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Memory retrieval and interference: Working memory issues ☆

Gabriel A. Radvansky [a,*], David E. Copeland [b]

[a] Department of Psychology, University of Notre Dame, Notre Dame, IN 46556, USA
[b] University of Southern Mississippi, USA

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Abstract

Working memory capacity has been suggested as a factor that is involved in long-term memory retrieval, particularly when that retrieval involves a need to overcome some sort of interference (Bunting, Conway, & Heitz, 2004; Cantor & Engle, 1993). Previous work has suggested that working memory is related to the acquisition of information during learning, along with the management of interference and the use of inhibition during long-term memory retrieval. This paper reports a study that further addressed the role of working memory capacity on long-term memory retrieval. Our results showed that working memory capacity is somewhat related to the integration of information into situation models, and the management of interference, but not to the ability to suppress irrelevant information. The role of other cognitive processes, such as general situation model processing and general inhibitory ability, were also explored.

Keywords: Mental models; Situation models; Fan effect; Working memory

The aim of this paper is to further assess how long-term memory retrieval is affected by working memory capacity. Working memory is the part of cognition responsible for the active processing of information, including retrieving information from long-term memory (Bunting et al., 2004; Cantor & Engle, 1993; Conway & Engle, 1994; Kane & Engle, 2000; Rosen & Engle, 1997). Of specific concern here is the role of working memory in the management of interference during: (a) the learning of new facts, (b) long-term memory retrieval, and (c) the use of inhibition during retrieval. To what degree does working memory span provide a partial index of how well someone deals with sources of interference?

This issue is addressed by looking at the influence of working memory capacity on processing in the face of different amounts of interference in the context of a classic memory interference paradigm, the *fan effect* (e.g. Anderson, 1974). In this paradigm, people memorize a set of facts in which concepts have different numbers of associations. In general, increases in the number of associations with a study concept leads to greater interference, although this can be overcome if the information is sufficiently integrated (e.g. Myers, O'Brien, Balota, & Toyofuku, 1984; Radvansky, 1999a, 1999b;

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* Corresponding author. Fax: +1 574 631 8883.
E-mail address: Gabriel.A.Radvansky.1@nd.edu (G.A. Radvansky).

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Radvansky & Zacks, 1991; Smith, Adams, & Schorr, 1978).

Cantor and Engle (1993)

The launching point for our work was a study by Cantor and Engle (1993). This study looked at the influence of working memory capacity on long-term memory retrieval and the fan effect using a method developed by Myers et al. (1984). In this paradigm, people learn sets of facts that are easy or difficult to integrate based on prior knowledge of scripted actions. For example, in one experiment, students memorized lists of sentences about people doing activities, such as "The teacher took a table near a window." Each person was doing either 3 or 6 activities. Moreover, the activities were either highly related, and thus easily integrated, or not. Cantor and Engle found that people who scored high on a working memory span test had a smaller fan effect than those who scored low. Furthermore, people who scored high actually showed some integration benefit, whereas the low scoring people did not. These findings are consistent with the idea that working memory capacity influences the effectiveness of long-term memory retrieval.

Cantor and Engle (1993) gave two major explanations for their finding. First, working memory capacity is related to the ability to *integrate* information during learning. Greater working memory capacity allows one to keep more information active at one time, making it more likely to be integrated. This integration leads to fewer sources of interference during retrieval, and therefore, a smaller fan effect. The second explanation was that people with smaller working memory capacities have difficulty controlling the flow of information during retrieval. Specifically, they have difficulty regulating retrieval *interference*. Cantor and Engle further suggested that low capacity people have difficulty suppressing related but irrelevant information, leading them to be more susceptible to interference. So, there are two components to their second explanation: the experience of *interference* and the ability to *inhibit* irrelevant representations. Thus, Cantor and Engle's explanations state that: (1) higher working memory capacity leads to better *integration*, (2) higher working memory capacity is related to experiencing less *interference*, and (3) higher working memory capacity is related to a better ability to *inhibit* irrelevant representations.

This finding and theoretical perspective was expanded recently in a paper by Bunting et al. (2004). In this study people memorized sentences about people in locations, such as "The lawyer is in the boat." There were 1–4 associations with either each person or location. Bunting et al. found that memory span was unrelated to overall learning rates, and that people who scored lower on a span test experience more interference, but only when there were multiple associations possible for both people and locations. This was true in both the response time and error rate data. Thus, Bunting et al. were able to support the second explanation of Cantor and Engle (1993). However, because they did not use materials that were clearly integrated in one way or another, and they had no direct measure of a suppression effect, they were not able to address the first and third accounts, which are examined in the current study.

To explore these ideas further, we first provide a description of the method used in the current study, and some qualities it has that the Myers et al. (1984) method does not. Then, in separate sections, we outline how working memory capacity might be related to performance using this method in terms of: (a) the use of integration during encoding, (b) the impact of interference during encoding and retrieval, and (c) the operation of inhibition during retrieval.

Situation models and fact retrieval

To address these issues, we used a fan effect paradigm developed by Radvansky and Zacks (1991; Radvansky, Spieler and Zacks, 1993), and augmented by Radvansky (1999b). In this paradigm, people are given sentences about objects in locations to memorize, such as "The ceiling fan is in the city hall." in which there are 1–3 associations with each object and location. The structure of object–location associations in a sample study list is shown in Fig. 1.

In this paradigm, we can broadly define two conditions of interest. These conditions are based on the

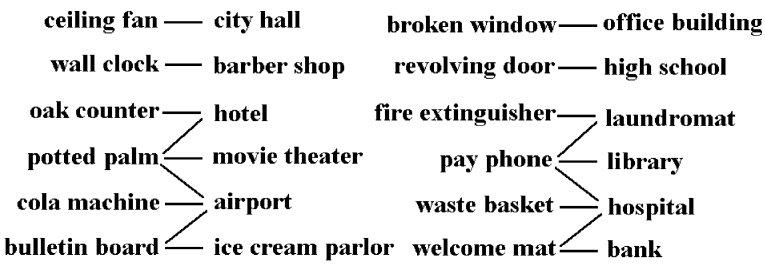

Fig. 1. Associative structure among concepts used to form the study sentences.

assumption that people are creating and using situation models (Johnson-Laird, 1983; Kintsch, 1998; Van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998) of the information in the study sentences, and that these situation models are used during memory retrieval. In short, a situation model is a mental simulation of a described situation. This is in line with the idea that people are more likely to actively engage in some sort of chunking or organizational process when trying to learn sentences (Jefferies, Lambon Ralph, & Baddeley, 2004). The first condition is the Multiple Location condition. These are sentences in which there is a single object associated with multiple locations, such as is the case with Sentences 1 to 3.

1. The welcome mat is in the movie theater.
2. The welcome mat is in the airport.
3. The welcome mat is in the hotel.

According to situation model theory, although all of these sentences share a common concept, the welcome mat, it is unlikely that they refer to a common situation in the world. Instead, they are more likely to be interpreted as referring to three different states-of-affairs. As such, a separate situation model would be created and stored in memory for each of these sentences. Importantly, because this information is not integrated in memory, during retrieval, the related but irrelevant models will cause interference, thereby causing retrieval to be slower and more error prone.

The second condition is the Single Location condition. These are sentences in which there are multiple objects associated with a single location, such as is the case with Sentences 4 to 6.

4. The pay phone is in the hospital.
5. The waste basket is in the hospital.
6. The welcome mat is in the hospital.

Because these sentences can be easily interpreted as referring to a common state-of-affairs in the world, this information can be integrated into a common situation model. As such, there is only a single representation stored in long-term memory. Because of this, during retrieval, there will be no sources of interference, and retrieval time will be constant and less error prone.

This differential fan effect has been observed under a variety of conditions, including those involving spatial (Radvansky, 1998, 1999b, 2005; Radvansky, Spieler, & Zacks, 1993; Radvansky & Zacks, 1991; Radvansky, Zacks, & Hasher, 1996), temporal (Radvansky, Zwaan, Federico, & Franklin, 1998), or ownership relations (Radvansky, Wyer, Curiel, & Lutz, 1997). It is not affected by the order of the concepts in the study sentences (Radvansky & Zacks, 1991; Radvansky et al., 1996), nor by the type of articles used in the study sentences (Radvansky et al., 1993).[1]

The paradigm developed by Radvansky and colleagues is advantageous for the current purposes because it readily allows for an evaluation of both integration and interference, two of the processes hypothesized to be influenced by working memory capacity according to Cantor and Engle (1993). Integration is assessed by looking at performance in the Single Location condition. The better someone has integrated this information, the less interference that should be observed. Furthermore, interference is assessed by looking at performance in the Multiple Location condition. The more susceptible someone is to interference, the greater their fan effect should be. These factors can be addressed both during learning and retrieval.

Another advantage of this paradigm is that it allows for an assessment of inhibition, the third process described by Cantor and Engle (1993), using a modification introduced by Radvansky (1999b; see also Radvansky, Zacks and Hasher, 2005). Performance is assessed on trials in which the model that is needed from long-term memory is one that was a competitor on the previous trial. To understand this, consider Fig. 2, which shows how the information from a hypothetical study list would be organized into location-based situation models.

Assume that on *trial 1* of a recognition test, the probe is "The potted palm is in the movie theater." Because the potted palm is in three locations, this is a Multiple Location condition, and people experience interference from the airport and hotel situation models. Now, on *trial 2*, the probe is "The cola machine is in the airport." Although this sentence does not share an object or location with the sentence on *trial 1*, the airport model was a source of interference. As such, if inhibition is operating, the airport model will be suppressed. As a result, on *trial 2*, people will respond more slowly. Because this condition looks at the retrieval of inhibited models, it is called the *Inhibition* condition. As a comparison, for a *Control*

[1] While the idea that people are using situation models is the view taken here, there is another interpretation of the differential fan effect. Specifically, according to some ACT-R (Adaptive Control of Thought—Rational) accounts, the differential fan effect is due to differences in attention allocated to the concepts in the study sentences (Anderson & Reder, 1999; Sohn, Anderson, Reder, & Goode, 2004). A study by Sohn et al. showed that differential attention can produce a differential fan effect, but failed to show that differential attention is driving this effect when it is not directly manipulated. Moreover, this study is problematic because it used concept pairs (e.g., hippie-park) during recognition, rather than sentences, which decreases situation model use (Radvansky, 2005). This ACT-R view has been refuted on the grounds that it makes implausible predictions, such as the suggestion that people are focusing all of their attention at retrieval on one concept and completely ignoring the other (Radvansky, 1999a).

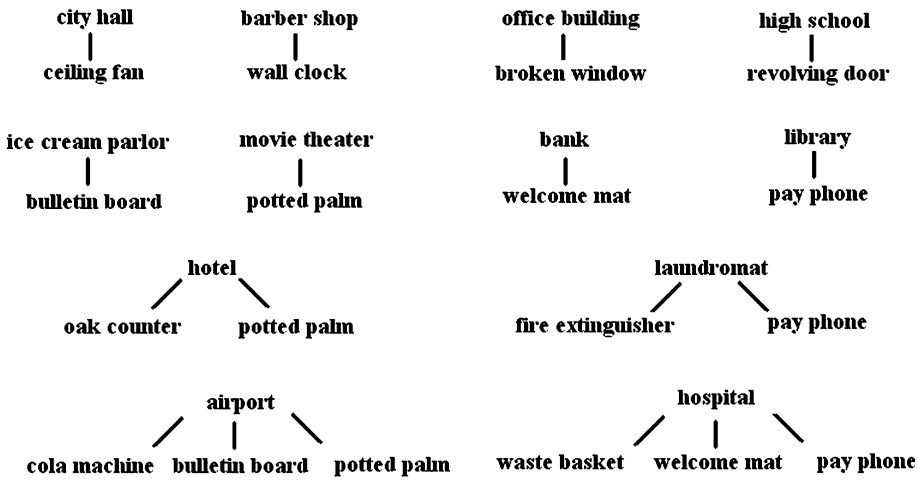

Fig. 2. Objects and locations from Fig. 1 shown in an organization by location.

condition, on *trial 1* assume the probe is "The pay phone is in the library." This has the same number of associations for the object and location as the first sentence of the Inhibition condition, but it is unrelated to the airport model. Thus, on *trial 2*, when the probe is "The cola machine is in the airport," response times should be unaffected by the operation of inhibition.

Thus, this paradigm allows for an evaluation of inhibition in addition to the measures of integration and interference. As such, using this paradigm we can evaluate all three hypotheses laid out by Cantor and Engle (1993).

Predictions

Using the paradigm described above, we can make predictions based on Cantor and Engle's (1993) hypotheses. First, with regard to integration, it is predicted that people who have a greater working memory capacity are more efficient at integrating information. This should be reflected in faster learning rates for the Single Location items, along with smaller fan effects in this condition. Second, with regard to interference, it is predicted that people who have a larger working memory capacity are more efficient at reducing the complicating effects of retrieval interference. This should be reflected in faster learning rates for the Multiple Location items where integration is less likely, along with smaller fan effects in this condition. Finally, with regard to inhibition, it is predicted that people with larger working memory spans are better at using inhibition, and they should show a larger inhibition effect.

Experiment

This experiment was done in the context of a larger study looking at a number of issues involving working memory capacity and the processing of situation-specific information. The focus here is on those tasks that illustrate how working memory capacity is related to long-term memory retrieval. The results of the other measures are reported elsewhere (Copeland & Radvansky, 2004; Radvansky & Copeland, 2004a, 2004b). In addition, we had two measures of inhibition to compare with our measure of retrieval inhibition in the fan effect paradigm. One of these tasks looked at preventing interfering information from entering working memory (Irrelevant Text task), and the other look at the removal of newly irrelevant information (Altered Inference task). Performance on these tasks was compared with performance on the measures that addressed our three points of concern.

In addition to working memory capacity and inhibitory processing measures, as an exploratory effort, we looked at some other measures that might provide some insight into how people create and retrieve situation models over and above what is observed with working memory span. The results of these measures are provided in Appendix A, although descriptions of these tasks are also provided in the method section.

Method

Participants

There were 150 native English speakers tested. They were recruited from the subject pools at the University of Notre Dame and Indiana University South Bend and given partial class credit for their participation. The data from 2 additional participants were excluded because of an excessive number of errors on the recognition test (>20%).

Materials

In this section we present the various tasks that were used in this study. First we present our description of

several individual difference measures. These include the Turner and Engle (1989) operation span task as a measure of working memory capacity, the Radvansky and Copeland (2001) situation identification task as a measure of memory for described events, the Mani and Johnson-Laird (1982) integration task as a measure of the ability to coordinate descriptions of an situation. There were also two measures of inhibition. These were the Connelly, Hasher, and Zacks (1991) Irrelevant Text task, and the Hamm and Hasher (1992) Altered Inference task. Finally, we present the primary measure, the fan effect task.

Working memory span. People were given the Turner and Engle (1989) operation span test. For this test, people saw sets of 2 to 6 math problems along with a solution (e.g., $(5 \times 2) - 1 = 8$?). The task was to read the problem aloud and to indicate whether the solution was correct. This was done by pressing one of two buttons on a computer mouse. Following each problem was a word. The task was to remember the words in a set and to report them in the correct order at the end of each set. The experimenter typed the words into the computer, using "dk" to indicate "don't know" when appropriate. Thus, the experimenter controlled the pacing of this task. Following La Pointe and Engle (1990), the working memory span score was the sum of the number of words from the correctly recalled sets.

Situation identification. The situation identification test assessed the degree to which people identified items that were consistent with a previously described situation. First, people read 24 sentences, such as "The hostess bought a mink coat from the furrier" and rated the pleasantness of the described situation. After rating all sentences, sets of 6 sentences were given for each item and people selected the one that described the same situation as the original. One sentence altered the prepositional phrase (e.g., "The hostess bought a mink coat at the furrier's"), another altered the object (e.g., "The hostess bought a fox stole from the furrier."), and a third altered the verb (e.g., "The hostess sold a mink coat from the furrier"). The remaining three had pair combinations of these changes (e.g., "The hostess sold a mink coat at the furrier's," "The hostess bought a fox stole at the furrier's," and "The hostess sold a fox stole from the furrier"). Only one option described the same situation as the original (The first one in this example). Each change type was the correct response equally often. The orders of the original sentences and the test options were randomized. Responses choices were entered on the computer keyboard.

Integration task. This task was modeled after a study by Mani and Johnson-Laird (1982). People were given three statements about the spatial arrangement of four objects. There were two conditions. In the *Continuous* condition, each subsequent sentence referred to objects in the previous sentence. An example of a Continuous description is:

1. The lily is in front of the rose.
2. The rose is to the left of the tulip.
3. The tulip is in front of the orchid.

In contrast, in the *Discontinuous* condition, the objects in the second sentence did not refer to either of the objects in the first sentence. This information could not be integrated until the third sentence. An example of a Discontinuous description is:

4. The lily is in front of the rose.
5. The tulip is in front of the orchid.
6. The rose is to the left of the tulip.

Sentences were presented one at a time on a computer. After all three sentences were read, a display was presented with the names of the four objects in eight different configurations. The task was to select the configuration that corresponded to the description. Responses were typed into the computer.

Inhibition measures. There were two inhibition measures. One was an Irrelevant Text task modeled after a study by Connelly et al. (1991). People were given 8 paragraphs, four of which included additional, irrelevant words. The task was to read the italicized text aloud while ignoring the irrelevant words, which were in a normal case font. A control condition was the same except that the irrelevant words were replaced by a string of Xs. Performance was measured by collecting reading times for each paragraph. Inhibitory ability was based on the proportion of reading times in the experimental compared to the control condition.

Another measure of inhibition was an Altered Inference test modeled after a study by Hamm and Hasher (1992). In this task people read a series of 12 stories. An example of one story is presented in Table 1. There were two versions of each story. For the *Unexpected* version, people were initially led to make an inference, but were then given information that made it clear that this inference was incorrect. In the *Expected* version, the final inference is always supported. After each story people were presented with a comprehension question that referred to either the initial incorrect inference or the final correct inference. The accuracy of answering these questions was the measure of primary interest. Of particular interest was the rate of erroneously producing answers consistent with an initial misleading inference.

Table 1
Sample story used for the altered inference task

Expected version
Carol was not feeling well and decided to find out what was wrong. Carol went into town and entered the large building hoping to find some books relevant to her problem. She walked through the doors and took an elevator to the third floor.
She found a book that seemed relevant to her problem. Carol then went to the main desk and checked out the book for two weeks so that she could read it carefully at home. When she left the building she saw that it had started snowing hard and she hailed a taxi to take her home.
Unexpected version
Carol was not feeling well and decided to find out what was wrong. She called her friend who was a nurse to ask her for some advice. The friend told Carol what to do. Carol went into town and apprehensively entered the large building hoping to find an answer. She walked through the doors and took an elevator to the third floor.
She found a book that seemed relevant to her problem. Carol then went to the main desk and checked out the book for two weeks so that she could read it at home. When she left the building she saw that it had started snowing hard and she hailed a taxi to take her home.
Inference Question: In what kind of building did Carol use the elevator?
Target Inference: Library
Competing Inference: Hospital

Fan effect study sentences. This task involved learning a set of sentences about the location of objects, for which people were tested in a later recognition task. The study facts were a set of concepts combined to create 18 sentences of the form "The *object* is in the *location*" (e.g. Radvansky et al., 1993). The associative structure of the study lists is given in Fig. 1 for a hypothetical person. A different random assignment of objects and locations to each condition was used for each person. For the recognition test, *Studied* probes were memorized sentences, and *Nonstudied* probes were generated from repairings of the object and location concepts from within the same cell of the design. For example, if the studied sentences from a cell were Sentences 7 and 8, the Nonstudied sentences would be Sentences 9 and 10.

7. The oak counter is in the hotel.
8. The pay phone is in the high school.
9. The oak counter is in the high school.
10. The pay phone is in the hotel.

Generating nonstudied probes in this way avoids the possibility that people will use plausibility judgments rather than recognition decisions (e.g. Reder & Anderson, 1980). Because the same numbers of associations are involved for the object and locations for the nonstudied sentences, they were assigned to Single and Multiple Location conditions, and were analyzed as such.

Procedure

The first of the tasks given was the situation identification task. Subjects rated the 24 sentences for pleasantness. People were then given the forced choice situation identification task. The operation span test was given after this, with people increasing from the smallest set size to the largest. After this people were given the integration task. Then, people were given the Irrelevant Text task. Each person saw each of these texts one at a time. Finally, people were given the Altered Inference task. They read each story, one sentence at a time, with memory probes inserted at the appropriate locations. At the end of each story, people were given two comprehension questions.

For the fan effect tasks, people memorized a list of 18 sentences using a study-test procedure. During memorization, each person was first presented with the study list and instructed to memorize them as efficiently as possible. The sentences were displayed one at a time in white on a black background for 7 s each on a PC-compatible computer running in 40-column mode. The sentences appeared half-way down the screen beginning on the left-hand edge. A different random presentation order was used on each cycle. After the list had been presented, a set of 36 test questions was given. The test questions were of the form "Where is the *object*?" and "What is in the *location*?" for each object and location, respectively. The test questions were randomly ordered on each cycle. Accompanying each test question was a number indicating the number of answers to each question (i.e., 1, 2, or 3). People responded by typing their answers into the computer. The computer provided feedback concerning the correctness of each answer. After the appropriate number of answers was given, if there were any incorrect answers, the computer displayed all of the correct answers together for 3 s per answer. After answering all of the questions, the participants returned to the study portion. This study-test procedure continued until a person was able to correctly answer all of the test questions twice.

The fan effect recognition test was timed and administered on the computer. Each probe sentence was presented 6 times, yielding a total of 216 recognition test trials. The left button on a computer mouse was pressed to indicate a studied sentence, and the right button to

indicate a nonstudied sentence. People were encouraged to respond as quickly and as accurately as possible. The order of probe presentation in the recognition test was randomized within each of 2 blocks with the constraint that prime-target trials follow one another. If an incorrect response was made, immediate feedback was given in the form of a line that read either "*ERROR* SENTENCE STUDIED" or "*ERROR* SENTENCE NOT STUDIED," whichever was appropriate. This feedback was presented for 1 s. A set of 18 practice trials was given to familiarize people with using the mouse buttons. On the practice trials the computer displayed either "SENTENCE STUDIED" or "SENTENCE NOT STUDIED," and the person pressed the appropriate button.

Experimental context. These measures were embedded in the context of a larger study. These measures were administered across three days of testing, with each day separated by 1 week. During the first day, people were given a vocabulary test, a measure of processing speed, the situation identification test, the working memory span test, and a test of logical reasoning. On the second day, people were given the integration test, the Irrelevant Text task, a spatial direction task, the Altered Inference task, a digit memory task, and a text comprehension task. Finally, on the third day they were given the fan effect task.

Design and analysis. The recognition test data were analyzed in terms of the differential fan effects for the Single and Multiple Location conditions. Only the data from probe sentences where there was 1 association with one concept and 1–3 associations with the other were analyzed. These data were submitted to a 2 (Studied–Nonstudied) × 2 (Location Type: Single Location vs. Multiple Location) × 3 (Fan) repeated measures ANOVA. Probes from cells in which several objects were associated with several locations were treated as fillers because they cannot be assigned to the Single Location and Multiple Location conditions.[2] The response time data were trimmed using the procedure outlined by Van Selst and Jolicoeur (1994) in which the proportion of data trimmed is a function of the number of trials in a condition. This accounted for 3.7% of the data. Errors were excluded from the response time analysis.

Results

Because of the complexity of this study, we have broken the results into six sections. The first provides a summary of the working memory and inhibition tests. The second looks at the learning rate data for the fan effect task. The third addresses the response time data for the differential fan effect. The fourth does the same except with the error rate data. Finally, the fifth and sixth sections look at inhibition in response time and error rates, respectively, in the fan effect task. A level of $p < .05$ was used for all significance tests, unless otherwise noted.

Working memory and inhibition tests

The results of the working memory and other individual difference tests are presented in Table 2. For the working memory span test, scores were tabulated using the La Pointe and Engle (1990) method of counting up the number correct from a correctly recalled set. Performance on this measure was reasonably reliable, Cronbach's $\alpha = .75$. For the Irrelevant Text task, people were significantly slower in the Irrelevant text condition ($M = 61$ s) than the Control condition ($M = 40$ s), $F(1,149) = 623.29$, $MSE = 56$. The proportion of response times in the Control relative to the response times in the Irrelevant text conditions was used as the index for this measure. Performance on this measure was reasonably reliable, Cronbach's $\alpha = .72$.

For the Altered Inference task, because we are interested in the suppression of irrelevant inferences we focused on memory for the initial, incorrect inference, both in the Expected and Unexpected stories. Incorrect inferences that were not successfully inhibited should be responded to less accurately than when they were not inferred (the Expected condition). For these probes, people were more accurate for the Expected ($M = .86$) than the Unexpected condition ($M = .80$), $F(1,149) = 8.28$, $MSE = .04$, however, there was no difference in response time ($M = 3166$ and 3123 ms, respectively), $F < 1$. For the comprehension questions, people were more accurate in the Expected ($M = .94$) than the Unexpected condition ($M = .88$), $F(1,149) = 10.32$, $MSE = .03$. Although there were significant effects for both probe and question accuracy, we only use the difference between these conditions for probe accuracy in the subsequent regression analyses. This was because this measure more closely corresponded to the time in which people would have altered their inferences. Performance on this measure was less reliable, Cronbach's $\alpha = .44$, most likely due to the smaller number of observations per cell.

The correlation among these tests is reported in Table 3. The only significant correlation was between span and irrelevant text, with people having higher span scores showing less of a slowdown when irrelevant information was present. This correlation is generally consistent with previous claims that working memory may involve a strong inhibition component (e.g. Kane & Engle, 2000).

[2] For interested readers, response time and error rate data for filler trials are presented in Appendix B.

Table 2
Summary of individual difference test scores

	Mean	*SD*	Min.	Max.	Scoring
Operation span	13.3	9.0	0	49	Count score
Inhibition measures					
Irrelevant text	1.54	.22	1.13	2.56	RT proportion
Altered inferences	−.07	.28	−.67	.67	Accuracy difference

Table 3
Correlations of the ability tests

	Span	Irr. text	Altered inferences
Span	1.00		
Irrelevant text	0.23*	1.00	
Altered inferences	0.01	0.05	1.00

* Represents $p \leqslant .05$ with a Bonferroni correction.

Fan effect (learning)

From the learning rate data, we address predictions concerning the relation between working memory span, integration and interference. Overall, people took 2 to 10 study-test cycles to memorize the study sentences ($M = 5.0$; $SD = 1.6$). These data were entered in a regression analysis with Span, Irrelevant Text and Altered Inferences as independent variables. The results of the learning rate regression analysis are presented in Table 4. Overall, it was observed that the general learning rate was significantly related to the memory span and irrelevant text tasks. Note that this finding is at odds with those results reported by Cantor and Engle (1993) and Bunting et al. (2004) who did not find a relation between working memory span and overall learning rate. This may be due to differences in how the sentences were learned. Specifically, Cantor and Engle, as well as Bunting et al., used a set-by-set dropout procedure, whereas we continued to present all of the materials until they had all been memorized.

For the predictions regarding integration and interference, using the study list design, we first divided the learning data into the Single and Multiple Location conditions. These data are summarized in Table 5. These data were submitted to a 2 (Location Type) × 3 (Fan) repeated measures ANOVA. There were significant main effects of Location Type, $F(1,149) = 12.24$, $MSE = .214$, and Fan, $F(1,149) = 22.65$, $MSE = .217$, as well as a significant interaction, $F(1,149) = 6.91$, $MSE = .164$. Although the fan effect for learning was significant for both the Single Location, $F(1,149) = 5.79$, $MSE = .122$, and Multiple Location conditions, $F(1,149) = 20.61$, $MSE = .26$, it was larger in the Multiple Location condition, consistent with the idea that people integrate information into situation models, thereby avoiding interference.

The sizes of the fan effect in the Single and Multiple Location conditions were calculated (i.e., the average difference between the fan levels). These data were then entered into regression analyses to address the integration and interference predictions, respectively. The results of these analyses are presented in Table 4. The integration prediction concerns the Single Location condition. Because each subject only contributed one observation, reliability was measured by comparing subjects with the same or similar number of learning trials on fan level 1. Performance on the Single Location measure was not reliable, Cronbach's $\alpha = .09$, which is not surprising given that any variation is likely due to random variation because this information is learned so quickly

Table 4
Regression analyses results

	Overall		Single location		Multiple location		Retrieval inhibition	
	β	t	β	t	β	t	β	t
Learning								
Memory span	**−.32**	**−4.19***	−.08	<1	−.11	−1.29		
Irrelevant text	**.24**	**3.19***	.03	<1	**.18**	**2.15***		
Altered inferences	−.05	<1	.03	<1	.03	<1		
Response times								
Memory span			**−.20**	**−2.49***	**−.15**	**−1.82 ** **	.01	<1
Irrelevant text			−.05	<1	.12	1.46	**−.21**	**2.57***
Altered inferences			.08	<1	**−.13**	**−1.66 ** **	−.01	<1
Error rates								
Memory span			−.04	<1	−.10	−1.24	−.05	<1
Irrelevant text			**.28**	**3.62***	.12	1.47	−.01	<1
Altered inferences			**−.15**	**−1.92 ** **	−.10	−1.27	.06	<1

* $p < .05$.
** $.05 < p < .10$.

Table 5
Learning rate data (in number of study trials to perfect performance) for the fine-grained analysis

	Fan level		
	1	2	3
Single location	1.53	1.62	1.66
Multiple location	1.53	1.70	1.90

by everyone. Importantly, there was no significant relation between memorization in the Single Location condition and working memory span. This finding works against Cantor and Engle's (1993) first prediction that larger memory spans allow for more integration to occur.

The interference prediction concerns the Multiple Location condition, where learning was more difficult. Performance on the Single Location measure was more reliable, Cronbach's $\alpha = .47$. Learning rate was related to the Irrelevant Text inhibition measure. Essentially, people who had difficulty keeping irrelevant information from entering working memory had greater difficulty learning facts that produced interference and needed more regulation of this interference. Although this is consistent with the inhibition prediction, we cannot be sure that inhibition is involved during learning because we do not have a direct measure of this process during learning. Finally, once again, working memory span was not significantly related to learning rate performance. Again, this failure to find a significant difference is inconsistent with Cantor and Engle's (1993) predictions.

Fan effects (response times)

The response time data are summarized in Table 6. These data were submitted to a 2 (Studied–Nonstudied) × 2 (Location Type) × 3 (Fan) repeated measures ANOVA. There were significant main effects of Location Type, $F(1,149) = 163.77$, $MSE = 97532$, and Fan, $F(2,298) = 59.58$, $MSE = 125754$, as well as a significant Location Type × Fan interaction, $F(2,298) = 43.41$, $MSE = 100118$. Simple effects tests showed that the fan effect was significant for the Multiple Location condition, $F(2,298) = 84.94$, $MSE = 136587$, and marginally significant for the Single Location condition, $F(2,298) = 2.65$, $MSE = 89283$, $p = .07$. Thus, consistent with previous work, the fan effect was dramatically smaller in the Single Location condition.

In addition to the effects of primary interest, there was a significant main effect of Studied–Nonstudied, $F(1,149) = 107.46$, $MSE = 96534$, with people responding faster to studied probes (1577 ms) than to nonstudied probes (1701 ms). There was also a significant Studied–Nonstudied × Location Type interaction, $F(1,149) = 3.89$, $MSE = 48908$, $p = .05$, with the difference between the Single Location and Multiple Location conditions being smaller for the Studied probes (168 ms) than for the Nonstudied probes (208 ms). Simple effects tests showed that the effect of Location Type was significant for both the studied, $F(1,149) = 83.00$, $MSE = 76370$, and the nonstudied probes, $F(1,149) = 140.20$, $MSE = 70069$. There was also a significant Studied–Nonstudied × Fan interaction, $F(2,298) = 6.66$, $MSE = 63222$, with the fan effect being smaller for the studied probes (168 ms) than the nonstudied probes (267 ms). Simple effects tests showed that the fan effect was significant for both the studied, $F(2,298) = 25.31$, $MSE = 86700$, and the nonstudied probes, $F(2,298) = 55.92$, $MSE = 102276$.

Turning to the individual differences predictions, we looked at performance on the Single Location condition to assess the integration prediction, and the Multiple Location condition to assess the interference prediction. The reliability of the Single and Multiple Location measures were Cronbach's $\alpha = .37$ and .67, respectively. The response time data were submitted to a pair of regression analyses that are shown in Table 4. The analysis of the Single Location condition showed an effect of working memory span. People who had a greater working memory capacity showed less interference (thus reflecting greater integration). This is consistent with Cantor and Engle's (1993) integration prediction.

Turning to Cantor and Engle's (1993) interference prediction, for the Multiple Location condition, working memory span was marginally significantly related to the fan effect. People with higher span scores had smaller fan effects. This is also consistent with the interference prediction. In addition, the ability to inhibit inappropriate inferences was marginally significantly related to the size of the fan effect. Again, this is consistent with the inhibition prediction, although the fan effect is not a direct measure of inhibition.

Table 6
Response time (in ms) and error rates (in percentages) for the differential fan effect analysis

	Studied			Nonstudied		
	Fan level			Fan level		
	1	2	3	1	2	3
Single location	1452 (2.9)	1476 (1.8)	1468 (2.5)	1545 (2.8)	1618 (2.8)	1627 (3.8)
Multiple location	1459 (3.4)	1662 (3.1)	1778 (4.2)	1549 (3.1)	1867 (4.7)	2000 (7.7)

Fan effects (errors)

The overall error rate was 3.6% and these data are shown in Table 6. The error rate data were submitted to a 2 (Studied–Nonstudied) × 2 (Location Type) × 3 (Fan) repeated measures ANOVA. This analysis revealed a main effect of Location Type, $F(1,149) = 31.57$, $MSE = 34$, with people making fewer errors in the Single Location (2.8%) than in the Multiple Location condition (4.3%). There was also a main effect of Fan, $F(2,298) = 12.81$, $MSE = 34$, with the number of errors increasing with increased fan (fan level 1 = 3.1%, 2 = 3.1%; 3 = 4.6%). The Location Type × Fan interaction was also significant, $F(2,298) = 5.58$, $MSE = 39$. Simple effects tests revealed that the fan effect was significant for the Multiple Location condition, $F(2,298) = 12.54$, $MSE = 48$, but not the Single Location condition, $F(2,298) = 2.13$, $MSE = 25$, $p = .12$. This is consistent with the response time data.

In addition to the effects of primary interest, there was a main effect of Studied–Nonstudied, $F(1,149) = 5.43$, $MSE = 113$, with fewer errors for the Studied probes (3.0%) than the Nonstudied probes (4.2%). Also, the Studied–Nonstudied × Fan interaction was significant, $F(2,298) = 7.76$, $MSE = 32$, with the fan effect being smaller for the Studied probes (fan level 1 = 3.2%, 2 = 2.4%; 3 = 3.4%), $F(2,298) = 2.37$, $MSE = 30$, $p = .10$, than for the Nonstudied probes (fan level 1 = 3.0%, 2 = 3.7%; 3 = 5.7%), $F(2,294) = 16.74$, $MSE = 37$.

Regarding Cantor and Engle's (1993) predictions, the error rate data were submitted to a pair of regression analyses shown in Table 4. The reliability of the Single and Multiple Location measures were Cronbach's $\alpha = .56$ and .32, respectively. For the integration effect, the data in the Single Location condition is important. This condition was not related to working memory span. However, there were some significant relations with inhibitory ability, but in opposite directions. Specifically, people who performed worse on the Irrelevant Text task produced a greater Single Location fan effect, but, conversely, people who had more intrusions on the Altered Inference task produced a smaller fan effect. For the interference effect, looking at the Multiple Location condition, there were no significant relations.

Inhibition analysis (response times)

Consistent with the idea that people suppress related but irrelevant models, people responded marginally significantly slower to Experimental (1589 ms) than to Control targets (1555 ms), $F(1,149) = 3.26$, $MSE = 26602$, $p = .07$. The reliability of the this measure was Cronbach's $\alpha = .53$. The difference between these conditions was submitted to a regression analysis, as shown in Table 4. Inconsistent with Cantor and Engle's (1993) prediction, the retrieval inhibition effect was not related to memory span. Retrieval inhibition was only related to the Irrelevant Text task, also an inhibition measure. These tasks both involve keeping irrelevant information from entering the stream of processing. People who had difficulty keeping irrelevant texts from entering working memory also showed smaller retrieval inhibition effects.

Inhibition analysis (errors)

There were no differences in the error rates for the responses to the Experimental (7.9%) and Control targets (8.2%), $F < 1$. Although there were no significant effects here, these data were submitted to a regression analysis to parallel the other measures. As can be seen in Table 4, none of the effects were significant.

Discussion

The results of the experiment replicated a number of previous findings. First, the interference observed at retrieval was influenced by whether the information could easily be integrated into a single situation model. Facts that could be integrated based on a common location produced less interference than information that had a common object, but referred to multiple locations. This differential fan effect has been observed repeatedly (e.g. Radvansky, 1999b; Radvansky & Zacks, 1991). This further reinforces the idea that people are using situation models during retrieval. In addition, related but irrelevant models were suppressed during retrieval. This is also consistent with previous research (Radvansky, 1999b) and suggests that in some way irrelevant memory traces are suppressed as a means of regulating interference that is experienced during retrieval. Now let us consider the role of working memory capacity and the predictions made by Cantor and Engle (1993).

Working memory and long-term memory retrieval

The primary aim of this study was to look at how working memory span is related to long-term memory learning and retrieval in light of the three predictions made by Cantor and Engle (1993). As a reminder, these were that increased working memory span was related to: (a) increased ability to integrate information, (b) decreased experience of interference, and (c) increased inhibitory abilities.

Before turning to the three predictions, it should be noted that there was a strong relation between memory span and overall learning rate, with a greater memory span being related to faster learning. This is consistent with the general idea that working memory span scores are related to performance on the processing of information at the propositional textbase level (Radvansky & Copeland, 2004a). In this case, each sentence is a single proposition that needs to be learned, which will involve

this level of representation, even if later memory retrieval may focus on the situation model level.

Integration

In terms of integration, we used performance on the Single Location condition as an indicator. In this condition people could integrate facts into a single location-based situation model. While memory span was unrelated to the learning and the error rates in this condition, it was related to the response time data, with increased memory span corresponding to increased ability to integrate information. People who are better able to hold multiple pieces of information in working memory were more likely to be able to integrate them together. Thus, we found support for this prediction in only one of the three potential dependent variables.

Of greatest important is the fact that memory span is not related to Single Location memorization. This is important because this is the data where the relation between memory span and integration is most expected. That is, we would expect an influence of memory span on the ability to keep multiple pieces of information active during learning so that they can be integrated and stored in working memory. This experiment did not provide any evidence to support this theoretical idea.

Interference

In terms of working memory span's relation to interference, we use performance on the Multiple Location condition as an indicator. Again, in the Multiple Location condition a fan effect is observed with response time increasing with an increase in the number of competing situation models that enter the retrieval process. Again, memory span was not related to the learning rate and error data, but it was related to the response time data. Specifically, people with greater memory span scores had lower interference effects. This result is consistent with those reported by Cantor and Engle (1993) in that people who have a greater working memory spans are better able to manage sources of interference.

The failure to find a relation in the learning rate data is less troubling because this data is less sensitive to the retrieval processes that would be influenced by memory span. Furthermore, the lack of a significant relation with the error rate data is also not troubling because these data are very low, close to floor, with little room for variability.

Inhibition

In terms of working memory span's relation to suppression, we can look at performance on the retrieval inhibition measure. Again, inhibition was primarily assessed in this task through our negative priming measure. In contrast with Cantor and Engle's (1993) predictions, there was no indication that memory span was related to performance. That is, the amount of inhibition experienced during the retrieval of facts was unrelated to a person's ability to regulate the contents of their working memory.

That said, we also like to note that span was correlated with performance on the Irrelevant Text inhibition task, consistent with the idea that it may be related to some inhibitory abilities (e.g. Kane & Engle, 2000). Although there may be some form of inhibition operating in working memory, we were not able to muster any support for the idea that this extends to suppression operating during long-term memory retrieval.

Inhibition measures

In addition to working memory span, we had two inhibition measures. The Irrelevant Text task had people focus on relevant information and keep irrelevant information from intruding into working memory. Performance was related to overall memorization. Consistent with expectations, performance on the Irrelevant Text task was related to the Multiple Location condition where there were related but irrelevant memory traces. This was clearest in the learning data. Moreover, there was a significant relation with the retrieval inhibition. This is consistent with the idea that both of these tasks use inhibition to keep related but irrelevant information from entering the current stream of processing (Radvansky, 1999a).

For the Altered Inference task, in which an incorrect inference was removed, performance was marginally related to the response times in a similar way for the Single and Multiple Location conditions. This suggests that this task reflects interference management broadly conceived. The lower correspondence of this task, relative to the Irrelevant Text task, is consistent with the fact that there is no management of incorrect information in the fan effect task.

Conclusions

There is ample evidence to suggest that working memory capacity, as measured by span tests, is of critical importance to human cognition. Moreover, problems that are encountered in any aspect of cognition that are affected by capacity limitations are bound to have spill-over effects on tasks that involve long-term memory. Using a relatively large sample, we found some evidence that working memory capacity is related to long-term memory retrieval.

Of the three predictions laid out by Cantor and Engle (1993), we found some support for the ideas that

working memory span is associated with the ability to integrate information, although this was confined to dependent measures at retrieval, not learning. That is, when people are able to keep multiple pieces of related information active in working memory, and prior knowledge about the structure of situations and events in the world allow for this information to be readily integrated into situation models, people may do so. By integrating information, there are fewer sources of interference that can be experienced later during memory retrieval.

Furthermore, during retrieval people may need to regulate sources of interference from competing memory traces. In this case, these are related situation models. If working memory acts as an attention regulator, as suggested by prominent theories of working memory, such as Shallice's (e.g., 1988) supervisory attentional control theory and the inhibitory control theory of Engle and colleagues (e.g. Kane & Engle, 2000), and long-term memory trace selection during retrieval involves some attention process (e.g. Carrier & Pashler, 1995), then it is possible to see how working memory processes influence the effectiveness of long-term memory retrieval. Specifically, when there are multiple competing memory traces that are activated by a memory probe, people need to regulate these competing sources of information to select the most appropriate one(s) for the current task. The attention processes of working memory provide this sort of cognitive control.

However, there was no support in our study for the idea that working memory span involves a coordination of retrieval inhibition. Thus, while it has been suggested that inhibition plays a role in working memory processing to help coordinate the flow of information processing, we did not find evidence of this process here. Consistent with previous work (Radvansky, 1999a, 1999b; Radvansky, Zacks, & Hasher, 2005), we did find evidence of inhibition at memory retrieval, suggesting that the suppression of irrelevant, but highly activated memory traces is an important process in the service of retrieval. However, if inhibition is also operating in working memory, it appears to be a different sort of inhibition than that which we have observed in long-term memory retrieval. And such an inhibitory mechanism operating in working memory, would seem to be more confined to the regulation of the current contents of working memory, not the regulation of memory trace activation in long-term memory.

This may be because these different types of inhibition are playing different roles in cognition. Specifically, any inhibition that is operating in working memory serves to govern the contents of the current flow of thought. This inhibition would remove irrelevant thoughts that have entered working memory, and keep unwanted external information from entering working memory processes for which they are irrelevant. In comparison, any inhibition operating during long-term memory is performing a different service. Specifically, rather than regulating the contents of the current stream of thought, this sort of inhibition is guiding the selection of which portions of prior knowledge are relevant. Some of that prior knowledge may be highly activated, but is counter-productive in the current task, and so needs to be removed from the set of knowledge that is being brought to bear. This is most salient in the current experiment because people were creating situation models of related information. Each situation model represents a distinct state of affairs, and so must be stored in a more or less compartmentalized manner in long-term memory. However, during retrieval, if there are multiple models that are activated by the memory probe, their contents cannot be blended if the retrieval process is to be selected, such as might be done in a more schema abstraction task (e.g. Hintzman, 1986). As such, the related, but irrelevant models, need to be suppressed. This is a particular type of suppression that seeks to prevent activated competitors in memory from entering the stream of processing.

In sum, this work illustrates that working memory span can have important consequences for long-term memory performance. Consistent with Cantor and Engle (1993), this includes both the integration of information during learning, and the coordination of sources of interference during long-term memory retrieval. However, the evidence that working memory capacity is involved in integration reveals itself only at retrieval, not during learning where it would be more expected, weakening our confidence in the idea that working memory capacity, as measured by the operation span test, is an effective predictor of performance. These results are consistent with previous work that working memory span is not a consistent predictor of processing at the situation model level (Radvansky & Copeland, 2004a). Finally, we were not able to find support for the idea that working memory span is related to the operation of a suppression mechanism during long-term memory retrieval.

Appendix A

In addition to the working memory span and inhibition tests, we also gave people two other tasks that have been found to be related to situation model process, and which we thought could be related to performance on the fan effect task. Because these tasks were used in a more exploratory manner, we report them here rather than the main body of the text. One of these tasks was a situation identification test (Radvansky & Copeland, 2001). This measure reflects the facility with which people use situation models to make memory decisions. People in our study scored from 6 to 29 (out of 30, $M = 19.9$, $SD = 4.5$; Cronbach's $\alpha = .70$) on this task.

Another task we looked at was the ability to integrate situational information, using a task modeled after a study by Mani and Johnson-Laird (1982). Basically, performance should be easier for continuous descriptions than discontinuous descriptions. For this Integration task, people had a mean accuracy rate of .55 ($SD = .25$). People were more accurate in the Continuous condition ($M = .60$, $SD = .27$) than the Discontinuous condition ($M = .46$, $SD = .26$), $F(1,149) = 65.97$, $MSE = .023$. The accuracy difference between these conditions was used as the index for this measure. The difference in accuracy between these conditions for people in our study was from −.38 to .63 ($M = 0.14$, $SD = 0.21$) on this task. These data were used in additional regression analyses to see what these measures would account for in addition to our working memory span and inhibition measures. The results of these regressions are presented at the end of this Appendix.

For the Single Location condition, performance on the situation identification test was related to the ease of learning. People who are better at using situation models in memory required fewer trials to learn the study sentences that were integrated into a common situation. This is consistent with the idea that there are differences in the ability to integrate information, and that this is related to the ability to remember situation model information in general. In addition, there were marginally significant effects of Situation Identification in the Learning and Response Time data. People who had better memory for described situations also showed more integration during learning. Finally, there was a significant relation with Integration in the error rate data, with people who showed a larger integration effect producing a smaller fan effect, suggesting that they were better at integrating this information.

For the interference effect, looking at the Multiple Location condition, there were no new relations with these two measures in the learning rate or the response time data, however, for the error rate data there was a marginally significant relation with the situation identification task, with people who had better situation memory producing a smaller fan effect.

	Overall		Single loc.		Multiple loc.		Retrieval inhibition	
	β	t	β	t	β	t	β	t
Learning								
Memory span	**−.30**	**−3.90***	−.06	<1	−.10	−1.26		
Situation identification	**−.13**	**1.68****	**−.15**	**−1.74****	−.01	<1		
Integration	−.03	<1	−.08	<1	−.01	<1		
Irrelevant text	**.23**	**2.97***	.01	<1	**.17**	**2.09***		
Altered inferences	−.04	<1	.04	<1	.03	<1		
Response times								
Memory span			**−.19**	**−2.29***	**−.13**	**−1.69****	.01	<1
Situation identification			**−.14**	**−1.71****	−.08	<1	.02	<1
Integration			.07	<1	−.05	<1	−.05	<1
Irrelevant text			−.06	<1	.10	1.22	−.21	**2.58***
Altered inferences			**−.14**	**−1.72****	**−.13**	**−1.66****	−.01	<1
Error rates								
Memory span			−.03	<1	−.08	<1	−.03	<1
Situation Identification			−.03	<1	**−.15**	**−1.83****	−.12	−1.40
Integration			**−.17**	**−2.14***	−.12	−1.44	.05	<1
Irrelevant text			**.26**	**3.30***	.09	1.13	−.02	<1
Altered inferences			**−.15**	**−1.94***	−.09	−1.15	.07	<1

* $p < .05$.
** $.05 < p < .10$.

Appendix B

Response times (in ms) for the filler trials. The notation X–Y is used where the first number corresponds to the number of associations with object concept and the second number corresponds to the number of associations with the location concept. Corrected response times for the Single Location Condition are presented beneath the uncorrected times.

	Fan level		
	2–3	3–2	3–3
Studied	1925	2022	2018
Nonstudied	2082	2260	2362

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