Journal of Experimental Psychology:
Learning, Memory, and Cognition
2007, Vol. 33, No. 6, 1020–1034

0278-7393/07/$12.00 DOI: 10.1037/0278-7393.33.6.1020

Individual Differences in Working Memory Capacity and Episodic Retrieval: Examining the Dynamics of Delayed and Continuous Distractor Free Recall

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Two experiments explored the possibility that individual differences in working memory capacity (WMC) partially reflect differences in the size of the search set from which items are retrieved. High- and low-WMC individuals were tested in delayed (Experiment 1) and continuous distractor (Experiment 2) free recall with varying list lengths. Across both experiments low-WMC individuals recalled fewer items than high-WMC individuals, recalled more previous list intrusions than high-WMC individuals, and recalled at a slower rate than high-WMC individuals. It is argued that low-WMC individuals' episodic retrieval deficits are partially due to the fact that these individuals search through a larger set of items than high-WMC individuals. Simulations based on a random search model were consistent with these general conclusions.

Keywords: working memory, recall, individual differences, random search

Complex working memory span tasks such as reading (Daneman & Carpenter, 1980) and operation (Turner & Engle, 1989) span have been shown to be important predictors of performance in a number of higher order (e.g., reading comprehension, fluid reasoning, vocabulary learning) and lower order (e.g., Stroop, dichotic listening, antisaccade, flankers) cognitive tasks (see Engle & Kane, 2004, for a review). In these tasks, to-be-remembered items are interspersed with some form of distracting activity, such as reading sentences or solving math operations. A number of theories have postulated a central mechanism as the main underlying construct responsible for the predictive power of these tasks. These include the inhibition view of Hasher, Zacks, and colleagues (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999), the controlled/executive-attention view espoused by Conway, Engle, Kane, and colleagues (Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007), and the capacity of attention view supported by Cowan (2001, 2005). The present work explored a specific possibility of individual differences in working memory capacity (WMC). Because complex spans are fundamentally memory tasks, the present work explored the possibility that the primary process tapped by these tasks is one of retrieval. Individual differences in WMC, therefore, are differences in the ability to effectively retrieve items.

Individual Differences in WMC and Episodic Retrieval

Over the last few years, a number of studies have convincingly demonstrated that variation in WMC is related to variation in the ability to retrieve information under conditions of interference. Under conditions of reduced competition or interference, however, WMC differences either do not appear or are greatly reduced. For instance, consider a study by Kane and Engle (2000). Kane and Engle had high- and low-WMC individuals perform a variant of the Brown–Peterson task (Brown, 1958; Peterson & Peterson, 1959) in order to assess the buildup of proactive interference (PI). High- and low-WMC individuals were shown a list of category exemplars followed by 15 s of distractor activity. Following the distractor task, the participants were instructed to recall the category exemplars. Kane and Engle (2000) found that high- and low-WMC individuals recalled a similar number of words on the first trial but that low-WMC individuals recalled fewer and fewer items than high-WMC individuals as the task progressed. That is, low-WMC individuals were much more susceptible to the buildup of PI than were high-WMC individuals.

Additional studies that have examined the relation between WMC and retrieval under conditions of interference have suggested similar results. For instance, using a variant of a probe recognition task, Conway and Engle (1994) found that high- and low-WMC individuals differed only when items were associated with multiple cues. Furthermore, Rosen and Engle (1998) found that low-WMC individuals made more first-list intrusions on second-list learning in a paired-associates task than high-WMC individuals. These results suggest that those participants who score high on measures of WMC tend to do better on memory retrieval measures than participants who score low on WMC measures,

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This research was completed in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the Georgia Institute of Technology. I thank Randy Engle, Rich Heitz, and Tom Redick for many stimulating discussions on the issues addressed in this article. I also thank my dissertation committee members (Randy Engle, Paul Corballis, Andy Smith, Dan Spieler, and David Washburn) for thoughtful comments in all phases of this project. Finally, I thank Jess Parsons and Liz Weldon for data collection assistance.

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particularly under conditions of interference (see also Bunting, 2006; Lustig, May, & Hasher, 2001).

On the basis of this and other evidence, Unsworth and Engle (2007) argued for a dual-component model combining a flexible attentional component (primary memory) with a cue-dependent search mechanism of secondary memory. Unsworth and Engle argued that individual differences in WMC result from differences in the ability to maintain items in primary memory and/or differences in the ability to guide a strategic search of memory. Furthermore, Unsworth and Engle argued that differences in susceptibility to PI arise primarily owing to differences in the ability to engage in a strategic search of memory, in which low-WMC individuals are unable to focus the search of secondary memory only on current target items and thus must search through a larger set of items than high-WMC individuals. It has been argued that this inability is due to the fact that low-WMC individuals rely on cues, or probes, that activate many items in secondary memory, whereas high-WMC individuals use more specific cues (particularly contextual cues) that activate fewer items in memory (see also Atkinson & Shiffrin, 1971). The aim of the present article was to better explore this possibility by examining individual differences in WMC and the dynamics of free recall. Note that the ability to limit the search set only to relevant item representations is necessary not only in basic memory tasks but also in higher order cognitive tasks, such as reasoning and reading comprehension (Unsworth & Engle, 2007).

Dynamics of Free Recall

One model that offers a useful framework for examining possible differences in the dynamics of free recall and theoretical differences in search-set size is the *random search model* (Bousfield, Sedgewick, & Cohen, 1954; Kaplan, Carvellas, & Metlay, 1969; McGill, 1963; Rohrer & Wixted, 1994; Wixted & Rohrer, 1994). In this model a retrieval cue delimits a search set that includes representations of target items as well as extraneous items. Item representations are randomly sampled from the search set at a constant rate, one item at a time (serial search; although parallel versions of the model also exist—see, e.g., Wixted & Rohrer, 1994). The retrieval process includes a sampling-with-replacement process such that after an item representation has been sampled and recalled, the same representation still has an equal chance of being selected on the next sample. Target items that have been previously recalled, intruding items, or target items that are not recoverable are not recalled but still can be sampled from the search set. As the retrieval process proceeds, the probability of recalling a new target item decreases because each sample is likely to be an already recalled target item or an extraneous item. Note that the random search model can be seen as a simplistic version of other sampling models of recall (e.g., Raaijmakers & Shiffrin, 1980; Shiffrin, 1970), which provide a more detailed account of the various facets of free recall.

Assuming a constant sampling time per item, McGill (1963) demonstrated how this simple random-sampling-with-replacement model predicted exponentially declining rates of recall and cumulative exponential recall curves (see also Rohrer & Wixted, 1994; Vorberg & Ulrich, 1987). Indeed, beginning with the work of Bousfield and colleagues (Bousfield & Sedgewick, 1944; see also Indow & Togano, 1970; Roediger, Stellon, & Tulving, 1977), research has found that cumulative latency distributions are well described by the cumulative exponential

$$F(t) = N(1 - e^{-\lambda t}), \tag{1}$$

where $F(t)$ represents the cumulative number of items recalled by time t, N represents asymptotic recall, and λ represents the rate of approach to asymptote. Using the random search model and the parameter estimates obtained from fitting the cumulative exponential to cumulative latency distributions, several studies have shown that N and λ change as a function of different task manipulations (see Wixted & Rohrer, 1994, for a review). For instance, Wixted and Rohrer (1993) had participants perform a variant of the Brown–Peterson task where the first three trials were all from the same category to see how the buildup of PI would affect the latency distributions. The authors found that as PI accrued, estimates of both N and λ decreased, suggesting that the search set increased for subsequent trials using the same category. Indeed, Wixted and Rohrer (1993) noted that "in a sampling-with-replacement serial search model, the average time required to find target items in a search set increases linearly with the size of that set" (p. 1036). That is, it takes more time in a large search set to find a new item that has not been recalled previously (see Rohrer & Wixted, 1994, for a similar result based on list-length effects). However, in the release from PI condition, estimates of N and λ increased slightly. These results suggested that as PI accrued, the search set became progressively larger because the search set was delimited to all category instances based on the retrieval cue. Under release conditions, the retrieval cue specified only the new category instances, and thus the search set excluded items from the previous trials.

Furthermore, Rohrer and Wixted (1994) found that increasing presentation duration and presumably increasing the amount of attention paid to items resulted in an increase in probability correct but no change in λ. The authors suggested that this was because the presentation duration manipulation increased the likelihood that a target would be recoverable during the recall phase but left the search set unaffected. That is, most search models assume that items that have an absolute strength greater than some value can be recovered but that items whose absolute strength falls below that value cannot be recovered. Increasing presentation duration and attention at encoding increases items' absolute strength but does not affect the size of the search set (see also Shiffrin, 1970). These and other results suggest that the random search model is a useful tool in interpreting recall performance under a variety of conditions.

Rationale for the Present Study

As an initial test of the notion that variation in WMC is partially due to differences in the size of the search set from which items are recalled, Unsworth and Engle (2007) had high- and low-WMC individuals perform an immediate free-recall task. According to the framework presented previously, if high-WMC individuals are better at delimiting the search set to only the current items whereas low-WMC individuals have trouble in this regard, then high-WMC individuals should recall more words than low-WMC individuals and their rate of approach to asymptotic recall levels should be faster than that of low-WMC individuals. This is precisely what was found. Fitting the cumulative exponential for each individual resulted in larger *N* and λ estimates for high-WMC individuals than for low-WMC individuals.

The Unsworth and Engle (2007) immediate free-recall findings provided initial support for the notion that part of low-WMC individuals' recall deficits are due to an inability to correctly delimit the search set compared with high-WMC individuals. However, these findings are limited by the fact that some of the items were recalled (theoretically) from primary memory, and thus, the results do not clearly demonstrate differences in the search process between the two groups. In order to better examine retrieval processes in the absence of retrieval from primary memory (e.g., Bjork & Whitten, 1974; Glanzer & Cunitz, 1966), the dynamics of free recall in both delayed (Experiment 1) and continuous distractor (Experiment 2) free-recall tasks was examined in the present experiments.

The present set of experiments also examined how manipulations of list length would affect individual differences in WMC. Because the Unsworth and Engle (2007) immediate free-recall experiment used list lengths of 12 items, it is possible that low-WMC individuals had trouble constraining their search sets to such a large number of items. Thus, there may be a point at which low-WMC individuals' ability to constrain the search set becomes ineffective, and if given fewer items, they may perform equivalently to high-WMC individuals. Furthermore, list length was also manipulated in order to try and gauge how different high- and low-WMC individuals are in terms of the size of their search sets. Specifically, the manipulation of list length should provide a means to determine where high- and low-WMC individuals show similar performance on the latency measures. For instance, if low-WMC individuals have larger search sets than high-WMC individuals, the list-length manipulation can provide a rough estimate of when these groups have equivalent search sets. That is, we can ask, "Do low-WMC individuals search through the same number of items at list length 6 as high-WMC individuals do at list length 9?" Although the manipulation of list length probably will not provide a precise estimate of differences in search-set size, it should provide a fairly gross measure of differences.

Although the current work explores the possibility that high- and low-WMC individuals' differences are due to differences in search-set size, other viable alternatives exist. Therefore, in both experiments four possibilities for differences between high- and low-WMC individuals in retrieval based on the random search model were tested. The first possibility (*low WMC large*) is that low-WMC individuals search through a larger search set of items than high-WMC individuals, resulting in fewer target items recalled and smaller values of λ. In particular, low-WMC individuals are unable to focus their search only on the current list representations and instead include many previous list items in their search sets (possibly owing to poor list-discrimination processes or poorer inhibitory abilities). This is reminiscent of Wixted and Rohrer's (1993) PI finding. Additional support for this position should come from an analysis of recall errors. If low-WMC individuals search through a larger set of items than high-WMC individuals owing to PI, then low-WMC individuals should recall more previous list intrusions than high-WMC individuals, and these intrusions should come predominantly from the immediately preceding list (e.g., Unsworth & Engle, 2007).

The second possible reason why low-WMC individuals recall fewer items than high-WMC individuals (*low WMC small*) is that low-WMC individuals search a much smaller set than high-WMC individuals (possibly owing to fewer resources being available to activate and retrieve the desired items). Because there are fewer target items within the search set, low-WMC individuals will subsequently recall fewer items and have lower values of *N*. However, this position suggests that low-WMC individuals should actually have larger values of λ than high-WMC individuals. Additionally, this scenario seems possible given that previous research examining the temporal dynamics of free recall has suggested that *N* and λ are inversely related (e.g., Herrmann & Chaffin, 1976; Johnson, Johnson, & Mark, 1951; Kaplan et al., 1969), with correlations ranging from –.48 to –.75.

A third possibility (*low WMC nonrecoverable*) is that high- and low-WMC individuals search through a set of the same size but that the low-WMC individuals' search set contains fewer recoverable targets (possibly owing to poorer encoding abilities whereby items are not rehearsed enough or encoded at a deep enough level). That is, most search models assume that items that have an absolute strength greater than some value can be recovered but that items whose absolute strength falls below that value cannot be recovered. Therefore, it is possible that low-WMC individuals have more nonrecoverable targets than high-WMC individuals. This would result in fewer items being recalled and low values of *N* but the same λ values because the two groups would be searching through the same size search set. A similar result has been reported by Rohrer and Wixted (1994) in terms of manipulations of presentation duration.

The final possibility (*low WMC slow*) is that high- and low-WMC individuals search through sets of the same size with the same number of recoverable targets but that low-WMC individuals have a slower sampling time than high-WMC individuals (possibly owing to differences in speed of processing abilities). Thus, the reason low-WMC individuals retrieve fewer items than high-WMC individuals is that they are not given enough time to sample and recover all of the target items. However, given enough time, low-WMC individuals should be able to recall as many items as high-WMC individuals. This would result in low-WMC individuals having smaller values of λ than high-WMC individuals. Crucially, however, given enough time, high- and low-WMC individuals should have equivalent values of *N*. Such a result has previously been reported by Burns and Schoff (1998) in the context of item-specific and relational processing.

In summary, four possible differences between high- and low-WMC individuals in recall were examined. The key differences between these possibilities lie in the pattern of parameter estimates obtained after fitting the cumulative exponential to the cumulative latency distributions. In particular, the low-WMC-large possibility predicts that low-WMC individuals will have lower values of *N* and smaller values of λ than high-WMC individuals, whereas the low-WMC-small possibility predicts that low-WMC individuals will have lower values of *N* and larger values of λ than high-WMC individuals, and the low-WMC-nonrecoverable possibility predicts that low-WMC individuals will have lower values of *N* but the same values of λ as high-WMC individuals. Thus, all three of these possibilities predict that low-WMC individuals should recall fewer items than high-WMC individuals, but they differ in the prediction of how quickly individuals will recall their items as indexed by λ. The final possibility (low WMC slow) predicts that given enough time, high- and low-WMC individuals will have similar values of N, but low-WMC individuals will have smaller values of λ. Thus, the key to distinguishing among the four possibilities lies in the pattern of parameter values. All four possibilities were tested by fitting the cumulative exponential to the cumulative latency distributions and examining differences in the parameter estimates.

Experiment 1

The purpose of Experiment 1 was to examine individual differences in WMC and the dynamics of free recall in the absence of recall from primary memory. In addition, because delayed free recall has been used previously when examining the random search model (e.g., Rohrer & Wixted, 1994), Experiment 1 provides a means of replicating and extending previous findings. In terms of individual differences, each of the four possibilities presented above of recall differences between high- and low-WMC individuals was examined. The expectation was that the differences would be most similar to the low-WMC-large possibility. In order to examine these possibilities, all participants performed delayed free-recall tasks using 21 lists of words with three different list lengths (6, 9, or 12 items).

Method

Participant Screening for WMC

All participants were prescreened on three complex memory span measures. These included operation span, reading span, and symmetry span. The tasks have been shown to have good reliability (with Cronbach's alpha estimates ranging from .78 to .86) and have been found to be highly correlated with one another and to load on the same basic factor (see Kane et al., 2004). Individuals were selected on the basis of a z-score composite of the three tasks. Only participants falling in the upper (high-WMC individuals) and lower (low-WMC individuals) quartiles of the composite distribution were selected.

Operation span. 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). After solving the first operation, the participant was presented with a letter for 1 s. Immediately after the letter was presented, the next operation was presented, and so on. Three trials of each list length (3–7) were presented, with the order of list length varying randomly. At recall, participants were required to recall letters from the current set 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 2) of practice. For all of the span measures, an item was scored if it was correct and in the correct position. The score was the proportion of correct items in the correct position.

Reading span. Participants were required to read sentences while trying to remember the same set of unrelated letters as in the operation span task. For this task, participants read a sentence and determined whether it made sense (e.g., "The prosecutor's dish was lost because it was not based on fact"). Half of the sentences made sense and the other half did not. Nonsense sentences were made by simply changing one word (e.g., *case* to *dish*) from an otherwise normal sentence. After participants indicated whether the sentence made sense, they were presented with a letter for 1 s. At recall, participants were required to recall letters in the correct order by clicking on the appropriate letters. There were three trials of each list length, with list length ranging from 3 to 7. The same scoring procedure as in the operation span task was used.

Symmetry span. 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 in which they had appeared by clicking on the cells of an empty matrix. There were three trials of each list length, with list length ranging from 2 to 5. The same scoring procedure as in the operation span task was used.

Composite Score

For the composite score, scores for each of the three complex span tasks were z-transformed for each participant. These z scores were then averaged together, and quartiles were computed from the averaged distribution. This distribution consisted of scores for over 600 individual participants who completed each of the three span tasks. High- and low-WMC participants in the current study were selected from this overall distribution. Additionally, participants were selected only if they maintained 80% accuracy on the processing component across the three span tasks.

Participants and Design

Participants were 25 high-WMC individuals and 20 low-WMC individuals, as determined by the composite measure. Participants were recruited from the subject pool at Georgia Institute of Technology and from the Atlanta community through newspaper advertisements. Participants were between the ages of 18 and 35 and received either course credit or monetary compensation for their participation. Each participant was tested individually in a laboratory session lasting approximately 1 hr. Participants performed 2 practice lists with letters and 21 lists with words with three different list lengths (6, 9, or 12 items). Words were common one- to four-syllable words taken from LaPointe and Engle (1990). All participants received the same initially randomized order of lists.

Procedure

Participants were tested individually in the presence of an experimenter. Items were presented alone for 1 s each. Participants were required to read each word aloud as it appeared. After list presentation, participants engaged in a 20-s distractor task before recall: Participants saw 10 three-digit numbers appear for 2 s each and were required to say the digits aloud in ascending order (e.g., Rohrer & Wixted, 1994). At recall, participants saw three question marks appear in the middle of the screen accompanied by a brief tone indicating that the recall period had begun. Participants had 45 s to recall as many of the words from the current trial as possible in any order they wished. For each spoken response (both correct and incorrect responses), an experimenter pressed a key indicating when in the recall period the response was given.[1]

Results

Participants

Data for 2 high-WMC individuals were excluded from analyses owing to data collection problems. The mean *z* scores for the final 23 high-WMC individuals (15 enrolled at Georgia Institute of Technology, 4 enrolled at other Atlanta area universities, and 4 not enrolled at any university) and 20 low-WMC individuals (7 enrolled at Georgia Institute of Technology, 5 enrolled at other Atlanta area universities, and 8 not enrolled at any university) were 0.98 ($SD = 0.15$, range 0.71 to 1.28) and –1.07 ($SD = 0.50$, range –2.36 to –0.53), respectively. The mean ages for the high- and low-WMC individuals were 20.43 ($SD = 3.54$) and 23.25 ($SD = 5.95$), respectively (see Appendix for information regarding each span task).

Accuracy

Probability correct. As shown in Table 1, the results suggest that classic list-length effects were apparent in which probability correct decreased as list length increased, $F(2, 82) = 56.94$, $MSE = 0.004$, $p < .01$, partial $\eta^2 = .58$. Additionally, as expected, high-WMC individuals consistently recalled more items than low-WMC individuals ($M = .58$, $SE = .02$ vs. $M = .42$, $SE = .03$), $F(1, 41) = 19.37$, $MSE = 0.04$, $p < .01$, partial $\eta^2 = .32$. Furthermore, these two factors interacted, suggesting that the high-WMC advantage was greatest at list length 6, $F(2, 82) = 6.78$, $MSE = 0.004$, $p < .01$, partial $\eta^2 = .14$.

Shown in Figure 1 is probability correct as a function of serial position for both high- and low-WMC individuals for each of the three list lengths. Both high- and low-WMC individuals generated serial position functions with intact primacy and diminished recency effects consistent with prior work using delayed free recall (Glanzer & Cunitz, 1966). Additionally, WMC differences occurred at many positions, with high-WMC individuals consistently recalling more items than low-WMC individuals. There were significant (i.e., all $ps < .05$) WMC × Serial Position interactions for each of the three list lengths.

Recall errors. In addition to probability correct, the different errors that individuals make in free recall were examined. Errors were classified as previous list intrusions (items from previous lists), extralist intrusions (items not presented in any other list), or repetitions (items from the current list that had already been recalled). Shown in Table 2 is the average number of each error type per list (collapsed on list length) as a function of WMC. The results suggest that high- and low-WMC individuals differ mainly in previous list intrusions, with low-WMC individuals making many more previous list intrusions than high-WMC individuals, $F(1, 41) = 10.59$, $MSE = 0.22$, $p < .01$, partial $\eta^2 = .21$. On average, these intrusions came from approximately two lists back ($M = 2.03$, $SE = 0.28$), with the majority coming from one list back (51% of all previous list intrusions). This did not differ as a function of either list length or WMC (both $ps > .20$). WMC differences did not occur for either extralist intrusions or repetitions (both $ps > .10$).

Table 1
Mean Probability Correct by Working Memory Capacity (WMC) and List Length for Experiment 1

WMC	List length 6	9	12
High	.68 (.03)	.57 (.03)	.48 (.02)
Low	.47 (.03)	.43 (.03)	.37 (.03)
Total	.58 (.02)	.50 (.02)	.42 (.02)

Note. Numbers in parentheses are standard errors.

Latency

Cumulative latency distributions. Shown in Figure 2A are the fits of the cumulative exponential to cumulative latency distributions for high- and low-WMC individuals (collapsed on list length). Figure 2B shows the fits of the cumulative exponential to the cumulative latency distributions for each list length. For each, responses were first placed into 45 1-s bins, and then the cumulative number of items recalled for each bin was computed. As can be seen, the fits for each function were acceptable, accounting for 98% of the variance. Furthermore, Kolmogorov–Smirnov tests examining differences between the raw and fitted values for each function resulted in nonsignificant *p* values (all $ps > .12$). As with the probability correct analyses, high-WMC individuals recalled more items than low-WMC individuals (i.e., higher asymptotic levels, *N*) and list-length effects were apparent. Additionally, as shown in Figure 2A low-WMC individuals tended to reach asymptotic levels at a slower rate (λ) than high-WMC individuals. Rate of approach to asymptote (λ) also changed as a function of list length, with rate decreasing as list length increased, consistent with Rohrer and Wixted (1994). Table 3 shows the parameter values from fitting the cumulative exponential to the cumulative latency distributions for each individual and each group for both *N* and λ as a function of list length and WMC.

To examine these observations, the cumulative exponential function was fit to each participant's cumulative latency distributions for each list length. The resulting parameter estimates were then submitted to separate analyses of variance (ANOVAs) examining WMC and list length. Examining first asymptotic levels of performance (*N*), the ANOVA demonstrated a main effect of list length, $F(2, 80) = 41.41$, $MSE = 0.84$, $p < .01$, partial $\eta^2 = .51$, with *N* increasing as list length increased.[2] The main effect of WMC approached conventional levels of significance, $F(1, 40) = 3.63$, $MSE = 4.10$, $p = .06$, partial $\eta^2 = .08$. The two-way interaction was not significant ($F < 1$). The results are generally consistent with the probability correct analyses, demonstrating list-length effects and WMC differences. The reason the WMC

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[1] Note that all participants were run by either the author or one of two research assistants (who were both blind to the hypotheses). None of the results of the current study (including recall accuracy, parameter estimates from the cumulative recall functions, and recall latency) differed as a function of experimenter.

[2] One low-WMC individual was dropped from these analyses for having extremely large (i.e., three standard deviations above the mean) estimates of *N*. Including this participant in the analyses led to qualitatively identical results.

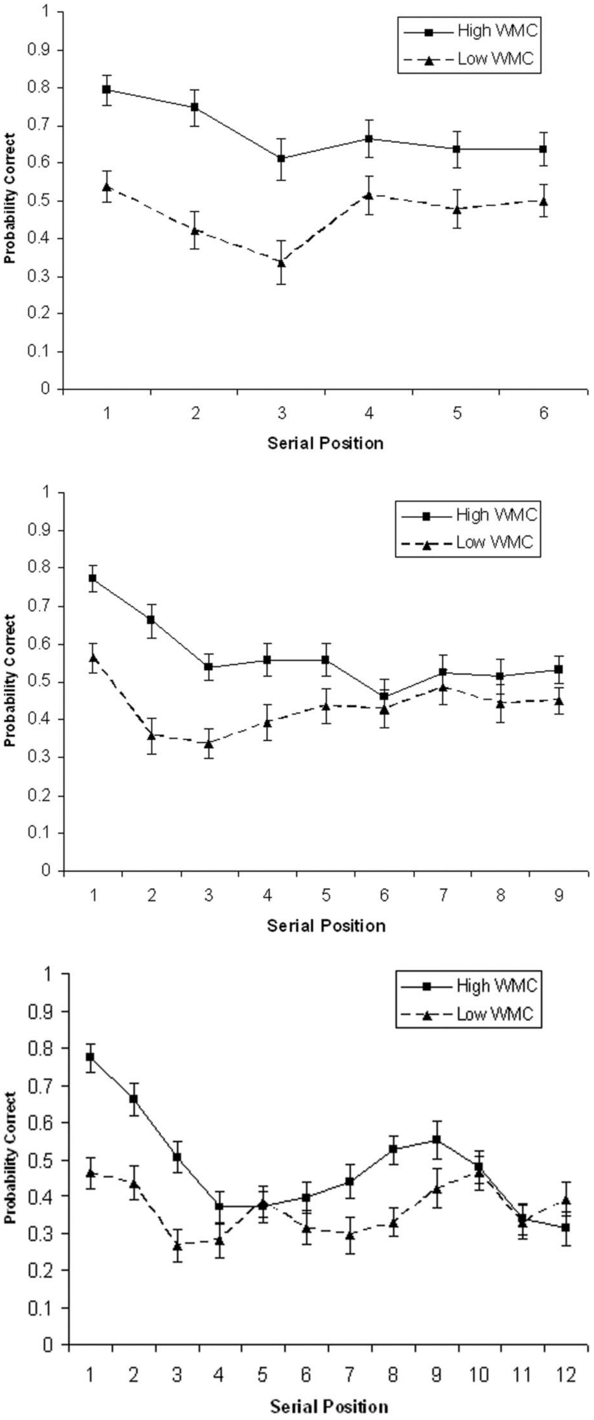

Figure 1. Probability correct as a function of serial position and working memory capacity (WMC) for each list length in Experiment 1. Top panel shows list length 6; middle panel shows list length 9; bottom panel shows list length 12. Error bars represent one standard error of the mean.

Table 2
Mean Number of Each Error Type per List by Working Memory Capacity (WMC) for Experiment 1

	Error type		
WMC	PLI	ELI	Repeat
High	.14 (.06)	.12 (.06)	.04 (.02)
Low	.41 (.06)	.28 (.07)	.07 (.02)

Note. Numbers in parentheses are standard errors. PLI = previous list intrusion; ELI = extralist intrusion; Repeat = repetition error.

effect did not reach conventional levels of significance is most likely the large amount of variability present within the parameter estimates.

Examining next rate of approach to asymptote (λ), the ANOVA demonstrated main effects of both list length, $F(2, 82) = 27.28$, $MSE = 0.001$, $p < .01$, partial $\eta^2 = .40$, and WMC, $F(1, 41) = 5.17$, $MSE = 0.007$, $p < .05$, partial $\eta^2 = .11$. The list-length effect suggests that as list length increased, rate of approach (λ) decreased (list length 6: $M = .15$, $SE = .01$; list length 9: $M = .11$, $SE = .01$; list length 12: $M = .10$, $SE = .01$). The WMC effect suggests that high-WMC individuals approached asymptotic levels at a faster rate than low-WMC individuals ($M = .14$, $SE = .01$ vs.

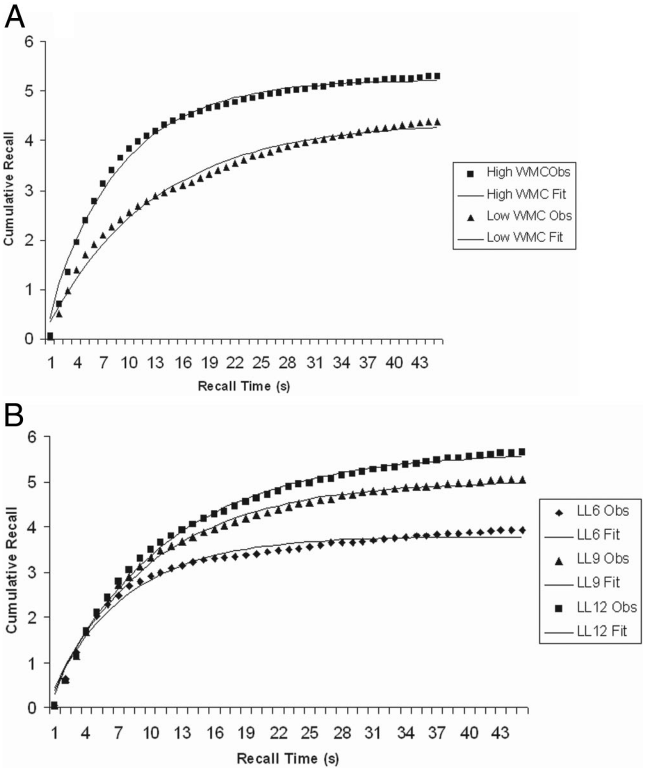

Figure 2. Cumulative recall functions for working memory capacity (WMC) and list length in Experiment 1. The symbols represent the observed data, and the solid lines represent the best fitting exponential (Equation 1). Obs = observed data; Fit = fitted function; LL = list length.

$M = .10$, $SE = .01$). The two-way interaction was not significant ($p > .32$).

Recall latency.[3] In addition to the cumulative latency distributions and the parameter estimates from fitting the cumulative exponential, recall latency was examined. Here recall latency refers to the time point in the recall period when a given response was emitted. Thus, if responses were emitted 5, 10, and 15 s into the recall period, mean recall latency would be 10 s. Recall latency was examined partially because the parameter estimates that are derived from fitting the cumulative exponential to the cumulative latency distributions tend to be somewhat variable and can lead to low statistical power. Additionally, the cumulative latency distributions provide a fairly gross measure of recall latency during the recall period. Therefore, mean recall latency was examined by both list length and WMC. Table 4 shows mean recall latency as a function of list length and WMC. The results suggest that high-WMC individuals had shorter recall latencies than low-WMC individuals ($M = 8.71$ s, $SE = 0.60$ vs. $M = 11.94$ s, $SE = 0.64$), $F(1, 41) = 13.53$, $MSE = 24{,}546{,}379$, $p < .01$, partial $\eta^2 = .25$, and recall latency increased with increases in list length, $F(2, 82) = 13.60$, $MSE = 4{,}549{,}335$, $p < .01$, partial $\eta^2 = .25$.

Discussion

The results from Experiment 1 were largely consistent with the predictions for the low-WMC-large hypothesis and inconsistent with the other three possibilities. Specifically, the low-WMC-large hypothesis suggests that low-WMC individuals search through a larger set of items than high-WMC individuals because they include more previous list intrusions in their search sets than high-WMC individuals. This predicts that low-WMC individuals should recall fewer items than high-WMC individuals and recall more previous list intrusions than high-WMC individuals. Both predictions were consistent with the data. Additionally, if low-WMC individuals are searching through a larger set of items than high-WMC individuals, then low-WMC individuals should recall items at a slower rate than high-WMC individuals, leading to overall differences in recall latency. These predictions were also consistent with the data. The latency analyses suggest that low-WMC individuals approached asymptotic levels of performance at a slower rate than high-WMC individuals and recalled responses at a slower rate than high-WMC individuals. Indeed, an examination of Tables 3 and 4 suggests that low-WMC individuals are searching through roughly the same number of items at a list length of 6 as high-WMC individuals are at a list length of 12. Specifically, at a list length of 6 it took low-WMC individuals roughly 11 s to emit items, and at a list length of 12 it took high-WMC individuals roughly 10 s to emit items, suggesting similar-size search sets. Additionally, probability correct for low-WMC individuals at a list length of 6 (.47) was very similar to probability correct for high-WMC individuals at a list length of 12 (.48). Thus, even at lower list lengths, low-WMC individuals' search sets are much larger than those of high-WMC individuals. Together, these results suggest that low-WMC individuals search through a larger set of items than high-WMC individuals, which leads to slower and less accurate recall than in high-WMC individuals.

Table 3
Parameter Estimates Obtained From Fitting the Cumulative Latency Distributions to a Cumulative Exponential as a Function of Working Memory Capacity (WMC) and List Length for Experiment 1

WMC (list length)	Individual estimates		Group estimates	
	λ	N	λ	N
Low (6)	.13	3.68	.10	3.39
High (6)	.17	4.30	.16	4.19
Low (9)	.09	4.96	.08	4.57
High (9)	.12	5.51	.12	5.48
Low (12)	.09	5.32	.07	5.24
High (12)	.11	6.22	.10	6.10

Note. Individual estimates are average parameter estimates obtained after fitting the cumulative exponential to each individual's cumulative latency distribution. Group estimates are aggregate parameter estimates obtained after fitting the cumulative exponential to overall group cumulative latency distribution. λ = rate of approach to asymptotic performance; N = asymptotic performance.

Table 4
Mean Latency (in Seconds) by Working Memory Capacity (WMC) and List Length for Experiment 1

	List length		
WMC	6	9	12
High	7.26 (0.82)	8.92 (0.63)	9.98 (0.63)
Low	10.73 (0.88)	12.39 (0.67)	12.68 (0.67)
Total	9.00 (0.60)	10.65 (0.46)	11.33 (0.46)

Note. Numbers in parentheses are standard errors.

Experiment 2

In Experiment 2, WMC differences in episodic retrieval and the dynamics of free recall were examined in the continuous distractor free-recall paradigm (Bjork & Whitten, 1974). The reasons for examining performance on the continuous distractor paradigm were threefold. First, continuous distractor free recall is very similar to the design of the complex working memory span tasks, differing only in type of recall (free vs. serial) and type of retention interval (filled vs. unfilled). Accordingly, examining the dynamics of free recall in the continuous distractor task should provide a fairly accurate portrayal of retrieval in the complex working memory span tasks. Second, no previous study has fully examined the time course of retrieval in the continuous distractor task and the possibility of important individual differences therein. Third, the results from continuous distractor free recall should replicate the basic pattern of results obtained with delayed free recall.

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[3] Interresponse times (IRTs) were also examined in both experiments. Consistent with the other latency analyses in Experiment 1, high-WMC individuals had significantly shorter IRTs than low-WMC individuals ($M = 3.65$ s, $SE = 0.34$ vs. $M = 5.66$ s, $SE = 0.36$), $F(1, 41) = 16.50$, $MSE = 7{,}857{,}606$, $p < .01$, partial $\eta^2 = .29$. High-WMC individuals also had shorter IRTs in Experiment 2 ($M = 2.62$ s, $SE = 0.31$ vs. $M = 4.97$ s, $SE = 0.31$), $F(1, 38) = 27.96$, $MSE = 5{,}899{,}990$, $p < .01$, partial $\eta^2 = .42$.

As with the original continuous distractor paradigm, to-be-remembered items were interspersed with a distracting activity. Between item presentations, participants were required to arrange a series of three-digit numbers in ascending order (the same distracting task as in Experiment 1). After the presentation of the last item, participants engaged in an additional 16 s of distractor activity during the retention interval. The hypotheses and analyses for Experiment 2 were exactly the same as those for Experiment 1.

Method

Participants and Design

Participants were 40 new high ($n = 20$) and low ($n = 20$) WMC individuals, as determined by the composite measure and selected from the same distribution as in Experiment 1. Participant recruitment and prescreening on complex memory span were exactly the same as in Experiment 1. Each participant was tested individually in a laboratory session lasting approximately 1 hr. Participants performed 2 practice lists with letters and 21 lists with words with three different list lengths (6, 9, or 12 items).

Procedure

Participants were tested one at a time in the presence of an experimenter. Items were presented alone for 1 s each. Participants were required to read each word aloud as it appeared. Before and after each item presentation, participants were required to arrange four separate three-digit numbers (presented for 2 s each) in ascending order aloud. After list presentation, participants engaged in an additional 16-s distractor activity (arranging eight three-digit numbers instead of four) before recall. At recall, participants saw three question marks appear in the middle of the screen accompanied by a tone that indicated that the recall period had begun. Participants had 45 s to recall as many of the words as possible in any order they wished. For each spoken response (whether correct or incorrect), an experimenter pressed a key indicating when in the recall period the response was given.

Results

Participants

The mean z scores for the 20 high-WMC individuals (12 enrolled at Georgia Institute of Technology, 3 enrolled at other Atlanta area universities, and 5 not enrolled at any university) and 20 low-WMC individuals (4 enrolled at Georgia Institute of Technology, 7 enrolled at other Atlanta area universities, and 9 not enrolled at any university) were 0.96 ($SD = 0.21$, range 0.71 to 1.39) and –1.11 ($SD = 0.56$, range –2.96 to –0.52), respectively. The mean ages for the high- and low-WMC individuals were 22.10 ($SD = 4.94$) and 25.45 ($SD = 5.67$), respectively (see Appendix for information regarding each span task).

Accuracy

Probability correct. As with Experiment 1, classic list-length effects were apparent in which probability correct decreased as list length increased and high-WMC individuals consistently recalled more items than low-WMC individuals. As shown in Table 5, the ANOVA yielded a main effect of list length, $F(2, 76) = 89.00$, $MSE = 0.004$, $p < .01$, partial $\eta^2 = .70$, with probability correct decreasing as list length increased. There was also a main effect of WMC, $F(1, 38) = 28.66$, $MSE = 0.06$, $p < .01$, partial $\eta^2 = .43$, in which high-WMC individuals recalled a higher proportion of items than low-WMC individuals ($M = .76$, $SE = .03$ vs. $M = .52$, $SE = .03$). The two-way interaction was not statistically significant ($F < 1$).

Table 5
Mean Probability Correct by Working Memory Capacity (WMC) and List Length for Experiment 2

	List length		
WMC	6	9	12
High	.86 (.03)	.74 (.03)	.69 (.04)
Low	.61 (.03)	.49 (.03)	.45 (.04)
Total	.74 (.02)	.61 (.02)	.57 (.02)

Note. Numbers in parentheses are standard errors.

Shown in Figure 3 is probability correct as a function of serial position for both high- and low-WMC individuals for each of the three list lengths. As expected, both high- and low-WMC individuals generated serial position functions with intact primacy and recency effects, consistent with prior work using continuous distractor free recall (Bjork & Whitten, 1974). Additionally, WMC differences occurred at all positions, with high-WMC individuals consistently recalling more items than low-WMC individuals. The only significant WMC × Serial Position interaction occurred for list length 12, $F(11, 418) = 1.96$, $MSE = 0.03$, $p < .05$, partial $\eta^2 = .05$.

Recall errors. As with Experiment 1, recall errors were also examined. Table 6 shows the average number of each error type per list (collapsed on list length) as a function of WMC. Similar to Experiment 1, the results suggest that high- and low-WMC individuals differ in previous list intrusions, with low-WMC individuals making many more previous list intrusions than high-WMC individuals, $F(1, 38) = 7.64$, $MSE = 0.58$, $p < .01$, partial $\eta^2 = .17$. These intrusions, on average, came from approximately two lists back ($M = 1.88$, $SE = 0.37$), with many coming from one list back (41% of all previous list intrusions). This did not differ as a function of either list length or WMC (both ps $> .20$). WMC differences did not occur for either extralist intrusions or repetitions (both ps $> .16$).

Latency

Cumulative latency distributions. Figure 4A shows the fits of the cumulative exponential to the cumulative latency distributions for high- and low-WMC individuals (collapsed on list length). Shown in Figure 4B are the fits of the cumulative exponential to the cumulative latency distributions for each list length. As with Experiment 1, responses were first placed into 45 1-s bins, and then the cumulative number of items recalled for each bin was computed. As can be seen, the fits for each function were acceptable, accounting for 98% of the variance. Furthermore, Kolmogorov–Smirnov tests examining differences between the

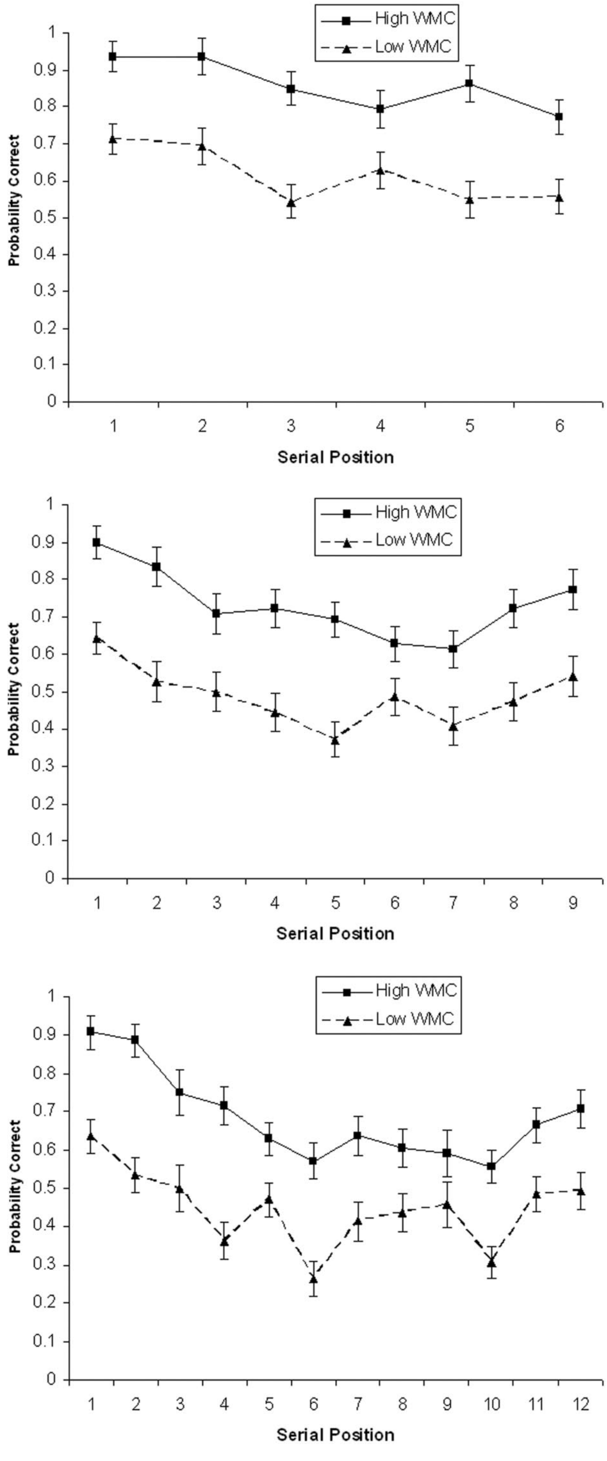

Figure 3. Probability correct as a function of serial position and working memory capacity (WMC) for each list length in Experiment 2. Top panel shows list length 6; middle panel shows list length 9; bottom panel shows list length 12. Error bars represent one standard error of the mean.

Table 6
Mean Number of Each Error Type per List by Working Memory Capacity (WMC) for Experiment 2

WMC	Error type PLI	 ELI	 Repeat
High	.05 (.10)	.06 (.06)	.06 (.03)
Low	.43 (.10)	.17 (.06)	.11 (.03)

Note. Numbers in parentheses are standard errors. PLI = previous list intrusion; ELI = extralist intrusion; Repeat = repetition error.

raw and fitted values for each function resulted in nonsignificant *p* values for all functions (all *p*s > .43). Similar to the probability correct analyses, high-WMC individuals recalled more items than low-WMC individuals (i.e., higher asymptotic levels, *N*), and list length effects were apparent. Furthermore, as shown in Figure 4A and consistent with Experiment 1, low-WMC individuals tended to reach asymptotic levels at a slower rate (λ) than high-WMC individuals. Rate of approach to asymptote (λ) also changed as a function of list length, with rate decreasing as list length increased, consistent with Experiment 1 and the work of Rohrer and Wixted (1994). Table 7 shows the parameter values from fitting the cumulative exponential to the cumulative latency distributions for each individual and each group for both *N* and λ as a function of list length and WMC.

Similar to Experiment 1, the cumulative exponential function was fit to each participant's cumulative latency distributions for each list length. The resulting parameter estimates were then

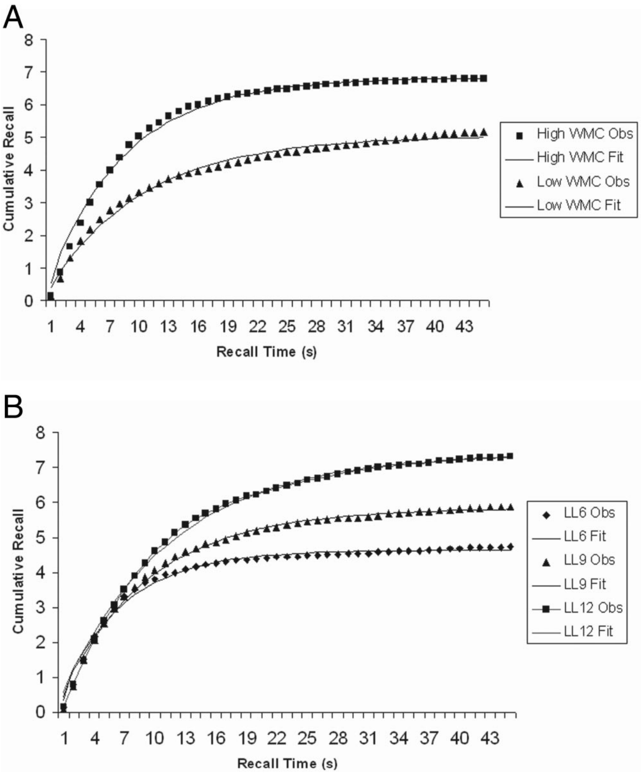

Figure 4. Cumulative recall functions for working memory capacity (WMC) and list length in Experiment 2. The symbols represent the observed data, and the solid lines represent the best fitting exponential (Equation 1). Obs = observed data; Fit = fitted function; LL = list length.

submitted to separate ANOVAs examining WMC and list length. The ANOVA examining asymptotic levels of performance (N) yielded a main effect of list length, $F(2, 76) = 59.67$, $MSE = 1.29$, $p < .01$, partial $\eta^2 = .61$, with N increasing as list length increased. The main effect of WMC was also significant, $F(1, 38) = 11.47$, $MSE = 4.10$, $p < .01$, partial $\eta^2 = .23$. Furthermore, these two factors interacted, $F(2, 76) = 4.87$, $MSE = 1.29$, $p < .01$, partial $\eta^2 = .11$, with the WMC differences increasing as list length increased. These results are generally consistent with the probability correct analyses, demonstrating list-length effects and WMC differences.

The ANOVA examining rate of approach to asymptote (λ) demonstrated a main effect of list length, $F(2, 74) = 56.61$, $MSE = 0.001$, $p < .01$, partial $\eta^2 = .61$.[4] The list-length effect suggests that as list length increased, rate of approach (λ) decreased (list length 6: $M = .15$, $SE = .01$; list length 9: $M = .11$, $SE = .01$; list length 12: $M = .10$, $SE = .01$). The main effect of WMC approached conventional levels of significance, $F(1, 37) = 3.51$, $MSE = 0.007$, $p = .07$, partial $\eta^2 = .09$. The WMC effect suggests that high-WMC individuals approached asymptotic levels at a faster rate than low-WMC individuals ($M = .15$, $SE = .01$ vs. $M = .12$, $SE = .01$). The two-way interaction was not significant ($p > .22$).

Recall latency. As with Experiment 1, recall latency was examined to get a better picture of the time taken to emit responses during the recall period. Again, recall latency refers to the time point in the recall period when a given response was emitted. Shown in Table 8 is mean recall latency as a function of list length and WMC. Consistent with Experiment 1 and the cumulative latency distribution analyses, the results suggest that high-WMC individuals had shorter recall latencies than low-WMC individuals ($M = 7.63$ s, $SE = 0.60$ vs. $M = 10.63$ s, $SE = 0.60$), $F(1, 38) = 12.61$, $MSE = 21{,}496{,}254$, $p < .01$, partial $\eta^2 = .25$, and recall latency increased with increases in list length, $F(2, 76) = 47.68$, $MSE = 2{,}281{,}961$, $p < .01$, partial $\eta^2 = .56$.

Table 7
Parameter Estimates Obtained From Fitting the Cumulative Latency Distributions to a Cumulative Exponential as a Function of Working Memory Capacity (WMC) and List Length for Experiment 2

	Individual estimates		Group estimates	
WMC (list length)	λ	*N*	λ	*N*
Low (6)	.15	4.23	.13	4.08
High (6)	.19	5.25	.18	5.24
Low (9)	.12	4.81	.10	4.91
High (9)	.14	6.85	.12	6.78
Low (12)	.09	6.20	.08	6.23
High (12)	.11	8.78	.10	8.64

Note. Individual estimates are average parameter estimates obtained after fitting the cumulative exponential to each individual's cumulative latency distribution. Group estimates are aggregate parameter estimates obtained after fitting the cumulative exponential to overall group cumulative latency distribution. λ = rate of approach to asymptotic performance; *N* = asymptotic performance.

Table 8
Mean Latency (in Seconds) by Working Memory Capacity (WMC) and List Length for Experiment 2

	List length		
WMC	6	9	12
High	5.77 (0.64)	8.02 (0.70)	9.09 (0.64)
Low	8.89 (0.64)	10.98 (0.70)	12.03 (0.64)
Total	7.33 (0.45)	9.5 (0.49)	10.56 (0.45)

Note. Numbers in parentheses are standard errors.

Discussion

As with Experiment 1, the results are largely consistent with the predictions of the low-WMC-large possibility and inconsistent with the other possibilities. That is, the results suggest that low-WMC individuals recalled fewer items than high-WMC individuals and recalled more previous list intrusions than high-WMC individuals. Both results are consistent with the view that low-WMC individuals' search sets contain a combination of both current and previous target items, which increases the overall size of their search sets. The latency analyses are consistent with these overall notions by demonstrating that low-WMC individuals reached lower asymptotic levels of recall than high-WMC individuals and their rate of approach was slower than that of high-WMC individuals. These results are inconsistent with the other possibilities because they predict that low-WMC individuals will either be faster to recall items than high-WMC individuals (low-WMC-small possibility), recall items at the same rate as high-WMC individuals (low-WMC-nonrecoverable possibility), or recall the same number of total items but at a slower rate than high-WMC individuals (low-WMC-slow possibility). Furthermore, and consistent with Experiment 1, an examination of recall latency by list length for high- and low-WMC individuals suggested that low-WMC individuals were searching through approximately the same number of items for list length 6 as high-WMC individuals were for list length 12 (see Table 8). Specifically, at a list length of 6 it took low-WMC individuals roughly 9 s to emit items, and at a list length of 12 it took high-WMC individuals roughly 9 s to emit items, suggesting similar-size search sets. Additionally, probability correct for low-WMC individuals at a list length of 6 (.61) was very similar to probability correct for high-WMC individuals at a list length of 12 (.69). The end result seems to be that low-WMC individuals search through a larger set of items than high-WMC individuals, resulting in slower and less accurate recall.

Simulations

A variant of the random search model was used to further examine individual differences in WMC in cumulative recall functions. Specifically, the four possibilities discussed previously were simulated for a list length of 12, and the results were compared

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[4] One low-WMC individual was dropped from these analyses for having extremely large estimates of λ. Including this participant in the analyses led to qualitatively identical results.

with the combined results from Experiment 1 and Experiment 2. In these simulations, items were randomly sampled with replacement from a pool of items. Items included recoverable targets, nonrecoverable targets, and intrusions. All items had the same probability of being sampled. Additionally, given that the participants were given 45 s to recall items, for simplicity, only 45 total samples were allowed. Two additional assumptions were added to the basic random search model for the simulations. First, it was assumed that there was a perfect monitoring system such that neither intrusions nor repetitions were allowed to be emitted. Although the recall error data demonstrated that participants do emit errors, the assumption seems warranted given that errors were quite rare. Second, a stopping rule was added in which sampling was terminated after 10 consecutive failures to retrieve any new recoverable items.

With these basic assumptions in place, cumulative recall functions for each of the four possibilities were simulated by varying the number of recoverable targets, the number of nonrecoverable targets, the number of intrusions, or the sampling rate of items. Specifically, one group of high-WMC individuals was simulated and compared with four different groups of low-WMC individuals on the basis of possible reasons for WMC differences in the cumulative recall functions. As shown in Table 9, a list length of 12 for high-WMC individuals was simulated by assuming that high-WMC individuals include all 12 targets (4 of which are nonrecoverable) and one intrusion in their search sets, making for a total of 13 items in their search sets. To simulate the low-WMC-large possibility, the values for targets remained the same, but the number of intrusions was increased to include six intrusions. For the low-WMC-small possibility, the numbers of both recoverable and nonrecoverable targets were reduced, leaving low-WMC individuals with an overall search set of 10 items. In order to simulate the low-WMC-nonrecoverable possibility, the number of nonrecoverable targets was increased to 6 items. Thus, all three possibilities were simulated by simply changing the number of either targets or intrusions within the search set. For the final possibility (low WMC slow), in which highs and lows differ in the speed with which items are sampled from the search set, the number of overall samples was changed. Specifically, for the high-WMC individuals (and all other possibilities) 45 total samples were allowed (assuming the stopping criterion was not reached), with 1 sample per second. In order to simulate differences in sampling rate, the number of samples allowed for this low-WMC group was cut in half. Thus, all other values remained the same as for the high-WMC individuals, but here low-WMC individuals were allowed to sample an item every 2 s. For each possibility, 20 participants were simulated and averaged together.

Shown in Figure 5 are the resulting cumulative recall functions for high-WMC individuals and the four groups of low-WMC individuals. As can be seen, with the exception of the low-WMC-slow group, there seems to be little difference between the different low-WMC groups. However, fitting Equation 1 to each simulated cumulative recall function suggests large differences between the groups in terms of λ. Specifically, as shown in Table 9, the simulations suggest that the low-WMC-large group has smaller values of λ than high-WMC individuals, whereas the low-WMC-small group has larger values of λ than high-WMC individuals, and the low-WMC-nonrecoverable group has roughly the same values of λ as high-WMC individuals. Thus, of these four possibilities, the only one consistent with the data is the low-WMC-large group. Only this group showed smaller values of both *N* and λ compared with high-WMC individuals. Therefore, in order to investigate this further, the simulated cumulative recall functions for the high-WMC group and low-WMC-large group were compared with average cumulative recall functions from Experiment 1 and Experiment 2 for high- and low-WMC individuals. The average functions were examined to rule out possible idiosyncratic differences between delayed and continuous distractor tasks. As shown in Figure 6, the simulated functions are quite close to the actual functions. Indeed, the resulting parameter estimates from fitting Equation 1 are nearly identical for both groups (high-WMC observed: $N = 7.37$, $\lambda = .10$; high-WMC predicted: $N = 7.87$, $\lambda = .09$; low-WMC observed: $N = 5.74$, $\lambda = .08$; low-WMC predicted: $N = 5.81$, $\lambda = .08$). Thus, a fairly simple simulation in which it was assumed that low-WMC individuals include five additional representations (intrusions) in their search sets compared with high-WMC individuals was able to accurately reproduce the differences in cumulative recall functions. Additionally, note that the decision to assume that low-WMC individuals have five additional intrusions compared with high-WMC individuals was not arbitrary but rather was based on the fact that in both experiments low-WMC individuals' response latency for a list length of 6 was similar to high-WMC individuals' response latency for a list length of 12, suggesting that low-WMC individuals have roughly 5–6 additional representations in their search sets compared with high-WMC individuals.

Table 9

Number of Recoverable Targets, Nonrecoverable Targets, Intrusions, and Total Items in the Search Set for Each Simulated Group as Well as Parameter Estimates Obtained From Fitting the Cumulative Exponential to the Simulated Cumulative Latency Distributions

Group	No. rec	No. nonrec	No. intrusions	No. in search set	λ	*N*
High WMC	8	4	1	13	.093	7.87
Low WMC large	8	4	6	18	.078	5.81
Low WMC small	6	3	1	10	.128	5.01
Low WMC nonrec	6	6	1	13	.099	5.45
Low WMC slow	8	4	1	13	.036	8.85

Note. All values are for a presented list length of 12 items. The low-WMC-slow group was simulated by reducing the number of allowable samples. Rec = recoverable; nonrec = nonrecoverable; λ = rate of approach to asymptotic performance; *N* = asymptotic performance; WMC = working memory capacity.

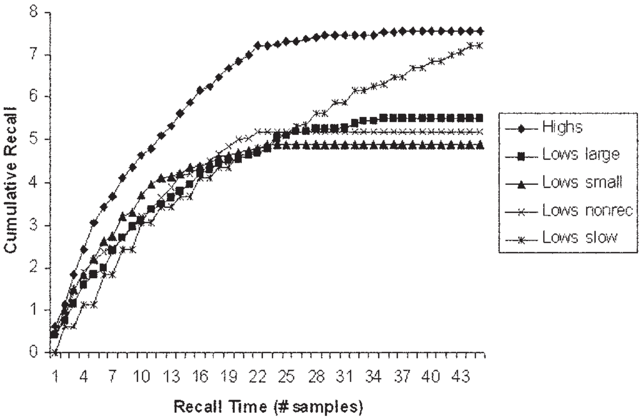

Figure 5. Simulated cumulative recall functions for each group based on values in Table 9. Highs = high working memory capacity (WMC) individuals; Lows large = low-WMC-large group; Lows small = low-WMC-small group; Lows nonrec = low-WMC-nonrecoverable group; Lows slow = low-WMC-slow group.

General Discussion

In two experiments, individual differences in WMC and episodic retrieval were investigated using versions of delayed and continuous distractor free recall. Across both experiments, it was shown that individuals who scored low on WMC measures recalled fewer items in free-recall tasks, made more intrusions from previous lists, and recalled at a slower rate than individuals who scored high on WMC measures. These differences in recall latency occurred even though low-WMC individuals consistently recalled fewer items than high-WMC individuals. That is, low-WMC individuals recalled fewer items than high-WMC individuals, and it took them longer than high-WMC individuals to recall those items. Together, the results suggest that low-WMC individuals' retrieval deficits are partially due to the fact that these individuals are searching through a larger set of items than high-WMC individuals. Indeed, an examination of recall latency differences by list length suggested that low-WMC individuals search through approximately the same number of items at list length 6 as high-WMC individuals do at list length 12. These notions were also consistent with a set of simple simulations of the random search model for each of the four possibilities. The simulations demonstrated that within the random search model, individual differences in WMC are likely due to the fact that low-WMC individuals tend to include more irrelevant representations in their search sets than high-WMC individuals.

The notion that individual differences in WMC are related to differences in the size of the set of items through which individuals search is consistent with several prominent models of working memory. In particular the current results are consistent with both the inhibition view of Hasher, Zacks, and colleagues (Hasher & Zacks, 1988; Hasher et al., 1999) and the executive attention view of Conway, Engle, Kane, and colleagues (Engle & Kane, 2004; Kane et al., 2007). Both views would likely predict that low-WMC individuals would be more susceptible to interference from previous trials and that this interference would result in recall problems on current trials (e.g., Kane & Engle, 2000; May, Hasher, & Kane, 1999). According to these views, the reason low-WMC individuals would search through a larger set of items than high-WMC individuals is that they are unable to suppress previous target items. Similar to Anderson and Spellman (1995), these views suggest that attention is focused internally on target representations while irrelevant representations are suppressed. On the basis of this notion of active suppression, both views would likely be able to handle the present results.

Additionally, it is possible that the present results can be handled by theories of working memory that suggest individuals differ in their ability to use list-discrimination processes to differentiate relevant from irrelevant representations at retrieval (e.g., Hedden & Park, 2001, 2003; Unsworth & Engle, 2007). These theories suggest that individual (and age) differences in WMC are not due to differences in inhibitory processes but rather are due to differences in the ability to use contextual cues to discriminate items at retrieval. That is, similar to Atkinson and Shiffrin (1971), these theories suggest that the cue, or probe, selection control process is important in accessing information from memory and that individuals differ in the ability to select and use cues to search memory. If the cues used do not effectively discriminate items, then many irrelevant items will be included in the search set, leading to poorer overall recall performance, a greater likelihood of intrusions, and slower overall recall. The current work does not provide evidence for one view or another, and therefore, future work is needed to examine differences between views that rely on inhibitory processes and views that rely on cues to correctly discriminate items that are included in the search set.

Limitations, Alternative Explanations, and Future Directions

There are two main limitations in the present work. First, it is apparent that there are several limitations that arise from using a basic random search model. Clearly, items are not retrieved randomly; rather, there appears to be order in the output of items. For instance, items tend to be retrieved in sequence owing to semantic

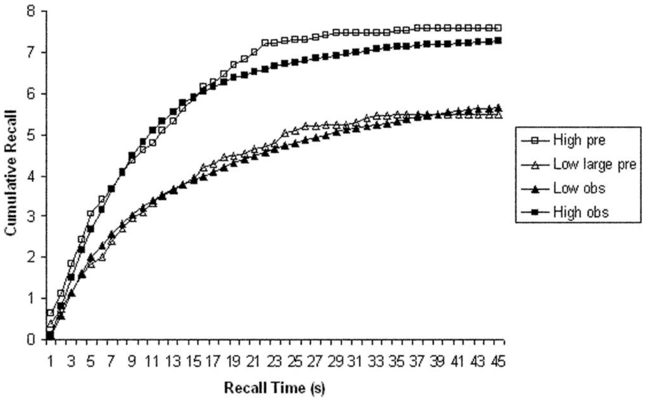

Figure 6. Comparison of simulated cumulative recall functions for high and low working memory capacity (WMC) large groups with actual high- and low-WMC cumulative recall functions (average of Experiment 1 and Experiment 2). High pre = high-WMC individuals' predicted functions based on simulations; Low large pre = low-WMC-large group predicted functions based on simulations; Low obs = low-WMC individuals' observed functions; High obs = high-WMC individuals' observed functions.

(Bousfield et al., 1954; Howard & Kahana, 2002) and temporal (Howard & Kahana, 1999) attributes. Furthermore, it is unlikely that items will have an equal probability of being accessed at any given moment, as the random search model assumes. These and other issues relating to the random search model have been pointed out before, and several articles have attempted to deal with these issues (see Rohrer & Wixted, 1994, and Wixted & Rohrer, 1994, for reviews). However, despite these apparent limitations with the random search model, overall it still provides a useful account of the search process that is thought to occur during recall and possible differences in the size of the search set (Rohrer & Wixted, 1994).

The second major limitation of the current work is the fact that only four fairly simple possibilities of differences in the dynamics of recall were examined, and it is possible that other (slightly more complex) alternatives could also account for the data. In particular for each alternative, either the size of the search set, the number of recoverable targets, or the sampling rate was changed while keeping other values fairly constant. However, by manipulating several factors at once it would be possible to generate similar results. For instance, differences in sampling rate and the number of recoverable targets (perhaps due to decay or degradation of representations) could lead to similar results as those found in the current study. That is, it is possible that low-WMC individuals have a slower sampling rate than high-WMC individuals and that while low-WMC individuals are recalling initial targets, other target representations are being lost owing to decay or degradation. This would likely lead to differences in both N and λ consistent with the data. This possibility was not simulated given that additional assumptions would be required. For instance, do high- and low-WMC individuals lose information at the same rate, and does the search set remain the same size throughout the recall period or does it get smaller as representations are lost? These and other considerations make this scenario quite complicated, whereas a rather straightforward scenario where one group simply has more nontarget representations in its search sets at the onset of recall seems to do a good job in accounting for the data.

Another potential explanation is that high- and low-WMC individuals may differ in both the size of the search set and the number of recoverable targets without the postulation that low-WMC individuals include many more previous list intrusions than high-WMC individuals. For instance, assume that high-WMC individuals include only two thirds of all current list representations in their search sets, all of which are recoverable. Low-WMC individuals, in contrast, include all current list representations in their search sets, only half of which are recoverable. This in principle would produce differences between high- and low-WMC individuals in both N and λ, as was found. However, although this current scheme is able to generate values of N that are fairly similar to the actual values, the values of λ will tend to be larger than what was actually found. Specifically, using the same simulation methodology discussed previously, the above scenario was simulated, resulting in values of N that were quite close to the actual values for both high (observed $N = 7.37$, predicted $N = 7.72$) and low (observed $N = 5.74$, predicted $N = 5.01$) WMC individuals. However, the values of λ for both high (observed $\lambda = .10$, predicted $\lambda = .13$) and low (observed $\lambda = .08$, predicted $\lambda = .10$) WMC individuals were larger than the observed values. Thus, these values of λ suggest that both WMC groups should be recalling items at a much faster rate than they actually do. The only way in the current framework to generate values of λ consistent with the data is to increase the size of the search set by including more intrusions (or by reducing the sampling rate).

Conclusions

Those individuals who score low on measures of WMC have impaired retrieval from episodic memory compared with individuals who score high on these measures. In two experiments this deficit was shown to be related not only to the recall of fewer items but also to the greater recall of previous list items and the slower recall of items throughout the recall period. Collectively, these results and subsequent simulations are consistent with the notion that high- and low-WMC individuals differ in recall abilities because low-WMC individuals search through a larger set of items than high-WMC individuals. These results are consistent with both inhibitory and list-discrimination (source-monitoring) accounts of working memory.

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(*Appendix follows*)

Appendix

Span Task Results for Experiments 1 and 2

Table A1
Mean Total Correct for Each Task by Working Memory Capacity (WMC) for Experiment 1

	Task		
WMC	Ospan	Symspan	Rspan
High	67.30 (5.58)	34.78 (3.61)	68.43 (3.69)
Low	37.15 (12.59)	19.65 (6.60)	30.60 (13.59)

Note. Operation span (Ospan) and reading span (Rspan) scores are out of a possible 75, and symmetry span (Symspan) score is out of a possible 42. Numbers in parentheses are standard deviations.

Table A2
Mean Total Correct for Each Task by Working Memory Capacity (WMC) for Experiment 2

	Task		
WMC	Ospan	Symspan	Rspan
High	66.75 (6.17)	35.55 (2.70)	67.30 (3.63)
Low	38.15 (13.52)	17.35 (6.16)	31.55 (12.93)

Note. Operation span (Ospan) and reading span (Rspan) scores are out of a possible 75, and symmetry span (Symspan) score is out of a possible 42. Numbers in parentheses are standard deviations.

Received October 4, 2006
Revision received May 22, 2007
Accepted June 11, 2007 ■