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# Working Memory Capacity and Recall From Long-Term Memory: Examining the Influences of Encoding Strategies, Study Time Allocation, Search Efficiency, and Monitoring Abilities

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The relation between working memory capacity (WMC) and recall from long-term memory (LTM) was examined in the current study. Participants performed multiple measures of delayed free recall varying in presentation duration and self-reported their strategy usage after each task. Participants also performed multiple measures of WMC. The results suggested that WMC and LTM recall were related, and part of this relation was due to effective strategy use. However, adaptive changes in strategy use and study time allocation were not related to WMC. Examining multiple variables with structural equation modeling suggested that the relation between WMC and LTM recall was due to variation in effective strategy use, search efficiency, and monitoring abilities. Furthermore, all variables were shown to account for individual differences in LTM recall. These results suggest that the relation between WMC and recall from LTM is due to multiple strategic factors operating at both encoding and retrieval.

*Keywords:* working memory, long-term memory, recall, individual differences

Measures of working memory capacity (WMC) such as reading (Daneman & Carpenter, 1980) and operation span (Turner & Engle, 1989) have been shown to be important predictors of a number of higher-order and lower-order cognitive processes. In these tasks, to-be-remembered items are interspersed with some form of distracting activity such as reading sentences or solving math operations. Recent work has suggested that individual differences in WMC reflect not only differences in active maintenance abilities (Engle & Kane, 2004) but also differences in the ability to retrieve information from long-term memory (LTM; Unsworth & Engle, 2007). Evidence consistent with this latter point comes from various studies that have demonstrated differences between high and low WMC individuals on various tests of LTM including free and cued recall as well as item and source recognition (e.g., Unsworth, 2010; Unsworth, Brewer, & Spillers, 2009). These results occur not only when examining extreme groups of high and low WMC individuals on single tests of LTM (Unsworth, 2007), but also when testing a full range of participants on multiple tasks and examining relations between latent variables of WMC and LTM (Unsworth et al., 2009). In each case, high WMC individuals demonstrate better remembering from LTM than low WMC individuals. Furthermore, several studies have suggested that WMC differences in LTM abilities partially account for the shared variance between WMC and intelligence (e.g., Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth, 2010; Unsworth et al., 2009). Thus, it is clear that that there is a strong and important relation between individual differences in WMC and remembering from LTM. The question remains, however, as to what is the nature of this relation.

Prior work has suggested that high and low WMC individuals will differ on tests of LTM especially when self-initiated processes are needed (Unsworth, 2009a). In order to account for these differences, we (Unsworth & Engle, 2007) suggested a search model similar to that of Shiffrin (1970). In particular, we suggested that covariation in WMC and recall from LTM could be accounted for by a relatively simple search model (Unsworth, 2007; Unsworth & Engle, 2007). In this model, it is assumed that there are both directed and random components to the overall search process (Shiffrin, 1970; Shiffrin & Atkinson, 1969). The directed component refers to those strategic processes that are under the control of the individual. These control processes include setting up a retrieval plan, selecting and utilizing appropriate encoding strategies, selecting and generating appropriate cues to search memory with, as well as various monitoring strategies and decisions to continue searching or not. The random component refers to the probabilistic nature of the search process in which a subset of information is activated by the cues (i.e., the search set), and representations are subsequently sampled and recovered from this subset (Raaijmakers & Shiffrin, 1980; Shiffrin, 1970).

Our prior work mainly focused on examining WMC differences in generating and using effective retrieval cues to focus the search set on target items suggesting that high WMC individuals search through a smaller set of items than low WMC individuals leading to better overall performance (Unsworth, 2007; Unsworth & Engle, 2007; Unsworth, Spillers, & Brewer, 2012). Evidence consistent with this interpretation came from studies suggesting that low WMC individuals recalled fewer correct items, had longer recall latencies (and interresponse times, IRT), and recalled more intrusions than high WMC individuals. Additional work has also suggested that WMC differences on long-term memory tasks arise due to differences in monitoring abilities such that low WMC

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individuals are poorer at monitoring the output of the recall process leading to more intrusions and less confidence in those intrusions (Lilienthal, Rose, Tamez, Myerson, & Hale, 2015; Rose, 2013; Unsworth, 2009b; Unsworth & Brewer, 2010a, 2010b). Thus, prior research suggests that WMC differences in the ability to recall information from episodic LTM are partially due to differences in search efficiency/search set size (indexed by recall latency and IRT) and monitoring the products of the search process (indexed by intrusion errors).

Considerably less work has specifically examined individual differences in WMC and strategic memory control processes such as encoding strategies. The notion that control processes are an important part of memory has long been acknowledged by memory researchers. Indeed, Atkinson and Shiffrin (1968) noted that their framework "emphasized the role of control processes—processes under the voluntary control of the subject such as rehearsal, coding, and search strategies. It was argued that these control processes are such a pervasive and integral component of human memory that a theory which hopes to achieve any degree of generality must take them into account" (p. 191). Likewise, in Nelson and Narens (1990) metamemory framework, control processes were integral in terms of encoding processes. Specifically, Nelson and Narens suggested that at encoding control processes were needed to select the kind of processing to be done on the items in terms of various encoding strategies (e.g., rote rehearsal, imagery, forming a sentence, grouping the words in a meaningful way, etc.) to decide which items to study and for how long, as well as deciding when to terminate studying (study time allocation). Thus, similar to Atkinson and Shiffrin (1968), Nelson and Narens suggested that control processes were needed during encoding in order to utilize various strategies and make decisions. Of course, the use of certain strategies is not always under direct control (such as when certain stimuli evoke an image), and thus there are other processes responsible for the use of strategies on various tasks. Importantly, the ability to decide which strategies are appropriate as well as the ability to actually utilize those strategies will be a strong contributor to overall performance and a likely reason for individual differences in performance. As such, this work points to the overall importance of control processes in terms of various strategies when examining memory (Benjamin, 2007). Indeed, in a recent critique of the field Hintzman (2011) noted that "the field could benefit greatly from a heightened awareness of strategies. Experimenters should try to identify and to control the strategies used by their subjects, and theorists should clearly delineate those aspects of theory that relate to optional strategies, as opposed to the fixed architecture that underlies all memory tasks" (p. 267).

The notion that performance on LTM tasks is driven, in part, by encoding strategies has a long history. As noted previously, encoding strategies such as rote rehearsal and coding were considered fundamental control processes in Atkinson and Shiffrin's (1968) model. A great deal of empirical work has demonstrated that effective encoding strategy use correlates strongly with overall recall performance (Richardson, 1998) and partially accounts for age differences in memory performance (Hertzog & Dunlosky, 2004). However, less is known regarding whether individual differences in encoding strategies account for the relation between WMC and performance on LTM measures (see Dunlosky & Kane, 2007; McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003 for evidence that encoding strategies influence performance on measures of WMC). Two recent studies suggest that at least part of the correlation between WMC and performance on LTM measures is due to differences in encoding strategies (Bailey, Dunlosky, & Kane, 2008; Unsworth & Spillers, 2010). Specifically, Bailey et al. (2008) found that measures of WMC correlated with reported strategy use such that high WMC individuals were more likely to report using more effective strategies (e.g., imagery and sentence generation) than low WMC individuals. Importantly, Bailey et al. found that individual differences in strategy use partially accounted for the relation between WMC and LTM measures. In a related vein, Unsworth and Spillers (2010) examined strategy use for high and low WMC individuals on the continuous distractor free-recall task and found that high WMC individuals reported using repetition more than low WMC individuals, and these differences in strategies partially accounted for the relation between WMC and recall performance. Thus, in both studies, high WMC individuals reported being more strategic than low WMC individuals, and differences in strategy usage partially mediated the correlation between WMC and LTM. Although this initial evidence is encouraging, there is one interesting difference between Bailey et al.'s (2008) results and those of Unsworth and Spillers (2010). Specifically, Bailey et al. (2008) found that high and low WMC individuals seem to differ on normatively effective strategies (e.g., imagery) whereas Unsworth and Spillers (2010) found that high and low WMC individuals did not differ in the use of effective strategies, but rather differed in the use of simple repetition (normatively ineffective strategies). Thus, in one case, the results suggest that the reason high and low WMC individuals differ in performance on LTM measures is because high WMC individuals use more effective strategies than low WMC individuals, whereas in the other case, the results suggest that the reason for differences is due simply to differences in repetition and rehearsal. A potential reason for this discrepancy could be due to differences in the presentation duration of individual words in each study. Specifically, in Bailey et al. (2008), words were presented individually for 5 s in their free-recall task, whereas in Unsworth and Spillers (2010), words were presented for 2.5 s each in a demanding continuous distractor task. With 5 s per word in the Bailey et al. (2008) study, it is likely that high WMC individuals had sufficient time to engage in more elaborate strategies to aid in their performance, whereas in the Unsworth and Spillers (2010) study with only 2.5 s per word, it is likely that individuals simply relied on a repetition strategy as there was not enough time to attempt to use more elaborate strategies. This suggests the possibility that high and low WMC individuals differ not only in the types of strategies they use to encode information, but also in the ability to dynamically shift strategies as a function of task demands. In particular, as presentation duration increases, perhaps high WMC individuals are better able to dynamically shift their strategies and utilize more elaborative strategies given more time than low WMC individuals. Such a notion is consistent with prior work that has demonstrated that as presentation duration increases, participants are more likely to use more elaborative strategies (such as organization) resulting in better recall performance (Stoff & Eagle, 1971). Thus, participants adaptively change their encoding strategies as a function of task demands and experience (Delaney & Knowles, 2005; Finley & Benjamin, 2012).

# The Present Study

The goal in the present study was to examine the nature of the relation between WMC and recall from LTM. In particular, the first main goal was to examine whether individual differences in WMC would relate to differences in self-reported encoding strategies during free recall and examine the extent to which individual differences in WMC are related to how participants dynamically adapt their strategies to the task at hand. In particular, participants performed three delayed free-recall tasks varying in the presentation duration of the words during encoding. In one task, the words were presented for only 1 s. In another task, the words were presented for 4 s. Finally, in the third recall task, participants were allowed to control the duration of each word. Specifically, with the presentation of each word, participants were allowed to determine how long the word stayed onscreen pressing the spacebar to move onto the next word (e.g., Engle, Cantor, & Carullo, 1992; Kellas, Ashcraft, Johnson, & Needham, 1973). This condition should allow all participants plenty of time to engage in elaborate strategies if they wish and to examine possible WMC differences in the allocation of study time. Following each task, participants indicated which strategies (if any) they used during the presentation of the words. By having participants perform multiple recall tasks with different presentation durations, we should be able to better examine the role of WMC in encoding strategies and how this changes as a function of task demands such as presentation duration. As presentation duration increases, we should see that the use of more elaborative strategies increases, and this ability may be related to WMC. Thus, the first main goal of the present study was to assess whether differences in encoding strategies and changes in encoding strategies are related to WMC.

The second main goal of the present study was to examine the relation between WMC and recall from LTM by examining the joint contributions of a number of variables. In particular, prior research has shown that the WMC–LTM recall relation is partially due to differences in search efficiency in terms of using cues to focus the search on correct items (based on recall latency and interresponse time; see, e.g., Rohrer & Wixted, 1994; Unsworth, 2007, 2009b; Wixted & Rohrer, 1994) and by differences in monitoring abilities (based on intrusion errors). At the same time, this work has consistently shown that WMC is related to LTM recall even after taking these other factors into consideration (Unsworth, 2009b). Likewise, prior research has shown that differences in encoding strategies partially accounts for the relation between WMC and recall (Bailey et al., 2008; Unsworth & Spillers, 2010). But, again the relation between WMC and recall was not fully accounted for. By examining differences in encoding strategies, study time allocation, search efficiency, and monitoring abilities, we should be able to fully account for the relation between WMC and recall from LTM. Therefore, the second main goal of the present study was to examine the relation between WMC and recall after taking into account individual differences in other variables thought to mediate the relation. If the relation between WMC and recall from LTM is multifaceted, we should see that WMC is related to these various components, that each of the components is related to recall performance, and importantly that these components mediate the relation between WMC and recall from LTM.

# Method

## Participants

A total of 135 participants were recruited from the subject pool at the University of Oregon. Data was collected over one full academic quarter. Eleven participants failed to complete one or more of the delayed free-recall tasks and were excluded from the analyses, leaving a final sample of 124 participants with full data. Participants were between the ages of 18 and 35 and received course credit for their participation. Each participant was tested individually.

## Materials and Procedure

After signing informed consent, all participants completed the operation span (Ospan) task, the symmetry span (Symspan) task, the reading span (Rspan) task, and the three free-recall tasks. The order of the free-recall tasks was counterbalanced across participants.

## WMC Tasks

**Operation span (Ospan).** Participants solved a series of math operations while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). Participants were required to solve a math operation, and after solving the operation, they were presented with a letter for 1 s. Immediately after the letter was presented, the next operation was presented. Three trials of each list-length (3–7) were presented, with the order of list-length varying randomly. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters (see Unsworth, Heitz, Schrock, & Engle, 2005 for more details). Participants received three sets (of list-length two) of practice. For all of the span measures, items were scored if the item was correct and in the correct position. The score was the total number of correct items in the correct position.

**Symmetry span (Symspan).** In this task, participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task, participants were shown an 8 × 8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 × 4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared by clicking on the cells of an empty matrix. There were three trials of each list-length with list-length ranging from 2–5. The same scoring procedure as Ospan was used (see Unsworth, Redick, Heitz, Broadway, & Engle, 2009 for more task details).

**Reading span (Rspan).** Participants were required to read sentences while trying to remember the same set of unrelated letters as Ospan. For this task, participants read a sentence and determined whether the sentence made sense or not (e.g., “The prosecutor’s dish was lost because it was not based on fact.”). Half of the sentences made sense while the other half did not. Nonsense sentences were made by simply changing one word (e.g., “dish” from "case") from an otherwise normal sentence. Participants were required to read the sentence and to indicate whether it made sense or not. After participants gave their response, they were presented with a letter for 1 s. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. There were three trials of each list-length with list-length ranging from 3–7. The same scoring procedure as Ospan was used (see Unsworth et al., 2009 for more task details).

## Free Recall Tasks

Participants performed three delayed free-recall tasks with five lists of 10 words per task. Words were nouns selected from the Toronto word pool (Friendly, Franklin, Hoffman, & Rubin, 1982). Words were initially randomized and placed into the lists, and all participants received the exact same lists of words. The tasks were counterbalanced across participants. On the delayed free recall, 1-s task participants were presented with 10 words at a rate of 1 s per word. On the delayed free recall, 4-s task participants were presented with 10 words at a rate of 4 s per word. On the delayed free recall, unlimited task participants were presented 10 words, and they were instructed to press the space bar to move the trial along. For each trial, participants were told that they would be presented with a list of words, and that following a brief distractor task, they would be prompted to recall the words. They were instructed to read the words silently as they were presented and to recall the words in any order they wished during the recall period. Each trial began with a Ready signal onscreen followed by a series of words presented one at a time in the center of the screen with a 1-s blank screen in between the presentation of each word. Following the list of words, participants engaged in a 16-s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each, and were required to write the digits in descending order (e.g., Rohrer & Wixted, 1994; Unsworth, 2007). At recall, participants saw three question marks appear in the middle of the screen indicating that they needed to begin recalling the words. Participants had 45 s to recall as many of the words as possible in any order they wished. Participants typed their responses and pressed "enter" after each response, clearing the screen. IRTs were measured with respect to when participants pressed enter after the word was typed (see also Mickes, Seale-Carlisle, & Wixted, 2013).

Immediately following each task, participants reported which strategies (if any) they used. Strategies included: reading each word as it appeared, repeating the words as much as possible, using sentences to link the words, using mental imagery, grouping the words in a meaningful way, or utilizing some other strategy. Participants could indicate that they used more than one strategy. The dependent variable was the proportion of reported strategy use in each recall task.

# Results

## Proportion Correct Recall

Replicating prior research, as presentation duration increased so did proportion correct with a greater proportion of words recalled in the 4-s ($M = .66$, $SE = .02$) and unlimited ($M = .65$, $SE = .02$) conditions than in the 1-s ($M = .46$, $SE = .01$) condition, $F(2, 244) = 104.59$, $MSE = .01$, $p < .01$, partial $\eta^2 = .46$. Follow-up comparisons suggested that both the 4-s and unlimited conditions recalled a higher proportion of items than the 1-s condition (both $p$ values $< .01$), but there was no difference between the 4-s and unlimited conditions, $p > .81$. The fact that the 4-s and unlimited conditions did not differ was likely due to the fact that when in the unlimited condition participants studied each word on average 3.56 s ($SE = .29$), thereby making those two conditions basically the same. Adding WMC in as a covariate suggested an effect of WMC, $F(1, 122) = 14.34$, $MSE = .07$, $p < .01$, partial $\eta^2 = .11$, demonstrating that higher WMC was related to higher recall, $r = .32$, $p < .01$. The interaction between task and WMC was not significant ($F < 1$, $p > .96$), suggesting that WMC differences did not change as a function of the different recall tasks.

## Encoding Strategies

Shown in Table 1 are the proportions of reported strategy use for each strategy and each task. Because only a few participants reported using every strategy, we divided responses into normatively effective and normatively less effective strategies (see also Bailey et al., 2008). Consistent with prior research, effective strategies were interactive imagery, sentence generation, and grouping, whereas less effective strategies were passive reading and simple repetition (Bailey et al., 2008; Richardson, 1998). To see if strategy use changed as a function of task, we compared effective and less effective strategies across the different tasks. As seen in Figure 1, participants reported using less effective strategies more than effective strategies, $F(1, 123) = 30.05$, $MSE = .41$, $p < .01$, partial $\eta^2 = .20$. Importantly, this changed as a function of task, with participants increasing the use of effective strategies with more study time, $F(2, 246) = 5.59$, $MSE = .07$, $p < .01$, partial $\eta^2 = .04$. Thus, consistent with prior research, participants reported using both effective and less effective strategies, and as the amount of study time increased, participants shifted to using more effective strategies (Stoff & Eagle, 1971). Next WMC was added in as a covariate to determine if there were WMC differences in strategy use and whether the shift in strategy use across tasks would be related to WMC. The only significant effect involving WMC was a WMC × Strategy Type interaction, $F(1, 122) = 1.42$, $MSE = .22$, $p < .05$, partial $\eta^2 = .05$, suggesting that variation in WMC was related to self-reports of effective strategy use, $r = .31$, $p < .01$, but not to less effective strategy use, $r = -.01$, $p > .87$. The Task × Type × WMC interaction was not significant, $F < 1$, $p > .93$, suggesting that although WMC was

Table 1
*Proportions of Reported Strategy Use as a Function of Strategy and Task*

| | Strategy | | | | | |
|---|---|---|---|---|---|---|
| Task | Read | Repetition | Imagery | Sentence | Grouping | Other |
| DFR1 | .77 (.04) | .61 (.04) | .31 (.04) | .52 (.05) | .42 (.04) | .10 (.03) |
| DFR4 | .79 (.04) | .64 (.04) | .53 (.05) | .54 (.05) | .54 (.05) | .18 (.03) |
| DFRU | .77 (.04) | .50 (.05) | .46 (.05) | .52 (.05) | .60 (.04) | .17 (.03) |

*Note*. Proportions of strategies sum to greater than 1.0 because participants were allowed to report using more than one strategy. DFR1 = delayed free recall 1-s; DFR4 = delayed free recall 4-s; DFRU = delayed free recall unlimited time.

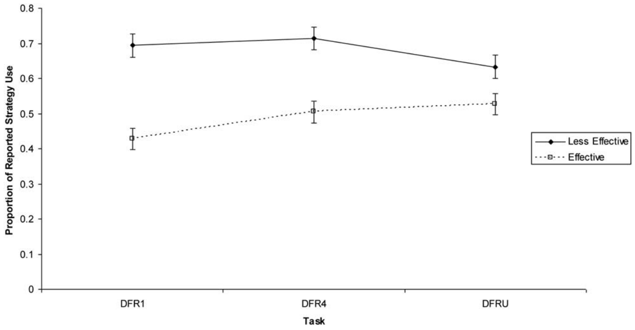

*Figure 1.* Proportions of reported strategy use for less effective and effective strategies as a function of task. Error bars reflect one standard error of the mean. DFR1 = delayed free recall 1-s; DFR4 = delayed free recall 4-s; DFRU = delayed free recall unlimited time.

related to the type of strategies used, it was not related to the shift in strategy use with more study time. That is, high and low WMC individuals both reported using more effective strategies as study time increased, but the increase in reported strategy use was the same for high and low WMC individuals. Specifically, low WMC individuals (the bottom 25% of WMC scorers) increased the use of effective strategies from 30% in the 1-s condition to 41% in the unlimited condition, and high WMC individuals (the top 25% of WMC scorers) increased the use of effective strategies from 48% in the 1-s condition to 61% in the unlimited condition. Thus, high WMC individuals reported using more effective strategies than low WMC individuals, and both groups reported increasing effective strategy use with more study time, but the increase in effective strategy use was comparable for high and low WMC individuals.

## Study Time Allocation

The next set of analyses focused on study time allocation in the self-paced recall task to determine if participants changed the amount of time they studied items as function of list and serial position and to see if variation in WMC would relate to study time allocation. As shown in Figure 2, examining study time allocation suggested that participants allocated more study time to items on early lists compared with later lists, $F(4, 492) = 4.36$, $MSE = 19127258$, $p < .01$, partial $\eta^2 = .04$. As shown in Figure 2b, examining study time allocation as a function of serial position within a list suggested participants tended to allocate more study time to later serial positions compared with early serial positions (although there was a clear primacy effect), $F(9, 1107) = 8.93$, $MSE = 29159113$, $p < .01$, partial $\eta^2 = .07$. The List × Serial Position interaction was not significant, $F(36, 4428) = 1.20$, $MSE = 9704899$, $p > .19$, partial $\eta^2 = .01$. Thus, participants changed their study time for each item across lists and serial positions, suggesting that participants adapt the amount of study time as the task progresses. Next, WMC was added in as a covariate to determine if there were WMC differences in study time allocation and whether there were WMC differences in how participants adapted the amount of time studying each item. However, none of the effects associated with WMC were significant (all $p$ values $> .41$), suggesting that variation in WMC was not related to the amount of time studying items, $r = .07$, $p > .40$, nor to changes in study time allocation across lists or serial positions. Thus, similar to the results on strategy use, WMC was not related to how individuals adapted or changed their studying.

## Latent Variable Analyses

The final set of analyses examined how the various recall variables were related and whether these different variables would mediate the relation between WMC and LTM recall that has been found many times previously. Shown in Table 2 are the descriptive measures for each task, and shown in Table 3 are the correlations among all of the measures.[1] As can be seen, the measures had moderate levels of internal consistency, and most of the measures were approximately normally distributed with values of skewness and kurtosis under the generally accepted values (i.e., skewness $< 2$ and kurtosis $< 4$; see Kline, 1998). Correlations were weak to moderate in magnitude with measures of the same construct generally correlating stronger with one another than with measures of other constructs, indicating both convergent and discriminant validity within the data.

Next, latent factors were created for WMC (based on the three WMC tasks), recall accuracy, less effective encoding, effective encoding, IRTs, and intrusions based on the respective measures across the three recall tasks. Additionally, a manifest variable of study time based on the unlimited free-recall task was included. These factors were submitted to a confirmatory factor analysis in which each measure was allowed to only load on the construct of interest, and each of the latent factors were allowed to correlate with one another. The fit of the model was acceptable, $\chi^2(132) = 284.53$, $p < .01$, RMSEA = .09, SRMR = .08, CFI = .90. Note the fit of the model could have been improved by allowing the errors for many of the recall variables to correlate. However, for simplicity, none of the errors were allowed to correlate. Shown in Table 4 is the resulting model. Each measure loaded significantly on its factor of interest. Examining the interfactor correlations suggested that WMC was related to overall recall accuracy, IRTs, and intrusions consistent with prior research (Unsworth, 2007, 2009b). Furthermore, consistent with prior research by Bailey et al. (2008), WMC was correlated with effective strategy use, but was not related to less effective strategy use. WMC was not related to study time allocation. However, examining variation in overall recall accuracy suggested that less effective strategy use, effective strategy use, IRTs, intrusions, and study time allocation were all significantly related to recall accuracy. Finally, less effective strategy use did not correlate with any of the other variables, whereas effective strategy use, IRTs, and intrusions were all interrelated, and IRTs and intrusions were related to study time allocation. Thus, although all of the factors were related to recall accuracy, there were clear separations among the factors with some factors relating to others and other factors being largely independent.

Next, structural equation modeling was used to better test one of the primary questions of interest. Specifically, a model was spec-

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[1] Note intrusions were also computed as the proportion of the total number of items recalled (e.g., Rose, 2013). Reanalyzing the data with the proportion of intrusions led to qualitatively similar results as those presented. This is largely due to the fact that the total number of intrusions and the proportion of intrusions were highly correlated (DFR1intru $r = .91$; DFR4intru $r = .97$; DFRU $r = .94$).

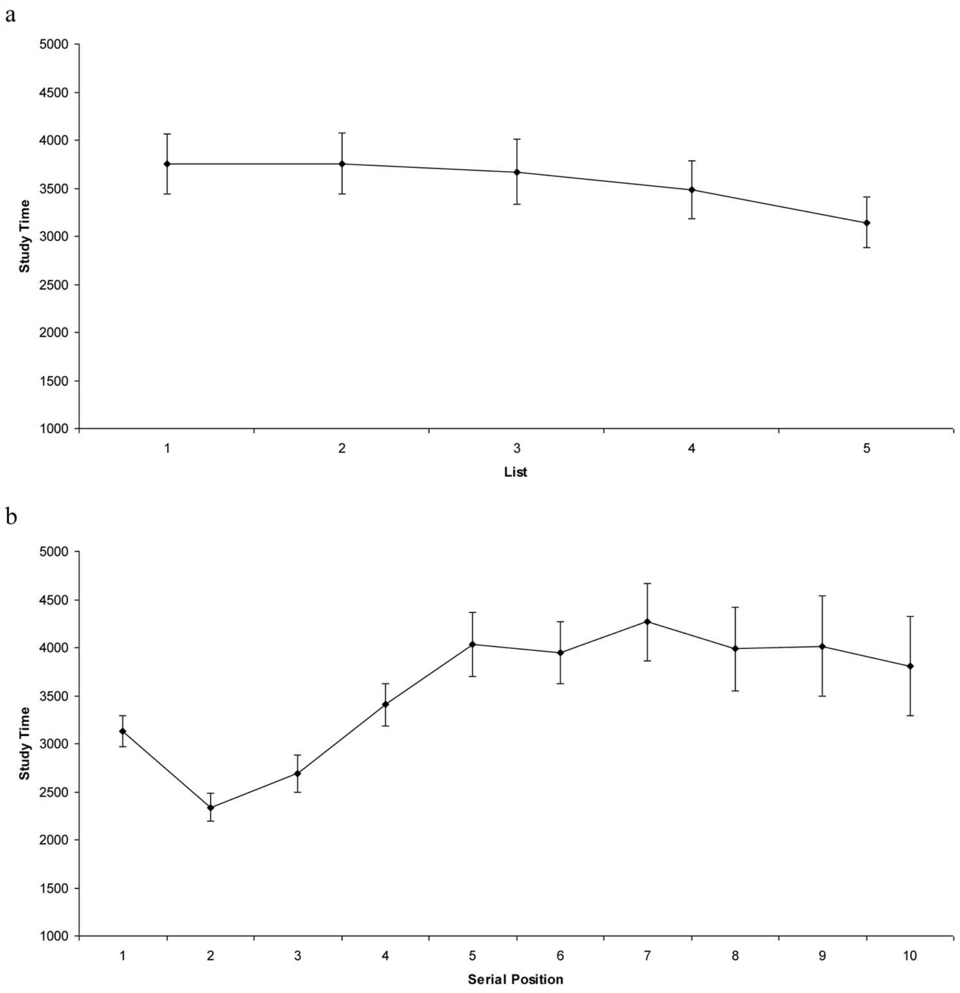

*Figure 2.* Study time allocation as a function of list (a). Study time as a function of serial position (b). Error bars reflect one standard error of the mean.

ified to determine whether each of the factors would account for unique variance in recall accuracy or whether the other factors would mediate the relations. As noted previously, prior research has demonstrated a consistent relation between WMC and recall accuracy. However, the reasons for this relation are not completely understood, with some research suggesting that the relation is due to search efficiency (indexed by IRTs), monitoring abilities (indexed by intrusions), or strategy usage at encoding (both less effective and effective strategy use). Prior research has suggested that each of these variables partially mediate the relation between WMC and recall, but it is not clear if these variables will fully mediate the relation when all are taken into account. To examine this, the same factors from the confirmatory factor analysis were used, but in this model, WMC, less effective strategy use, effective strategy use, IRTs, intrusions, and study time all predicted recall accuracy. This model tests the extent to which the factors account for shared or unique variance in recall accuracy at the same time. The fit of the model was acceptable, $\chi^2(132) = 284.53$, $p < .01$, RMSEA = .09, SRMR = .08, CFI = .90. Shown in Figure 3 is the resulting model. As can be seen, ineffective strategy use, effective strategy use, IRTs, intrusions, and study time allocation all accounted for significant unique variance in recall accuracy. Importantly, WMC was no longer related to recall accuracy after taking into account the other variables. Specifically, the relation between WMC and recall went from a significant .41 to a nonsignificant −.04. Overall, the factors accounted for 88% of the variance in recall performance. These results suggest that individual differences in recall from LTM are driven by variability in strategy use, search efficiency, monitoring abilities, and study time allocation and further suggest that the relation between WMC and LTM recall is driven by some of these factors.

To more formally test the notion that some factors mediate the relation between WMC and LTM recall, another structural equation model was specified. In this model, WMC predicted less effective strategy use, effective strategy use, IRTs, intrusions, study time allocation, and recall accuracy. Additionally, less effective strategy use, effective strategy use, IRTs, intrusions, and study time allocation all predicted recall accuracy. If certain factors mediate the relation between WMC and LTM recall, we should see that WMC is related to only those factors, those factors

Table 2
*Descriptive Statistics and Reliability Estimates for All Measures*

| Measure | *M* | *SD* | Skew | Kurtosis | Reliability |
|---|---|---|---|---|---|
| Ospan | 58.59 | 10.23 | −.49 | .14 | .80 |
| Symspan | 30.46 | 6.61 | −.60 | −.38 | .82 |
| Rspan | 53.46 | 11.48 | −.49 | .07 | .80 |
| DFR1acc | .46 | .16 | .51 | .12 | .81 |
| DFR4acc | .66 | .17 | −.12 | −.75 | .84 |
| DFRUacc | .65 | .22 | −.15 | −.91 | .89 |
| DFR1ineff | .69 | .37 | −.76 | −.78 | .72 |
| DFR1eff | .42 | .33 | .17 | −1.05 | .68 |
| DFR4ineff | .71 | .37 | −.88 | −.65 | .70 |
| DFR4eff | .51 | .34 | −.04 | −1.03 | .67 |
| DFRUineff | .63 | .37 | −.48 | −1.06 | .68 |
| DFRUeff | .53 | .33 | −.10 | −1.05 | .69 |
| DFR1IRT | 4351 | 150 | .83 | .39 | .66 |
| DFR4IRT | 3483 | 80 | .64 | .35 | .68 |
| DFRUIRT | 3449 | 112 | 1.27 | 1.27 | .66 |
| DFR1intru | 3.53 | 3.21 | 1.86 | 5.72 | .71 |
| DFR4intru | 2.15 | 3.08 | 4.21 | 10.61 | .69 |
| DFRUintru | 2.48 | 2.56 | 1.43 | 2.16 | .67 |
| Studytime | 3560 | 3180 | 2.84 | 9.66 | .96 |

*Note*. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; DFR1 = delayed free recall 1-s; acc = accuracy; DFR4 = delayed free recall 4-s; DFRU = delayed free recall unlimited time; ineff = less effective strategy use; eff = effective strategy use; IRT = inter-response time; intru = intrusion; Studytime = study time during DFRU.

are related to recall accuracy, and critically WMC no longer has a direct effect on recall accuracy (although there should be a strong indirect effect). The fit of this model was acceptable, $\chi^2(142) = 306.54$, $p < .01$, RMSEA = .09, SRMR = .08, CFI = .90. Shown in Figure 4 is the resulting model. As shown in the model, WMC predicted effective strategy use, IRTs, and intrusions. Less effective strategy use, effective strategy use, IRTs, intrusions, and study time allocation all predicted recall accuracy. Importantly, the direct effect of WMC on LTM recall was not significant although there was a strong indirect effect (indirect effect = .64, $p < .01$). These results suggest that the relation between WMC and LTM recall is due to effective strategy use at encoding, search efficiency, and monitoring abilities at retrieval. Examining the path coefficients, the relation between WMC and IRTs was particularly strong (45% shared variance), with the relations between WMC and effective strategy use and intrusions being a bit weaker (both sharing 15% of variance). Importantly, eliminating any of the paths from WMC to these three variables resulted in significantly worse model fits (all $p$ values $< .05$). Thus, although much of the relation between WMC and LTM recall is due to differences in search efficiency (as indexed by IRTs), effective strategy use and monitoring abilities are also crucial.

Finally, as can be seen, all of the factors accounted for 89% of the variance in LTM recall. Eliminating any one of the paths to recall (except for WMC) resulted in significantly worse model fits (all $p$ values $< .05$). Thus, variation in LTM recall is due to individual differences in a number of factors operating at both encoding and retrieval.

## Discussion

What accounts for the relation between WMC and LTM recall, and what factors give rise to individual differences in LTM recall? The results from the current study suggest that a number of factors are important in accounting for the covariation between WMC and LTM recall. Replicating prior research, the current results demonstrated that WMC was related to self-reports of effective strategy use, but not to self-reports of ineffective strategy use (Bailey et al., 2008). Furthermore, although participants adapted their strategy use as the amount of study time increased across tasks (Stoff & Eagle, 1971), this dynamic shift in strategy usage was not related to WMC. Thus, WMC is related to the selection and use of effective strategies, but it is not related to the ability to shift

Table 3
*Correlations Among All Measures*

| Measure | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Ospan | — | | | | | | | | | | | | | | | | | | |
| 2. Symspan | 0.41 | — | | | | | | | | | | | | | | | | | |
| 3. Rspan | 0.52 | 0.30 | — | | | | | | | | | | | | | | | | |
| 4. DFR1acc | 0.21 | 0.13 | 0.36 | — | | | | | | | | | | | | | | | |
| 5. DFR4acc | 0.21 | 0.12 | 0.36 | 0.50 | — | | | | | | | | | | | | | | |
| 6. DFRUacc | 0.10 | 0.00 | 0.37 | 0.53 | 0.64 | — | | | | | | | | | | | | | |
| 7. DFR1ineff | −0.04 | −0.02 | −0.03 | −0.24 | −0.17 | −0.11 | — | | | | | | | | | | | | |
| 8. DFR1eff | 0.11 | 0.07 | 0.16 | 0.44 | 0.38 | 0.20 | −0.12 | — | | | | | | | | | | | |
| 9. DFR4ineff | 0.05 | −0.04 | −0.03 | 0.06 | −0.25 | 0.01 | 0.38 | 0.02 | — | | | | | | | | | | |
| 10. DFR4eff | 0.15 | 0.07 | 0.22 | 0.24 | 0.47 | 0.35 | 0.14 | 0.50 | 0.07 | — | | | | | | | | | |
| 11. DFRUineff | 0.01 | 0.03 | 0.03 | −0.17 | −0.17 | −0.20 | 0.47 | 0.02 | 0.53 | 0.03 | — | | | | | | | | |
| 12. DFRUeff | 0.19 | 0.05 | 0.22 | 0.37 | 0.47 | 0.40 | −0.02 | 0.56 | 0.01 | 0.51 | −0.05 | — | | | | | | | |
| 13. DFR1IRT | −0.25 | −0.19 | −0.29 | −0.48 | −0.17 | −0.22 | 0.13 | −0.21 | −0.04 | −0.09 | 0.03 | −0.18 | — | | | | | | |
| 14. DFR4IRT | −0.28 | −0.27 | −0.31 | −0.27 | −0.42 | −0.19 | 0.05 | −0.04 | −0.02 | −0.19 | −0.08 | −0.07 | 0.46 | — | | | | | |
| 15. DFRUIRT | −0.30 | −0.26 | −0.37 | −0.34 | −0.32 | −0.53 | 0.05 | −0.13 | −0.09 | −0.17 | −0.01 | −0.27 | 0.50 | 0.41 | — | | | | |
| 16. DFR1intru | −0.02 | −0.13 | 0.03 | −0.28 | −0.14 | −0.18 | 0.06 | −0.10 | −0.15 | −0.06 | −0.07 | −0.25 | 0.15 | 0.17 | 0.10 | — | | | |
| 17. DFR4intru | −0.05 | −0.09 | −0.22 | −0.26 | −0.53 | −0.44 | 0.21 | −0.14 | 0.05 | −0.23 | 0.07 | −0.30 | −0.07 | 0.19 | 0.09 | 0.39 | — | | |
| 18. DFRUintru | −0.15 | −0.08 | −0.27 | −0.33 | −0.41 | −0.57 | 0.17 | −0.23 | 0.09 | −0.25 | 0.15 | −0.27 | 0.16 | 0.22 | 0.31 | 0.40 | 0.49 | — | |
| 19. Studytime | −0.10 | −0.02 | 0.14 | −0.03 | 0.17 | 0.51 | 0.08 | −0.10 | −0.04 | −0.01 | 0.06 | 0.05 | −0.01 | 0.00 | −0.28 | −0.02 | −0.25 | −0.31 | — |

*Note*. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; DFR1 = delayed free recall 1-s; acc = accuracy; DFR4 = delayed free recall 4-s; DFRU = delayed free recall unlimited time; ineff = less effective strategy use; eff = effective strategy use; IRT = inter-response time; intru = intrusion; Studytime = study time during DFRU.

Table 4
*Confirmatory Factor Analysis for Working Memory Capacity, Recall Accuracy, Ineffective Strategy Use, Effective Strategy Use, Inter-Response Times, Intrusions, and Study Time Allocation*

| | Latent factor | | | | | | |
|---|---|---|---|---|---|---|---|
| Measure | WMC | Acc | Ineffective | Effective | IRT | Intrusion | Studytime |
| Ospan | .72* | | | | | | |
| Symspan | .50* | | | | | | |
| Rspan | .72* | | | | | | |
| DFR1acc | | .61* | | | | | |
| DFR4acc | | .76* | | | | | |
| DFRUacc | | .86* | | | | | |
| DFR1ineff | | | .57* | | | | |
| DFR4ineff | | | .61* | | | | |
| DFRUineff | | | .86* | | | | |
| DFR1eff | | | | .71* | | | |
| DFR4eff | | | | .71* | | | |
| DFRUeff | | | | .76* | | | |
| DFR1IRT | | | | | .62* | | |
| DFR4IRT | | | | | .59* | | |
| DFRUIRT | | | | | .79* | | |
| DFR1intru | | | | | | .45* | |
| DFR4intru | | | | | | .69* | |
| DFRUintru | | | | | | .77* | |
| Studytime | | | | | | | 1.0* |
| | Interfactor correlations | | | | | | |
| WMC | — | | | | | | |
| Acc | .41* | — | | | | | |
| Ineffective | .01 | −.26* | — | | | | |
| Effective | .32* | .64* | .01 | — | | | |
| IRT | −.62* | −.63* | −.02 | −.33* | — | | |
| Intrusion | −.29* | −.77* | .10 | −.45* | .35* | — | |
| Studytime | .02 | .41* | .05 | −.02 | −.21* | −.35* | — |

*Note*. Ospan = operation span; Symspan = symmetry span; Rspan = reading span; DFR1 = delayed free recall 1-s; acc = accuracy; DFR4 = delayed free recall 4-s; DFRU = delayed free recall unlimited time; ineff = less effective strategy use; eff = effective strategy use; IRT = inter-response time; intru = intrusions on the recall tasks; Studytime = study time during DFRU; WMC = working memory capacity.
$^* p < .05$.

strategies as task demands change. Earlier we speculated that differences between prior studies may have been due to differences in how participants change encoding strategies across tasks with high WMC individuals being better able to shift strategies with changes in task demands. However, this was clearly not the case. Consistent with this conclusion, in the unlimited delayed recall task, participants changed how they allocated study time to items within and across lists, but again this was unrelated to WMC. Thus, within the current data, WMC does not seem to be related to the ability to dynamically shift strategies and change how study time is allocated. These results extend prior research by showing that not all strategic encoding factors are related to WMC. Although, these factors are related to individual differences in LTM recall. Thus, it is not the case that WMC predicts all recall factors as one might expect if all the variables were interrelated, but rather that the relations are more specific in nature. Future work is needed to better examine under what situations (if any) WMC is related to dynamic shifts in encoding strategies.

Examining the relations among all of the variables at the latent level suggested that WMC was related to recall accuracy, IRTs, intrusions, and effective strategy use replicating prior research (Bailey et al., 2008; Unsworth, 2007; Unsworth, 2009b). Importantly, these factors were shown to fully mediate the relation between WMC and recall accuracy. Thus, the current results extend prior research by demonstrating that the relation between WMC and LTM recall is fully mediated by processes occurring at both encoding and retrieval. That is, prior research has consistently found a relation between WMC and LTM recall, and has found that some factors partially mediate this relation with WMC always accounting for unique variance in LTM recall after accounting for other factors. By examining all factors in the same data set, the current study demonstrated for the first time that the relation between WMC and LTM recall is multifaceted in that a number of important strategic control factors are responsible for the relation. Furthermore, by examining all factors at the same time, the current results suggest that each of these factors (effective strategy use, search efficiency, and monitoring abilities) accounted for both shared and unique sources of variance between WMC and LTM recall. Thus, it is not the case that only one of these factors accounts for the strong relation between WMC and LTM recall, but rather that individual differences in each are important.

In terms of encoding strategies, the current results suggests that WMC was related to the ability to select and use effective strategies such as using imagery ($r$ = .30), forming sentences to link the words ($r$ = .17), grouping or chunking the words ($r$ = .18), but not to the selection and use of normatively less

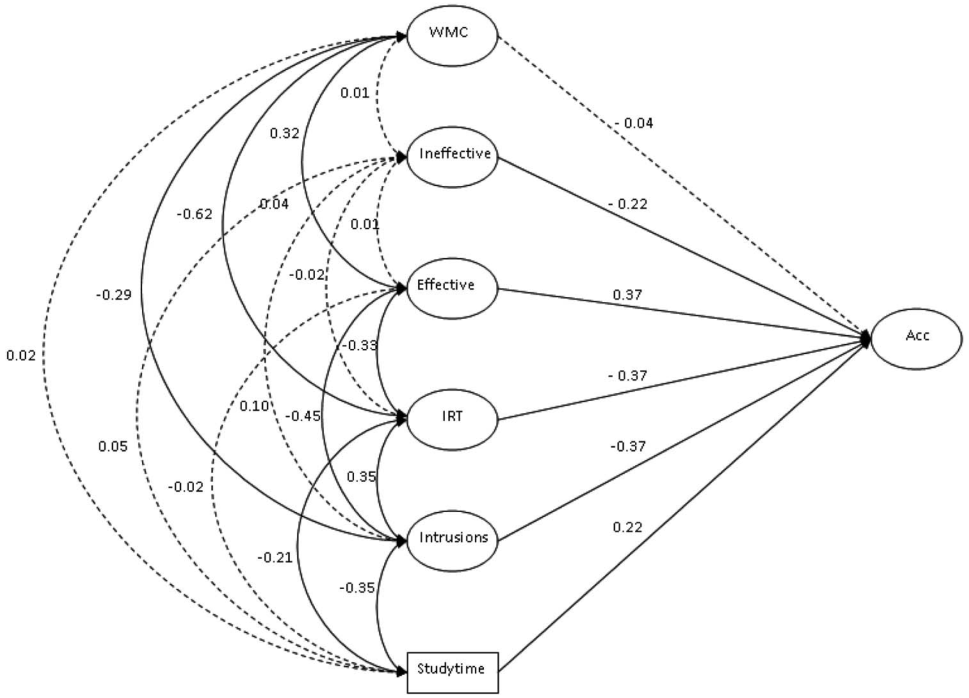

*Figure 3.* Structural equation model predicting recall accuracy (Acc) with working memory capacity (WMC), less ineffective strategy use (ineffective), effective strategy use (effective), interresponse times (IRT), intrusions, and study time. Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients, indicating the unique contribution of the latent variable. Double-headed arrows connecting the latent factors represent the correlations among the factors. Solid lines are significant at the $p < .05$ level, and dotted lines are not significant at the $p < .05$ level.

effective strategies such as simply reading the words ($r = .07$) or using rote repetition ($r = -.09$). Along with prior research, these results suggest that during item presentation WMC is needed to select and implement effective encoding strategies (e.g., Bailey et al., 2008; Dunlosky & Kane, 2007; Unsworth & Spillers, 2010). This could be due to differences in attention control processes whereby effective strategies require more resources than less effective strategies, and low WMC individuals may be less able than high WMC individuals to fully implement effective strategies or to consistently implement effective strategies throughout a trial. Furthermore, although variation in study time allocation is an important predictor of overall recall performance, this ability is not related to WMC suggesting that WMC is related to some strategic processes occurring at encoding, but not to all strategic encoding processes.

At retrieval, WMC is needed to select appropriate retrieval strategies, to generate appropriate contexts to search, to elaborate on cues needed for search, to verify the products of the search, and to adequately use the products of the search to better focus the search (Spillers & Unsworth, 2011; Unsworth, 2007; Unsworth, Brewer, & Spillers, 2013; Unsworth et al., 2012). Prior research has shown that when self-initiated retrieval is required, high and low WMC individuals differ in their ability to recall information from LTM, and these differences are partially due to differences in generation and implementation of retrieval strategies (Unsworth et al., 2013). However, giving participants effective retrieval cues reduces and in some cases eliminates WMC differences in recall, suggesting a main difference between high and low WMC individuals is the ability to use effective search strategies to self-generate appropriate retrieval cues (Unsworth et al., 2013; Unsworth et al., 2012). Because high WMC individuals are better at selecting and implementing effective retrieval strategies than low WMC individuals, this leads to overall more efficient searches for high WMC individuals than low WMC individuals as indexed by overall faster IRTs and higher levels of recall. Thus, high WMC individuals are better at searching for target information at retrieval than low WMC individuals.

Finally, after items have been retrieved from LTM, individual differences in WMC are related to the ability to effectively monitor the products of the search process and effectively edit out intrusions (Lilienthal et al., 2015; Rose, 2013; Unsworth, 2009b; Unsworth & Brewer, 2010a, 2010b). Prior research has shown low WMC individuals make more intrusions than high WMC individuals because they are poorer at monitoring the products of retrieval and correctly recognizing and editing out errors due to deficits in source monitoring (Lilienthal et al., 2015; Rose, 2013; Unsworth, 2009b; Unsworth & Brewer, 2010a, 2010b). Thus, WMC is needed at both encoding and retrieval in order to select and implement effective encoding strategies leading to strong representations, select and implement effective retrieval strategies leading to a more focused search, and to monitor and edit the products of the search to

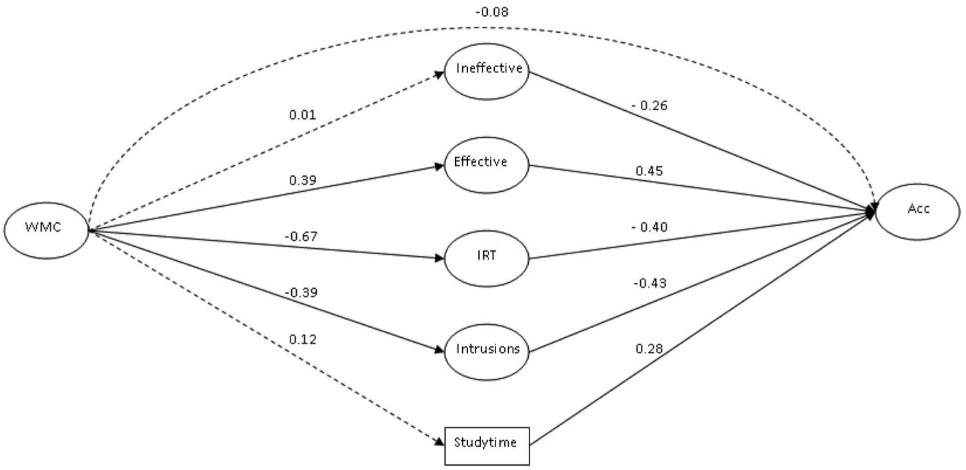

*Figure 4.* Structural equation model in which working memory capacity (WMC) predicts recall accuracy (Acc), less ineffective strategy use (ineffective), effective strategy use (effective), interresponse times (IRT), intrusions, and study time; and less ineffective strategy use (ineffective), effective strategy use (effective), interresponse times (IRT), intrusions, and study time all predict recall accuracy (acc). Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients, indicating the unique contribution of the latent variable. Solid lines are significant at the $p < .05$ level, and dotted lines are not significant at the $p < .05$ level.

limit the number of erroneously recalled items. The current results demonstrate that these three factors completely mediate the relation between WMC and LTM recall. As such, the current results go significantly beyond prior work by demonstrating that WMC is not only related to each of these factors, but that these three strategic factors drive the relation between individual differences in WMC and recall from LTM.

In addition to explaining the relation between WMC and LTM recall, the current results also demonstrated important factors that give rise to overall individual differences in LTM recall. Specifically, as shown in Figure 4, 89% of the variance in LTM recall was accounted for by a joint combination of encoding strategies (both effective and less effective), search efficiency, monitoring abilities, and study time allocation. In particular, the current results suggest that 7% of the variability in recall is due to less effective strategy use, 20% is due to effective strategy use, 16% is due to search efficiency, 18% is due to monitoring abilities, 9% is due to study time allocation, and the remaining 19% is shared across the factors. Thus, individual differences in LTM recall, which have been shown to be important predictors of intelligence (Beier & Ackerman, 2004; Bors & Forrin, 1995; Unsworth, 2009b, 2010), are the result of variability in a number of component processes at encoding and retrieval, all of which are critical for accurate recall from LTM.

Collectively, the current results suggest that the relation between WMC and recall from LTM is due to strategic control factors operating at both encoding and retrieval. At the same time, the results suggest that not all strategic factors are related to WMC (i.e., adaptive strategy usage, study time allocation), but these factors are related to individual differences in LTM recall. Future research is needed to better detail how WMC is used to select and implement encoding and retrieval strategies and to determine if the relations found in the current study generalize to other LTM tasks. Examining individual differences in strategic control processes that operate at encoding and retrieval will be important not only for elucidating the reasons for the relation between WMC and LTM, but also for understanding the nature of WMC more broadly.

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**Call for Papers**
**"Translating Research to Practice in the Language Sciences"**

**Special Issue of**
***Translational Issues in Psychological Science***

We are encouraging submissions for consideration in a special issue titled "Translating Research to Practice in the Language Sciences" in the innovative journal *Translational Issues in Psychological Science* (*TPS*), cosponsored by the American Psychological Association (APA) and the American Psychological Association of Graduate Students (APAGS).

"Translating Research to Practice in the Language Sciences" is due out in March 2017. For this issue the Editors will consider manuscripts across a broad area of language science research concerning such topics as

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- enhancing second language learning,
- raising bilingual children,
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