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Variation in Working Memory Capacity and Temporal–Contextual Retrieval From Episodic Memory

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Unsworth and Engle (2007) recently proposed a model of working memory capacity characterized by, among other things, the ability to conduct a strategic, cue-dependent search of long-term memory. Although this ability has been found to mediate individual variation in a number of higher order cognitive tasks, the component processes involved remain unclear. The current study was designed to investigate individual variation in successfully retrieving information from episodic memory by examining various aspects of the retrieval process. Both high– and low–working memory capacity participants were found to initiate recall in a similar fashion; however, low–working memory capacity participants did not show the classic asymmetry in their conditional-response probabilities that is typically observed. Overall, the retrieval deficits observed in low–working memory capacity individuals appear to be rooted in their inability to use the products of retrieval to further aid their search.

Keywords: working memory capacity, temporal context, long-term memory

Since its inception, the nature of working memory has been a topic of considerable debate. However, at its most distilled, the working memory concept can be best described as a collection of control processes used in managing the memory system (Baddeley & Hitch, 1974; Moscovitch & Winocur, 1992; Unsworth & Engle, 2007). Consistent with this view, in recent work, Unsworth and colleagues (Unsworth, 2007; Unsworth & Engle, 2007) have argued that working memory can be characterized by two distinct component processes, the maintenance of information within the focus of attention and the retrieval of information from long-term memory. Individual variation within these two components has been found to mediate much of the relation between measures of working memory capacity (WMC) and higher order cognitive tasks, such as reading comprehension and fluid intelligence (Engle & Kane, 2004; Unsworth, Brewer, & Spillers, 2009). Although researchers have extensively investigated the processes involved in active maintenance (Engle & Kane, 2004), there remain several fundamental and unanswered questions concerning how individuals successfully conduct a strategic search of memory. Two of particular importance concern how individuals self-initiate retrieval in the absence of any external cues and why some individuals are much more successful at doing so than are others. In the current work, we address these questions by investigating individual differences in WMC and variation in the use of temporal–contextual cues to organize and direct retrieval during episodic recall.

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WMC and Strategic Search of Memory

A fruitful advancement to the study of working memory has been the idea that participants must retrieve from long-term memory information that has been displaced from the focus of attention (Unsworth & Engle, 2007). Indeed, several studies by Unsworth and colleagues (e.g., Unsworth & Spillers, 2010) have found a strong relation between measures of WMC and retrieval across a number of episodic recall tasks, such that individuals in the upper quartile of WMC abilities (as indexed by complex span measures) recall more items correctly, recall these items faster, and output fewer errors than those in the lower quartile. Importantly, high- and low-WMC individuals have been found to differ primarily on tasks that require self-initiated processing (e.g., free recall) rather than tasks that provide participants with an external cue (e.g., recognition; Unsworth, 2009).

Generally, researchers have argued that high- and low-WMC individuals differ in retrieval because of variation in their respective ability to self-generate retrieval cues. Converging evidence from multiple measures of performance, including proportion correct, intrusion error analyses, and recall latencies, are consistent with the idea that low-WMC individuals search memory with cues that are too broad, limiting their ability to focus and select correct items from intruding competitors (Unsworth, 2007; Unsworth & Engle, 2007). How diagnostic a cue is of a given target item depends primarily on its relative overlap with the item *and* the number of other items the cue is also related to (Nairne, 2002). Therefore, low-WMC individuals are assumed to recall less efficiently because the cues they generate are not diagnostic of the information for which they are searching. Although this general point has been consistently shown, more direct evidence of how low-WMC individuals differ from high-WMC individuals in their use of internally generated cues is lacking. Thus, our concern in the present article is to understand how the misuse of contextual-cues during retrieval changes how low-WMC individuals initiate and focus their search.

Temporal–Contextual Retrieval

Over the last few decades, there has been an increasing effort by researchers to examine the dynamics of retrieval in a number of recall paradigms. Work in this area has converged on the idea that retrieval from episodic memory is driven by the use of contextual cues to probe the memory system (Anderson & Bower, 1972; Howard & Kahana, 2002; Polyn, Norman, & Kahana, 2009; Raaijmakers & Shiffrin, 1980). Indeed, many formal theories of memory have incorporated context as an essential component in both the storage and retrieval of information from memory. These theories assume that at encoding, there are associations that are formed between an item's content information and various active elements of the current context that create an episodic representation in memory. When items are unrelated, as they often are in most recall tasks, temporal information is argued to predominate. Subsequently, at retrieval, it is assumed that contextual-cues composed of these temporal–contextual elements are then used to focus the search process. The extent to which a search is focused and successful (i.e., a target representation is recovered) depends primarily on the amount of overlap between the contextual elements used as cues and those that were present at encoding.

These assumptions are not without scientific merit. In fact, they have proven fruitful for explaining a variety of systematic effects that have been observed in free recall over the last several years. In particular, Kahana and colleagues have found that when individuals must self-initiate retrieval, their recall tends to follow a general pattern whereby items presented in close temporal proximity are subsequently recalled in succession (i.e., *the lag-recency effect*; Kahana, 1996). That is, if a participant recalls a word from the third serial position, the very next word recalled has a higher probability of being from the fourth serial position than from the ninth or tenth. Further, this effect has been found to show a distinct asymmetry, in which contiguous items are more likely to be recalled in a forward direction, as opposed to a backward direction (Kahana, 1996). To explain this effect, Kahana and his colleagues have appealed to the idea that context continually fluctuates, such that certain elements of the current context become active, whereas others become inactive over time (Howard & Kahana, 1999). Because of this fluctuation, items on a list being encoded can differ contextually from each other by varying degrees, with those items that are presented closer together sharing more contextual features than those that are more remote. By this theory, at retrieval, when an item is sampled and recovered, its bound temporal–contextual information is then used as a cue in conjunction with the current context to continue the search. Therefore, neighboring items sharing the most contextual features with the item being used as a cue will have a greater probability of being subsequently recalled (Howard & Kahana, 1999). Further, Kahana and colleagues (Howard & Kahana, 1999; Kahana, Howard, Zaromb, & Wingfield, 2002) have summarized the course of retrieval as a two-stage process wherein individuals must first initiate retrieval using the context available during the recall period and, second, after recall has been initiated, begin subsequently updating their retrieval cues with contextual-information retrieved with each new response.

The Present Study

In theory, if high- and low-WMC individuals differ in how they generate and use cues during retrieval then there should be distinct, observable differences in how their recall is organized. With reference to the above *retrieved-context framework* of Kahana and colleagues, individuals could differ significantly in either stage of the contextual cue production process, which should have clear implications for the number of items they retrieve and how organized their search process is, more generally. Therefore, this framework provides a useful means for inferring how high- and low-WMC individuals differ in their ability to use temporal–contextual cues. That is, higher levels of organization are indicative of more diagnostic retrieval cues.

To examine this question, high- and low-WMC individuals were presented with multiple lists of unrelated words followed by a delayed test for all of the lists at once (see Unsworth, 2008, for a similar procedure).[1] With this paradigm, several predictions can be made concerning how high- and low-WMC individuals should differ in their patterns of retrieval. Most generally, low-WMC individuals should have lower overall correct performance levels, compared with high-WMC individuals, given the evidence that they are much poorer at using contextual-cues to guide the search process (Unsworth, 2007; Unsworth & Engle, 2007). More specifically, if high-WMC individuals are in fact using cues more diagnostic of the memory traces they are trying to retrieve then one would also expect distinct departures in the recall pattern of low-WMC individuals, compared with high-WMC individuals. For instance, if low-WMC individuals have trouble self-generating and effectively using contextual-cues at retrieval, one could speculate that the types of items they most often begin their search with (e.g., primacy items) should be different from that of high-WMC individuals and might vary from trial to trial. Further, low-WMC individuals might have trouble transitioning between responses once the retrieval process has been initiated and, thus, should show significantly reduced lag-recency effects compared with high-WMC individuals. Put simply, one would expect high-WMC individuals' recall to appear far more systematic, with clear contiguity among items present in their recall. By contrast, low-WMC individuals' recall should appear more random, with variable contiguity compared among recalled items.

Method

WMC Screening

All participants were prescreened on three complex memory span measures. These included operation span, reading span, and symmetry span. These 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.

[1] Note that this procedure differs from the one used by Unsworth (2008) in that participants are not tested on each individual list. By not testing each list individually, one can ensure that temporal–contextual organization effects (i.e., lag-recency, probability of first recall, etc.) observed in the data will be based on the original serial positions of list items rather than on the possible output positions of items recalled during individual tests of the lists.

Complex Memory Span Measures

Operation span. Participants solved a series of math operations while trying to remember a set of unrelated letters. 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. At recall, participants were asked to recall all the letters from the current set in the correct order by clicking on the appropriate letters. 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. Participants read a sentence and determined whether it made sense. 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 gave their response, 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. The same scoring procedure as in the operation-span task was used.

Symmetry span. 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. The same scoring procedure as in the operation-span task was used.

Participants and Composite Scores

Participants were 20 high-WMC individuals (z-WMC $= 0.74$, $SD = 0.39$) and 20 low-WMC individuals (z-WMC $= -1.15$, $SD = 0.75$), as determined by the composite measure. All participants were between the ages of 18 years and 35 years.

For the composite measure, scores on 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 1,000 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.

Delayed Free Recall

Materials. Stimuli consisted of 200 nouns from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982).

Design and procedure. Participants were told that they would be presented with a series of four lists and that their task was to try to remember the words from each list for a later test. Before beginning, participants completed a practice list to establish familiarity with typing their responses. The practice list consisted of a series of 15 letters presented at 2 s each and was followed by a 16 s distractor task requiring participants to arrange 3-digit numbers from largest to smallest. The distractor task stimuli were presented for 2 s each, and responses were recorded on paper. At recall, participants saw three question marks (???) appear in the middle of the screen, indicating that the recall period had begun. Participants had 60 s to recall as many of the letters from the practice list as possible in any order they wished.

Following the practice phase, participants completed the experimental session. The paradigm used consisted of five trials with four lists of 10 words each in every trial. All words were presented alone for 2 s each. Preceding each list presentation, a screen denoting the current list was presented (e.g., List 1) for 2 s. At the end of each trial, participants were required to complete the 16 s distractor task before being given 3 min to freely recall as many words from the four lists as they could.

Results

Shown in Table 1 are the mean proportions of items correctly recalled by each group. As expected, high-WMC individuals correctly recalled significantly more items overall than did low-WMC individuals, $t(38) = 4.42$, $p < .001$.[2] In order to examine recall accuracy more thoroughly, we examined probability correct as a function of serial position. Figure 1 shows recall probability plotted as a function of within-trial serial position (see Figure 1A) and within-list serial position (see Figure 1B) for both high- and low-WMC individuals. As seen in Figure 1A, high-WMC individuals tended to recall more items than did low-WMC individuals at nearly all serial positions across the entire trial, $F(1, 38) = 19.47$, $MSE = 10.17$, $p < .001$. In addition, there was a pronounced primacy effect, in which the first several items presented on List 1 were recalled significantly more often than other serial positions, $F(39, 1482) = 8.41$, $MSE = 0.34$, $p < .001$. These two factors did not interact ($p > .15$). Figure 1B plots recall probability as a function of within-list serial position. High-WMC individuals clearly recalled more items correctly than did low-WMC individuals at all serial positions within a list, $F(1, 38) = 19.47$, $MSE = 2.5$, $p < .001$. Importantly, however, both groups showed significant primacy effects, $F(9, 342) = 11.73$, $MSE = 0.10$, $p < .001$, suggesting that with the presentation of each new list, primacy items were rehearsed more often than succeeding items. Again, these two factors did not interact ($p > .65$).

To understand in greater detail how exactly high- and low-WMC individuals conduct retrieval in free recall, the serial position function was further broken down into probability of first recall (PFR) and lag-recency effects. These two analyses provide an assessment of how individuals initiate and transition, respectively, during retrieval (Howard & Kahana, 1999).

In Figure 2, PFR is plotted as a function of within-trial serial position (see Figure 2A) and within-list serial position (see Figure

[2] In addition to calculating the mean number of items recalled, we also computed the number of clusters of items recalled and the interresponse times within and between these clusters. See the Appendix for more information on these analyses.

Table 1
Mean Proportion Correct as a Function of WMC

	WMC	
Measure	High	Low
Proportion correct	.39 (.02)	.23 (.02)

Note. Numbers in parentheses represent 1 standard error of the mean. WMC = working memory capacity.

2B). Specifically, PFR refers to the number of times the first word recalled comes from a given serial position divided by the number of times the first word recalled could have come from that serial position. As is evident from Figure 2A, high- and low-WMC participants did not differ in any significant respect with how they began their recall ($p > .32$).[3] Indeed, both groups tended to begin recall by outputting the first couple of items from List 1, $F(19, 722) = 11.73$, $MSE = 0.02$, $p < .001$. These two factors did not interact ($p > .93$). We also examined this by comparing PFR for the very first item in each list with PFR for all other items. Consistent with the prior analyses, there was a main effect of serial position, such that participants were more likely to start with the first position than with other positions, $F(1, 38) = 26.68$, $MSE = 0.002$, $p < .001$, and this did not change as a function of WMC, $F(1, 38) = 1.80$, $MSE = 0.002$, $p > .18$. The results shown in Figure 2B mirror those of Figure 2A, indicating that within a given list, the item most likely to be recalled first did not differ as a function of WMC ($p > .32$), with both high- and low-WMC individuals tending to begin their recall with a primacy item, $F(9, 342) = 10.89$, $MSE = 0.24$, $p < .001$.

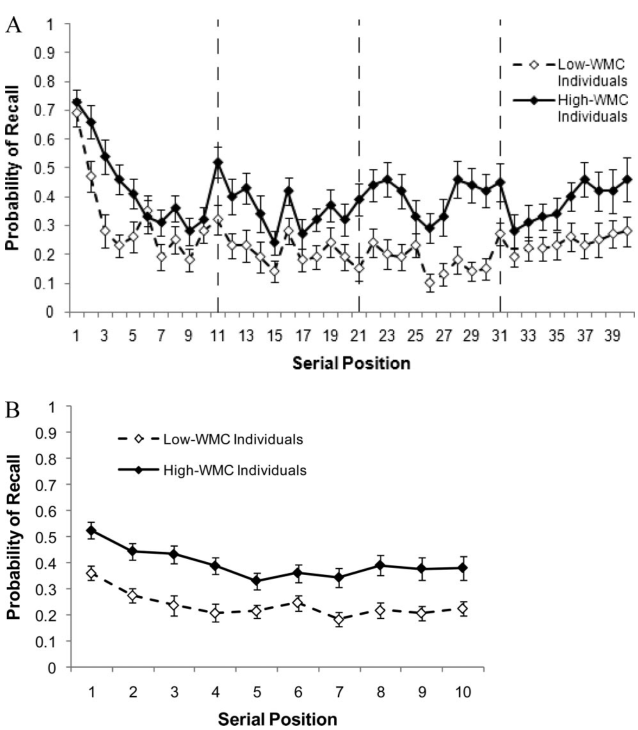

Figure 1. A: Probability of correct recall as a function of within-trial serial position. Vertical dashed lines indicate the start of a new list. B: Probability of correct recall as a function of within-list serial position. Note that the error bars reflect 1 standard error of the mean. WMC = working memory capacity.

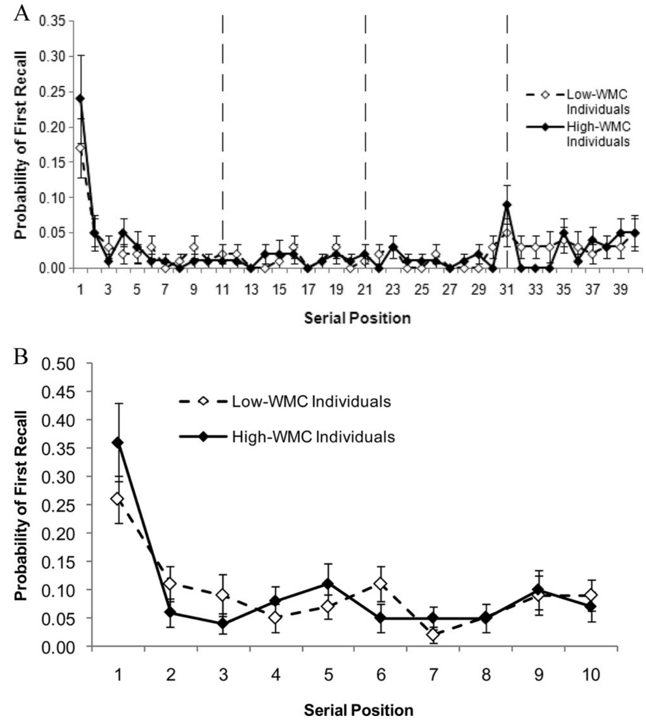

Figure 2. A: Probability of first recall as a function of serial position in each trial. Vertical dashed lines indicate the start of a new list. B: Probability of first recall of serial position within each list. Note that the error bars reflect 1 standard error of the mean. WMC = working memory capacity.

As mentioned, lag-recency effects provide a quantitative assessment of how individuals transition between their responses. These effects are plotted as lag-conditional response probabilities (lag-CRP) that represent the probability of forward and backward transitions made between correctly recalled items based on presentation lag. Lag-CRP functions were computed within a trial (see Figure 3A) and within a list (Figure 3B) and were calculated in accordance with previous research (Howard & Kahana, 1999; Kahana, 1996).[4]

[3] Note that in order to analyze within-trial PFR, an average was computed for every two serial positions, given that some serial positions were never recalled first. Therefore, tests were conducted on 20 aggregate serial positions rather than on 40.

[4] To calculate the lag-CRPs, we first tallied the number of times a transition of a certain lag, *x*, was made and then counted the number of times that a transition of lag *x* could have been made within a given trial. Summing overall trials for a given subject, the lag-CRP function plots the number of times a transition of lag *x* was made *divided* by the number of times that a transition lag *x* could have been made. The absolute value of the lag is a measure of the degree of remoteness at the encoding of successively recalled items (e.g., a lag of +2 indicates item *y* succeeded item *x* by two serial positions).

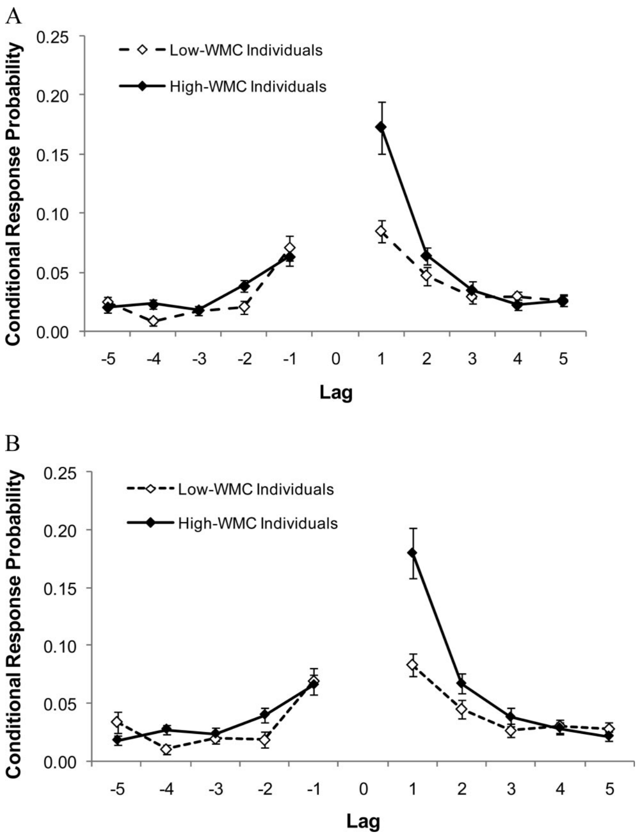

Figure 3. A: Conditional response probability functions for forward and backward within-trial transitions as a function of lag. B: Conditional response probability functions for forward and backward within-list transitions as a function of lag. Note that the error bars reflect 1 standard error of the mean. WMC = working memory capacity.

Figure 3A shows that high- and low-WMC individuals differed in both the direction and the degree of transition between their responses, as supported by a repeated-measures analysis of variance (ANOVA) with direction (forward or backward) and lag (1, 2, 3, 4, or 5) as within-subjects factors and span (high or low) as a between-subjects factor, $F(4, 152) = 8.53$, $MSE = 0.10$, $p < .001$. Follow-up analyses indicated the Direction (forward or backward) × Lag (1, 2, 3, 4, or 5) interaction was significant for high-WMC individuals, $F(4, 76) = 12.25$, $MSE = 0.02$, $p < .001$, but not for low-WMC individuals ($p > .33$). That is, after outputting a response, the very next item that high-WMC individuals recalled was most likely to be a contiguously presented item (Lags 1 or −1) that initially succeeded their first response at presentation (Lag 1). For instance, if a high-WMC individual were to recall the fifth item presented in the trial, the results suggest the very next item output would most likely be the sixth item rather than the 10th or even the fourth. In contrast, low-WMC individuals' recall transitions appear less systematic. Although low-WMC individuals were more likely to recall items originally presented together in succession, compared with those more remote, this probability was significantly reduced, compared with high-WMC individuals. Further, the lag-CRPs of low-WMC individuals are not characteristic of those observed in previous studies in that there is no asymmetry between forward and backward transitions ($t < 1$). We also examined these differences with another index of asymmetry. Specifically, if F is the +1 CRP and B is the −1 CRP, then $(F - B)/(F + B)$ provides an index of the amount of asymmetry, with larger values indicating more asymmetry than smaller values. Applying this to each individuals data, we see that high-WMC individuals demonstrated more asymmetry ($M = .42$, $SE = .06$) than did low-WMC individuals ($M = .11$, $SE = .09$), $t(38) = 2.92$, $p < .01$. Furthermore, the amount of asymmetry was significantly different from zero for high-WMC individuals, $t(19) = 7.43$, $p < .001$, but not for low-WMC individuals ($p > .21$. Note that these results are in contrast to the PFR analyses in which high- and low-WMC individuals began recall in a similar manner—namely, with primacy items from List 1. After recall of these first several items, it is apparent the two groups begin to diverge. In fact, these results suggest that high-WMC individuals capitalized on the information provided by their initial responses and continued recalling successive items, whereas low-WMC individuals began sampling more indiscriminately after initiating recall.

One possible problem with Figure 3A and the subsequent analyses is that high-WMC individuals recalled more items overall, compared with low-WMC individuals, and thus, the lag-CRPs observed for both groups may be exaggerated or underestimated. To remedy this situation, we recalculated the lag-CRPs for only the first four output positions (see Kahana et al., 2002).[5] This procedure ensures that high- and low-WMC individuals are more evenly matched in the total number of items they recalled at test. Importantly, output position as a factor did not interact with span ($p > .25$). A repeated-measures ANOVA with direction (forward or backward) and lag (1, 2, 3, 4, of 5) as within-subjects factors and span (high or low) as a between-subjects factor approached conventional levels of significance, $F(4, 140) = 2.17$, $MSE = 0.04$, $p < .07$. Follow-up analyses indicated that the Direction (forward or backward) × Lag (1, 2, 3, 4, or 5) interaction was significant for high-WMC individuals, $F(4, 72) = 5.88$, $MSE = 0.56$, $p < .001$, but not for low-WMC individuals ($p > .28$). These recalculated CRP analyses are in accordance with the initial findings and further substantiate the notion that low-WMC individuals show significantly reduced asymmetry, compared with high-WMC individuals.

Finally, Figure 3B mirrors the results observed in Figure 3A but report lag-CRPs within a list for all output positions. Once items within a list were sampled, high WMC individuals were much more likely to transition to a contiguously presented item in the forward direction than were low WMC individuals, as supported by a repeated-measures ANOVA with direction (forward or backward) and lag (1, 2, 3, 4, or 5) as within-subjects factors and span (high or low) as a between-subjects factor, $F(4, 152) = 7.36$, $MSE = 0.01$, $p < .001$. Follow-up analyses again indicated that the Direction (forward or backward) × Lag (1, 2, 3, 4, or 5) interaction was significant for high-WMC individuals, $F(4, 76) = 12.64$, $MSE = 0.02$, $p < .001$, but not for low-WMC individuals ($p > .26$).

[5] In the process of recalculating the lag-CRPs to be conditional on only the first four output positions, three participants (1 high-WMC individual and 2 low-WMC individuals) did not meet the criteria and were, therefore, left out of the analyses.

Discussion

The general purpose of the current study was to examine the dynamics of retrieval from episodic memory in high- and low-WMC individuals. The primary motivation for conducting this investigation was to understand the specific ways in which high- and low-WMC individuals differ in their use of internally generated temporal–contextual cues, in terms of both the number and the types of items they recall and how these items are organized. Collectively, the results reveal novel insight into how these two groups differ at retrieval in free recall by moving beyond measures of overall proportion correct. In fact, it was found that the lag-CRPs of low-WMC individuals were not characteristic of those typically observed (i.e., no asymmetry between forward and back transitions; Howard & Kahana, 1999; Kahana, 1996). Although both groups of participants were found to initiate recall in the same fashion, high-WMC individuals were most likely to transition in a forward direction between items at neighboring input positions, whereas low-WMC individuals were no more likely to transition forward than to transition backward and had a significantly reduced probability of recalling items presented contiguously at encoding in the forward direction.

WMC and the Retrieved-Context Framework

To understand these results, one can refer to the framework of Kahana and colleagues discussed previously (Kahana et al., 2002; Howard & Kahana, 1999). Recall that in this framework, episodic retrieval is guided by self-generated temporal–contextual cues and is argued to progress in two distinct stages. In the first stage, it is assumed participants begin their search by using the time-of-test context to initiate retrieval. Once participants successfully retrieve their first item, it is assumed that participants also retrieve the state of context encoded with the item when it was originally presented. This retrieved-context is then used as an updated retrieval cue to further specify the search. As context-cues are retrieved and continually updated, both the content and the size of an individual's search set necessarily change. When a search set is more focused, the probability of sampling a target item is higher because of less competition from other items. Presumably, if only general contextual-cues are used, more items are included in the overall search set, and the probability of recalling any one item is decreased dramatically. Thus, the better able an individual is at retrieving contextual-information and using that information to further generate other items, the more items they are likely to recall. The systematic tendencies observed in the recall of high-WMC individuals are a manifestation of this general process, whereas the erratic recall of low-WMC individuals presumably represents the lack thereof.

Broadly stated, it appears as though high-WMC individuals strategically use temporal information to their advantage in order to better constrain their search. That is, once high-WMC individuals recovered their first item, they then used that item and its bound contextual-information to continue retrieving neighboring items. Indeed, this process readily explains the lag-CRP functions observed for high-WMC individuals and is consistent with major models of free recall like *Search of Associative Memory* (SAM; Raaijmakers & Shiffrin, 1980) and the temporal context model (TCM; Howard & Kahana, 1999, 2002) that specify that once an item is retrieved, it is combined with the broader contextual-cue to further delimit the search. Thus, high-WMC individuals not only use broad experimental cues to initiate and sample items but also continuously integrate contextual-information retrieved during the recall session as well, capitalizing on both sources of information in order to search efficiently.

In contrast, low-WMC individuals appear less likely to capitalize on the contextual-information retrieved with each recalled item or, alternatively, fail to even retrieve the contextual-information in the first place. This is an important finding because it suggests that low-WMC individuals' retrieval deficit is limited only to the stages of retrieval after the recall process has begun; that is, they show a clear deficit in the ability to use retrieved-context to their advantage but not in initiating retrieval. Indeed, the PFR analyses indicate that high- and low-WMC individuals do not differ in how they initiate retrieval, it is simply how these groups capitalize on the information provided once retrieval is initiated that dissociates the two. When beginning recall, participants in both groups typically resorted to sampling and recalling the strongest items (i.e., primacy items). After these first few items, high-WMC individuals used the information they gained from these recalls and continued to search. Low-WMC individuals, however, continued to use a broad cue without updating it with new, more specific contextual information; thus, their recall tapered off considerably, whereas high-WMC individuals continued to sample and recall additional items from each of the lists.

These results are especially notable because of previous efforts by researchers to clarify the link between WMC and various other forms of higher order cognition. Specifically, we have shown in prior work using structural equation modeling that WMC relates very highly with constructs of recall and general fluid intelligence (gF) and, even further, have shown that recall from long-term memory partially mediates the relation between WMC and gF (Unsworth et al., 2009; Unsworth & Spillers, 2010). Although our focus has been on differences in search set size (i.e., the number of items a given individual is theoretically searching through during retrieval), the present results suggest a new and interesting subtlety not considered previously; namely, that differences in individuals also arise due to the inability of low-WMC individuals to use retrieved information to probe memory and generate subsequent items. This is important not only for accounting for differences in free recall when search set size does not differ (e.g., no proactive interference on the first trial of a Brown–Peterson task) but also for accounting for differences in verbal fluency and autobiographical search. Further, as it has become too commonplace to assume that high and low WMC individuals will differ in all aspects of effortful cognition, the present results provide a testament to how subtle and yet profound the differences truly are.

One possible reason low-WMC individuals appear to have a variable search process may be that they do not actually retrieve the contextual-information that is bound to each item representation stored in memory. Indeed, Kahana et al. (2002) have proposed a similar deficit to explain retrieval differences between younger and older adults. In their second experiment, Kahana et al. (2002) found that older adults show significantly reduced lag-CRP functions compared with younger adults in a delayed free recall task, although both groups still showed asymmetry. They argued that older adults, when recalling an item, do not retrieve the pattern of context activity associated with that item, preventing them from harnessing that information and further focusing their search. Although it is puzzling as to why the older adults in Kahana et al. (2002) still showed (albeit reduced) forward asymmetry and the low-WMC younger adults reported herein did not, it seems reasonable to presume that younger adults with low-WMC abilities may be falling victim to a similar contextual-retrieval deficit.

Conclusions

The current work contributes to burgeoning research concerning retrieval with temporal-cues in free recall. The results also add to the overall understanding of how individuals vary in the controlled search of episodic memory using self-generated retrieval cues. Indeed, both groups tended not to differ in many respects as to how they retrieve information. However, high-WMC individuals displayed a greater capacity for recalling items in a systematic fashion based on the temporal order in which they were presented. This suggests that once an item on a particular list was recalled, high-WMC individuals used that item plus the overarching context-cue to retrieve further items, whereas low-WMC individuals continued to recall without capitalizing on the newly retrieved information. Thus, the current study makes abundantly clear that how an individual manages temporal–contextual information greatly determines their ability to conduct a successful search of long-term memory. That is, it is not just how many items one recalls but also how they recall those items that is important. Future work will be needed to determine what prevents low-WMC individuals from capitalizing on (and possibly retrieving) the contextual-information bound with individual items.

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Appendix

Analyses of Clusters

In addition to analyzing serial position, PFR, and lag-CRPs, we also calculated the number of clusters participants output and the size of these clusters (see Table A1). Clusters were defined as two or more items presented on the same list that were output in succession. Interresponse times were also calculated for both within and between clusters (see Table A2). Interresponse times were measured as the difference between the first key stroke of item n and the first key stroke of item $n + 1$.

Table A1
Mean Number of Clusters and Cluster Size as a Function of WMC

	WMC	
Measure	High	Low
Number of clusters	4.42 (0.34)	2.53 (0.27)
Cluster size	3.24 (0.18)	2.96 (0.12)

Note. Numbers in parentheses represent 1 standard error of the mean. WMC = working memory capacity.

Table A2
Mean Interresponse Times (in Seconds) Between and Within Clusters as a Function of WMC

	WMC	
Measure	High	Low
Between clusters	7.09 (0.64)	9.51 (0.86)
Within clusters	4.27 (0.31)	5.59 (0.60)

Note. Numbers in parentheses represent 1 standard error of the mean. WMC = working memory capacity.

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