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Examining variation in working memory capacity and retrieval in cued recall

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Two experiments examined the notion that individual differences in working memory capacity (WMC) are partially due to differences in search set size in cued recall. High and low WMC individuals performed variants of a cued recall task with either unrelated cue words (Experiment 1) or specific cue phrases (Experiment 2). Across both experiments low WMC individuals recalled fewer items, made more errors, and had longer correct recall latencies than high WMC individuals. Cross-experimental analyses suggested that providing participants with more specific cues decreased the size of the search set, leading to better recall overall. However, these effects were equivalent for high and low WMC. It is argued that these results are consistent with a search model framework in which low WMC individuals search through a larger set of items than high WMC individuals.

Keywords: Working memory; Individual differences; Cued recall.

A number of recent studies have suggested that although active maintenance is an important component of working memory (e.g., Miyake & Shah, 1999) retrieval of information from long-term memory is also an important component of working memory (e.g., Cowan et al., 2003; Healey & Miyake, 2009; Kane & Engle, 2000; McCabe, 2008; Nelson & Goodmon, 2003; Rosen & Engle, 1997; Towse, Hitch, Hamilton, & Pirrie, 2008; Unsworth & Engle, 2007). As the results of these studies attest, it is becoming increasingly clear that working memory and individual differences in working memory capacity (WMC), as measured by complex span tasks, are about more than just active maintenance; retrieval is also important. For instance, Unsworth and Engle (2007) argued that performance on many tasks will be determined by both active maintenance and controlled search processes on which individuals differ. At the same time, some tasks will primarily rely on active maintenance in the absence of controlled search processes (e.g., antisaccade), while other tasks will primarily rely on controlled search in the absence of active maintenance (e.g., delayed free recall). In these latter situations we argued that individual differences in working memory capacity (WMC) will be apparent because low WMC individuals will be poorer at focusing their search on relevant information than high WMC individuals and thus will include many more irrelevant representations in their search sets leading to poorer overall performance. The primary aim of the current study was to examine this notion in the context of cued recall.

VARIATION IN WMC AND CONTROLLED SEARCH

In the current view, when information cannot be actively maintained a controlled/strategic search of memory will need to be undertaken to retrieve

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task-relevant information. This search process is based on classic search models which assume that the search process has both directed and random components (Shiffrin, 1970; Shiffrin & Atkinson, 1969). Specifically, the directed component refers to strategic processes under the direct control of the individual that include things like setting up a retrieval plan, selecting appropriate cues/probes to search memory with, as well as various monitoring strategies and decisions to continue searching or not. The random component refers to the probabilistic nature of the search process in which a subset of information is activated by the probes/cues (i.e., the search set) and representations are subsequently sampled and recovered from this subset (Raijmakers & Shiffrin, 1980). In these and related models it is assumed that individuals rely on internally generated context (particularly temporal context in episodic memory tasks) cues to define the search set along with any other externally presented cues or other internally generated cues that may be of assistance in focusing the search set on the desired information.

In terms of individual differences in WMC, recent work has suggested that individual differences in WMC partially reflect differences in the directed components of the search process (Rosen & Engle, 1997; Unsworth & Engle, 2007). In particular, it has been suggested that low WMC individuals are less capable of focusing their search sets than high WMC individuals due to the use of noisier or less efficient cues. The inability to use precise cues to focus the search leads to an increase in the size of low WMC individuals' search sets (cue-overload; Watkins, 1979) due to an increase in the number of irrelevant representations being included in the search set. According to basic search models, this increase in the overall size of the search set for low WMC individuals should lead to lower overall performance, longer recall latencies, and an increase in intrusion errors compared to high WMC individuals. Recent work examining individual differences in WMC and free recall has generated results consistent with these predictions. For instance, previous research examining immediate, delayed, and continuous distractor free recall found that high WMC individuals correctly recalled more target items than low WMC individuals and were both faster to recall those target items and were less likely to recall non-target items (Unsworth, 2007; Unsworth & Engle, 2007).

THE PRESENT STUDY

The aim of the present study was to extend the idea that high and low WMC individuals differ in the size of their search sets due to differences in the directed component of the search process to cued recall. As noted above, previous work that has found evidence consistent with WMC differences in search set size has primarily used free recall tasks. However, search models in general make very similar predictions for cued-recall measures (Raaijmakers & Shiffrin, 1980; Shiffrin, 1970). Specifically, in cued recall, like free recall, it is assumed that individuals use an internally generated context cue to focus the search on the most recently presented information. This internally generated context cue is combined with the externally presented cue to delimit a search set. As with free recall, representations are then sampled from the search set, and if there is enough information indicating that the item representation is correct, the representation is recovered and subjected to a monitoring process. There are, however, a few differences between free and cued recall. For instance, in cued recall typically a single item is generated in response to the cue whereas in free recall the number of responses generated depends on the overall list length. Thus, in cued recall when the cue is presented a search is undertaken for a single correct item, and the search set includes a single item amid many incorrect items. In free recall, however, there are likely several (depending on how many items have been sampled previously) correct responses in the search set along with several incorrect responses. This requires that cued recall searches be more focused than free recall searches because if too many irrelevant representations are included in the search set the probability of selecting the correct representation will be very small. Additionally, given that there is usually a time limit for responding to each cue, the number of samples that can be made before time runs out will usually be very small possibly leading to no response being given in the allotted time (i.e., an omission). Finally, and most importantly, because an external cue is provided in cued recall, searches will depend heavily on the association between the cue and response and the ability to generate the response from the cue. The greater the association between the external cue and the response (e.g., based on prior associations or greater attention at encoding) the greater the focus of the search set and the higher the probability of selecting the correct item will be.

Given that previous studies have found WMC differences on cued recall tasks (e.g., Daniels, 2003; Friedman & Miyake, 2004; Park et al., 1996; Rosen & Engle, 1998), Unsworth and Engle (2007) suggested that a search model of this type could account for these differences in cued recall. Specifically, like free recall the notion of differences in overall search set size should be able to account not only for overall differences in accuracy, but also differences in recall latency for correct trials as well as differences in the number of intrusions emitted. Indeed, Shiffrin and Atkinson (1969, p. 188) noted in the context of search models that "When the size of the subset is increased (i.e., the number of *i* codes is increased), then the probability of giving an intrusion will increase, the average time until the *c* code is examined will increase, and the probability of giving a correct response will decrease", where here an *i* code refers to an intrusion and the *c* code refers to a correct response. Thus, WMC differences in cued recall can be seen as arising from the fact that low WMC individuals are poorer at using internally generated context cues in combination with the externally presented cue to the focus the search on only the relevant items.

Although the current work explores the possibility that high and low WMC differences in retrieval in cued recall are due to differences in search set size, other viable alternatives exist. Therefore, similar to Unsworth (2007), five possibilities for high and low WMC differences in retrieval in cued recall based on a basic search model were tested. In all possibilities low WMC individuals should recall fewer correct responses than high WMC individuals (as has been found previously), but the pattern of results across other measures (i.e., correct recall latency, number of intrusions, number of omissions, and error recall latency) should differ. Thus, each possible reason for high and low WMC differences should generate a unique pattern of results across a number of measures. This is important because previous work has typically only shown differences in overall proportion correct, and thus it is unclear what mechanism(s) is responsible for the differences in retrieval.

The first possibility (*low WMC large*) is that low WMC individuals search through a larger set of items (both targets and intrusions) than high WMC individuals. This would result in low WMC individuals recalling fewer target items, emitting more intrusions, and recalling correct items at a slower rate than high WMC individuals. As noted throughout, this pattern of results would be consistent with prior work on free recall suggesting that high and low WMC individuals differ in retrieval due to differences in the directed component of the search process, whereby low WMC individuals are unable to focus the search as well as high WMC individuals.

The second possibility (*low WMC small*) is that low WMC individuals actually have smaller search sets than high WMC individuals. This would result in the recall of fewer target representations, more omissions (because the target representation may not be included in the search set), and faster correct recall latency than high WMC individuals. This could be due to differences in overall resources that can be devoted to retrieval (e.g., Cantor & Engle, 1993; Just & Carpenter, 1992). In this case low WMC individuals would not be able to activate as many representations as high WMC individuals leading to an overall smaller search set that may not include the target representation.

The third possibility (*low WMC nonrecoverable*) is that low WMC individuals have fewer recoverable targets than high WMC individuals. In this possibility, high and low WMC individuals search through search sets of the same size, but low WMC individuals' search sets contain weaker or more degraded target representations, which cannot be recovered. This would result in low WMC individuals recalling fewer target items, having more omissions, but having the same correct recall latencies as high WMC individuals. This is because, according to a search model framework, each representation, regardless of its strength, has a probability of being sampled, but only strong representations can be recovered. Thus, if high and low WMC individuals have the same size of search sets, but low WMC individuals have more degraded representations, then low WMC individuals will have poorer overall performance, but the same correct recall latencies. This possibility is consistent with the notion that high and low WMC differences are actually due to differences in encoding processes (e.g., rehearsal, elaboration, bindings items together), which manifest themselves at retrieval. As such, this possibility really suggests that differences at retrieval are due, in part, to inherent differences at encoding.

The fourth possibility (*low WMC monitoring*) is that perhaps high and low WMC individuals have the same size of search sets, with the same number of recoverable targets, but differ in their ability to monitor and catch errors from being emitted. This would suggest that the reason low WMC individuals recall fewer target items than high WMC individuals is because on some trials low WMC individuals sample an intrusion but do not recognise it as such and emit it before they have a chance to sample and recover the target item. This would lead to the recall of fewer correct items, more intrusions, but the same correct recall latency as high WMC individuals. Thus, overall this possibility is very similar to the *low WMC large* possibility, but differs critically in that the *low WMC large* possibility predicts differences in correct recall latency, whereas this possibility suggests no differences.

The final possibility (*low WMC willingness/motivation to continue searching*) is that low WMC individuals search through the same size of search set as high WMC individuals with the same number of recoverable targets, but they differ in that high WMC individuals are more likely to continue searching throughout the recall period than low WMC individuals. In particular, this possibility suggests that after several samples from the search set if low WMC individuals have not yet sampled the correct target representation they will either decide to emit an incorrect representation (an intrusion) or will just give up and not recall anything, leading to an omission. This possibility is thus a basic difference in motivation between high and low WMC individuals, whereby low WMC individuals recall fewer correct target items because they are simply not motivated to do the work necessary to find the correct target item. Important for this view is that error recall latencies should be different forhighs and lows, with low WMC individuals having significantly faster error recall latencies than high WMC individuals. This is because previous work (MacLeod & Nelson, 1984; Millward, 1964) has suggested that error recall latencies provide an index of the willingness to continue searching. Thus, if low WMC individuals are less willing to continue searching than high WMC individuals, then low WMC individuals should recall fewer target items, have more omissions and/or intrusions, and have faster error recall latencies than high WMC individuals.

In summary, five different possibilities for high and low WMC differences in cued recall were tested. The key differences between these possibilities are in the different pattern of results across the different measures. Specifically, although each possibility predicts that low WMC individuals should recall fewer target items than high WMC individuals (which is normally the case), the five possibilities differ in terms of the type and number of errors (omissions and intrusions) that should be emitted, as well as correct and incorrect recall latencies for high and low WMC individuals. Thus, each possibility is associated with a unique pattern of results across proportion correct, errors, and recall latency (both correct and incorrect) extracted from the cued recall task. By examining these multiple measures (and the patterns across the measures) it should be possible to elucidate the mechanism(s) responsible for WMC differences in cued recall and retrieval.

EXPERIMENT 1

The purpose of Experiment 1 was to examine WMC differences in a basic cued recall task via a search model framework in terms of proportion correct, errors, and recall latency.

Method

Participants and WMC screening

Participants were recruited from the participant pool at the University of Georgia. Individuals were selected based on a *z*-score composite of three complex span tasks. Only participants falling in the upper (high WMC individuals) and lower (low WMC individuals) quartiles of the composite distribution were selected.

Operation span (Ospan). Participants solved a series of math operations while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). Participants were required to solve a maths operation and after solving the operation they are presented with a letter for 1 second. Immediately after the letter was presented, the next operation was presented. Three trials of each list length (3–7) were presented, with the order of list length varying randomly. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters (see Unsworth, Heitz, Schrock, & Engle, 2005, for more details). Participants received three sets (of list length 2) of practice. For all of the span measures, items were scored if the item was correct and in the correct position. The score was the proportion of correct items in the correct position.

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

Symmetry span (Symspan). In this task participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgement task. In the symmetry-judgement task participants were shown an 8×8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4×4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared by clicking on the cells of an empty matrix. There were three trials of each list length with list length ranging from 2 to 5. The same scoring procedure as Ospan 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. Participants were 42 high WMC individuals (z-WMC = .91, $SD = 0.18$) and 42 low WMC individuals (z-WMC = –1.29, $SD = 0.57$), as determined by the composite measure.

Cued recall procedure

In this task participants were given three lists of 10 word pairs each. All words were common nouns and the word pairs were presented vertically for 2 seconds each. Participants were told that the cue would always be the word on top and the target would be at the bottom. After the presentation of the last word participants saw the cue word and ??? in place of the target word. Participants were instructed to type in the target word from the current list that matched cue and then to press ENTER to indicate their response. The cues were randomly mixed so that the corresponding target words were not recalled in the same order as they were presented. Participants had 5 seconds to type in the corresponding word. This same procedure was done for all three lists. Prior to the cued recall task, participants received a brief typing exercise (typing the words one-ten) to assess their typing efficiency.[1]

Results

Accuracy

As shown in Table 1, high and low WMC individuals differed in overall proportion correct, with high WMC individuals outperforming low WMC individuals, $t(82) = 3.26$, $p < .01$, $\eta^2 = .12$. Next error responses were examined. Errors were classified as omissions where no response was given, list intrusions where an item presented in the experiment was incorrectly recalled, and extra-list intrusions where an item that was not presented was incorrectly recalled. An analysis of errors suggested that there were more omission ($M = 11.01$, $SE = 0.68$) than either type of intrusion (both ps $< .01$), but list ($M = 2.76$, $SE = 0.26$) and extra-list intrusions ($M = 3.21$, $SE = 0.36$) did not differ from one another, $t(83) = 1.38$, $p > .17$. As shown in Table 1, examining each error type by WMC suggested no differences in omissions, $t(82) = 0.93$, $p > .35$, but differences in both types of intrusions, both ps $< .05$, η^2s $> .06$. Type of intrusion did not interact with WMC, $F < 1, p > .42$.

Recall latency

Next recall latency was examined. Recall latency was measured as the time between the

[1] Note that there were no differences in typing speed for high and low WMC individuals based on the typing exercise (both Fs <1, both ps $>.55$).

TABLE 1
Cued recall memory measures as a function of WMC for Experiment 1

	Measure					
WMC	*Pcorr*	*Omissions*	*LIntr*	*EIntr*	*Acc Lat*	*Err Lat*
High	0.50 (0.03)	10.38 (0.87)	2.19 (0.27)	2.38 (0.38)	2799 (61)	3502 (106)
Low	0.35 (0.03)	11.64 (1.04)	3.33 (0.43)	4.05 (0.58)	3077 (74)	3603 (99)

Pcorr = proportion correct; LIntr = number of list intrusions; EIntr = number of extra-list intrusions; Acc Lat = latency for correct recalls; Err Lat = latency for errors. Standard errors are in parentheses.

onset of the recall cue and the first keystroke. As shown in Table 1, high WMC individuals had shorter recall latencies for correct recalls than low WMC individuals, $t(82) = 2.89$, $p < .01$, $\eta^2 = .09$. Consistent with previous research (Millward, 1964) correct recall latencies ($M = 2961$, $SE = 50$) were shorter than error latencies ($M = 3555$, $SE = 72$), $t(79) = 7.55$, $p < .01$.[2] Additionally, recall latencies associated with the two types of intrusions were not different, $t(53) = 0.73$, $p > .47$. Finally, as shown in Table 1 there were no WMC differences in error recall latencies, $t(82) = 0.70$, $p > .49$.

Discussion

The results from Experiment 1 were rather straightforward in suggesting that high and low WMC participants differed in basic cued recall performance. Specifically, low WMC individuals were less accurate, made more intrusion errors, and recalled items at a slower rate than high WMC individuals. These results are broadly consistent with the *low WMC large* possibility, suggesting that low WMC participants are less able to focus their search on only relevant target representations and instead include many irrelevant representations in their search sets. The results are generally inconsistent with the other possibilities due to the fact that high and low WMC individuals differed in the number of intrusions emitted and in correct recall latency, with low WMC individuals having slower recall latencies than high WMC individuals. Thus, the results from Experiment 1 are consistent with previous work with free recall (e.g., Unsworth, 2007) suggesting that WMC differences can be interpreted within basic search models of memory, and that low WMC individuals search through a larger set of items than high WMC individuals.

EXPERIMENT 2

Experiment 2 sought to replicate and extend the findings from Experiment 1 by pairing target words with specific cue phrases (Craik, Byrd, & Swanson, 1987). Specifically, during the presentation of the target word participants were also given a short cue phrase that was associated with the presented word. These cue phrases were specific to the associated target word, but were not specific enough that the target word would be generated via the cue phrase alone (Craik et al., 1987). Examples of the cue phrases and targets words are ‘‘Something that gives off light – LAMP’’, ‘‘A family member – DAD’’, and ‘‘Used for fishing – HOOK’’. The use of specific cue phrases should focus the search, leading to higher levels of proportion correct, fewer intrusions, and faster rates of recall overall. Additionally, this task was used to examine how providing more specific cues would help both high and low WMC individuals.

Method

Participants and WMC screening

Participants were recruited from the participant pool at the University of Georgia. Individuals were selected based on a z-score composite of the three complex span tasks. Only participants falling in the upper (high WMC individuals) and lower (low WMC individuals) quartiles of the composite distribution were selected. The procedures for the complex span tasks were exactly the same as Experiment 1. Participants were 23 high WMC individuals (z-WMC = .88, $SD = 0.15$) and 25 low

[2] Note that there were no differences in the two different intrusion error latencies in either experiment (both ts < 1, both ps > .44). Furthermore, although based on a reduced number of participants, this also did not differ for high and low WMC individuals (both Fs < 1, both ps > .56).

WMC individuals (z-WMC = –1.18, $SD = 0.77$), as determined by the composite measure.

Cued recall procedure

In this task participants were given three lists of 10 words each. The target words were the same targets from Experiment 1. All words were common nouns that were presented for 2 seconds each. During the presentation of the word participants were also given a short cue phrase that was associated with the presented word. After the presentation of the last word, participants saw??? and a cue phrase. Participants were instructed to type in the target word from the current list that matched cue phrase and then to press ENTER to indicate their response. Cue phrases were randomly mixed so that the corresponding words were not recalled in the same order as they were presented. Participants had 5 seconds to type in the corresponding word. This same procedure was done for all three lists. Prior to the cued recall task, participants received a brief typing exercise (typing the words one to ten) to assess their typing efficiency.

Results

Accuracy

As shown in Table 2, high and low WMC individuals differed in overall proportion correct with high WMC individuals outperforming low WMC individuals, $t(46) = 2.59$, $p < .05$, $\eta^2 = .13$. Next, error responses were examined. Errors were classified exactly the same as in Experiment 1. An analysis of errors suggested that there were more omissions ($M = 4.60$, $SE = 0.61$) than either type of intrusion (both $ps < .01$), and there were more extra-list intrusions ($M = 2.92$, $SE = 0.45$) than list intrusions ($M = 0.38$, $SE = 0.09$), $t(47) = 5.49$, $p < .01$. As shown in Table 2, examining each error type by WMC suggested differences in omissions, $t(46) = 2.11$, $p < .05$, $\eta^2 = .09$, but no differences in either type of intrusion, both $ps > .26$. Type of intrusion did not interact with WMC, $F < 1$, $p > .35$.

Recall latency

Next, recall latency was examined. As with Experiment 1, recall latency was measured as the time between the onset of the recall cue and the first keystroke. As shown in Table 2 high WMC individuals had shorter recall latencies for correct recalls than low WMC individuals, $t(46) = 2.71$, $p < .01$, $\eta^2 = .14$. Correct recall latencies ($M = 2678$, $SE = 55$) were shorter than error latencies ($M = 3639$, $SE = 121$), $t(39) = 8.60$, $p < .01$. Additionally, recall latencies associated with the two types of intrusions were not different, $t(12) = 0.81$, $p > .43$. Finally, as shown in Table 2 and consistent with Experiment 1, there were no WMC differences in error recall latencies, $t(38) = 0.52$, $p > .60$.

Discussion

The results from Experiment 2 were largely in line with the results of Experiment 1, suggesting WMC differences in cued recall even when more specific cues were provided. Specifically, consistent with Experiment 1, low WMC individuals recalled fewer correct items than high WMC individuals and were slower to recall items than high WMC individuals. However, unlike Experiment 1 there were no differences in either type of intrusion error, rather differences now appeared in omission errors. These results are broadly consistent with a search framework suggesting that more specific cues lead to a greater focusing of the search set, yet this occurred for both high and low WMC individuals (see below). In terms of the five possibilities outlined earlier, the results are most consistent with the *low WMC large* possibility, which predicts differences in correct

TABLE 2
Cued recall memory measures as a function of WMC for Experiment 2

	Measure					
WMC	*Pcorr*	*Omissions*	*LIntr*	*EIntr*	*Acc Lat*	*Err Lat*
High	0.80 (0.03)	3.26 (0.61)	0.30 (0.12)	2.39 (0.61)	2532 (61)	3560 (202)
Low	0.64 (0.03)	5.84 (1.03)	0.44 (0.13)	3.40 (0.65)	2811 (81)	3691 (153)

Pcorr = proportion correct; LIntr = number of list intrusions; EIntr = number of extra-list intrusions; Acc Lat = latency for correct recalls; Err Lat = latency for errors. Standard errors are in parentheses.

recall latency. However, that possibility also predicts differences in intrusions even when the search is focused. Thus the finding that there were no differences in intrusions, but there were differences in omissions, is also consistent with the *low WMC nonrecoverable* possibility, which suggests that low WMC individuals should have more omissions due to the fact that their representations are likely degraded. This suggests that these WMC differences might arise from both differences in the size of the search set as well as differences in the strength of the representations suggesting that high and low WMC differences are multifaceted. To examine this more thoroughly a set of cross-experimental analyses were conducted.

Cross-experimental analyses

The final set of analyses examined how providing participants with more specific cues (Experiment 2) would change performance compared to less specific cues (Experiment 1) and how this would interact with WMC. In order to examine this, analyses of variance (ANOVAs) were run for each dependent variable with both WMC groups (high vs low) and experiment (1 vs 2) as the between-participants variables. Note that although there are differences in the overall number of participants tested in each study (Experiment 1 = 84; Experiment 2 = 48) an examination of cross-experimental effects can still provide potentially interesting information in terms of how the specificity of the cues influences performance overall and for high and low WMC groups separately.

First, overall proportion correct was examined. The ANOVA resulted in main effects of both WMC, $F(1, 128) = 16.38$, $MSE = 0.04$, $p < .01$, partial $\eta^2 = .11$, and experiment, $F(1, 128) = 64.75$, $MSE = 0.04$, $p < .01$, partial $\eta^2 = .34$, suggesting that high WMC individuals were more accurate than low WMC individuals and performance was better in Experiment 2 than Experiment 1. However, these two factors did not interact ($F < 1$), suggesting that providing participants with more specific cues increased performance equally for both high and low WMC groups. An examination of omission errors suggested a main effect of experiment, $F(1, 128) = 40.98$, $MSE = 31.09$, $p < .01$, partial $\eta^2 = .24$, with more omissions in Experiment 1 than Experiment 2, and the main effect of WMC approached conventional levels of significance, $F(1, 128) = 3.62$, $MSE = 31.09$, $p < .06$, partial $\eta^2 = .03$, suggesting that low WMC individuals made more omissions than high WMC individuals. These two factors did not interact ($F < 1$). Next, an examination of list intrusions suggested a main effect of experiment, $F(1, 128) = 48.82$, $MSE = 3.57$, $p < .01$, partial $\eta^2 = .28$, with more intrusions in Experiment 1 than Experiment 2, and the main effect of WMC approached conventional levels of significance, $F(1, 128) = 3.49$, $MSE = 3.57$, $p < .07$, partial $\eta^2 = .03$, suggesting that low WMC individuals made more intrusions than high WMC individuals. The two-way interaction was not significant, $F(1, 128) = 2.17$, $MSE = 3.57$, $p > .14$. An examination of extra-list intrusions suggested a main effect of WMC, $F(1, 128) = 5.50$, $MSE = 9.93$, $p < .05$, partial $\eta^2 = .04$, with low WMC individuals making more extra-list intrusions than high WMC individuals, but there was no effect of experiment and the two-way interaction was not significant (both Fs < 1). An examination of correct recall latency suggested a main effect of WMC, $F(1, 128) = 13.92$, $MSE = 169698$, $p < .01$, partial $\eta^2 = .10$, with high WMC individuals recalling items at a faster rate than low WMC individuals, and a main effect of experiment with shorter recall latencies in Experiment 2 than Experiment 1, $F(1, 128) = 12.77$, $MSE = 169698$, $p < .01$, partial $\eta^2 = .09$. The two-way interaction was not significant ($F < 1$). Finally, an examination of error recall latencies indicated that none of the effects was significant (all Fs < 1).

Collectively, these results suggest that providing participants with more specific cues lead to better overall performance, fewer omissions and list intrusions, and shorter correct recall latencies, and this occurred for both high and low WMC individuals. Thus, providing more specific cues in Experiment 2 served to focus the search to a greater extent than the cues in Experiment 1 and this helped highs and lows equally. Interestingly, the more specific cues used in Experiment 2 did not change the number of extra-list intrusions nor did it change error recall latencies. This suggests that these effects are likely due to something other than cue specification processes and may be due to monitoring processes as well as decisions related to the willingness to continue searching.

GENERAL DISCUSSION

In two experiments, individual differences in WMC and retrieval in cued recall was tested. Across both experiments it was shown that low

WMC individuals recalled fewer correct items, made more errors, and recalled correct items at a slower rate than high WMC individuals. These results are broadly consistent with previous work examining variation in WMC and various free recall tasks such as immediate, delayed, and continuous distractor free recall (Unsworth, 2007; Unsworth & Engle, 2007). In the context of search models of recall these results suggest that low WMC individuals search through a larger set of items than high WMC individuals. As noted previously, search models predict that as the search size increases due to the inclusion of irrelevant representations (intrusions), the probability of selecting the correct representation should decrease, the probability of selecting an intrusion should increase, and the time it takes to select a correct representation should increase. Thus, like the results from studies utilising free recall, the current results suggest that performance differences between high and low WMC individuals can be seen as arising partially due to the fact that low WMC individuals include more irrelevant representations in their search sets than high WMC individuals leading to more cue-overload (Watkins, 1979) for low than for high WMC individuals. These results extend the notion that high and low WMC differences are partially due to differences in controlled retrieval and suggest that variation in WMC will appear when a controlled cue-dependent search is undertaken. Furthermore, the results suggest that providing participants with cues helps focus the search leading to better overall performance, but the presence of more specific external cues influenced high and low WMC individuals equally. This suggests that high and low WMC individuals differ in the use of internally generated cues that are needed to focus the search (Unsworth & Engle, 2007) and that even when salient external cues are presented, high and low WMC differences are likely to remain.

As noted in previous work (Unsworth, 2007), WMC differences in the size of the search set could be due to either differences in the specificity of internally generated cues that focus the search set, or due to differences in the ability to inhibit competitors (e.g., Hasher, Lustig, & Zacks, 2007). That is, as implicated throughout, it is possible that high and low WMC individuals differ in their ability to generate internal cues (particularly context cues) to focus the search only on relevant representations stored in memory. This is akin to differences in selective attention where attention is focused internally on particular representations at the expenses of other representations. Important in this regard is the notion that high and low WMC individuals differ in the ability to set up appropriate cues/probes that will focus the search on relevant items and thus discriminate between relevant and irrelevant items (Unsworth, 2007; Unsworth & Engle, 2007). Conversely it is possible that high and low WMC individuals differ not in the ability to select and use cues to focus the search set, but rather differ in the ability to inhibit irrelevant representations. In these suppression views, it is assumed that high WMC individuals are better at suppressing irrelevant information which leads to a more tightly focused search set for high WMC individuals than for low WMC individuals (e.g., Hasher et al., 2007; Rosen & Engle, 1998). Thus, both views make similar predictions in terms of low WMC individuals having larger search sets than high WMC individuals, but the reason for the differences in search set size differ, with one view suggesting that the differences arise due to differences in cue specification processes, and the other view suggesting differences due to differences in inhibitory abilities. Clearly more work is needed to test differences between these two views. At the very least, the current results suggest that WMC differences in many recall paradigms are due in part to differences in the size of the set of items that participants search through.

Furthermore, the results from Experiment 2 suggested that not only were low WMC slower to recall correct target items, but they also made more omissions. This suggests the possibility that not only do high and low WMC individuals differ in the size of the set of items through which they are searching, but they also differ in the number of degraded target representations in the search sets. Thus WMC differences in recall are likely multifaceted, with some low WMC individuals having problems delimiting the search set, some low WMC individuals having encoding deficits leading to a large number of degraded representations, and possibly even some low WMC individuals with problems in monitoring leading a large number of intrusions being emitted. Indeed, the finding that the use of more specific cues in Experiment 2 did not change the number of extra-list intrusions suggests the possibility that these errors arise primarily from monitoring deficits on which high and low WMC individuals differ (see the cross-experimental analyses).

The current results also have interesting implications for the relationship between recall latency and recall accuracy (MacLeod & Nelson, 1984). Specifically, MacLeod and Nelson (1984) suggested that recall accuracy and recall latency measure different aspects of memory, with recall accuracy being linked with encoding operations, and recall latency being linked with retrieval operations. In support of this MacLeod and Nelson (1984) cited work by Scheirer (1971) that found a non-significant correlation between recall accuracy and recall latency. As suggested by MacLeod and Nelson (1984) it is likely that recall accuracy is in part influenced by the strength of the encoding operations, but according to search models of the type used here, recall accuracy and recall latency should be negatively related to the extent that both are partially determined by the overall size of the search set. As the number of irrelevant representations within the search set increases, recall accuracy should decrease and recall latency should increase. Thus, in order to examine this more thoroughly a correlation analysis was conducted combining participants from both experiments and proportion correct, omission, total number of intrusions, as well as correct recall latency and error recall latency were the measures of interest. Shown in Table 3 are the resulting correlations. As would be expected proportion correct was highly correlated with both omissions and total intrusions. Interestingly, the two error types were not correlated (see Unsworth & Engle, 2006, for similar results in complex span tasks). Importantly, correct recall latency was correlated with both overall proportion correct and total number of intrusions. Thus, consistent with a search set size notion, accuracy and latency were related and both were related to the total number of intrusions. Finally, the only significant correlation involving error recall latency was a slight correlation with correct recall latency. Consistent with previous work (MacLeod & Nelson, 1984; Millward, 1964) it would seem that correct and error recall latencies largely measure different aspects of recall. According to Millward (1964) and MacLeod and Nelson (1984) correct recall latency provides an index of the overall search process (as noted throughout), while error recall latency reflects the willingness to continue searching for the desired item. The present results suggest that high and low WMC individuals do not differ in the willingness to continue searching, and this willingness does not seem to be related other measures of performance on the task at hand.

TABLE 3
Correlations for cued recall measures for Experiment 1 and 2 combined

Variable	*1*	*2*	*3*	*4*	*5*
1. Pcorr	–				
2. Omissions	−.78**	–			
3. Intrusions	−.55**	−.03	–		
4. Acc Lat	−.48**	.42**	.24**	–	
5. Err Lat	−.06	.03	.03	.26**	–

** = correlation significant at $p < .01$ level; $N = 132$ for all measures except Err Lat where $N = 120$; Pcorr = proportion correct; Intrusions = total number of list and extra-list intrusions; Acc Lat = latency for correct recalls; Err Lat = latency for errors.

In conclusion, the present results extend previous work suggesting that high and low WMC individuals differ in their recall performance partially due to differences in the size of the set of items through which they search. High WMC individuals are better able to constrain their search sets in both free and cued recall than low WMC individuals, leading to better overall performance for high than low WMC individuals. This ability to engage in a strategic search of memory is important when information cannot be actively maintained due either to the amount of information presented (which exceeds capacity limits) or due to the amount of internal and external distraction. Additionally, the results suggested that high and low WMC differences were also likely due to differences in the number of recoverable targets in the search set, as well as differences in monitoring abilities suggesting that high and low WMC differences are multifaceted. Consistent with previous research these results suggest that individual differences in WMC reflect more than just differences in active maintenance abilities, strategic search and retrieval abilities are also important (e.g., Cowan et al., 2003; Healey & Miyake, 2009; Rosen & Engle, 1997; Unsworth & Engle, 2007).

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