VARIATION IN WORKING MEMORY CAPACITY AND

TEMPORAL CONTEXTUAL RETRIEVAL FROM EPISODIC MEMORY

by

GREGORY JOSEPH SPILLERS

(Under the Direction of Nash Unsworth)

ABSTRACT

Unsworth and Engle (2007) recently proposed a model of working memory capacity characterized by, amongst 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 lag recency effects and temporal clustering. Both high and low working memory capacity participants were found to initiate recall in a similar fashion, however, low working memory capacity participants showed far less temporal organization in their recall. Overall, the retrieval deficits observed in low working memory capacity individuals appear to be rooted in both their inability to self-generate overarching temporal-contextual cues and their inability to use the products of retrieval to further aid their search. Possible neuroscientific explanations of these retrieval deficits are discussed.

INDEX WORDS: WORKING MEMORY, EPISODIC MEMORY, CONTEXT, DELAYED FREE RECALL

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B.A., University of North Carolina, Greensboro, 2008

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2010

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May 2010

DEDICATION

To Sara, whose untimely death could not have stirred in me a greater desire for life

ACKNOWLEDGEMENTS

This work marks a milestone in my life; it is at once a hard earned academic accomplishment and a symbol of resilience. That being said, it would have been impossible for me to get to this point on my own and, indeed, without the continued support I have received from my family, friends, and mentors, I would not be here.

Strong-willed with impeccable intellect, Nash Unsworth has proven to be the best advisor any naïve graduate student could have wished for. He is both a machine in his consumption of science and a romantic in his appreciation for it. Without a doubt, the two years I have spent under his guidance have been the most fruitful of my academic career and I would hope that these few short years I have as his student are merely the beginnings of a life-long friendship.

My mother and grandmother—two strong women with very different opinions. No matter how often they disagree they share one important commonality, their unconditional faith in me and the choices I make. From my mother I have learned that no matter how broken down you feel, you should never allow yourself to be beaten. From my grandmother I have learned that success comes one day at a time and is measured by what you can give, not what you can get.

Miranda Hayworth is and will remain the most important person in my life. Her influence on me has known no boundaries. She has affected in me change, when I was certain I was stuck; wisdom, when I trespassed through ignorance; and patience, when I felt weary of my circumstances. If I do nothing but follow her lead for the rest of my life, I will have lived more fully than anyone could imagine.

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CHAPTER 1

INTRODUCTION

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 employed for use in managing the memory system (Baddeley & Hitch, 1974; Moscovitch & Winocur, 1992; Unsworth & Engle, 2007a). Consistent with this view, recent work by Unsworth and colleagues 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 (Unsworth, 2007; Unsworth & Engle, 2007a; 2007b). 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; Mogle, Lovett, Stawski, & Sliwinski, 2009; Unsworth, Brewer, & Spillers, 2009). Although researchers have extensively investigated the processes involved in active maintenance (Engle & Kane, 2004; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2002; Miyake & Shah, 1999), 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 others. The current work addresses 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.

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, 2007a; 2007b). Indeed, several studies by Unsworth and colleagues (Unsworth, 2009a; Unsworth et al., 2009; Unsworth & Spillers, in press) 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, are faster to recall these items, 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, 2009b).

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, the concern of the present paper 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 increasing effort by researchers to examine and understand 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; Capaldi & Neath, 1995; Howard & Kahana, 2002; Polyn, Norman, & Kahana, 2009; Mensink & Raaijmakers, 1988; Raaijmakers & Shiffrin, 1980; 1981; Unsworth, 2008). 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 which 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 consistently 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*;

Howard & Kahana, 1999; 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, where contiguous items are more likely to be recalled in a forward direction as opposed to backward (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 while others become inactive over time (Howard & Kahana, 1999; see also Estes, 1955; Mensink & Raaijmakers, 1988). Because of this fluctuation, items on a list being encoded can differ contextually from each other by varying degrees, with those items presented closer together sharing more contextual features than those 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).

Lag recency effects are but a subset of the more general organizational phenomenon of clustering in free recall. Clustering refers to the phenomenon in which items closely associated on some given characteristic are recalled together and in often quick succession (Bousfield, 1953). Much of the early research examining clustering has been conducted using free recall of semantically categorized lists. For instance, Pollio, Richards, and Lucas (1969) presented participants with words from five different categories and examined not only clustering but also within and between cluster inter-response times (IRTs). Pollio et al. found that participants recalled items in bursts based on category membership with relatively fast IRTs within a cluster and much slower IRTs between clusters. In a similar study, Patterson, Meltzer, and Mandler

(1971) found that if one group of participants were given category labels at retrieval, their between cluster IRTs remained constant throughout the recall period whereas the between cluster IRTs for a non-cued group steadily increased. To account for these results, Patterson et al. suggested a hierarchical sampling-with-replacement search model (e.g., Shiffrin, 1970) in which participants first search for categories, and then once a category is sampled, search for items within the category. Thus, the increase in IRTs for participants not cued with category labels was because as the number of categories that have been sampled increased, the longer it took participants to sample a new category. Presenting participants with category labels, however, obviated the need to search for labels leading not only to increased recall, but also to constant between category IRTs.

Although clustering has typically been investigated using semantically related categories, recent work has highlighted the importance of temporally related clusters (Kahana, 1996; Unsworth, 2008). In particular, Unsworth (2008) found that when given a final free recall test for unrelated items studied across several trials of delayed free recall, participants typically recalled and clustered items based on the delayed free recall trial that they were originally presented in. In addition, participants were found to be much faster to output items within a temporal cluster than between, similar to the work examining semantic categories. Thus, providing strong evidence that participants can use temporal information to help initiate and organize the search process. To account for these results and other systematic effects in episodic recall (including lag recency and IRTs), Unsworth (2008) proposed a multi-stage hierarchical sampling framework similar to Patterson et al. (1971; see also Rundus, 1973; Shiffrin, 1970) but instead detailing how individuals search using self-generated temporal-contextual cues.

In this framework, encoded items are associated with different contextual elements from varying levels of a hierarchy, with the rate at which these contextual elements fluctuate changing depending upon the specific tier (Brown, Preece, & Hulme, 2000; Glenberg et al., 1980; Unsworth & Engle, 2006). At the top of the hierarchy are global contextual elements that are associated with features that typically remain invariable during an experiment such as the time of day or the room the experiment is in. Subsumed under this global level are contextual elements that are assumed to change slightly more so, like each specific list of items presented. Finally, at the lowest level of the hierarchy are rapidly changing contextual elements associated with each to-be-remembered item. In order to generate the desired information during recall, participants must initiate retrieval using a general context cue to generate information and then use the products of this search to further specify the search process Unsworth (2008). In terms of the proposed hierarchy, this process would mean that participants begin their search with cues comprised of global elements of the current context. Specific lists are then sampled depending upon the associative strength between each list and the global context. Then items within the lists are sampled based on the associative strength between the items and the current list context. After an item has been sampled and recalled, it remains in the search set and information from that item is then used along with the current context cue to generate the next item (see also Howard & Kahana, 2002; Raaijmakers & Shiffrin, 1980; 1981). In other words, retrieval in this framework can be best understood as an iterative multi-stage search process in which participants move up and down the hierarchy as they continually update their retrieval cues.

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 search framework, individuals could differ significantly in the stage in which they generate their retrieval cues, which should have clear implications for the amount of items they can 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. 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 and clustering) observed in the data will be based upon the original serial positions of list items rather than on the possible output positions of items recalled during individual tests of the lists.

Using this paradigm and the hierarchical framework, 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, however, and more to the point of the present investigation, if high WMC individuals are in fact using cues more diagnostic of the memory traces they are trying to retrieve, then we would also expect distinct departures in the recall pattern of low WMC individuals compared with high WMC individuals. In particular, if low WMC individuals have trouble reinstating lower-order list cues, then they should show far less clustering of items based on list membership as compared with high WMC individuals and should show significant slowing between clusters. Similarly, if low WMC individuals are unable to generate subsequent items using information from previous recalls then the average size of their clusters should be smaller than high WMC individuals and they should have significantly reduced lag-recency effects as well. Put simply, we would expect high WMC individuals' recall to appear far more systematic, with recall of each list organized by clusters and clear contiguity among items within these clusters. By contrast, low WMC individuals' recall should appear much more random, with some clusters (but fewer than high WMC individuals) and more variable item contiguity within clusters.

CHAPTER 2

METHOD

Participant Screening for WMC

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.

Complex Memory Span Measures

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 the end of each trial, participants were asked to recall all the 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 X 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 X 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.

Participants and Composite Scores

Participants were 20 high WMC individuals (z-WMC = .74, SD = .39) and 20 low WMC individuals (z-WMC = -1.15, SD = .75), as determined by the composite measure. All participants were between the ages of 18 and 35 and received course credit for their participation.

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 have 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 were informed that the experimental session was about to begin. The paradigm used consisted of 5 trials with 4 lists of 10 words each in each trial. All words were presented alone for 2 s each. Preceding each list presentation, a 2 s screen denoting the current list was presented. At the end of each trial, participants were required to complete the 16 s distractor task before being given 3 minutes to recall as many words from the 4 lists as they could in any order they wish.

CHAPTER 3

RESULTS

Shown in Table 1 are the means for proportion of items correctly recalled, the number of clusters output, and cluster size as a function of WMC. As expected, high WMC individuals correctly recalled significantly more items overall than low WMC individuals, $t(38) = 4.42$, $p < .001$. More importantly, high WMC individuals also recalled significantly more clusters compared with low WMC individuals, $t(38) = 4.29$, $p < .001$. Here clusters refer to two or more items presented on the same list that were output in succession. The average size of each cluster, however, did not significantly differ between groups, $p > .22$.

Table 1. Mean proportion correct, number of clusters, and cluster size as a function of WMC.

Measure	WMC High	WMC Low
Proportion correct	.39 (.02)	.23 (.02)
No. of clusters	4.42 (.34)	2.53 (.27)
Cluster size	3.24 (.18)	2.96 (.12)

Note. Numbers in parentheses represent one standard error of the mean.

Inter-response times (IRTs) were also examined between and within clusters. Between-cluster IRTs have been argued to reflect the amount of time needed to search for and access higher-order cues while within-cluster IRTs presumably reflect the time needed to access the individual items subsumed under the higher-order cues once they have been retrieved (Pollio, Richards, & Lucas, 1969). IRTs were measured as the difference between the first key stroke of item *n* and the first key stroke of item *n* + 1. Consistent with previous research (Unsworth, 2008), between-cluster IRTs (M = 8.3, SE = .56) were much slower overall than within-cluster

IRTs (M = 4.9, SE = .35), $t(39) = 6.78$, $p < .001$. Further, as shown in Table 2, high WMC individuals were faster to switch between clusters than low WMC individuals, $F(1, 39) = 5.03$, MSE = 5.82, $p < .05$, $\eta_p^2 = .34$, and marginally quicker to output items within a cluster $F(1, 39) = 3.74$, MSE = 1.74, $p < .06$, $\eta_p^2 = .30$.

Table 2. Mean IRTs (in seconds) between and within clusters as a function of WMC.

	WMC	
Measure	High	Low
Between-clusters	7.09 (.64)	9.51 (.86)
Within-clusters	4.27 (.31)	5.59 (.60)

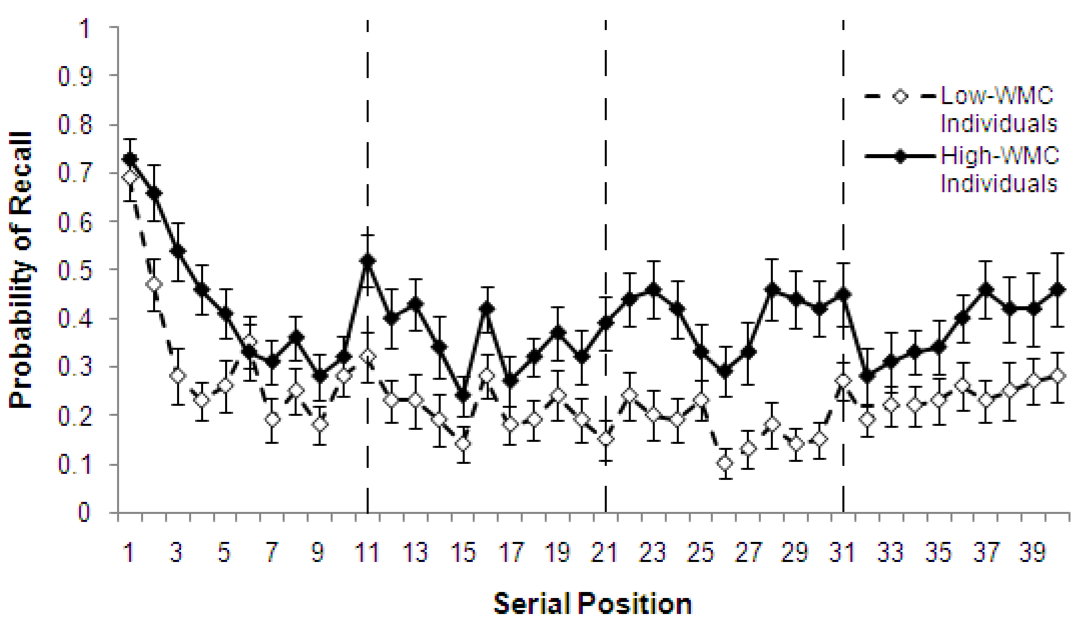
Note. Numbers in parentheses represent one standard error of the mean.

In order to examine recall accuracy more thoroughly, probability correct was examined as a function of serial position. Figure 1 shows recall probability plotted as a function of within-trial serial position (Figure 1A), across lists (Figure 1B), and within-list serial position (Figure 1C) for both high and low WMC individuals. As seen in Figure 1A, high WMC individuals recalled significantly more items than low WMC individuals at nearly all serial positions across the entire trial, $F(1, 38) = 19.47$, MSE = 10.17, $p < .001$, $\eta_p^2 = .33$. In addition, there was a pronounced primacy effect, where the first several items presented on List 1 were recalled significantly more often than other serial positions, $F(39, 1482) = 8.41$, MSE = .34, $p < .001$, $\eta_p^2 = .18$. These two factors did not interact, $p > .15$.

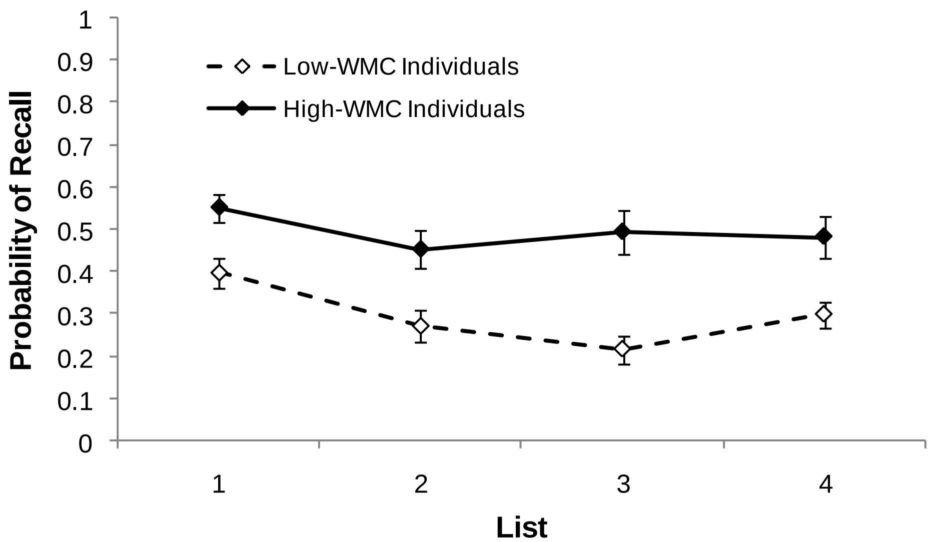
Beyond the obvious primacy effect early in the trial, further inspection of Figure 1A yields cursory evidence of mid-trial serial position effects. Indeed, the noise present in the mid-trial serial positions appears to mark approximately where Lists 2, 3, and 4 began, suggesting that each list within the trial has its own serial position effects. If this were true, it would lend credence to the idea that participants are sampling lists individually and those items within each list are competing to be recalled. To examine this possibility, the aggregate within-trial serial position function was further broken down into recall probability across lists and within a list. As shown in Figure 1B, high WMC individuals recalled a greater proportion of items correctly in each individual list than low WMC individuals, $F(1, 38) = 19.56$, MSE = 1.5, $p <. 001$, $\eta_p^2 = .34$. In addition, items from List 1 were recalled more often than the other three lists, $F(3, 114) = 7.52$, MSE = .12, $p <. 001$, $\eta_p^2 = .16$. These two factors did not interact, $p >.14$.

Figure 1C plots recall probability as a function of within-list serial position. High WMC individuals clearly recalled more items correctly than low WMC individuals at all serial positions within a list, $F(1, 38) = 19.47$, MSE = 2.5, $p <. 001$, $\eta_p^2 = .33$. Importantly, however, both groups showed significant primacy effects, $F(9, 342) = 11.73$, MSE = .10, $p <. 001$, $\eta_p^2 = .23$, supporting the above observation concerning mid-trial serial position effects and providing evidence that once a list was sampled, primacy items on that list were the most likely to be recalled (see Watkins & Peynircioglu, 1983). Again, these two factors did not interact, $p >.65$.

A.



B.



C.

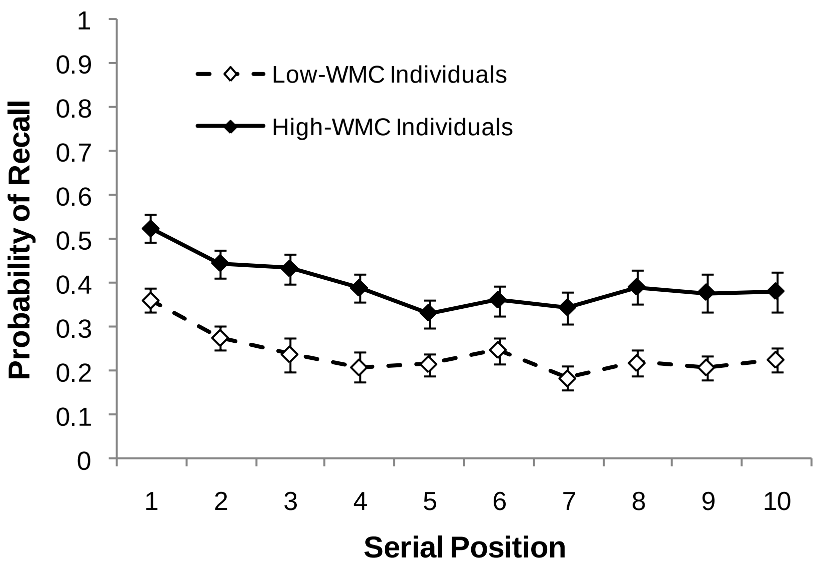


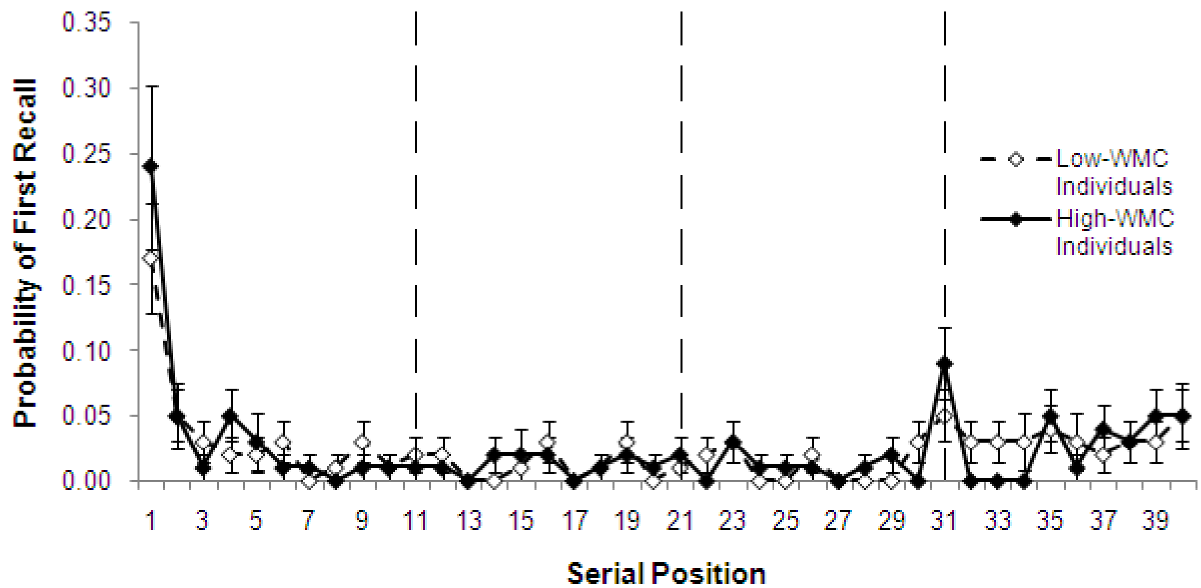
Figure 1. (A) Probability of correct recall as a function of within-trial serial position. Vertical dashed lines indicate start of a new list. (B) Probability of correct recall as a function of list. (C) Probability of correct recall as a function of within-list serial position.

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 during retrieval, respectively (Howard & Kahana, 1999).

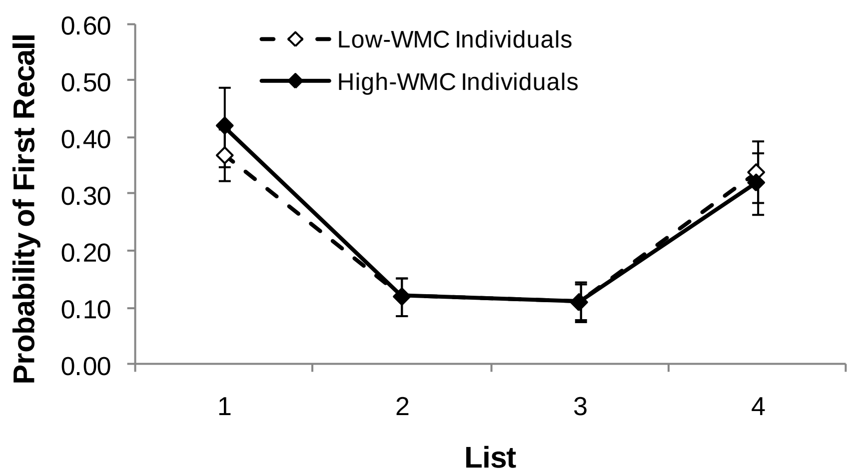
In Figure 2, PFR is plotted as a function of within-trial serial position (Figure 2A), across lists (Figure 2B), and within-list serial position (Figure 2C). Specifically, PFR refers to the number of times the first word recalled comes from a given serial position divided by the number of times the first 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. Indeed, both groups tended to begin recall by outputting the first couple of items from List 1, $F(19, 722) = 11.73$, MSE = .02, $p <. 001$, $\eta_p^2 = .23$. These two factors did not interact, $p > .93$.

As with the serial position function, the within-trial PFR function can be broken down into PFR as a function of list and within a list. As shown in Figure 2B, high and low WMC individuals did not differ in the list from which they output their first item, $p > .32$. In fact, when beginning their search both groups of participants most often started with retrieval of the list most recently presented (List 4) or the one likely to have received the most rehearsals (List 1), $F(3, 114) = 14.63$, MSE = .84, $p <. 001$, $\eta_p^2 = .28$. The difference between the two lists appears rooted in the serial positions that participants recalled first (see Figure 2A). In List 1, the items came primarily from the first two serial positions; whereas in List 4 the PFR values are more distributed across serial positions. Figure 2C reveals that once a list was sampled, the item most likely to be recalled first did not differ as a function of WMC, $p > .32$. Both high and low WMC individuals tended to begin their recall with a primacy item, $F(9, 342) = 10.89$, MSE = .24, $p <$. 001, $\eta_p^2 = .22$.

A.



B.



C.

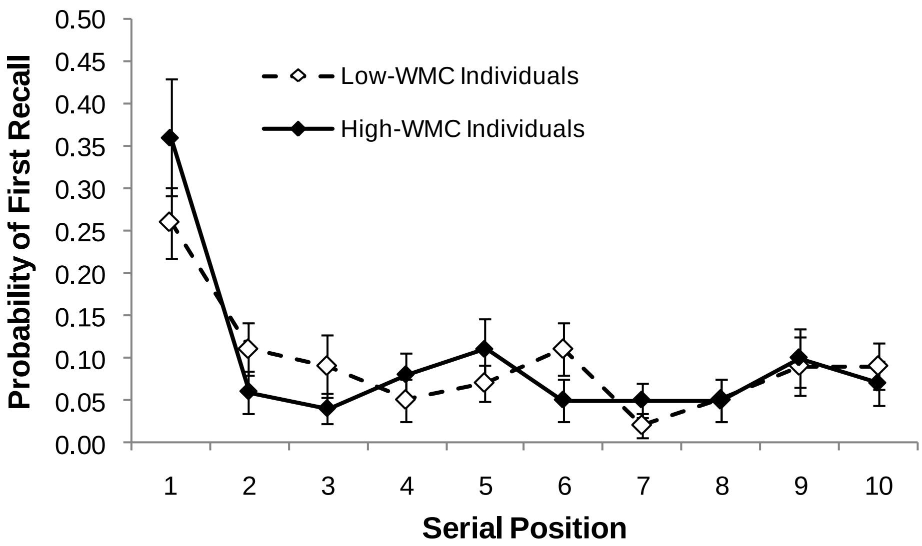


Figure 2. (A) Probability of first recall as a function of serial position in each trial. Vertical dashed lines indicate start of a new list. (B) Probability of first recall as a function of list. (C) Probability of first recall of serial position within each list.

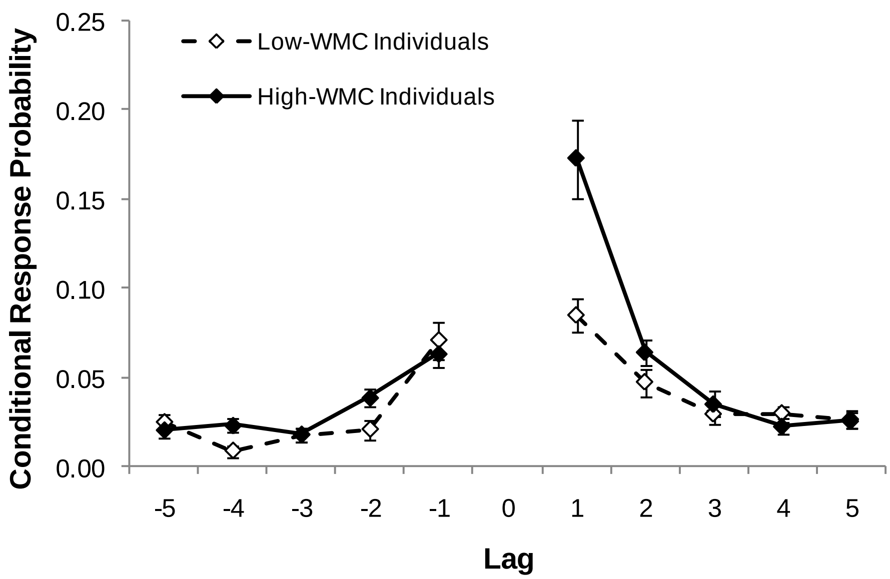
As mentioned, lag recency effects provide a quantitative assessment of how individuals transition between their responses. Given that participants were clustering items based on list membership, then items within these clusters may be further organized by temporal contiguity. These effects are plotted as lag-conditional response probabilities (lag-CRP) which 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 (Figure 3A), across lists (Figure 3B), and finally within a list (Figure 3C) and were calculated in accordance with previous research (Howard & Kahana, 1999; Kahana, 1996; Unsworth, 2008).

Figure 3A shows that high and low WMC individuals differed dramatically in both the direction and degree of transition between their responses, $F(4, 152) = 8.53$, MSE = .10, $p <. 001$, $\eta_p^2 = .18$. 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 that the very next item output would most likely be the sixth item presented rather than the tenth or even the fourth. In contrast, low WMC individuals' recall transitions appear far less systematic. Although low WMC individuals were more likely to recall items originally presented together in succession compared with those presented further away, this probability was significantly reduced compared with high WMC individuals. In addition, low WMC individuals were no more likely to transition backward than forward, $t < 1$.

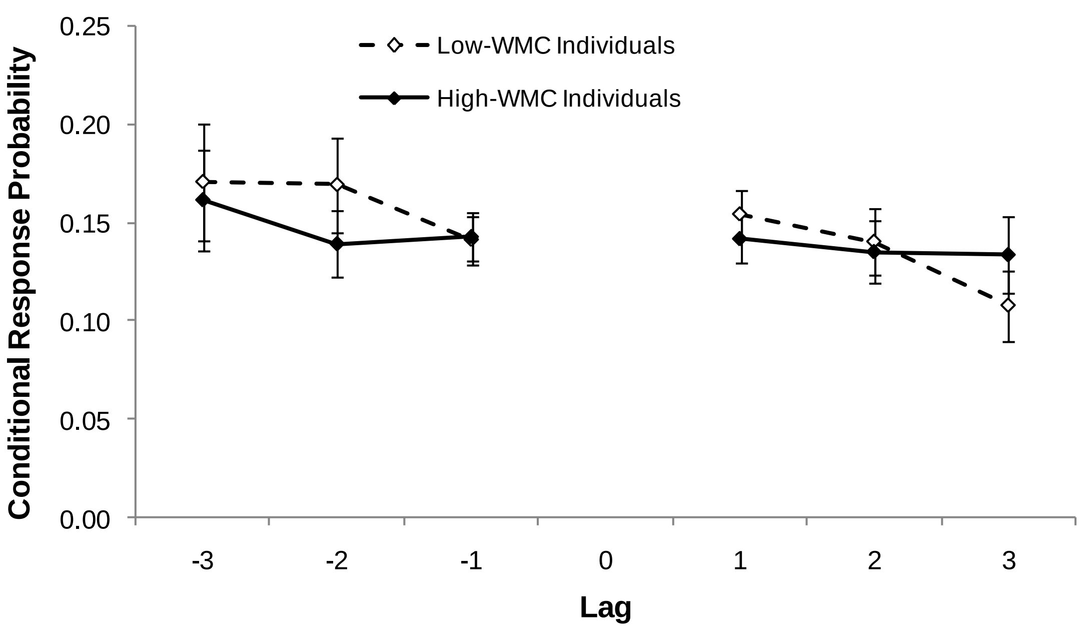
Note that these results are in stark contrast to our PFR analyses where high and low WMC individuals began recall in a similar manner, namely, with primacy items from List 1. After recall of these first several items, it is apparent the two groups begin to diverge. In fact, these results seem to suggest that high WMC individuals capitalized on the information provided by their initial responses and continued recalling successive items, whereas low WMC individuals began sampling far more indiscriminately after initiating recall.

Figure 3B provides additional information concerning transitions between high and low WMC individuals. There was a marginal main effect of direction, $F(1, 38) = 3.39$, MSE = .02, $p < .07$, $\eta_p^2 = .08$, such that both high and low WMC individuals were slightly more inclined to make backward list transitions than forward. This is an interesting outcome considering the results seen in Figure 2A indicating that participants were most likely to begin recall with items from List 1. However, keep in mind that both Lists 1 and 4 were about equal in their probability of being recalled first (Figure 2B), and thus, the marginal effect of direction may be indicative of participants often switching between the two lists. Finally, Figure 3C mirrors the results observed in Figure 3A. 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 low WMC individuals, $F(4, 152) = 7.36$, MSE = .01, $p < .001$, $\eta_p^2 = .16$.

A.



B.



C.

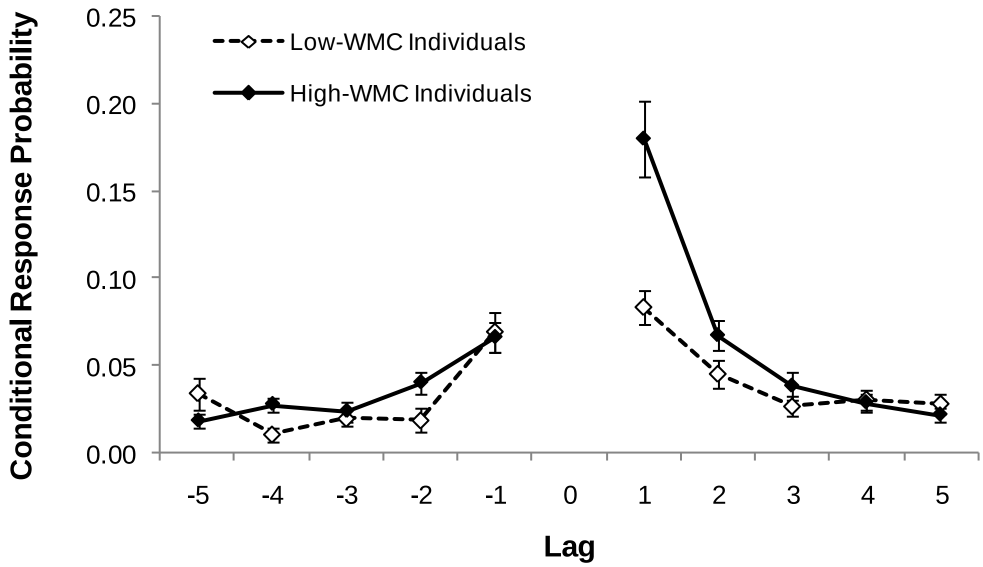


Figure 3. (A) Conditional response probability functions for forward and backward within-trial transitions as a function of lag. (B) Conditional response probability functions for forward and backward list transitions as a function of lag. (C) Conditional response probability functions for forward and backward within-list transitions as a function of lag.

CHAPTER 4

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 types of items they recall and how these items are organized. Collectively, the results amount to two major findings concerning how these two groups differ at retrieval in free recall.

First, it was found that when given a delayed-free recall test for several lists of unrelated items, high and low WMC participants tended to output items in clusters based on the lists they were originally presented on; thus providing further evidence that participants can use temporal information to organize recall in the absence of any external cues. Importantly, however, low WMC individuals recalled significantly less items overall compared with high WMC individuals, presumably because they generated far fewer clusters on average and were much slower to produce and switch between these clusters. Second, the lag-CRPs of low WMC individuals were not characteristic of those typically observed (Howard & Kahana, 1999; Kahana, 1996; Unsworth, 2008). Indeed, 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 while low WMC individuals were no more likely to transition forward than backward and had a significantly reduced probability of recalling items presented contiguously at encoding.

WMC and the Hierarchical-Sampling Framework

To understand these results, one need only to refer to the hierarchical sampling framework discussed earlier. Recall that in this framework, context exists at various levels of a hierarchy that differ primarily in specificity (i.e. Global, List, and Item). As an individual searches at each level of the hierarchy, both the content and size of their search-set necessarily changes as context-cues are being continually updated. When a search-set is more focused, the higher the probability of sampling a target item because of less competition from other items (i.e. a reduction in cue-overload). Therefore, if lower-level cues are not 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 using higher-order cues to generate lower-order cues, 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 principle while 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. With respect to the current findings, high WMC individuals were better able to access higher-order list cues, enabling them to sample each list individually and recall items in clusters. Importantly, once high WMC individuals accessed a list cluster and recovered their first item, they then used that item in conjunction with the list cue to continue retrieving neighboring items from the list. 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; 1981) and the Temporal Context Model (TCM; Howard & Kahana, 1999; 2002) that specify 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 list cues to produce clusters but integrate contextual information from items recalled as well, capitalizing on both sources of information in order to search efficiently.

In contrast to high WMC individuals, one can reasonably assume that low WMC individuals are more likely to search at the global experimental-context level. This is evident in not only the number of clusters they output but the relatively random organization of items observed within these clusters as well. Presumably, if low WMC individuals could generate more list-level cues their recall would rival that of high WMC individuals, especially given that once a list was accessed, the size of their clusters did not significantly differ. Beyond the inability to access list cues, another interesting characteristic of low WMC individuals' retrieval deficit is that it appears limited 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. Indeed, the PFR analyses clearly 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 initiated that dissociates the two. When beginning recall, participants in both groups typically resorted to sampling and recalling items from the strongest lists (Lists 1 & 4). After these first couple of items, high WMC individuals used the information they gained from these recalls and continued to search. Low WMC individuals, on the other hand, resorted back to the global context level and appeared unable to access further list clusters; thus, their recall tapered off considerably while high WMC individuals continued to access and recall clusters of items from the other lists. The inter-response time analyses both within and between clusters provide further support for this notion. Specifically, low WMC individuals showed significant slowing between clusters compared with high WMC individuals, consistent with the notion that they were having difficulty accessing new list cues.

Evidence for a Contextual Retrieval Deficit

While the results presented in the current study provide a descriptive account of how high and low WMC individuals differ in their use of temporal-contextual information during search of episodic memory, the question of why low WMC individuals appear unable to use context as efficiently as high WMC individuals still remains.

One possible reason for the seemingly erratic search process of low WMC individuals could be that these individuals do not retrieve the contextual information that is bound to each item representation stored in memory. Indeed, Kahana, Howard, Zaromb, and Wingfield (2002) have proposed a similar deficit to explain retrieval differences between younger and older adults. In their second experiment, Kahana et al. 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 younger adults with low WMC abilities may be falling victim to a similar contextual-retrieval deficit.

Although still in its early stages, there is promising neuroscientific evidence that provide insight into how a contextual-retrieval deficit might occur. Howard, Fotedar, Datey, and Hasselmo (2005), in particular, endeavored to map TCM (Howard & Kahana, 1999; 2002) onto the medial temporal lobe (MTL) both anatomically and functionally. Howard et al. proposed that individual item representations reside in cortical association areas that project to the parahippocampal region (i.e. entorhinal cortex), where temporal context is argued to be represented, and that a function of the hippocampus proper is to affect new item-to-context associations. Once an item is recovered during retrieval, it is argued that the set of elements activated in the hippocampus by the item at presentation are retrieved and reinstated in the entorhinal cortex. Thus, item information and contextual information are provided to the individual, who then continues to search using the newly updated pattern of activity as a cue. Therefore, a disruption in hippocampal functioning would mean a disruption in any recall task requiring self-generated retrieval cues and, presumably, a distinct inability to organize recall. The model of Howard et al. predicts then, that the differences observed between high and low WMC individuals in free recall are the result of differences in hippocampal functioning.

An alternative to Howard et al. (2005)'s hippocampal hypothesis is recent work by Polyn and Kahana (2008) arguing temporal-context information is managed primarily in the prefrontal cortex (PFC). In their paper, Polyn and Kahana (2008) argue that temporal-contextual representations reside in PFC while stimulus-related representations reside in the temporal cortex. Both of these representations are then projected into the hippocampus where they are associated with one another, creating an episodic representation in memory. Once associated, any subsequent changes in these prefrontal representations are argued to alter the relative accessibility of the bound associations, thus, contributing to retrieval failure. Polyn and Kahana (2008) argue that while hippocampal disruption would certainly impair the ability for individuals to perform well on tasks requiring them to recall the source of a given item, PFC disruption would be characterized by an inability to maintain and update context in a flexible manner. That is, PFC is crucial for initiating a strategic, cue-driven search of memory, or memory "targeting;"

such that individuals with frontal deficits should show reductions in not only the number of items they recall but also in the number of clusters and degree of contiguity, predictions consistent with the pattern of results observed by low WMC individuals in the current paper (see also Unsworth & Engle, 2007b).

CHAPTER 5

CONCLUSIONS

The current work contributes to burgeoning research concerning retrieval with temporal cues in free recall. Further, the results also add to the overall understanding of how individuals vary in controlled search of episodic memory using self-generated retrieval cues. Indeed, high WMC individuals showed a far greater capacity for generating lower-order contextual cues based on the temporal order of the lists presented and tended to recall items subsumed under these lower-order cues in a systematic fashion. 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 while low WMC individuals continued to recall without capitalizing on the newly retrieved information. We have argued that a deficit in either hippocampal or prefrontal functioning that manifests itself as an inability to retrieve contextual information should be able to account for the pattern of results exhibited by low WMC individuals, although further work is necessary for any serious determination on the issue. Nevertheless, the current study makes abundantly clear that how an individual manages temporal-contextual information greatly determines their ability to self-initiate a successful search of long-term memory.

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