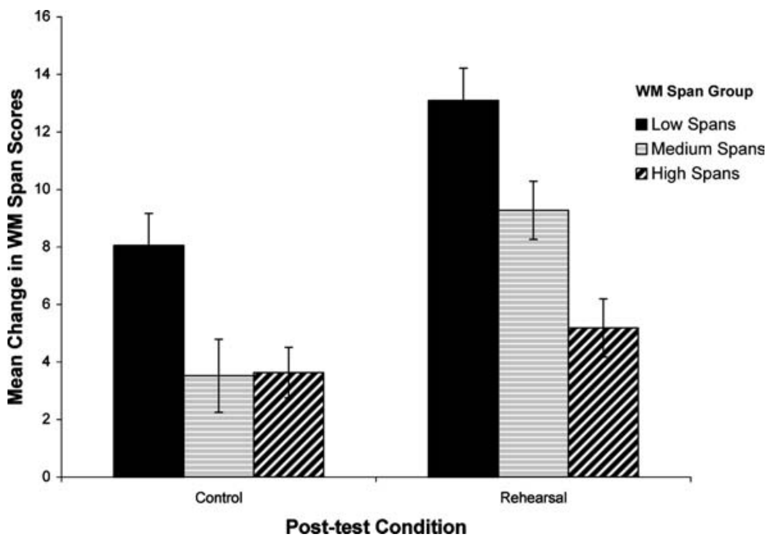

Fig. 1. Mean change in WM span scores as a function of post-test condition and WM span group: Study 1.

rehearsal condition suggested that low spans might have benefited more from such instruction. If low spans improved their WM span scores more as a result of rehearsal strategy instruction, then this raises an interesting question. Why do low spans benefit more from rehearsal strategy instruction? Low spans might have benefited from strategy instruction because the rehearsal strategy helped them manage the demands of the task, solving math problems and maintaining unrelated TBR words in memory. In other words, utilization of the rehearsal strategy might have helped low spans reallocate their WM resources to better accommodate the dual task at hand. Alternatively, low spans might have benefited from rehearsal strategy instruction simply because use of the strategy increased the amount of time they spent processing the TBR words, increasing the likelihood that the TBR words would be recalled later. In the analyses that follow, we address this possibility.

From our perspective, there are two possible explanations for the limited improvement in performance by high spans in the rehearsal strategy condition. First, the performance of high spans in this condition could have been limited as a result of a ceiling effect. Although the maximum score possible on the operation span test was 60 points, no participant received a perfect score on the post-test. The fact that no participant performed at the ceiling level makes it unlikely that a ceiling effect could account completely for this finding. An alternative explanation is that high spans were already performing near their optimal level. The use of a rehearsal strategy to assist in the management of demands placed on WM resources might have been negligible. It was unclear from the present data whether limited improvement in the WM span scores of high spans was a function of having adequate capacity to manage the demands of both tasks or utilization of some type of WM strategy on the pre-WM span test. Based upon the unpublished data discussed earlier (Turley, 1997), we believe the latter to be the case.

Post-WM viewing times of TBR words. To determine whether increases in WM spans scores on the post-test were due to an increase in the average time spent on the TBR words, average time spent on the TBR words for the pre-test and codes representing post-test condition (rehearsal vs. control) were entered as predictor variables into the first step of a hierarchical analysis. The cross-product of average time spent on the TBR words for the pre-test and codes representing post-test condition was entered in to the second step along with the predictors for the first step.

Time spent on the TBR words in the post-test as a function of pre-WM span scores and post-test condition are presented in Fig. 2. As indicated in Table 3, time spent on the pre-WM span TBR words accounted for 22% [$F(1,122) = 34.63,\ p < .01$] of the variance in time spent on post-WM span TBR words. Pre-WM span scores and post-test condition accounted for 35% [$F(2,120) = 49.25,\ p < .01$] of the variance. Post-test condition, rehearsal compared to control, accounted uniquely for a majority ($p < .01$) of the variance ($sr^2 = .315$). Pre-WM span scores also accounted for a portion ($p = .06$) of the variance ($sr^2 = .013$). The two-way interaction was nonsignificant.

As was expected, time spent on the TBR words for the pre-test was related to time spent on the TBR words for the post-test.[4] More importantly, these data indicate that participants in the rehearsal condition spent more

[4] In the present studies, we focused primarily on how strategy training influenced processing and storage of the TBR words. We acknowledge that strategy training also could change how participants complete the processing component of the span measure. To examine the impact of strategy training on math performance, a Test × Condition mixed ANOVA was conducted for each study. Test served as the within-subjects variable (pre, post) and condition served as the between-subjects variable (control and rehearsal for Study 1; control, rehearsal, imagery, and semantic for Studies 2 and 3). Number of math problems solved correctly served as the dependent variable. For Studies 1 and 2, math performance improved significantly from pre to post [$F(1,122) = 16.99,\ p < .01$ and $F(1,356) = 90.70,\ p < .01$, respectively]. Math scores improved from pre- to post-test, regardless of strategy instruction, in both Study 1 ($M_{pre} = 54.93,\ SD_{pre} = 4.63$ and $M_{post} = 56.17,\ SD_{post} = 4.40$) and Study 2 ($M_{pre} = 53.49,\ SD_{pre} = 5.76$ and $M_{post} = 55.55,\ SD_{post} = 4.44$). However, math performance did not interact with condition in either study ($ps > .05$). We assume that improvement in math performance across conditions from pre to post was a function of practice. In Study 3, there was a main effect for test [$F(1,176) = 33.27,\ p < .01$] and an interaction between test and condition [$F(3,176) = 10.62,\ p < .01$]. There was not a difference in math performance as a function of condition for the pre-test ($M_{pre} = 48.31,\ SD_{pre} = 7.85$), but there was a difference in math performance for the post-test [$F(3,176) = 9.11,\ p < .01$] as indicated by post hoc analyses. A Tukey's HSD ($ps < .05$) revealed that the math performance of those assigned to the semantic condition ($M_{post} = 46.47,\ SD_{post} = 9.60$) was different from those assigned to both the control ($M_{post} = 53.24,\ SD_{post} = 6.29$) and rehearsal ($M_{post} = 53.04,\ SD_{post} = 4.98$) conditions. The math performance of those assigned to the control [$F(1,44) = 56.47,\ p < .01; M_{pre} = 48.00,\ SD_{pre} = 8.57$ and $M_{post} = 53.24, SD_{post} = 6.29$] and rehearsal [$F(1,44) = 21.64,\ p < .01; M_{pre} = 49.69,\ SD_{pre} = 6.68$ and $M_{post} = 53.04,\ SD_{post} = 4.98$] conditions improved significantly from pre to post as observed in Studies 1 and 2. There are a number of possible explanations for the poorer post-test math performance of those assigned to the semantic condition (e.g., the instructions for the semantic strategy might have implied to participants that coming up with a story /sentence was more important than solving the math problems) under the time constraint imposed in Study 3. Such explanations could be explored in future research. However, this result does not impact the critical findings reported in Study 3, namely that rehearsal strategy instruction changed how participants managed the dual demands of the WM task and enhanced predictions of reading ability.

Table 2
Hierarchical regression analysis predicting post-WM span scores: Study 1

Step	Inc. R^2	F change	B	t value	sr^2
Step 1	.611	95.193*			
Pre-WM span			.658	12.285*	.484
Rehearsal			4.542	5.199*	.087
Step 2	.009	2.820+			
Pre-WM span × Rehearsal			.181	1.679+	.009

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .01$.
\+ $p < .10$.

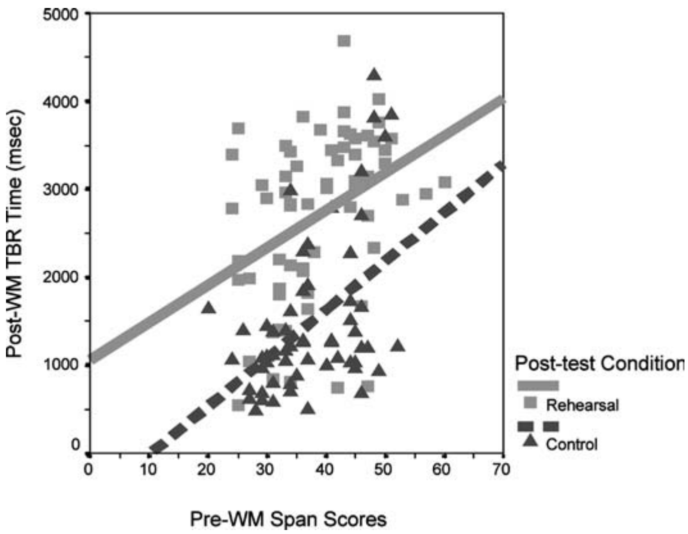

Fig. 2. Pre-WM span scores vs. post-WM TBR word time as a function of post-test condition: Study 1.

time on the TBR words for the post-test than did participants in the control condition. Pre-WM span scores also were related to time spent on the TBR words for the post-test; high spans spent more time on the TBR words than did low spans. However, these two variables did not interact. In other words, all participants, regardless of pre-WM span score, spent more time on the TBR words when assigned to the rehearsal condition. All participants increased the amount of time they spent on the TBR words in the post-test rehearsal condition, but, as we reported earlier, it might be low spans, in particular, who show the most improvement in their WM span scores. Therefore, if rehearsal training interacts with WM span scores as our marginal finding ($p = .10$) may suggest, then the benefits of rehearsal strategy instruction for low spans cannot be attributed solely to increased time spent on the TBR words. What is unclear from these data is whether rehearsal strategy training helps low spans because they generally do not employ WM management strategies, or whether the strategies they do use are less effective given this particular task. We will try to address these questions in Studies 2 and 3.

Regardless of the reason why strategies enhanced WM span scores for low spans, a better understanding of how span scores obtained using a strategy impact the correlation between WM span and indices of higher-order cognition is needed. As we see it, there are two possibilities. First, using a rehearsal strategy might artificially inflate WM span scores of low spans, decreasing our ability to predict accurately higher-order cognitive function. Second, the use of a rehearsal strategy might better reflect "true" capacity differences across individuals. If high spans are using strategies and low spans are not, or if high spans use effective strategies and low spans do not, controlling for strategy use might result in a more accurate assessment of individual differences in capacity. In this case, we would expect post-WM span scores for the rehearsal condition to be a better predictor of higher-order cognition, namely reading ability.

Table 3
Hierarchical regression analysis predicting average time spent on post-WM span TBR words: Study 1

Step	Inc. R^2	F change	B	t value	sr^2
Step 1	.221	34.632*			
Pre-WM TBR time			.801	5.885*	.221
Step 2	.351	49.254*			
Pre-WM span			17.873	1.909+	.013
Rehearsal			1244.277	9.400*	.315
Step 3	.002	.472			
Pre-WM span × Rehearsal			11.232	.687	.002

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .01$.
+ $p < .10$.

Table 4
Hierarchical regression analysis predicting reading ability composite scores: Study 1

Step	Inc. R^2	F change	B	t value	sr^2
Step 1	.172	25.316*			
Pre-WM span			.045	5.032*	.172
Step 2	.063	4.932*			
Post-WM span			.046	3.079*	.061
Rehearsal			−.296	−1.878+	.023
Step 3	.013	2.127			
Post-WM span × Rehearsal			−.029	−1.458	.013

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient. sr^2, squared semipartial correlation.
* $p < .01$.
+ $p < .10$.

Reading ability. Scores on the vocabulary and reading comprehension subtests were highly correlated ($r = .59,\ p < .01$). An unit-weighted composite variable reflecting overall reading ability was created by averaging the z-scores for the vocabulary and reading comprehension subtests. The reliability for this variable was .74.[5]

To understand how rehearsal strategy instruction impacts the relationship between WM span and reading ability scores, regression analyses were conducted. In the first step, pre-WM span scores were entered as a predictor variable to control for the association between these scores and reading ability scores. In the second step, post-WM span scores and codes representing post-test condition (rehearsal vs. control) were entered as predictor variables to assess the main effects of these variables on reading ability scores. The cross-product of post-WM span scores and codes representing post-test condition was entered in to the third step.

As indicated in Table 4, pre-WM span scores accounted for 17% $[F(1,122) = 25.32,\ p < .01]$ of the variance in reading ability scores. Post-WM span scores and post-test condition accounted for 6% $[F(2,120) = 4.93,\ p < .01]$ of the variance in reading ability scores with post-WM span scores ($sr^2 = .061$) contributing uniquely. The rehearsal condition ($sr^2 = .023$) contributed marginally ($p = .06$) to the prediction of post-WM span scores. The two-way interaction was nonsignificant, accounting for only 1% $[F(1,119) = 2.13,\ p = .15]$ of the variance in post-WM span scores.

Consistent with most WM studies, WM span scores obtained without strategy instruction (pre-WM span scores) predicted reading ability. Post-WM span scores also predicted reading ability. Post-WM span scores obtained using the rehearsal strategy differed marginally from control in their ability to predict reading ability composite scores. However, the interaction between post-WM span scores and post-test condition failed to achieve significance, suggesting that post-WM span scores in the rehearsal condition were not a better predictor of reading ability as might have been expected.

[5] A unit-weighted composite variable reflecting overall reading ability was created in a similar manner for Studies 2 and 3 as well. As with Study 1, vocabulary and reading comprehension scores for Studies 2 and 3 were highly correlated ($r = .62$ and $r = .75$, ps $< .01$, respectively). The reliability for the composite variable was .76 for Study 2 and .67 for Study 3.

Although the interaction was nonsignificant, as seen in Table 5 the correlation between post-WM span scores in the rehearsal condition and reading ability composite scores is slightly higher. It is possible that the present study was not powerful enough to detect the interaction, suggesting that span scores obtained using the rehearsal strategy were a better predictor of reading ability than the control condition. Studies 2 and 3 were designed to be a more powerful test of the extent to which different types of strategy instructions differ from control in their ability to predict reading ability composite scores.

If the enhanced correlation in the rehearsal condition is meaningful and reliable (again Studies 2 and 3 will help us make this determination), then this finding could have implications for the administration of WM measures. We believe that is likely that on the WM pre-test and in the post-test control condition participants might have used a variety of different strategies (or some might not have used any strategy) to manage the demands of the operation span test. When strategy use was controlled for via strategy instruction, participants managed the demands of the task in a similar manner. As a result, post-WM span scores in the rehearsal condition were a slightly better predictor of reading ability. These results suggest that having all participants utilize a rehearsal strategy when measuring WM span might produce a more accurate assessment of WM span and serve as a better predictor of reading ability.

Based upon the analyses presented here, use of a rehearsal strategy might be an effective way to help low spans manage the competing demands of the operation span task. Using the rehearsal strategy, low spans improved their WM span scores somewhat. Our data suggest that such improvement could not be attributed solely to time spent on the TBR words. Finally, these data indicate that WM span scores obtained while controlling for strategy use might result in a more accurate assessment of WM that is reflective of the participants' ability to engage in cognitively demanding tasks.

Study 2

In Study 2, we were interested in how different WM strategies influence measures of WM and the correlation between WM span scores and reading ability. More specifically, we were interested in whether or not the pattern of results observed in Study 1 hold for other strategies. In the present study, we assessed the efficacy of three different strategies: a rehearsal strategy, an imagery strategy, and a semantic strategy. These three memory strategies, or some subset of these three strategies, have been used previously to study memory (e.g., Belmore, 1981; Bower & Winzenz, 1970; Craik & Tulving, 1975; Crovitz & Harvey, 1979; Roediger & Payne, 1985; Swanson, Overholser, & Conney, 1988), and we were curious whether the results of Study 1 were specific to the rehearsal strategy manipulation, or whether the results would generalize to other types of strategies. Turley (1997) asked participants what type of strategies they used to help manage the demands of the operation span measure. Some participants, primarily higher span participants, indicated that they had tried to form a picture of the TBR words or create a sentence/story using the TBR words to facilitate memory of those items. In McNamara and Scott (2001), participants also reported using similar types of strategies to assist in the recall of TBR information. Therefore, in the present study, imagery and semantic conditions were included in addition to the rehearsal condition used in Study 1.

Study 2 was also intended to be better test of the effects of strategy training on WM span and the relationship between WM span and reading ability scores. The interactive effects between WM span scores and the rehearsal condition, as compared to the control condition, were either nonsignificant or marginally significant for two of the three criterion variables of interest, post-WM span scores ($p = .10$) and reading ability composite scores ($p = .15$). In the present study, 90 participants were assigned randomly to each strategy condition, as opposed to 62 participants in Study 1. If the interactions

Table 5
Correlations between reading ability composite scores and pre- and post-WM span scores

Study	WM span test				
	Pre-test	Post-test Control	Post-test Rehearsal	Post-test Imagery	Post-test Semantic
Study 1	.415**	.432**	.521**		
	(124)	(58)	(66)		
Study 2	.295**	.300**	.560**	.316**	.465**
	(360)	(90)	(90)	(90)	(90)
Study 3	.389**	.470**	.791**	.369*	.385**
	(180)	(45)	(45)	(45)	(45)

Note. Sample sizes presented in parentheses.
* $p < .05$.
** $p < .01$.

between WM span and the rehearsal condition are reliable, then they should achieve significance with an increase in sample size.

In Study 2, it was predicted that individuals from different WM span groups would benefit from different types of WM strategy instruction. We were unsure which strategies would prove most beneficial for each span group. Previous research has demonstrated that, in general, elaborative (e.g., Anderson & Reder, 1979; Craik & Lockhart, 1986) and interactive (e.g., McKelvie, Sano, & Stout, 1994; West, 1995) forms of encoding produce superior memory. The imagery and semantic strategies in the present study were thought to be more integrative and interactive than the rehearsal strategy. Although the literature suggests these types of strategies might enhance memory more so than rote rehearsal, it was unknown the degree to which these strategies tax WM. We thought that the rehearsal strategy might be less resource demanding and more likely to benefit lower spans, but this was simply our hunch. Also, based upon the results of Study 1, we predicted that when strategy use was held constant that the relationship between WM span and reading ability would be enhanced, especially when a strategy facilitated the allocation of WM resources.

In Study 2, we included an outcome assessment measure to clarify the results of Study 1. Because it was unclear in Study 1 why high spans did not improve as much as low spans following strategy instruction, an outcome assessment measure was included. One possible explanation as to why high spans did not improve as dramatically as low spans was that they were already using some sort of strategy to assist in the allocation of their WM resources. Our previous unpublished research (Turley, 1997) suggested that might be the case as well. To further investigate whether high spans were using strategies, participants were administered the same outcome assessment measure used previously by Turley.

Method

Participants

Participants were 360 undergraduate students at Idaho State University who were enrolled in psychology courses. For participation each participant received either extra credit or partial fulfillment of a course requirement. All participants were native English speakers.

Procedure

The same procedures outlined in Study 1 were used to administer the pre- and post-WM span tests. Participants were assigned randomly in equal numbers to the control and each of the three experimental conditions. As in Study 1, participants in the control condition were given a paraphrased version of the original instructions before completing the post-WM span test. Like participants in the rehearsal strategy condition of Study 1, participants in the strategy conditions were told "Before starting a second version of the computer task you just completed, we ask that you try a particular strategy that may improve your performance on this second version of the task. As before, work as quickly and as accurately as possible on the math operations."

Participants in the rehearsal condition were given the same instructions as in Study 1. Participants in the imagery condition were instructed, "When you are presented with a to-be-remembered word, we would like you to create a visual image or picture of the to-be-remembered word. Describe aloud the visual image or picture you have created and maintain the visual image or picture in memory as long as you can or until running out of time. You may want to begin with "I see..." when briefly describing your image or picture. As additional words are added to a set, please add to your previously created image or picture of the new words."

Participants in the semantic condition were told, "When you are presented with a to-be-remembered word, we would like you to create a brief sentence or story containing the to-be-remembered word. Say the sentence/story aloud and maintain the brief sentence/story in memory until running out of time and going on to the next math operation. As additional words are added to a set, please include the new words in your sentence/story and say the entire sentence/story aloud. In other words, each time you are presented with a new to-be-remembered word include that word and any previous to-be-remembered words in that set in your sentence/story. Maintain the sentence/story as long as you can when presented with a to-be-remembered word." This strategy was similar to the one used by McNamara and Scott (2001).

To ensure participants were using their assigned strategy, participants were trained to verbally report the use of their assigned strategy. As in Study 1, an additional 12 practice trials were completed by all participants before completing the actual post-test. Experimenters were well trained to prompt participants to use their assigned strategy.

Participants also completed an outcome assessment form that asked participants to write about what, if any, strategy they had used while performing the operation span test. Participants who were assigned to one of the three strategy conditions completed this form following the pre-WM span test and prior to reading strategy instructions. To avoid inducing strategy use, participants assigned to the control condition completed the same form after completing both WM span tests. Finally, participants completed the Nelson–Denny measure of reading ability.

Results and discussion

Hierarchical regression analyses

The same regression analyses conducted in Study 1 were conducted for Study 2 with only one change. Because we were assessing the effects of three different strategies, as compared to the control condition, a dummy code was created for each training condition. The dummy code was used to create the cross-product terms for interactions that included a training condition.

Post-WM span scores. To determine the impact of strategy instruction on post-WM span scores, pre-WM span scores and codes representing post-test condition (rehearsal vs. control, imagery vs. control, and semantic vs. control) were entered as predictor variables into the first step of the hierarchical analysis. The cross-products of pre-WM span scores and codes representing post-test conditions were entered into the second step along with the predictors for the first step.

The change in WM span scores from pre-test to post-test as a function of post-test condition and span group are presented in Fig. 3. As indicated in Table 6, pre-WM span scores and post-test conditions accounted for 52% $[F(4,355) = 95.30,\ p < .01]$ of the variance in post-WM span scores. All of the predictor variables, with the exception of the imagery condition ($sr^2 = .003,\ p = .11$), contributed uniquely to post-WM span scores: pre-WM span scores ($sr^2 = .504$), the rehearsal condition ($sr^2 = .014$), and the semantic condition ($sr^2 = .006$). Only the two-way interaction between pre-WM span scores and the rehearsal condition ($sr^2 = .017$) achieved significance, accounting for an additional 3% $[F(3,352) = 6.53,\ p < .01]$ of the variance in post-WM span scores. The two-way interactions between pre-WM span scores and the imagery condition, and pre-WM span scores and the semantic condition failed to achieve significance.

As with Study 1, the present data set indicated that pre- and post-WM span scores were highly related. Post-WM span scores for participants assigned to the rehearsal and semantic strategies were significantly different from those assigned to the control condition after controlling for pre-WM span scores. The effect for the rehearsal condition, but not the semantic condition, was qualified by a significant interaction between pre-WM span scores and the rehearsal condition as compared to control. This interaction indicated that low spans, in particular, benefited from rehearsal strategy instructions. WM span scores improved significantly from pre- to post-test for low spans assigned to the rehearsal condition compared to the control condition. This effect can be seen in Fig. 3. The marginally significant interaction observed in Study 1 and the present finding suggests that the rehearsal strategy does indeed assist low spans in managing the demands of the operation span task. Although not the case in Study 1, an alternative explanation is that low spans benefited from rehearsal strategy instructions simply because use of the rehearsal strategy increased the amount of time they spent processing the TBR words. We address this concern when we evaluate the data for time spent on the TBR words.

As can be seen in Fig. 3, again high spans did not benefit as much from the rehearsal strategy instructions. In some cases, high spans obtained lower WM span scores when performing the operation span measure using the rehearsal strategy. Why high spans did not benefit from rehearsal strategy instructions to the same

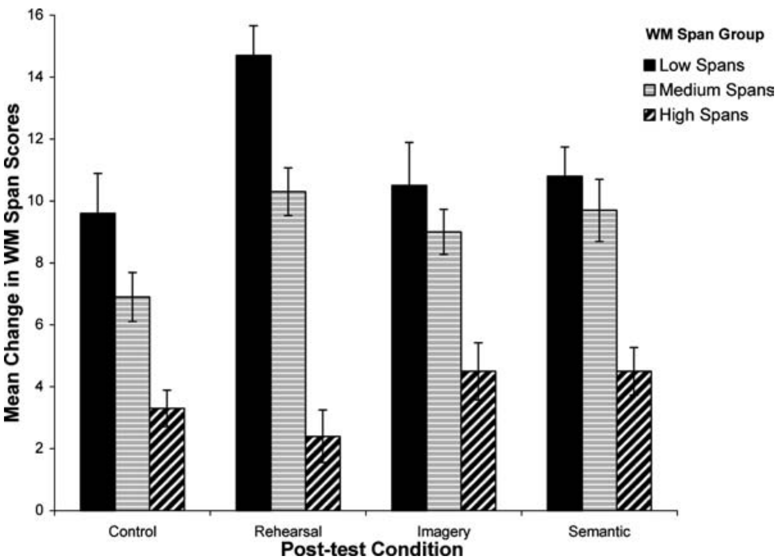

Fig. 3. Mean change in WM span scores as a function of post-test condition and WM span group: Study 2.

Table 6
Hierarchical regression analysis predicting post-WM span scores: Study 2

Step	Inc. R^2	F change	B	t value	sr^2
Step 1	.518	95.303**			
Pre-WM span			.628	19.261**	.504
Rehearsal			2.513	3.196**	.014
Imagery			1.260	1.602	.003
Semantic			1.619	2.059*	.006
Step 2	.025	6.527**			
Pre-WM span × Rehearsal			−.321	−3.672**	.017
Pre-WM span × Imagery			.040	.045	.000
Pre-WM span × Semantic			−.074	−.831	.001

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .05$.
** $p < .01$.

extent as low spans will be discussed when we examine the outcome assessment data. Another concern that will be addressed is how WM span scores obtained using the rehearsal strategy impact the relationship between WM span and higher-order cognition. More specifically, are span scores obtained using the rehearsal strategy more or less related to indices of reading ability?

Post-WM viewing times of TBR words. To determine whether WM span scores on the post-test were due to an increase in the average time spent on the TBR words, the average time spent on the TBR words for the pre-test was entered as a predictor in the first step of a hierarchical analysis. To determine whether pre-WM span scores or post-test condition were predictors of time spent on the TBR words in the post-test, pre-WM span scores and codes representing post-test condition (rehearsal vs. control, imagery vs. control, and semantic vs. control) were entered as predictor variables into the second step of a hierarchical analysis. To test for interactions between span scores and post-test condition, the cross-products of pre-WM span scores and codes representing post-test conditions were entered into the third step.

Time spent on the TBR words in the post-test as a function of pre-WM span scores and post-test condition are presented in Fig. 4. As indicated in Table 7, time spent on the pre-WM span TBR words accounted for 30% [$F(1, 358) = 153.48,\ p < .01$] of the variance in time spent on post-WM span TBR words. Main effects of pre-WM span scores and each strategy condition as compared to control were observed and accounted for 19% [$F(4, 354) = 33.73,\ p < .01$] of the variance in time spent on post-WM span TBR words; each variable contributed uniquely: pre-WM span scores ($sr^2 = .011$), rehearsal ($sr^2 = .173$), imagery ($sr^2 = .074$), and semantic ($sr^2 = .034$). However, the two-way interactions

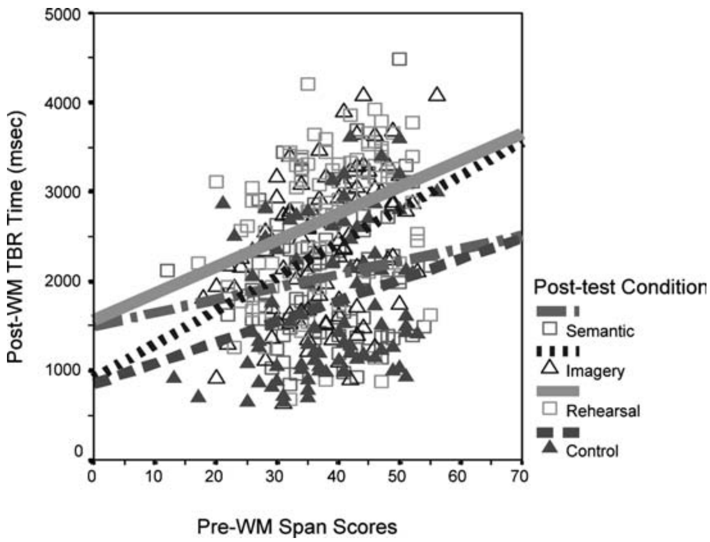

Fig. 4. Pre-WM span scores vs. post-WM TBR word time as a function of post-test condition: Study 2.

Table 7
Hierarchical regression analysis predicting average time spent on post-WM span TBR words: Study 2

Step	Inc. R^2	F change	B	t value	sr^2
Step 1	.300	153.476*			
Pre-WM TBR time			.782	12.389*	.300
Step 2	.193	33.727*			
Pre-WM span			11.088	2.800*	.011
Rehearsal			1005.687	11.003*	.173
Imagery			656.627	7.184*	.074
Semantic			450.257	4.898*	.034
Step 3	.002	.488			
Pre-WM span × Rehearsal			4.636	.445	.000
Pre-WM span × Imagery			3.960	.371	.000
Pre-WM span × Semantic			−7.262	−.679	.001

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .01$.

between pre-WM span scores and the post-test conditions were nonsignificant.

As was expected, time spent on the TBR words for the pre-test was related to time spent on the TBR words for the post-test. Consistent with Study 1, pre-WM span scores predicted time spent on the TBR words for the post-test. In general, high spans spent more time on the TBR words than low spans. Finally, these data indicated that participants in each of the strategy conditions spent more time on the TBR words for the post-test than did participants in the control condition. However, pre-WM span scores did not interact with any of the strategy conditions. In other words, all participants, regardless of span, assigned to a strategy condition increased the amount of time they spent viewing the TBR words on the post-test in comparison to the control condition. Although all participants increased the amount of time they spent on the TBR words in the post-test strategy conditions, only low spans in the rehearsal condition significantly improved their WM span scores from pre- to post-test. As we argued before, the results of Study 2 and the marginal findings in Study 1 indicate that the benefits of rehearsal strategy instruction for low spans cannot be attributed solely to increased time spent on the TBR words. Certainly, low spans increased the amount of time they spent viewing TBR words on the post-test, but so did other span groups. Yet, only low spans showed a significant improvement in WM span scores as a result of rehearsal strategy training.

One reasonable interpretation of these data is that the rehearsal strategy was especially useful in helping low spans manage a task that places substantial demands on WM resources. It could be that rehearsal was helpful for low spans because the strategy itself did not require as many WM resources to successfully implement the strategy. The imagery and semantic strategies might have been, in and of themselves, too resource demanding, taking up limited WM resources. Or, it might have been the case that describing one's image or a generating a sentence/story containing the TBR words introduced irrelevant information (i.e., unrelated words that were used to maintain sentence/story line cohesiveness) that interfered with the retention of the TBR information. This might have been a more serious problem for those with less WM resources. These types of issues should be addressed in future work.

Next, we examine how WM span scores obtained using the described strategies impacted the relationship between measures of WM and reading ability. Given the change in span scores from pre to post and the TBR data, we were interested in whether span scores obtained using the rehearsal strategy were a better predictor of reading ability. In Study 1, the rehearsal condition was a somewhat ($p = .06$) better predictor of reading ability than the control condition, but the interaction between post-WM span scores and the rehearsal condition failed to achieve significance. It was our hope that the improved methodology of Study 2 would provide evidence as to whether or not span scores obtained using the rehearsal strategy were a better estimate of capacity as we contended in Study 1.

Reading ability. To understand how strategy instructions impact the relationship between WM span and reading ability composite scores, regression analyses were conducted. In the first step, pre-WM span scores were entered as a predictor variable to control for the association between these scores and reading ability scores. In the second step, post-WM span scores and codes representing post-test condition (rehearsal vs. control, imagery vs. control, and semantic vs. control) were entered as predictor variables to assess the main effects of these variable on reading ability scores. The cross-products of post-WM span scores and codes representing post-test condition were entered in to the third step.

Pre-WM span scores accounted for 9% [$F(1, 358) = 34.02$, $p < .01$] of the variance in reading ability scores

Table 8
Hierarchical regression analysis predicting reading ability composite scores: Study 2

Step	Inc. R^2	F value	B	t value	sr^2
Step 1	.087	34.023**			
Pre-WM span			.031	5.833**	.087
Step 2	.069	7.270**			
Post-WM span			.043	5.082**	.062
Rehearsal			−.080	−.636	.001
Imagery			.151	1.216	.003
Semantic			.023	.188	.000
Step 3	.022	3.086*			
Post-WM span × Rehearsal			−.048	2.568**	.015
Post-WM span × Imagery			−.004	−.239	.000
Post-WM span × Semantic			.019	1.168	.003

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .05$.
** $p < .01$.

(see Table 8). Post-WM span scores and post-test condition accounted for 7% [$F(4, 354) = 7.27$, $p < .01$] of the variance in reading ability scores with only post-WM span scores ($sr^2 = .062$) contributing uniquely. The two-way interaction between post-WM span scores and the rehearsal condition ($sr^2 = .015$) was significant, accounting for 2% [$F(3, 351) = 3.09$, $p < .05$] of the variance in post-WM span scores. The other two-way interactions did not achieve significance.

As expected, pre-WM span scores predicted reading ability. Post-WM span scores also predicted reading ability, even after controlling for pre-WM span scores. The main effects for the strategy conditions did not predict reading ability composite scores. However, there was an interaction between post-WM span scores and the rehearsal condition, suggesting that span scores obtained in the rehearsal condition were better predictors of reading ability composite scores than the control post-test condition. The interaction between these variables produced an enhanced correlation between WM span scores obtained using the rehearsal strategy and reading ability composite scores. The correlation for the rehearsal condition was .56 compared to .30 in the control condition (see Table 5). From these data, we conclude that WM assessments obtained while using the rehearsal strategy provide even more accurate true-score estimates of WM. Because we observe an increase in the correlation between WM span scores and reading ability, we believe that variability of strategy use in the control condition suppressed the relationship between WM span scores and reading ability. When strategy training reduced variability in strategy use, the correlation was increased.

Outcome assessment

In order to clarify the findings in Studies 1 and 2, participants were asked to describe what, if any, strategy they had used to manage the demands of the operation span measure prior to receiving any strategy instruction. Overall, 42% of participants reported engaging in some sort of strategy to manage the demands of the operation span measure. High spans were more likely to report using a strategy (62%) than either medium (39%) or low spans (25%). The most frequently reported strategy was the rehearsal strategy (44%) followed by the semantic strategy (35%) and the imagery strategy (21%). However, in many cases when participants described their use of a semantic strategy there was generally some reference to repetition consistent with our conceptualization of the rehearsal condition.

These data have at least two implications for the present research. First, consistent with our explanation in Study 1 and Turley (1997), high spans were more likely to report strategy use than medium and low spans prior to strategy instruction. These results suggest that the limited improvement in WM performance on the post-WM span test following strategy instruction by high spans might be, in part, the result of strategy use on the pre-WM span test. Acknowledgement of strategy use and longer viewing times for the TBR words on the WM pre-test suggest that high spans were engaging in a strategy to manage the demand of the operation span measure. Therefore, rehearsal strategy instruction might not have had the same effect for high spans as it did for lower span participants. Limited improvement in span scores for high spans might reflect a ceiling in their WM span rather than a ceiling in the assessment tool.

Also of interest were the types of strategies reported by participants. Of those reporting the use of a strategy, most participants reported using some type of rehearsal and/or semantic strategy. Fewer participants made reference to creating an image of the TBR words. This might suggest that the imagery strategy was more difficult or resource demanding for participants.

Study 3

In Study 3, we addressed a concern of both Studies 1 and 2 that improvement in WM span scores was simply a product of time spent processing the TBR words. We have argued that time spent on the TBR words cannot account completely for the improved WM performance of low spans in the rehearsal condition. In both studies, increased time spent on the post-WM span TBR words was accompanied by increases in WM span scores for low spans in the rehearsal condition (but only marginally so in Study 1). Note that all participants, not just low spans, increased how much time they spent on the TBR words when assigned to the rehearsal condition. In Study 2, strategy instructions, in general, increased the amount of time participants spent processing the TBR words. The relationship between time spent on the TBR words and WM span performance was different for the semantic and imagery strategy conditions. Although TBR time increased when participants used either the semantic or imagery strategies, WM span scores were significantly different from pre to post for participants in the semantic condition as compared to the control condition. No such difference was observed for participants assigned to the imagery condition.

Although all types of strategy instruction resulted in participants spending more of their 7 s on the TBR words, as evident in Fig. 5, the increase in time spent processing the TBR words across strategy conditions was not uniform, more time was spent on the TBR words when participants were assigned to use the rehearsal strategy. Therefore, the possibility still exists that the rehearsal condition might be a better predictor of reading ability because of allocation of time to the TBR words. It also could explain why the other strategy conditions failed to predict reading composite scores better than the control condition.

Study 3 was designed to assess the extent to which processing time for the TBR words account for the improved span scores in the rehearsal condition of Studies 1 and 2. The same conditions used in Study 2 were used in Study 3, except that participants had 4 s to solve the math problems and 3 s to process the TBR words. In other words, all participants had the same amount of time to use the assigned strategy to help them remember the TBR words. This manipulation allowed us to determine whether improvements in WM span scores and the enhanced prediction of reading ability composite scores based upon span scores obtained using the rehearsal strategy were due to processing time or strategy use.

Method

Participants

Participants were 180 undergraduate students at Idaho State University who were enrolled in psychology courses. In exchange for participation, each participant received either extra credit or partial fulfillment of a course requirement. All participants were native English speakers and were not the same participants used in Study 2.

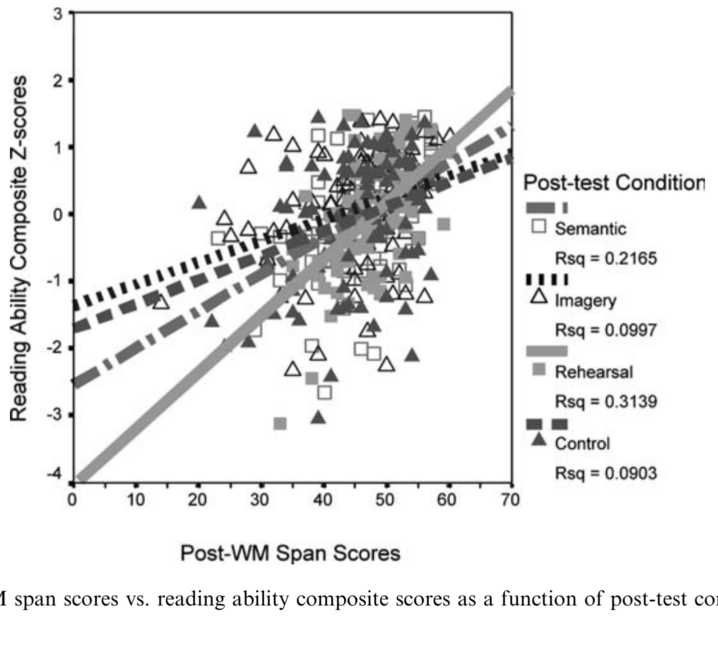

Fig. 5. Post-WM span scores vs. reading ability composite scores as a function of post-test condition: Study 2.

Procedure

The same procedures outlined in Study 1 and 2 were used to administer the pre- and post-WM span tests. Participants were assigned randomly in equal numbers to the four conditions: rehearsal, imagery, semantic, and control. As in Studies 1 and 2, participants in the control condition received a paraphrased version of the original instructions before completing the post-WM span test. Participants assigned to the strategy conditions received the same strategy instructions as were used in Study 2. However, this time participants had 4 s to work through the math operation and 3 s to use the assigned strategy when the TBR words were presented. Participants in the control group were exposed also to the TBR words for 3 s. The outcome assessment tool used in Study 2 was omitted in Study 3. As in Studies 1 and 2, participants completed the Nelson–Denny reading test.

Results and discussion

Hierarchical regression analyses

The same regression analyses conducted in Study 2 were conducted for Study 3 with one exception. Because the intent of Study 3 was to control for time spent on the TBR words, the regression analysis using the average time spent on the post-WM span TBR words was not conducted. The same coding procedure used in Study 2 was used in Study 3 to represent the three strategy conditions and interactions between other variables and the strategy conditions.

Post-WM span scores. To determine the impact of strategy instruction on post-WM span scores, pre-WM span scores and codes representing post-test condition (rehearsal vs. control, imagery vs. control, and semantic vs. control) were entered as predictor variables into the first step of the hierarchical analysis. The cross-products of pre-WM span scores and codes representing post-test conditions were entered into the second step along with the predictors for the first step.

As indicated in Table 9, pre-WM span scores and post-test conditions accounted for 59% [$F(4, 175) = 63.55$, $p < .01$] of the variance in post-WM span scores. Only pre-WM span scores ($sr^2 = .567$) contributed uniquely to the prediction of post-WM span scores. The main effects for the three strategy conditions were not significant. Also, none of the two-way interactions between pre-WM span scores and the three strategy conditions achieved statistical significance.

As with the previous studies, pre- and post-WM span scores were highly related. Unlike Studies 1 and 2, there was no difference between the strategy conditions and the control condition in predicting post-WM span scores. In other words, the control condition and the strategy conditions were equally good predictors of post-WM span scores when time spent on the TBR words was controlled for. WM span scores improved from pre to post similarly across the strategy and control conditions when all participants spent 3 s processing the TBR words. From these results it would be reasonable to conclude that post-WM span scores are a product of time spent on the TBR words. If that is the case, then post-WM span scores should predict reading ability composite scores equally well. If post-WM spans scores obtained using a particular strategy more accurately reflect differences in an individual's ability to manage both the processing and storage demands of the operation span task then differences in how predictive span scores are of reading ability might emerge as a function of strategy condition. In other words, some strategies might produce meaningful changes in span scores that are related to an individual's ability to read for comprehension. The following analysis assessed the likelihood of this possibility.

Reading ability. To understand how strategy instruction impacts the relationship between WM span and reading ability composite scores while holding constant time spent on the post-test TBR words,

Table 9
Hierarchical regression analysis predicting post-WM span scores: Study 3

Step	Inc. R^2	F-change	B	t-value	sr^2
Step 1	.592	63.553*			
Pre-WM span			.672	10.854*	.567
Rehearsal			−.030	−.023	.000
Imagery			.594	.444	.000
Semantic			−1.486	−1.110	.003
Step 2	.009	1.236			
Pre-WM span × Rehearsal			−.170	−1.424	.005
Pre-WM span × Imagery			.043	.334	.000
Pre-WM span × Semantic			−.016	.135	.000

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .01$.

regression analyses were conducted. In the first step, pre-WM span scores were entered as a predictor variable to control for the association between these scores and reading ability scores. In the second step, post-WM span scores and codes representing post-test condition (rehearsal vs. control, imagery vs. control, and semantic vs. control) were entered as predictor variables to assess the main effects of these variables on reading ability scores. The cross-products of post-WM span scores and codes representing post-test condition were entered in to the third step.

The relationship between WM span scores and reading ability scores as a function of condition is presented in Fig. 6. As indicated in Table 10, pre-WM span scores accounted for 14% [$F(1, 181) = 29.91,\ p < .01$] of the variance in reading ability scores. Post-WM span scores and post-test condition accounted for 7% [$F(4, 177) = 3.82,\ p < .01$] of the variability in reading ability composite scores with only post-WM span scores ($sr^2 = .006$) contributing uniquely. The two-way interaction between post-WM span scores and the rehearsal condition ($sr^2 = .029$) was significant, accounting for 4% [$F(3, 174) = 2.96,\ p < .05$] of the variance in post-WM span scores. The other two-way interactions did not achieve significance.

Although WM span scores increased similarly from pre to post across conditions when time spent on the TBR words was held constant, these data indicated that

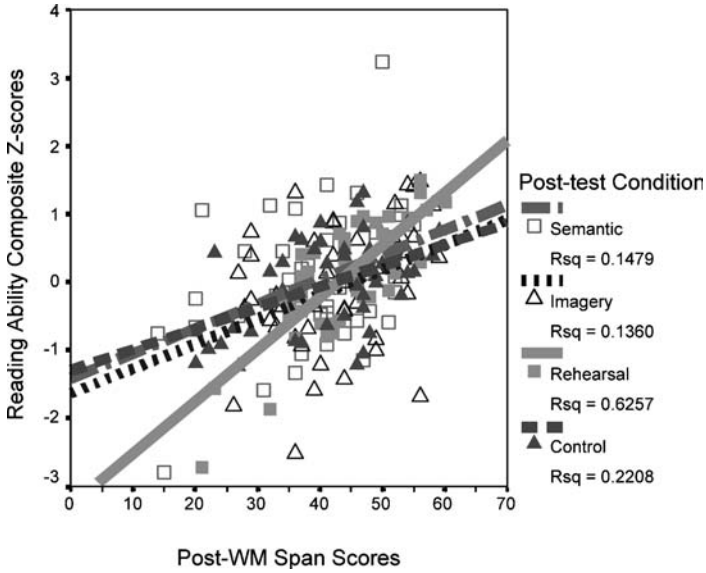

Fig. 6. Post-WM span scores vs. reading ability composite scores as a function of post-test condition: Study 3.

Table 10
Hierarchical regression analysis predicting reading ability composite scores: Study 3

Step	Inc. R^2	F change	B	t value	sr^2
Step 1	.142	29.909**			
Pre-WM span			.029	5.469**	.142
Step 2	.068	3.821**			
Post-WM span			.035	3.852**	.006
Rehearsal			−.022	−.138	.000
Imagery			−.114	−.716	.002
Semantic			.044	.281	.000
Step 3	.038	2.963*			
Post-WM span × Rehearsal			−.044	2.595**	.029
Post-WM span × Imagery			.005	.333	.000
Post-WM span × Semantic			−.016	−.104	.000

Note. Inc. R^2, increment in variance accounted for; B, unstandardized regression coefficient; sr^2, squared semipartial correlation.
* $p < .05$.
** $p < .01$.

changes in WM span scores for individuals assigned to the rehearsal condition were more predictive of reading ability composite scores than the control condition. This was not the case for the other strategy conditions. The relationship between WM span scores obtained using the rehearsal strategy and reading ability composite scores can be seen in both Fig. 6 and Table 5. The correlation between WM span and reading ability was greatest in the rehearsal condition. For the rehearsal condition the correlation was .79 compared to .47 in the control condition. These results are consistent with the results of Study 2. Controlling for strategy use by employing the rehearsal strategy and controlling time spent on the TBR words did not eliminate the correlation between WM span and reading ability. Controlling for these factors actually influenced WM assessments in a meaningful way. When strategy use was controlled for using the rehearsal strategy, the correlation between WM span and reading ability composite scores was enhanced. Therefore, failure to control for strategies in a way that assists low spans in managing the demands of the WM task underestimates the true relationship between WM span scores and measures of reading ability.

Taken together, these findings suggest that although time spent on the TBR words impacts the magnitude of WM span scores it is what the strategy does during processing of the task that is most important. Utilization of a rehearsal strategy appeared to be especially helpful for low spans in managing the demands of a WM task and was more predictive of how they carryout cognitively demanding tasks like reading. This has important practical implications regarding the use of WM assessments in predicting higher-order functioning like reading ability.

General discussion

The present research was conducted to address two fundamental questions about WM span and higher-order cognition. We were interested in what accounts for individual differences in WM span scores, and the correlation between WM span scores and assessment of higher-order cognition. We thought that strategy use might influence both span scores and the said correlation. Thus, we set out to answer three specific questions about the importance of strategies when assessing WM span and predicting higher cognitive function. From previous research it was unclear how strategies impact assessments of WM span, whether span groups differentially benefit from different types of strategy instruction, and how WM strategies impact the correlation between WM span scores and higher cognitive function. Insight into these questions was gained as a result of the three studies discussed in the present manuscript. Practical and theoretical implications of the present research are discussed in conjunction with empirical evaluation of the above set of questions.

Strategies and assessment of WM span

In the present set of studies, it was found that certain types of strategy training influenced assessments of WM. In Study 1, we found a marginally significant interaction between pre-WM span scores and rehearsal training, as compared to the control condition, when predicting WM spans scores. As seen in Fig. 1, low spans, in particular, increased their WM span scores on the post-test when they were taught to use the rehearsal strategy. In Study 2, the same interaction achieved significance, again indicating that low spans benefited from rehearsal strategy instruction. The same pattern emerged in Study 3 when time spent processing the TBR words was controlled.

The effectiveness of imagery and semantic strategy training for assessments of WM is less clear. In Study 2, the semantic condition differed from control in predicting post-WM span scores. However, the semantic condition did not interact with pre-WM span scores. Based upon Study 2, it was unclear how the semantic strategy altered WM performance, and there was no evidence suggesting that one particular span group benefited from such training. No effects were observed for semantic strategy training in Study 3 when we controlled for time spent on the TBR word. In both Studies 2 and 3, imagery strategy instruction did not differ from control or interact with pre-WM span scores when predicting post-WM span scores.

Why is rehearsal the optimal strategy for low spans?

From the present results, we are left wondering why the rehearsal strategy was the "optimal" strategy for low spans? There are a number of possible explanations. First, the rehearsal strategy might have been the easiest to learn. Experiencing the benefits of either the imagery or semantic strategies might have required more practice with the strategy than was provided. In the present research, participants were given 12 practice trials of a set size of two following presentation of strategy instructions and prior to administration of the test trials. McNamara and Scott (2001) observed an increase in WM scores when participants had been taught to use a chaining strategy, similar to our semantic strategy, following four sessions of training with multiple word lists. With more training, it is possible that low spans, or other span groups, might have benefited from semantic and imagery strategy training.

Second, the rehearsal strategy might be the preferred or default strategy for low spans. However, as indicated in the outcome assessment data from Study 2, few low spans reported using strategies on the WM span test. Of those that did report using a strategy, only a small proportion reported using a rehearsal strategy.

A third explanation is that low spans benefited more from the rehearsal strategy because it was less resource demanding. Although the imagery and semantic strategies might aid in the allocation of WM resources, these strategies might require more resources to enact. Low spans might not have adequate resources to enact the strategy and perform the operation span test, limiting the benefit of these strategies for low spans.

A fourth explanation is that the imagery and semantic strategies might have introduced interference that limited the degree to which low spans benefited from these strategies. Previous research has documented differences between high and low spans in their susceptibility to interference and intrusions, and their ability to inhibit or suppress irrelevant information. Low spans are more susceptible to interference and intrusions than high spans (Kane & Engle, 2000; Rosen & Engle, 1997, 1998). High spans are more likely than low spans to allocate resources to inhibit or suppress irrelevant information, decreasing their susceptibility to interference and intrusions (Conway et al., 1999; Rosen & Engle). In other words, high spans engage in strategies that allow them to focus on the relevant aspects of a task without being distracted by irrelevant information. The rehearsal strategy might have served the same purpose for low spans in the present research. Rehearsing the TBR words repeatedly might have activated the relevant information, while indirectly preventing irrelevant information from entering WM. Thus, low spans might have been less distracted by intrusions in the rehearsal condition, enhancing WM performance.

Low spans might not have benefited as much from the imagery or semantic strategies because there was more opportunity for intrusions to enter WM. Creating an image might conjure up other thoughts not directly related to the task at hand. Similarly, creating a story or sentence using the TBR words might include context that could serve as a distractor at the time of recall. Therefore, the rehearsal strategy might be the "optimal" strategy for low spans, in the present study, because it is fairly easy to learn, directs attention towards relevant information, and limits the availability of potential intrusions. Because there are a number of reasonable explanations for the superiority of the rehearsal strategy for low spans, we believe future research is needed.

What is the optimal strategy for high spans?

High spans did not benefit as much from strategy instruction as did low spans. There were differences between high and low spans to begin with that might explain why their span scores did not improve as a function of strategy training. First, high spans spent more time viewing the TBR words regardless of condition. Second, high spans were more likely than low spans to report engaging in a strategy prior to strategy instruction (Study 2). The fact that high spans "understood" the importance of processing the TBR words, as indicated by viewing times and self-reported strategy use, suggests that this group might have been already using a strategy to help manage the demands of the WM task. It is also possible that the strategy instructions provided might have impeded, in some cases, optimal performance. If the strategy that a high span was engaging in initially (pre-test) was more effective than the one provided (post-test), then strategy instruction might have negatively impacted that individual's WM span score. Therefore, we believe that it is likely that high spans had reached a ceiling in their WM performance because of their greater capacity and "awareness" that strategy use could facilitate performance on such tasks.

Thus, we believe that the present set of studies indicate that WM span scores represent individual differences in both capacity and strategy. High spans have more capacity and are more strategic in their approach to the operation span measure. Low spans have less capacity, but this may be due, in part, to their failure to use a strategy to manage the demands of the task. Low spans are limited in their WM capacity, but may not be as limited as their WM scores indicate when there is no information about how to effectively manage the demands of the task.

Strategy instruction and the relationship between WM span scores and reading ability

Although it is noteworthy that certain strategies are effective in facilitating controlled processing for low spans, understanding how these strategies influence the ability to use WM span scores to predict higher-level cognition is critical. If enhancing span scores by using strategies only artificially inflates spans scores, then knowing span scores can be improved is less meaningful. If strategy instructions eliminate or facilitate predictions regarding higher cognitive function, then this information has both practical and theoretical implications.

In the introduction, we argued that strategies could either account for or attenuate the relationship between WM span scores and indices of higher-order cognition. If strategy use accounts for the said relationship, then we would expect the correlation between WM span scores and reading ability composite scores to be reduced when we control for strategy use. If strategies suppress the said relationship, then we would expect the correlation between WM span and reading ability composite scores to increase when we control for strategy use. Because we believed that there was variability in strategy use during assessments of WM span we predicted the latter. We thought it was likely that holding strategies constant while participants completed the operation span measure would enhance the predictive validity of operation span scores for reading ability scores. Support was obtained for this prediction.

In Study 1 when participants completed the operation span test using the rehearsal strategy, the correlation between measures of WM and reading ability were higher for those assigned to the rehearsal condition (.52) than the control condition (.43), although the interaction between post-WM spans scores and the rehearsal condition failed to achieve significance. In Study 2, the interaction between post-WM spans scores and the rehearsal condition achieved significance, suggesting that there was a meaningful difference in the predictive validity of WM post-test scores for reading ability scores between the rehearsal (.56) and control (.30) conditions. This was also the case in Study 3 when we controlled for time spent using a given strategy. The correlation between post-WM span scores and reading ability composite scores was .79 in the rehearsal condition compared to .47 in the control condition. Enhancement of the correlation between WM span and reading ability composite scores could not be attributed to time spent processing the TBR words. This was demonstrated indirectly in both Studies 1 and 2, and directly in Study 3.

Taken together, these data suggest that controlling for strategy use does impact the correlation between measures of WM span and reading ability. However, how you control for strategy use is critical. In the present study, the rehearsal strategy facilitated WM performance and enhanced the predictive validity of span scores for one index of higher-order cognition. This finding has important practical implications for WM researchers. The fact that strategy use contributed to the assessment of WM span and the predictive validity of WM span for measures of reading ability calls into question the procedures often used when measuring WM span. Our review of the literature found only on study (McNamara & Scott, 2001) that assessed WM task performance while holding strategy use constant. Unfortunately, correlational values between span scores and indices of higher cognitive function were not reported. If strategies impact other assessments of WM span (e.g., McNamara & Scott used the reading span test), it is likely that strategies impact the predictive validity of WM span scores for other criterion tasks (e.g., VSAT scores). WM researchers need to consider how best to control for variability in strategy use when assessing WM span and making predictions about higher cognitive functioning. Rather than letting strategic factors detract from the predictive validity of the measure, we recommend controlling for such factors. Thus, careful consideration of techniques to control for strategy use when assessing WM span is warranted.

Limitation of present research

There are a number of limitations to the present research that should be examined in more detail in future research. First, the amount of practice participants received in using the described strategies could have limited the benefits of the semantic and imagery strategies. With more practice, these strategies might prove also to be effective ways to control for strategy use when assessing WM span.

Second, there are other ways to conceptualize and train participants to use imagery or semantic techniques to facilitate recall of TBR words. Our description of these strategies might have been too vague, complex, or abstract for participants to benefit fully from these techniques. Controlling how participants, for instance, create interactive images of the TBR words might result in different conclusions than those presented here.

Third, there are other strategies that could facilitate processing that were not examined in the present research. For instance, mnemonic devices, such peg word or method of loci, might prove beneficial and adequately control for strategy use when making predictions about higher-order condition based upon WM span scores.

Finally, we recognize that relationships observed in the present research might be limited to use of operation span scores and Nelson–Denny reading comprehension scores. We believe that this is unlikely given the existing literature in which the relationship between various span measures and various indices of higher-level cognition are well documented; yet, future research would benefit from such inquiries.

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