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Variation in working memory capacity and forgetting over both the short and the long term: An application of the Population Dilution model

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Variation in working memory capacity and forgetting over both the short and the long term: An application of the Population Dilution model

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The current study examined the notion that individual differences in working memory capacity (WMC) are partially due to differences in retrieval from long-term memory. High and low WMC participants performed a running paired-associates task with 10 different lags across both the short and the long term. High WMC individuals outperformed low WMC individuals on both short and long lags, but were not different when tested immediately (i.e., lag of zero). Furthermore, low WMC individuals recalled more intrusions and recalled at a slower rate than high WMC individuals. The results are consistent with the notion that variation in WMC is partially due to differences in the ability to guide a strategic search process of long-term memory. Simulations based on the Population Dilution model were consistent with these notions. Thus, WMC is more than just active maintenance over the short term; retrieval of information that could not be maintained is also important regardless of the timescale.

Keywords: Forgetting; Individual differences; Working memory.

Working memory has typically been characterised as a system responsible for the active maintenance and manipulation of information (see Miyake & Shah, 1999). Recently, work has suggested that the ability to engage in controlled retrieval to bring information back into the focus of attention is also reliant on working memory processes (Unsworth & Engle, 2007; see also Conway & Engle, 1994; Healey & Miyake, 2009; Kane & Engle, 2000; McCabe, 2008; Nelson & Goodmon, 2003; Rosen & Engle, 1997). Our main goal in the current study was to examine the extent to which differences in WMC and cued recall would arise over both the short and the long term and whether the results could be accounted for differences in strategic search processes.

WMC AND STRATEGIC SEARCH

Recent work (Unsworth & Engle, 2007) has suggested that variation in working memory capacity (WMC) and episodic recall is due to differences in the ability to use cues (particularly context) to guide a controlled search of memory. This view is consistent with the notion that individual differences in WMC are more about the ability to work with memory (Moscovitch, 1992) than just the ability to actively maintain information over the short term. Accordingly, this view suggests that individual differences in WMC should be apparent not only on attention and short-term maintenance tasks, but also in more traditional long-term memory tasks that require a strategic search of memory such as free and cued recall.

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This search process relies on cues to focus the search on a subset of relevant items (i.e., the search set) and thus, reduces the amount of competition at retrieval. A simplified version of the search process is provided by the random search model (Bousfield, Sedgewick, & Cohen, 1954; Kaplan, Carvellas, & Metlay, 1969; McGill, 1963; Rohrer & Wixted, 1994; Wixted & Rohrer, 1994). In the random search model, a retrieval cue (i.e., a context cue) first delimits a search set that includes representations for target items as well as extraneous items. The search set is delimited by cues generated by the participant and possibly by external cues presented during the retrieval period (i.e., cued recall). As with other search models, we assume that participants will always use internally generated context cues (particularly temporal context) to attempt to focus the search on only the relevant representations. Once the search set has been delimited, item representations are randomly sampled from the search set at a constant rate, one item at a time (serial search). The random search model assumes, for simplicity, that all items are of equal strength (e.g., Rohrer, 1996). Thus, all items comprising the search set have an equally likely chance of being sampled.

Within this type of model assume that there are C recoverable targets within a search set of size S, which includes both target and nontarget representations (Wixted & Rohrer, 1994). That is, the search set is composed of target items and nontarget items (E = intrusions). Furthermore, correct items can be further broken down into those items that can be recovered (CR) and those that cannot (CN). Likewise errors can be further broken down into intraexperimental intrusions (a word that was presented in the experiment but was not the target response; IE), and extraexperimental intrusions (a word not presented in the experiment was given instead of the target response; EE). Thus, the search set is composed of several classes of items such that:

$$\mathrm{S} = \mathrm{CR} + \mathrm{CN} + \mathrm{IE} + \mathrm{EE} \tag{1}$$

During recall the probability of selecting a target item is therefore:

$$p(\mathrm{R}) = \mathrm{CR}/(\mathrm{CR} + \mathrm{CN} + \mathrm{IE} + \mathrm{EE}) \tag{2}$$

In terms of individual differences in WMC we (Unsworth, 2007; Unsworth & Engle, 2007) suggested that one of the main reasons high and low WMC individuals differ in recall performance is because low WMC individuals are unable to focus the search as well as high WMC individuals (due to poorer use of probes/cues) and thus low WMC individuals search through a larger set of items than high WMC individuals. That is, low WMC individuals have larger values of S than high WMC individuals due to the inclusion of more intrusions (IE and EE). We have argued previously that low WMC individuals have larger values of S because they rely on noisier context cues than high WMC individuals and thus sample from a much broader temporal distribution than high WMC individuals (e.g., Unsworth, 2007; Unsworth & Engle, 2007).

The net effect of having a larger value of S is that the probability of sampling a correct target item is lower overall. Furthermore, according to models of this type, given a larger value of S, low WMC individuals should recall items at a slower rate (leading to slower recall latencies) and should be more likely to output errors (intrusions) than high WMC individuals. A number of recent studies have found just this pattern of results (i.e., lower correct recall performance, longer recall latencies, and greater frequency of intrusions for low WMC individuals than for high WMC individuals) in a number of free (e.g., Unsworth, 2007, 2009b; Unsworth & Engle, 2007) and cued (Unsworth, 2009a) recall paradigms. Thus, there is ample evidence suggesting that WMC differences in recall are, at least partially, due to differences in search set size.

In recent work it has also been suggested that high and low WMC individuals will differ somewhat in the number of recoverable (CR) and nonrecoverable (CN) target items (Unsworth, 2009a, 2009b). This is because, high WMC individuals utilise elaborative encoding strategies compared to low WMC individuals (e.g., Bailey, Dunlosky, & Kane, 2008), and thus low WMC individuals will have smaller CR values and larger CN values than high WMC individuals. Note, for simplicity, we are assuming here that high and low WMC individuals have the same overall number of target items, but differ in the balance of CR and CN. It is also possible that the groups differ in the overall number of target representations within the search set, but this assumption awaits future research. Overall then, not only do low WMC individuals have larger search sets than high WMC individuals due to the inclusion of more errors, but they will also have more nonrecoverable (CN) compared to recoverable (CR) target items than high WMC individuals. Thus, low WMC individuals' recall deficits are partially due to inabilities to use cues (particularly temporal context in episodic memory tasks) to focus the search on only relevant target items and are partially due to differences in strategic encoding processes.

POPULATION DILUTION MODEL OF FORGETTING

Recently, Lansdale and Baguley (2008) have proposed a population dilution model of forgetting. In this model it is assumed that participants sample from a population of items consisting of correct items (C), errors (E), as well as null traces (W). Null traces represent those items which are not recoverable or are errors that the participant knows are incorrect and decide not to emit. Thus, the overall population size (P) is given by:

$$P = C + E + W \tag{3}$$

Notice that this is quite similar to the equation for overall search set size given by the random search model. In both models, participants attempt to sample correct items amongst other irrelevant or nonrecoverable representations. Thus, in both cases the probability of selecting a correct target item, $p(\mathrm{R})$ is simply the number of correct targets (C) divided by the total number of items in the search set (S) or the total number of items in the population (P).

Importantly, in terms of accounting for forgetting functions, in the Population Dilution model it is assumed that population size (P) increases as a linear function of time. That is, as the lag between the presentation of an item and the eventual recall test for that item increases so does the overall number of items within the population (or search set). Accordingly, the probability of sampling a correct target item is:

$$p(\mathrm{R}) = \mathrm{C}/(\mathrm{C} + \mathrm{E} + \mathrm{k}t) \tag{4}$$

where C, E, and k are constants that characterise representations in the population and t is the amount of time between presentation of the target item and the recall test. According to the Population Dilution model, forgetting over time occurs because more irrelevant items are included in the population relative to the number of correct items. That is, k provides an estimate of how many null traces are added to the population as a function of time. This serves to dilute the population leading to lower and lower probabilities of actually selecting the correct target representation.

In the Population Dilution model it is assumed that the increase of irrelevant representations in the population over time is due to the fact that temporal-context cues are less likely to be focused exclusively on the target representations as the lag between presentation and test increases. Thus, items presented in close temporal proximity to the target representation (presented both before and after the target) will be increasingly included in the population as the lag increases. Similar to the random search model described previously, this suggests that probability of recall should decrease as lag increases, the probability of sampling intrusions (particularly intrusions presented in close proximity to the target) should increase with lag, and recall latency should increase as a function of lag.

Lansdale and Baguley (2008) examined the predictions of the model for probability of correct recall in 10 published data sets (including five cued recall studies). In each case, they found that the Population Dilution model accounted for the forgetting functions and provided a principled account for why probability correct decreased as a function of the lag between presentation and test. These results suggest that the notion that forgetting occurs because overall population size (or search set size) increases as a function of time between presentation and test is a viable account of forgetting and provides overall support for the validity of the Population Dilution model.

PRESENT STUDY

The goal of the present study was to extend previous work demonstrating individual differences in WMC and recall. In particular, prior work which has examined variation in WMC and recall (both free and cued recall) has typically examined recall performance after relatively short lags and it is not known if variation in WMC and recall will also be found after longer lags. Furthermore, will WMC differences in recall stay the same from short to long lag, increase, or decrease? In order to address these questions, we examined high and low WMC individuals and forgetting over both the short and the long term. Specifically, in the current study we used a running paired-associates task developed by Rubin, Hinton, and Wenzel (1999) to assess forgetting over both short and long lags. Across all lags proportion correct, errors, and recall latency were examined. Furthermore, in order to examine these issues more fully we also used a variant of the Population Dilution model (Lansdale & Baguley, 2008) to simulate the results.

Theories suggesting that individual differences in WMC are partially due to differences in controlled search abilities (e.g., Unsworth, 2007) in secondary/long-term memory should predict differences at all lags where the information is no longer in the focus of attention (i.e., lags > 0; Atkinson & Shiffrin, 1968). This is because when information has been displaced from the focus of attention (due to new incoming items) it will have to be retrieved from secondary/long-term memory regardless of how long ago it was displaced (Unsworth & Engle, 2007). As such, we have suggested in previous work that low WMC individuals are poorer at focusing the search on the correct representations and thus search through a larger set of items than high WMC individuals. These differences in strategic search abilities lead to low WMC individuals recalling fewer correct target items, emitting more intrusions, and recalling correct items at a slower rate than high WMC individuals (Unsworth, 2007). Thus, if high and low WMC individuals differ in strategic search abilities across both the short and long term we should see that low WMC individuals recall fewer target items, emit more intrusions, and recall at a slower rate than high WMC individuals and this occurs at lags where retrieval from secondary memory is required (i.e., lags > 0).

Additionally, given that prior work has suggested that WMC differences may also be due to strategic encoding differences (e.g., Bailey et al., 2008; Unsworth, 2009a, 2009b), it is likely that any differences in forgetting that are found might be due to these encoding differences. That is, low WMC individuals cannot encode items as well as high WMC individuals, which leads to low WMC individuals having more degraded representations in their search sets at retrieval than high WMC individuals. 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. This explanation predicts that high and low WMC individuals should have the same correct recall latencies to the extent that changing the strength of an item changes the probability that it will be recovered, but does not change the probability it will be sampled (Raaijmakers & Shiffrin, 1980). That is, prior work has suggested that recall accuracy provides an index of the probability of recovering information based on the strength of encoding operations, but recall latency provides and index of the probability of sampling information during retrieval (MacLeod & Nelson, 1984; Rohrer & Wixted, 1994). Specifically, Rohrer and Wixted (1994) found that manipulating presentation duration (and presumably manipulating the amount of attention paid at encoding) changed overall proportion correct but did not change recall latency. Thus, if high and low WMC individuals are searching through the same sized search set but differ in the strength of representations within the search set, then low WMC individuals should recall fewer correct items, make more omission errors, and recall at the same rate as high WMC individuals.

The aim of the current study was to examine WMC differences in episodic recall over the short and the long term in terms of both differences in encoding and strategic search. Importantly, encoding and strategic search explanations predict different patterns of results across correct, error, and latency measures. Thus, it should be possible to choose between them based on the overall pattern of data across multiple dependent variables rather than just examining proportion correct. In order to examine this, high and low WMC individuals were determined based on a composite measure of two complex span tasks (operation and reading span) and these participants performed a running paired-associates tasks with lags ranging from 0 to 99. By using a wide range of lags that require recall after several minutes in some cases, the current study provides a much stronger test of the notion that high and low WMC individuals differ in long-term memory abilities than has been shown previously (e.g., Unsworth, 2007).

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 two 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. Participants solved a series of maths operations while trying to remember a set of unrelated letters that were presented for 1 s each. 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. Participants received three sets (of list length 2) of practice. For all of the span measures, 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 operation span. For this task, participants read a sentence and determined whether the sentence made sense or not (e.g., "The prosecutor's dish was lost because it was not based on fact."). Half of the sentences made sense, and the other half did not. Nonsense sentences were made by simply changing one word (e.g., "dish" from "case") from an otherwise normal sentence. After participants indicated whether the sentence made sense or not, they were presented with a letter for 1 s. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. There were three trials of each list length, with list length ranging from three to seven. The same scoring procedure as operation span was used.

Composite score

For the composite score, scores for the two complex span tasks were z-transformed for each participant. These z-scores were then averaged together and quartiles were computed from the averaged distribution.[1] Participants were 25 high WMC individuals (z-WMC $= 0.95$, $SD = 0.21$) and 24 low WMC individuals (z-WMC $= -1.06$, $SD = 0.53$), as determined by the composite measure. The mean age for both groups was roughly 18.5 years, which did not differ as a function of WMC, $p > .71$. Both groups were composed of 66% females.

[1]Scores for the two complex span tasks were all correlated in our overall distribution, $r = .58$.

Running paired associates

In the running paired-associates task, which is based on a task used by Rubin et al. (1999), participants were presented with two words (i.e., cue and target) simultaneously onscreen for 5 s. After a variable number of to-be-remembered intervening cue–target pairs, participants were presented with the cue word and were required to recall the target word that was paired with the cue word. For instance, participants would be shown "BASKET-RENT" for 5 s. Then another cue–target pair was shown for 5 s. After a number of cue–target pairs (i.e., lag) had been presented, participants would be shown "BASKET-???", which indicated that the participant needed to type in the word that was previously paired with basket. Participants had 5 s to type their response. Participants received 10 learning and 10 test trials at each of 10 different lags (0, 1, 2, 4, 7, 12, 21, 35, 59, and 99). Thus, participants were either tested immediately (lag $= 0$) or after a number of intervening items had been presented (i.e., lags 1–99). Learning and test trials for all the lags were intermixed. Additionally, in order to fill in spaces in the order, there were 40 filler learning trials for which there was no test. Overall there were 240 trials (100 learning, 100 test, and 40 filler trials). All participants received the same order of word pairs. Cue words were common six-letter words; target words were common four-letter words and the pairing of cue– target pairs was initially randomised. Each response was hand scored to make sure that responses that were accurate but simply misspelled were credited as being correct. This ensures that any differences between high and low WMC individuals were not due to differences in spelling ability.

RESULTS

Shown in Figure 1 are the resulting forgetting functions for the high and low WMC groups. As can be seen, high and low WMC individuals did not differ at a lag of 0, but there were differences at all other lags. These observations were supported by a 2 (WMC) $\times$ 10 (Lag) mixed-factorial analysis of variance (ANOVA) with lag as the within-subjects factor. There was a main effect of lag, demonstrating classic forgetting functions where proportion correct dropped as a function of lag, $F(9, 423) = 146.73$, $MSE = 0.02$, $p < .01$, partial $\eta^2 = .76$. There

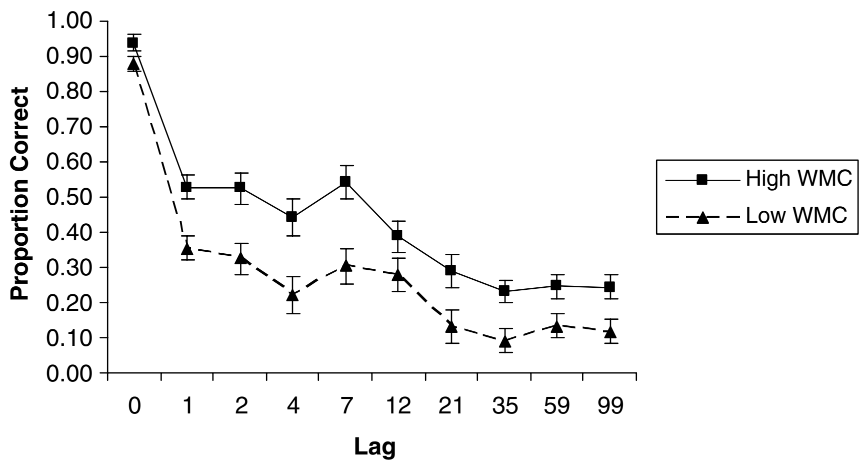

Figure 1. Proportion correct as a function of lag and WMC. Error bars represent one standard error of the mean.

was also a main effect of WMC with high WMC individuals recalling a greater proportion of target items ($M = 0.44$, $SE = 0.03$) than low WMC individuals ($M = 0.28$, $SE = 0.03$), $F(1, 47) = 11.07$, $MSE = 0.26$, $p < .01$, partial $\eta^2 = .19$. Additionally, these two factors interacted such that WMC differences were seen at long lags, but not at a lag of 0, $F(9, 423) = 2.33$, $MSE = 0.02$, $p < .05$, partial $\eta^2 = .05$. Specifically, the difference between high and low WMC individuals at a lag of 0 was not significant ($p > .07$), whereas the differences at all other lags (except lag 12; $p > .10$) were significant, all ps $< .05$.

Next, errors were examined to better understand these differences. Errors were classified as omissions (no response was given), intraexperimental intrusions (a word that was presented in the experiment but was not the target response), or extraexperimental intrusions (a word not presented in the experiment was given instead of the target response). An analysis of errors suggested that there were more omissions ($M = 36.53$, $SE = 2.91$) than intrusions (both ps $< .01$), but intra- ($M = 9.10$, SE $= 1.19$) and extraexperimental intrusions ($M = 11.86$, $SE = 1.99$) did not differ from one another, $t(48) = 1.64$, $p > .11$. Next, each error type was examined as a function of lag and WMC. As shown in Figure 2A, for omissions, there was a significant main effect of lag, $F(9, 423) = 39.74$, $MSE = 2.53$, $p < .01$, partial $\eta^2 = .46$, but no effect of WMC and no interaction, both ps $> .14$. As shown in Figure 2B, for intraexperimental intrusions there were significant main effects of both lag, $F(9, 423) = 5.86$, $MSE = 0.78$, $p < .01$, partial $\eta^2 = .11$, and WMC, $F(1, 47) = 4.49$, $MSE = 6.44$, $p < .05$, partial $\eta^2 = .09$, but no interaction between the two, $F < 1$. Additionally, in order to understand these WMC differences in intraexperimental intrusions, the number of intervening trials between the initial presentation of the word and the subsequent incorrect recall of the word was tallied for each individual. This provides an examination of whether low WMC individuals are more likely to intrude recent items than high WMC individuals. On average there were roughly 22 intervening trials between presentation and incorrect recall for low WMC individuals and roughly 32 intervening trials for high WMC individuals. This numerical difference, however, was not statistically significant, $t(43) = 1.49$, $p > .14$. Thus, although low WMC individuals made more intraexperimental intrusions, these intrusions tended to come from similar trials as intraexperimental intrusions for high WMC individuals (see also Unsworth & Engle, 2007). Finally, as shown in Figure 2C, for extraexperimental intrusions there were significant main effects of both lag, $F(9, 423) = 8.70$, $MSE = 1.11$, $p < .01$, partial $\eta^2 = .16$, and WMC, $F(1, 47) = 4.97$, $MSE = 17.93$, $p < .05$, partial $\eta^2 = .10$, but no interaction between the two, $p > .43$. Thus, as shown in Table 1, high and low WMC individuals differed in intra- and extraexperimental intrusions, but no differences were found for omissions.

Finally, recall latency was examined. Recall latency was measured as the time between the onset of the recall cue and the first keystroke.[2] In

[2]Note, all analyses were redone after log-transforming the latency results. The results from these analyses were identical to those reported in the article. Furthermore, note each response was hand scored for accuracy and latency was checked to make sure that there were no hesitations between the start of recall and the end of recall that could distort the latency results.

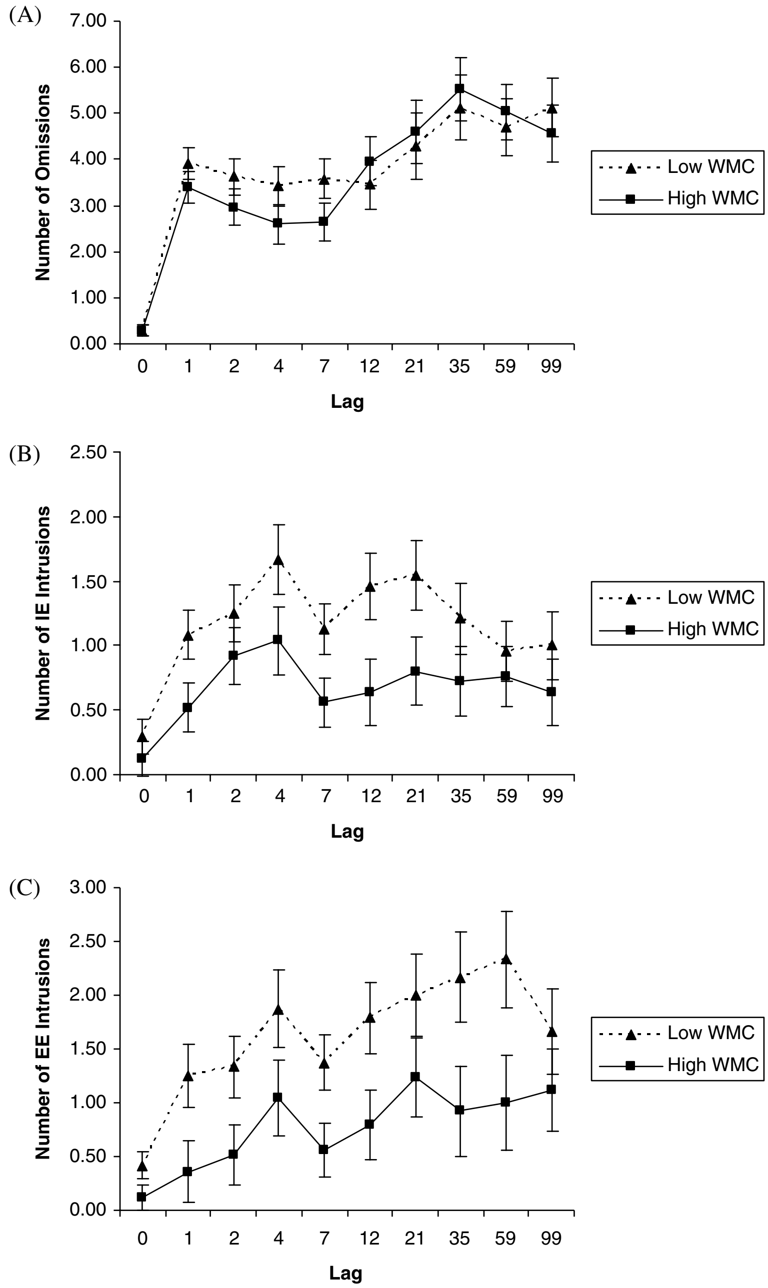

Figure 2. (A) Number of omission errors as a function of lag and WMC. (B) Number of intraexperimental (IE) intrusion errors as a function of lag and WMC. (C) Number of extraexperimental (EE) intrusion errors as a function of lag and WMC. Error bars represent one standard error of the mean.

TABLE 1
Number of errors as a function of type and WMC

	Errors		
WMC	*Omissions*	*IE intrusion*	*EE intrusion*
High	35.56 (4.70)	6.72 (1.29)	7.68 (2.13)
Low	37.54 (3.47)	11.58 (1.92)	16.21 (3.21)

IE = intraexperimental intrusions; EE = extraexperimental intrusions. Numbers in the parentheses are standard errors.

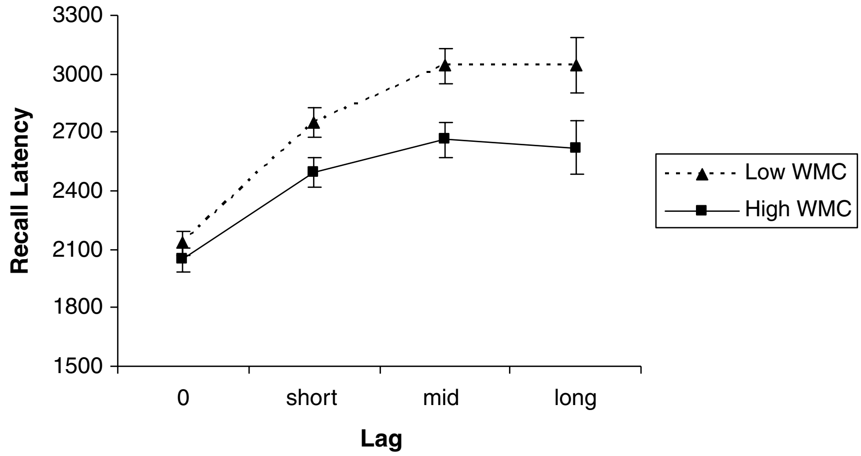

Figure 3. Recall latency as a function of lag and WMC. Error bars represent one standard error of the mean.

order to ensure enough correct recall latencies for analysis, lags 1, 2, and 4 were combined into a single short-lag measure, lags 7, 12, and 21 were combined into a single mid-lag measure, and lags 35, 59, and 99 were combined into a single long-lag measure. Lag 0 was treated as a separate measure. As shown in Figure 3, examining correct recall latency as a function of lag suggested that lag 0 responses were the fastest and then recall latency slowed and tended to level out by the longest lags. Furthermore, as shown in Figure 3, low WMC individuals tended to recall at a slower rate than high WMC individuals and this occurred primarily for lags greater than zero. These observations were supported by a 2 (WMC) $\times$ 4 (lag) mixed-factorial analysis of variance (ANOVA) with lag as the within-subjects factor. There was a main effect of lag, demonstrating a general increase in latency across lags, $F(3, 141) = 37.30$, $MSE = 166134$, $p < .01$, partial $\eta^2 = .44$. There was also a main effect of WMC, demonstrating that high WMC individuals recalled at a faster rate ($M = 2456$, $SE = 65$), than low WMC individuals ($M = 2742$, $SE = 66$), $F(1, 47) = 9.56$, $MSE = 418649$, $p < .01$, partial $\eta^2 = .17$. These two factors did not interact, $F(1, 47) = 1.68$, $MSE = 418649$, $p > .17$, partial $\eta^2 = .04$. However, upon further examination it was found that high and low WMC individuals did not differ at a lag of 0, $t(47) = .99$, $p > .33$, but they did differ at all of the other lags, all ps $< .05$, η^2s $> .09$. Thus, high and low WMC individuals differed in recall latency overall, and this difference was especially pronounced for lags greater than zero.

Population Dilution model

A variant of the Population Dilution model (Lansdale & Baguley, 2008) was used to further examine individual differences in WMC and forgetting. Specifically, we simulated one group of high WMC individuals and three groups of low WMC individuals who differed from the high WMC group in either the total number of target representations in the population (i.e., low WMC-C), the total number of intrusions in the population (i.e., low WMC-E), or in the overall rate of forgetting due to the inclusion of null traces as a function of time (i.e., low WMC-k). These simulated results were then compared to the actual results from high and low WMC individuals to determine if differences in forgetting were due primarily to one of these parameters. Initial parameter values for the high WMC group were based on values reported in Lansdale and Baguley (2008) that fit the Population Dilution model to data from Rubin et al. (1999) that used the same running-paired associates task as that used in the current study. Shown in Table 2 are the parameter values used in the simulations. Note, we did not specifically fit the Population Dilution model to the data because we were interested in the qualitative pattern of results rather than actual fits to the data. Thus, we did not attempt to fit the model, but rather examined how variations in specific parameters would change the qualitative pattern of results (e.g., Unsworth, 2007). Researchers interested in fitting the model to the data can obtain the data from the authors.

TABLE 2
Parameter values for each group for the population dilution simulations

Group	*C*	*E*	*k*
High WMC	8	5.5	0.303
Low WMC-C	3.5	5.5	0.303
Low WMC-E	8	19.5	0.303
Low WMC-k	8	5.5	1.000

As can be seen in Table 2, the groups differ only in one of the parameters of interest. Specifically, group low WMC-C differs from the high WMC group only in that they have fewer correct target items (i.e., C) in their population than the high WMC group. As noted previously, this could be due to overall differences in encoding where low WMC individuals do not encode items as well as high WMC individuals leading to lower numbers of correct items within the population. The low WMC-E group differs from the high WMC group in that this group includes many more intrusions (i.e., E) in their population than the high WMC group. As suggested previously, this suggests that low WMC individuals are not as adept as high WMC individuals at focusing their search sets on the relevant representations, leading to the inclusion of many irrelevant representations. Finally, the low WMC-k group differs from the high WMC group in that this group is far more susceptible to the inclusion of null traces into the population as a function of time leading to a greater rate of forgetting over time than the high WMC group.

Next, for each group the resulting forgetting function was obtained by using the parameter values in Table 2. Note that we only simulated lags 1– 99 and assumed that in each group performance at lag 0 would be perfect, given that the information should still be in the focus of attention. The resulting forgetting functions for each of the simulated groups are shown in Figure 4. As can be seen, manipulating the values of C or E for the low WMC groups led to qualitatively similar forgetting functions with both functions being different from the high WMC group's function at all lags > 0. Manipulating k, however, led to a forgetting function in which high and low WMC groups were qualitatively similar at short lags and then the differences increased. Comparing the simulated functions with the actual results shown in Figure 1 suggests that the low WMC-C and low WMC-E groups are consistent with the data, but the low WMC-k group is not given that high and low WMC individuals were not similar at short lags.

It would seem that differences between high and low WMC individuals in forgetting could be due either to differences in the number of correct items within the population (i.e., C) or to differences in the number of intrusions within the population (i.e., E). An examination of the overall forgetting functions and simulations based on the Population Dilution model do not conclusively suggest one over the other. However, as noted in the introduction, an examination of proportion correct alone is not sufficient for choosing between these two explanations. Rather, what is needed is an examination of errors and recall latency in addition to proportion correct. If high and low WMC individuals differ in performance due to differences in the number of targets within the population (i.e., C), but do not differ in

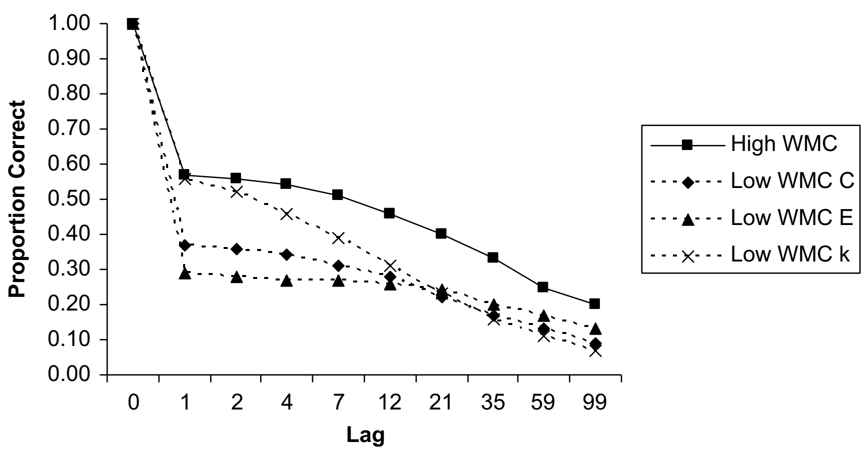

Figure 4. Simulated forgetting functions for each group based on values in Table 2.

the number of intrusions (i.e., E), then high and low WMC individuals should differ in the number of omissions (because low WMC individuals have more nonrecoverable target items than high WMC individuals), should emit a similar number of intrusions (because there are no differences in the number of intrusions within the population), and should recall at a similar rate (because the overall number of items within the population are the same). If, however, high and low WMC individuals differ in the number of intrusions, but do not differ in the number of correct targets in the population, then high and low WMC individuals should have a similar number of omissions (because there are no differences in the number of recoverable targets in the population), should differ in the number of intrusions emitted (because low WMC individuals have more intrusions within their populations than high WMC individuals), and should differ in recall latency (because low WMC individuals have more overall items within their populations than high WMC individuals). As noted previously, the results are more in line with the notion that high and low WMC individuals differ primarily in the number of intrusions within their populations given that high and low WMC individuals did not differ in the number of omissions, but low WMC individuals emitted more intrusions (both intra- and extraexperimental intrusions), and low WMC individuals recalled at a slower rate than high WMC individuals. Thus, although varying either the number of targets in the population (i.e., C) or varying the number of intrusions in the population (i.e., E) lead to similar qualitative patterns of results in terms of overall forgetting functions, these two possibilities could be distinguished based on both the type and number of errors made as well as recall latency.

DISCUSSION

The goal of the current study was to examine variation in WMC and forgetting over both the short and the long term. Using a running paired-associates task, it was found that high WMC individuals outperformed low WMC individuals at both short and long lags. Furthermore, low WMC individuals recalled correct items at a slower rate and recalled more intrusions than high WMC individuals. Yet, high and low WMC individuals did not differ in the number of omission errors. These results are broadly consistent with the notion that WMC measures index, in part, controlled retrieval processes which may be important in a number of higher order tasks and may help explain why WMC measures are related to so many cognitive abilities (Unsworth & Engle, 2007; see also Conway & Engle, 1994; Healey & Miyake, 2009; Kane & Engle, 2000; McCabe, 2008; Nelson & Goodmon, 2003; Rosen & Engle, 1997). That is, it is very unlikely that high WMC individuals were able to actively maintain or covertly rehearse the cue–target pairings presented during the encoding phase until they were represented during the test phase. Indeed, it was found that high WMC individuals remembered more items after a lag of 99 items or roughly 8 minutes than low WMC individuals. It seems very unlikely that high WMC individuals were able to actively maintain these cue–target pairings for 8 minutes amongst other cue–target pairs that also had to be remembered.

As suggested by Unsworth (2007) these results are consistent with the notion that high and low WMC individuals differ in retrieval due to differences in size of the set of items they are searching through. We have previously argued that high and low WMC differences on traditional long-term memory tasks reflect differences in search set size, where low WMC individuals include many more irrelevant representations (intrusions) in their search sets than high WMC individuals. This leads to low WMC individuals recalling fewer correct target items, recalling items at a slower rate, and emitting more intrusions than high WMC individuals (Unsworth, 2007). The results of the current study clearly show this exact pattern of results and suggest that differences in search set size occur at both short and long lags where the possibility of rehearsing has been severely diminished. Furthermore, a variant of the Population Dilution model (Lansdale & Baguley, 2008) in which high and low WMC individuals differed only in the number of intrusions within the search set (population) led to a qualitatively similar pattern of results in terms of overall forgetting functions, providing further support for the notion that differences between high and low WMC individuals are primarily due to differences in search set size.

An alternative explanation that was examined in the current study was that high and low WMC individuals differ in encoding abilities such that low WMC individuals cannot encode items as well as high WMC individuals which leads to low

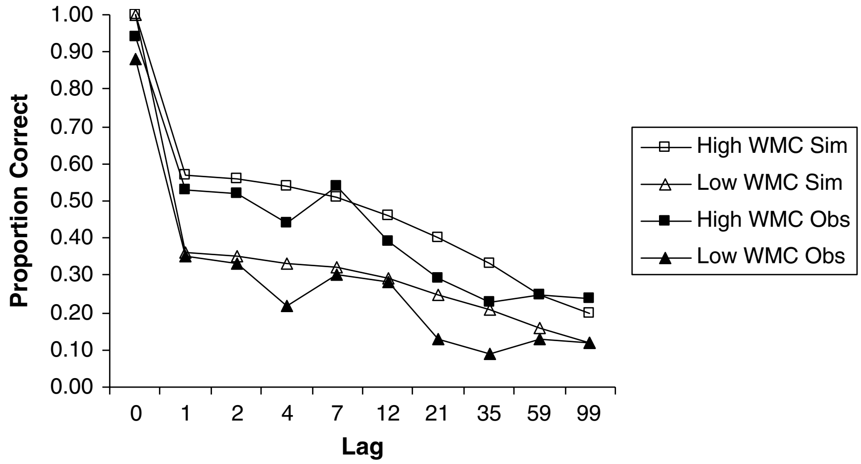

Figure 5. Comparison of simulated forgetting functions for the high WMC and low WMC (C and E combined) groups with actual high and low WMC recall functions. High WMC sim = high WMC simulated group; low WMC sim = low WMC C and E simulated group; high WMC Obs = actual results for high WMC group; low WMC Obs = actual results for low WMC group.

WMC individuals having more degraded representations in their search sets at retrieval than high WMC individuals.[3] Within a basic search model, differences in basic encoding abilities would predict that low WMC individuals should have more omissions (because the correct item was too degraded to be recalled) and should recall items at the same rate as high WMC individuals (Rohrer & Wixted, 1994; Unsworth, 2007). 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 low WMC individuals have more degraded representations (leading to more omissions) within a search set of the same size as high WMC individuals, then low WMC individuals will have a lower proportion correct, but the same recall latencies as high WMC individuals. Although varying the number of correct target representations within the search set did lead to the same qualitative pattern of data in terms of overall forgetting functions, results based on omission errors and recall latency did not support this explanation. That is, the behavioural results clearly demonstrated that high and low WMC individuals differed in correct recall latency and there were no differences in omissions. Thus, a simple encoding explanation does not seem to account for the present results.

One way to reconcile these two views (i.e., differences in search set size vs. differences in encoding) is to assume that WMC differences occur in both. As suggested previously, it is likely that high and low WMC individuals differ not only in strategic search, but they also differ in the ability to utilise encoding strategies (e.g., Bailey et al., 2008), which partially accounts for differences in recall. Therefore, in order to examine the possibility that WMC differences found in the current study are due to both strategic encoding and retrieval we used the same variant of the Population Dilution model (Lansdale & Baguley, 2008) as was used previously. In this version we simulated a group of low WMC individuals who differed from the high WMC individuals in both the number of recoverable target items (i.e., C) and the number of intrusions (i.e., E) in their search sets, but did not differ in the rate if forgetting (i.e., k). Specifically, we kept the parameter values of the high WMC group the same as before, but now simulated a new group of low WMC individuals who had fewer correct items ($C = 5.5$) and more intrusions ($E = 9.5$) than the high WMC group, but the same rate of forgetting ($k = 0.303$). Shown in Figure 5

[3]One potential explanation, not considered previously, for the current results is that high and low WMC individuals simply differ in basic verbal ability or vocabulary size which accounts for the differences in recall. That is, because the stimuli were words and because participants had to type their responses, it is possible that basic word knowledge differences could have influenced the results. However, as part of our initial laboratory screening procedure all participants completed a number of cognitive ability tests including a basic vocabulary test. Examining high and low WMC differences in vocabulary for the current sample suggested no differences, $t(47) = 1.43$, $p > .16$, and none of the results changed when partialling vocabulary out. Thus, the differences found in the current study were not due to differences in vocabulary size.

are the observed data for the high and low WMC groups along with the two simulated groups. Note, again that we did not attempt to fit the data, but rather examine if the simulated results were qualitatively similar to the actual results. As can be seen, there is a good degree of correspondence between the observed and simulated results. Thus, the notion that high and low WMC individuals differ in both the number of correct and target items within their population/search set seems to correspond quite well with the observed pattern of data. Clearly, future work is needed to examine the possibility that high and low WMC individuals differ in both strategic encoding and controlled search processes.

At the very least, the current results demonstrate that high and low WMC individuals differ in their ability to recall information after both short and long lags. Thus, it is clear that differences in WMC are more than just differences in short-term maintenance abilities; rather, these differences occur at much longer time scales than would typically be associated with working memory. As such, the current results strongly suggest that working memory (and individual differences in WMC) is not a time limited process, but rather working memory will be needed over both the short and the long term as long as controlled processes are required.

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