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The influence of encoding manipulations on the dynamics of free recall

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Abstract In three experiments, the influence of various encoding manipulations on the dynamics of free recall were investigated. In Experiment 1, increasing study time increased the number of items recalled with no change in recall latency. In Experiment 2, a levels-of-processing manipulation increased the number of items recalled with no change in recall latency. Finally, in Experiment 3, massed presentations of items increased the number of items recalled with no change in recall latency; however, spaced presentations of items increased both the number of items recalled and recall latency. These results suggest that some encoding manipulations serve to increase the absolute strength of items, whereas other encoding manipulations create copies of target items. In both cases, the number of items recalled is increased, but differences arise in recall latency. These results point to the importance of examining both the number of items recalled and recall latency as means of better understanding encoding and retrieval processes that lead to successful remembering.

Keywords Recall · Memory

A great deal of prior research has shown that various encoding manipulations such as increasing study time, increasing depth of processing, and increasing item repetitions can increase the probability of recalling items from memory. However, relatively less work has examined how these same encoding manipulations influence the time taken to recall items, which is theoretically related to how individuals search for information from memory. The purpose of the present set of experiments was to evaluate the influence of various encoding manipulations on the time take to recall items in order to better understand the dynamics of retrieval from memory.

Examining recall latency can be particularly informative in terms of understanding how participants search for target items in free recall tasks. Recall latency refers to the time point during the recall period when any given item is recalled, and mean recall latency is simply the average time it takes to recall items. For instance, if items are recalled 6, 12, and 18 s into the recall period, mean recall latency would be 12 s. Prior work has suggested that recall latency distributions provide important information on the dynamics of free recall. In particular, prior work (Bousfield & Sedgewick, 1944; Indow & Togano, 1970; McGill, 1963; Roediger, Stellon, & Tulving, 1977; Rohrer & Wixted, 1994; Wixted & Rohrer, 1994) has suggested that cumulative recall curves are well described by a cumulative exponential

$$F(t) = N\left(1 - e^{-\lambda(t-c)}\right),$$

where $F(t)$ represents the cumulative number of items recalled by time t, N represents asymptotic recall, λ represents the rate of approach to asymptote, and c represents the initiation pause that typically precedes recall (see also Mickes, Seale-Carlisle, & Wixted, 2013; Rohrer, 1996). Thus, if given enough time to recall, N should roughly be equal to the number of items recalled. However, these items can be recalled either quickly or slowly, and this information is captured by λ. Specifically, when items are recalled quickly during the recall period, λ is relatively large, whereas when items are recalled slowly during the recall period, λ is relatively small. Thus, cumulative recall curves provide information not only on how many items are recalled, but also on how quickly those items are retrieved. Importantly, overall mean recall latency is simply the inverse of λ when the cumulative functions are perfectly exponential (e.g., Wixted, Ghadisha, & Vera, 1997), and thus it is possible either to estimate recall

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latency from λ or to compute it directly from the latencies associated with each recalled item.

Overall recall latency distributions are consistent with search models of free recall (Rohrer, 1996; Shiffrin, 1970). In these models, it is assumed that during recall, a retrieval cue activates a subset of representations in memory that are related to the cue in some fashion. This delimited subset is known as the *search set*, and during recall, item representations are sampled (with replacement) from the search set on the basis of a relative strength rule (Raaijmakers & Shiffrin, 1980; Rohrer, 1996; Shiffrin, 1970). Specifically, in search models of this type, the probability of sampling any particular item is equal to the strength of the item divided by the sum of all item strengths within the search set. After an item has been sampled, it must then be recovered into consciousness. In these search models, recovery of an item depends on the item's absolute strength rather than on its relative strength. Specifically, items whose strength exceeds some critical threshold will be recovered and can be recalled, whereas weak items that do not exceed the threshold will not be recovered (Rohrer, 1996). Important for models of this type is the notion that all items can be sampled, but only those items whose strength exceeds the threshold can actually be recalled. Thus, it is possible to differentiate these two aspects of recall (sampling and recovery). Finally, after an item has been recovered, it is subjected to a monitoring and editing process that determines whether the item is correct and recalled or incorrect and not recalled.

According to search models of this type, N reflects the number of target items in the search set whose absolute strength exceeds some threshold (i.e., the numerator in the relative strength rule; e.g., Rohrer, 1996). Recall latency and λ reflect the number of items within the search and, thus, reflect relative strength. The larger the search set, the longer, on average, it will take to recall any given item. Importantly, evidence for this type of model, as well as for a distinction between N and λ, comes from a number of studies that have manipulated aspects of free recall and found that some variables affect N but have no effect on λ, whereas other variables seem to primarily affect λ. For instance, Rohrer and Wixted (1994) manipulated list length and found that as list length increased, the number of items recalled increased (although probability of recall decreased) and recall latency increased (see also Unsworth, 2007). This is consistent with the notion that as list length increased, so did the size of the search set, resulting in a drop in probability of recall and an overall increase in recall latency. Further evidence consistent with this notion comes from a study by Wixted and Rohrer (1993) that examined the build and release of proactive interference. In this study, Wixted and Rohrer found that as proactive interference increased and the overall number of items recalled subsequently decreased, overall recall latency increased (see also Unsworth, 2009). Similar to the list length effects, this is presumably because as proactive interference built up, more items were included in the search set and relative strength decreased (i.e., the denominator increased in the relative strength rule). Thus, although N decreased, this was due to a change in relative strength, rather than to absolute strength, given that the search set was likely composed of both target items and intrusions from prior lists. Similar results have been found when examining directed forgetting (Bäuml & Kliegl, 2013; Spillers & Unsworth, 2011) and retroactive interference (Unsworth, Brewer, & Spillers, 2013; Unsworth, Spillers, & Brewer, 2012b). In each case, the number of items recalled decreased and recall latency increased, suggesting that these manipulations primarily influenced the size of the search set but did not influence the absolute strength of items within the search set.

Other research, however, has found that certain manipulations influence the number of items recalled but do not influence recall latency. For example, Unsworth, Spillers, and Brewer (2012a) found that context change manipulations (changing physical locations or changing mental context) reduced the number of items recalled but did not change recall latency. Unsworth et al. (2012a) suggested that changes in context resulted in a reduction in recovery probabilities, given that with a change in context, there are fewer overlapping contextual features between encoding and test. More germane to the present topic, Rohrer and Wixted (1994) manipulated presentation duration and found that this manipulation affected the number of items recalled but had no effect on recall latency. Specifically, as study time increased, so did the number of items recalled, but there was no change in overall recall latencies. Consistent with search model explanations of the presentation duration (e.g., Gillund & Shiffrin, 1984), this is because presentation duration influenced the absolute strength of each item but did not affect the relative strength of the items (i.e., all items had the same boost in strength, and thus, relative strength was unchanged). In another study, Wixted et al. (1997) manipulated the number of times items were presented during study (one, two, or three times) and found that more repetitions of an item led to greater recall, but increasing item presentations had only a small effect on recall latency, with recall latency increasing slightly. Similar to the manipulations of presentation duration, Wixted et al. argued that repeating items led to an increase in absolute strength and recovery probabilities but did not change relative strength and sampling probabilities.

It should be noted that this simple random search model assumes that items are randomly sampled and recalled. Clearly, there are nonrandom forces at play, resulting in serial position functions, probability of first-recall functions, semantic clustering, and lag-recency effects. However, the random search model has been validated by prior research suggesting that despite nonrandom recall, the overall interpretation provided by the random search model still holds (e.g., Rohrer, 1996; Vorberg & Ulrich, 1987; Wixted & Rohrer, 1994). Thus, the random search model is a useful tool for interpreting the effect of various manipulations on recall latency. More complex search models that allow for variable item strengths, interitem associations, and strategic search processes like search termination rules would likely make similar predictions as the simple random search model, but these models could also provide slightly different interpretations (e.g., Raaijmakers & Shiffrin, 1980). Important for the present study, examining the dynamics of free recall (using the random search model) can provide valuable information regarding how certain manipulations—in particular, encoding manipulations—influence recall performance.

Collectively, the above studies suggest that some manipulations serve to increase the size of the search set and reduce relative strength, leading to changes in both the number of items recalled and recall latency, whereas other manipulations serve to increase the absolute strength of items, leading to changes in the number of items recalled but no change in recall latency, given that the overall size of the search set did not change. The aim of the present study was to examine these notions in more detail. In Experiment 1, presentation duration was manipulated in an attempt to replicate and extend Rohrer and Wixted (1994). Experiment 2 used a levels-of-processing manipulation to change item strengths. Finally, Experiment 3 examined potential differences between massed versus spaced repetitions on recall latencies. Understanding under which conditions recall latency does and does not change will go a long way toward better understanding search models of free recall and validating recall latency as a measure of search set size.

Experiment 1

The purpose of Experiment 1 was to replicate and extend Rohrer and Wixted's (1994) findings that increases in presentation duration lead to subsequent increases in the number of items recalled but do not affect recall latency. Participants performed a delayed free recall task in which items were presented for 1 s per word or 4 s per word or participants were allowed to determine how long each word was presented on screen (e.g., Engle, Cantor, & Carullo, 1992; Kellas, Ashcraft, Johnson, & Needham, 1973). Specifically, with the presentation of each word, participants were allowed to determine how long the word stayed onscreen. When participants wanted to move onto the next word, they pressed the space bar. This condition should allow all participants plenty of time to engage in elaborate strategies to encode the words. It was expected that as presentation duration increased, so would the number of items recalled, with no change in recall latency.

Method

Participants and design

Participants were 34 undergraduate students recruited from the subject pool at the University of Oregon. Participants received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately 30 min. Words were nouns selected from the Toronto word pool (Friendly, Franklin, Hoffman, & Rubin, 1982). Words were initially randomized and placed into the lists, and all participants received the exact same lists of words. Eighteen lists of 10 words each were created. The experiment was a within-subjects design with each participant being exposed to all three conditions.

Procedure

Participants received a total of 18 experimental trials. On 6 trials, participants were presented with 10 words at a rate of 1 s per word. On 6 trials, participants were presented with 10 words at a rate of 4 s per word. On the remaining 6 trials, participants were presented with 10 words, and they were instructed to press the space bar to move the trial along. The three conditions were presented in a block format, with the different conditions presented randomly for each participant.

For each trial, participants were told that they would be presented with a list of words and that, following a brief distractor task, they would be prompted to recall the words. They were instructed to read the words silently as they were presented and to recall the words in any order they wished during the recall period. Each trial began with a *ready* signal onscreen, followed by a series of words presented one at a time in the center of the screen, with a 1-s blank screen in between the presentation of each word. In the 1-s condition, the words were presented onscreen for 1 s each. In the 4-s condition, the words were presented onscreen for 4 s each. Finally, in the unlimited condition, participants decided how long each word was presented onscreen, and when they wanted to move on to the next word, they were instructed to press the space bar. Following the list of words, participants engaged in a 16-s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each and were required to write the digits in descending order (e.g., Rohrer & Wixted, 1994; Unsworth, 2007). At recall, participants saw three question marks appear in the middle of the screen, indicating that they needed to begin recalling the words. Participants had 45 s to recall as many of the words as possible in any order they wished. Participants typed their responses and pressed Enter after each response clearing the screen. Recall latency was measured with respect to when participants pressed Enter after the word was typed (see also Mickes et al., 2013).

Results and discussion

Replicating prior research, as presentation duration increased, so did proportion correct, with a greater proportion of words recalled in the 4-s ($M = .69$, $SE = .03$) and unlimited ($M = .72$, $SE = .03$) conditions than in the 1-s ($M = .44$, $SE = .01$) condition, $F(2, 66) = 61.58$, $MSE = .01$, $p < .01$, partial $\eta^2 = .65$. Follow-up comparisons suggested that in both the 4-s and unlimited conditions, a higher proportion of items was recalled than the 1-s condition (both ps $< .01$), but there was no difference between the 4-s and unlimited conditions ($p > .36$). The fact that the 4-s and unlimited conditions did not differ was likely due to the fact that when in the unlimited condition, participants studied each word on average 3.77 s ($SE = 0.51$), thereby making those two conditions basically the same.

Next, the cumulative recall curves were examined. As is shown in Fig. 1, although more words were recalled in the 4-s and unlimited conditions than in the 1-s condition, all three conditions seemed to have a similar rate of approach to asymptotic performance. Specifically, as is shown in Table 1, there were only very slight differences between the conditions in terms of λ. To examine this in more detail, recall latency was directly computed for each condition. Similar to the examination of λ, the conditions demonstrated nearly equivalent recall latencies (1 s, $M = 13.90$, $SE = 0.67$; 4 s, $M = 14.03$, $SE = 0.52$; unlimited, $M = 13.80$, $SE = 0.50$), $F(2, 66) = 0.08$, $MSE = 5{,}590{,}748$, $p > .92$, partial $\eta^2 = .00$.

Overall, the present results replicate and extend prior research suggesting that as presentation duration increases, so does the number of items recalled, but this has no effect on recall latency (e.g., Rohrer & Wixted, 1994). These results are consistent with search models suggesting that increases in study time serve to increase the absolute strength of items leading to higher recovery probabilities without influencing the size of the search and sampling probabilities.

Table 1 Parameter estimates obtained from fitting the cumulative recall curves to a cumulative exponential for Experiment 1

Condition	c	λ	N	VAF
1 s	1.97	.072	4.66	.99
4 s	2.32	.067	6.81	.99
Unlimited	2.47	.066	7.21	.99

Note. c = initiation pause; λ = rate of approach to asymptotic performance; N = asymptotic performance; VAF = variance accounted for

Experiment 2

The purpose of Experiment 2 was to examine whether manipulating levels of processing would lead to changes in the number of items recalled without influencing recall latency in a manner similar to manipulating presentation duration. A great deal of work has demonstrated that the type of activity performed during encoding influences the probability of recalling items (e.g., Craik & Lockhart, 1972). Specifically, items are more likely to be remembered when encoding processes are focused on the item's meaning (deep processing) than when processes are focused on orthographical or phonological features (more shallow processing) of the item (e.g., Craik & Lockhart, 1972; Craik & Tulving, 1975). Thus, levels-of-processing manipulations are thought to potentially increase the absolute strength of items by increasing coding processes (e.g., Malmberg & Shiffrin, 2005; Raaijmakers, 1993). Similar to increasing study time, this predicts that the number of items recalled should increase with no change in recall latency. To examine this, participants performed a delayed free recall task in which, during encoding, participants either performed a shallow processing task (indicating whether the presented word contained the letter r) or a deep processing task (providing an animacy judgment on the word by indicating whether the word was alive or dead; cf. Malmberg & Shiffrin, 2005).

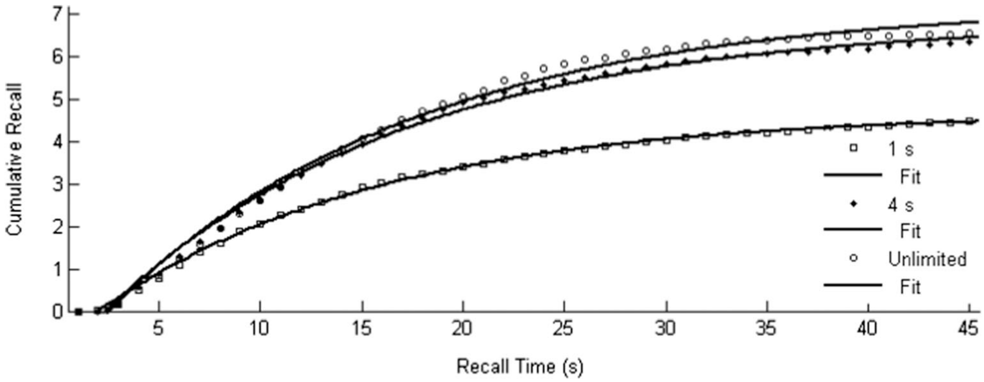

Fig. 1 Cumulative recall curves as a function of recall time and presentation duration condition. Symbols represent the observed data, and the solid line represents the best-fitting exponential

Method

Participants and design

Participants were 60 new undergraduate students recruited from the subject pool at the University of Oregon. Participants received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately 30 min. Words were nouns selected from the Toronto word pool (Friendly et al., 1982). Words were initially randomized and placed into the lists, and all participants received the exact same lists of words. Five lists of 10 words each were created. Participants were randomly assigned to either the encoding condition, with 30 participants per condition.

Procedure

For each trial, participants were told that they would be presented with a list of words and that, following a brief distractor task, they would be prompted to recall the words. They were instructed to read the words silently as they were presented and to recall the words in any order they wished during the recall period. Each trial began with a *ready* signal onscreen, followed by a series of words presented one at a time in the center of the screen for 4 s each, with a 1-s blank screen in between the presentation of each word. During the presentation of each word, participants were required to answer a question about the presented word. In the shallow condition, participants were presented with the target word, and below the target word, participants were asked "Is there an 'r' in this word?" In the deep condition, participants were presented with the target word, and below the target word, participants were asked "Is this word alive?" For both questions, participants indicated *yes* by pressing the F key or *no* by pressing the J key. Following the list of words, participants engaged in a 16-s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each and were required to write the digits in descending order. At recall, participants saw three question marks appear in the middle of the screen, indicating that they needed to begin recalling the words. Participants had 45 s to recall as many of the words as possible in any order they wished. Participants typed their responses and pressed Enter after each response, clearing the screen. Recall latency was measured with respect to when participants pressed Enter after the word was typed.

Results and discussion

Consistent with prior levels-of-processing research, a greater proportion of words were recalled with deep processing ($M = .53$, $SE = .02$) than with shallow processing ($M = .44$, $SE = .02$), $t(58) = 3.12$, $p < .01$, $\eta^2 = .14$. As is shown in Fig. 2, examining the cumulative recall curves suggested that more words were recalled with deep than with shallow processing, words were recalled at a similar rate in the two conditions. Specifically, as is shown in Table 2, there were only slight differences between the conditions in terms of λ. To examine this in more detail, recall latency was directly computed for each condition. Similar to the examination of λ, the conditions demonstrated nearly equivalent recall latencies (shallow, $M = 13.34$, $SE = 0.58$; deep, $M = 14.10$, $SE = 0.40$), $t(58) = 1.08$, $p > .28$, $\eta^2 = .02$. Like manipulating presentation duration, the present results demonstrate that levels-of-processing manipulations influence the number of items recalled but do not influence recall latency, suggesting that deep levels of processing lead to changes in absolute strength and changes in recovery probabilities without affecting the size of the search set and sampling probabilities.

Experiment 3

The two prior experiments demonstrated that various encoding manipulations influence the number of items recalled without changing recall latency. The purpose of Experiment 3 was to examine how increasing item presentations would influence recall latency. As was noted previously, Wixted et al. (1997) presented participants with a list of six items presented once, twice, or three times. Wixted et al. found that recall latency increased slightly with more item presentations but argued that the effects were small and, thus, the overall results were consistent with those from increasing presentation duration. However, a study by Bousfield, Sedgewick, and Cohen (1954) suggests that increasing the number of times an item is presented does increase recall latency. Specifically, Bousfield et al. presented participants with a list of 60 words one to five times. With increasing item presentations, they found a consistent decrease in rate of approach to asymptotic performance, which translates to an increase in recall latency. Thus, one study shows a marginal increase in recall latency with increases in item presentations, whereas another study demonstrates a larger increase in recall latency. One important difference between these studies is that in the Bousfield et al. (1954) study, the item repetitions were spaced but, in the Wixted et al. (1997) study, there was a mixture of massed and spaced repetitions dependent on the outcome of the random ordering. Thus, the differences could be due to differences in massed repetitions, which should be very similar to increasing presentation duration versus spaced repetitions, which could create additional copies of the items, leading to changes in the size of the search set. To examine this, participants performed a delayed free recall task in which items were presented once, twice, or three times and item repetitions were either massed or spaced.

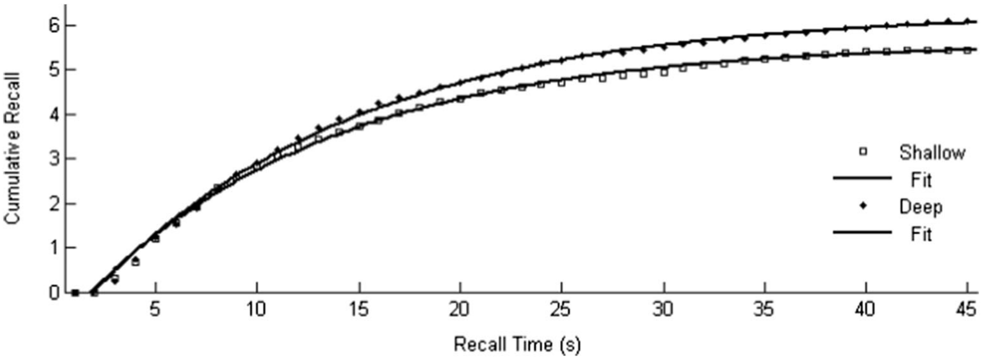

Fig. 2 Cumulative recall curves as a function of recall time and levels of processing. Symbols represent the observed data, and the solid line represents the best-fitting exponential

Method

Participants and design

Participants were 40 new undergraduate students recruited from the subject pool at the University of Oregon. Participants received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately 30 min. Words were nouns selected from the Toronto word pool (Friendly et al., 1982). Words were initially randomized and placed into the lists, and all participants received the exact same lists of words. Twelve lists of 10 words each were created. Items were presented once, twice, or three times (four lists per presentation) within subjects, with the order of presentations randomized. Participants were randomly assigned to either the massed or the spaced encoding condition, with 20 participants per condition. In the massed condition, item repetitions occurred in succession, with a 1-s blank screen in between. In the spaced condition, the entire list was presented and then presented again either once or twice.

Procedure

For each trial, participants were told that they would be presented with a list of words and that, following a brief distractor task, they would be prompted to recall the words. They were instructed to read the words silently as they were presented and to recall the words in any order they wished during the recall period. Each trial began with a *ready* signal onscreen, followed by a series of words presented one at a time in the center of the screen for 1 s each, with a 1-s blank screen in between the presentation of each word. Following the list of words, participants engaged in a 16-s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each and were required to write the digits in descending order. At recall, participants saw three question marks appear in the middle of the screen, indicating that they needed to begin recalling the words. Participants had 45 s to recall as many of the words as possible in any order they wished. Participants typed their responses and pressed Enter after each response, clearing the screen. Recall latency was measured with respect to when participants pressed Enter after the word was typed.

Table 2 Parameter estimates obtained from fitting the cumulative recall curves to a cumulative exponential for Experiment 2

Condition	c	λ	N	VAF
Shallow	1.80	.082	5.59	.99
Deep	1.92	.077	6.28	.99

Note. c = initiation pause; λ = rate of approach to asymptotic performance; N = asymptotic performance; VAF = variance accounted for

Results and discussion

As is shown in Fig. 4a, more presentations resulted in better recall, and when items were repeated, spaced repetitions led to better recall than did massed repetitions. These observations were confirmed with a 2 (condition: massed vs. spaced) × 3 (number of presentations) ANOVA with number of presentations as the within-subjects variable. There was a main effect of number of presentations, $F(2, 76) = 67.65$, $MSE = .01$, $p < .01$, partial $\eta^2 = .64$. There was also a significant condition × number of presentations interaction, $F(2, 76) = 3.95$, $MSE = .01$, $p < .05$, partial $\eta^2 = .09$, suggesting that there were no differences between the conditions when items were presented once or twice (both ps > .58), but when items were presented three times, spaced repetitions led to higher levels of recall than did massed repetitions ($p < .05$).

Turning to recall latency, an examination of the cumulative recall curves suggested that in the massed condition, items were recalled at a similar rate, but in the spaced condition, as item presentation increased, the rate of approach to asymptote decreased (see Fig. 4). Specifically, as is shown in Table 3,

Table 3 Parameter estimates obtained from fitting the cumulative recall curves to a cumulative exponential for Experiment 3

Condition	c	λ	N	VAF
Massed 1	1.74	.093	5.70	.99
Massed 2	1.86	.081	6.60	.99
Massed 3	1.87	.083	7.42	.99
Spaced 1	1.71	.091	5.67	.99
Spaced 2	2.03	.072	7.23	.99
Spaced 3	2.29	.067	8.54	.99

Note. c = initiation pause; λ = rate of approach to asymptotic performance; N = asymptotic performance; VAF = variance accounted for

there were only slight differences between the conditions in terms of λ in the massed condition, but in the spaced condition, λ decreased as a function of the number of repetitions. To examine this in more detail, recall latency was directly computed for each condition. The results are shown in Figs. 3b and 4. As can be seen, recall latency did not change as a function of the number of presentations in the massed condition, but in the spaced condition, there was a steady increase in recall latency with increases in the number of presentations. These observations were confirmed with a 2 (condition: massed vs. spaced) × 3 (number of presentations) ANOVA with number of presentations as the within-subjects variable. There was a main effect of number of presentations,

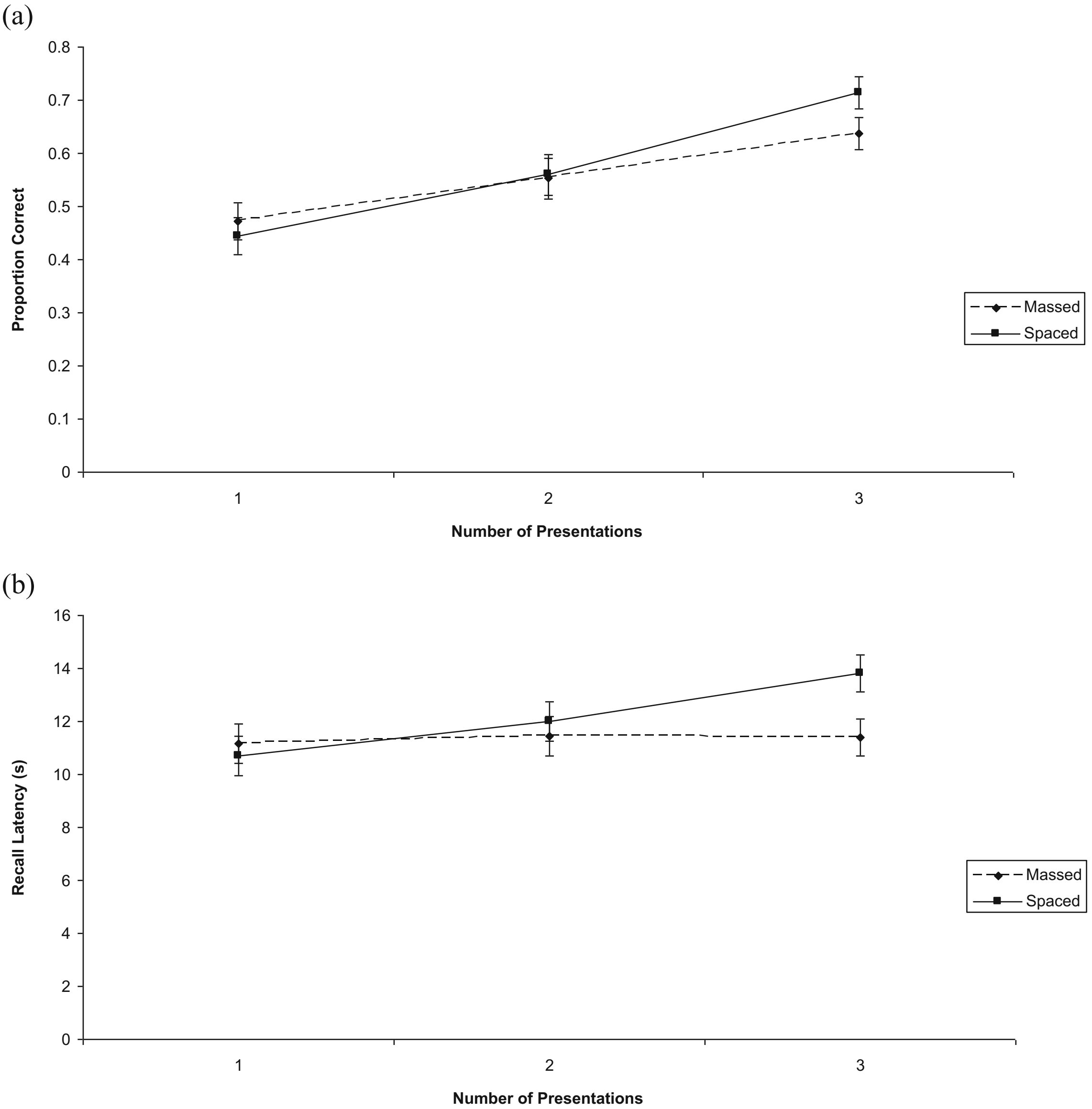

Fig. 3 **a** Proportion correct as a function of the number of presentations for massed and spaced repetitions. **b** Recall latency as a function of the number of presentations for massed and spaced repetitions. Error bars represent one standard error of the mean

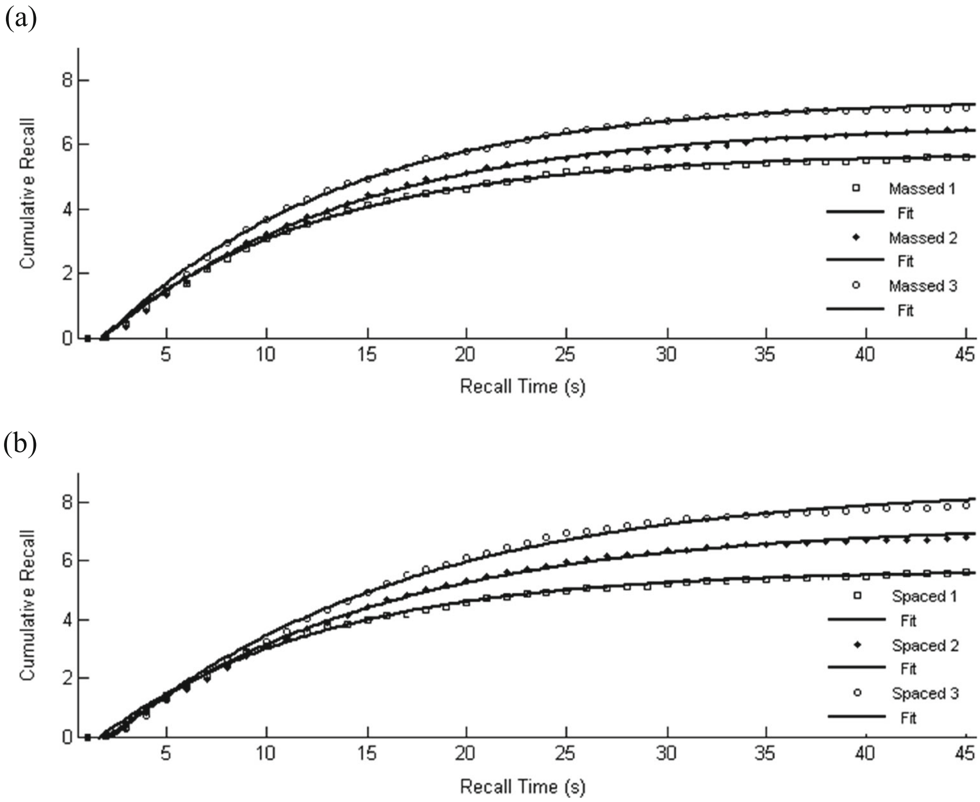

Fig. 4 **a** Cumulative recall curves as a function of recall time and number of presentations in the massed condition. **b** Cumulative recall curves as a function of recall time and number of presentations in the spaced condition. Symbols represent the observed data, and the solid line represents the best-fitting exponential

F(2, 76) = 4.34, *MSE* = 6,611,140, $p < .05$, partial $\eta^2 = .10$, such that with increases in the number of presentations, recall latency increased slightly (one, *M* = 10.92, *SE* = 0.53; two, *M* = 11.73, *SE* = 0.53; three, *M* = 12.62, *SE* = 0.50). This increase in recall latency with increases in item presentations replicates the slight increase observed by Wixted et al. (1997). Importantly, there was also a significant condition × number of presentations interaction, *F*(2, 76) = 3.27, *MSE* = 6,611,140, $p < .05$, partial $\eta^2 = .08$, suggesting that there were no differences between the conditions when items were presented once or twice (both *p*s > .60) but, when items were presented three times, spaced repetitions led to higher levels of recall than did massed repetitions ($p < .05$). Analyzing each condition separately suggested that there was no effect of the number of presentations on recall latency in the massed condition, *F*(2, 38) = 0.12, *MSE* = 4,068,998, $p > .89$, partial $\eta^2 = .01$, but there was an effect in the spaced condition, *F*(2, 38) = 5.44, *MSE* = 9,153,282, $p < .05$, partial $\eta^2 = .22$. These results suggest that massed repetitions act in a manner similar to increases in presentation duration and levels of processing by potentially increasing absolute strength and recovery probabilities without changing the size of the search set. Spaced repetitions, however, lead to better levels of recall with corresponding increases in recall latency, suggesting that the size of the search set increases with increases in the number of repetitions. These results help to reconcile prior research by suggesting that spaced but not massed repetitions lead to changes in search set size (cf. Bousfield et al., 1954; Wixted et al., 1997).

General discussion

The present set of experiments was concerned with evaluating under what conditions encoding manipulations lead to changes in the number of items recalled and, potentially, changes in recall latency. Consistent with prior research (e.g., Rohrer & Wixted, 1994), Experiment 1 showed that increases in study time lead to increases in the number of items recalled but no changes in recall latency. Experiment 2 demonstrated that a levels-of-processing manipulation changed the number of items recalled, with no change in recall latency. Finally, Experiment 3 demonstrated that massed repetitions lead to increases in the number of items recalled, with no change in recall latency, but spaced repetitions lead to increases in the number of items recalled and recall latency.

Collectively, these results suggest that various encoding manipulations (increases in study time, levels of processing, massed repetitions) serve to increase the absolute strength of items, which leads to increases in recovery probabilities, but do not change the size of the search set or sampling probabilities. However, other encoding manipulations, such as spaced repetitions, likely increase the number of copies of an item within a search set, which not only leads to a higher likelihood of sampling the correct items, but also leads to an overall increase in the size of the search set. That is, with spaced repetitions, it is likely that each presentation creates a new copy (with new contextual associations) and, thus as more copies are created, there are more items added to the search set. During retrieval, there are multiple copies of the same target, leading to a higher likelihood of sampling a correct item (and thus a higher subsequent probability of recall), but finding correct target items can be slowed given an overall increase in the size of the search set. Thus, the finding that recall latency increases with spaced repetitions is consistent with multiple-copies models of memory (e.g., Bower, 1967; Hintzman, 1988) and, in particular, with search models that suggest that massed repetitions serve to strengthen a single trace, whereas spaced repetitions can produce multiple copies of the item (Gillund & Shiffrin, 1984). The recall latency results for spacing are also broadly consistent with recent work suggesting that spaced (but not massed) repetitions increase the likelihood of reminding the participant of the earlier presentation of the item (Benjamin & Tullis, 2010; Delaney, Verkoeijen, & Spirgel, 2010; Hinztman 2010). In this case, it is possible that reminding not only serves to strengthen the prior item, but also creates a copy/new item (the reminder), and both the prior presentation and the reminder can be recalled. That is, Hinztman (2010) suggested that the second presentation of an item reminds the participant of the first presentation and the experience of being reminded also is encoded into memory, allowing both to be used for retrieval. A slightly different alternative comes from Delaney et al., who suggested that on the second presentation of an item, participants undergo a search for the prior presentation. If the prior item is found, then it is strengthened. If it is not found, the second presentation is encoded as a new item/copy. In either case, it would be expected that the overall search set would increase, given that new items/copies are being included in the search set, leading to higher levels of recall and an increase in recall latency, given an overall increase in the number of correct items.

The present results provide further supporting evidence for the use of examining recall latency in order to understand search processes during recall. In particular, the present results build on prior work by demonstrating dissociations between N and λ in the simple random search model. As was mentioned previously, prior work has shown that some manipulations influence N without influencing λ (i.e., study time, context change, levels of processing, massed repetitions). In these situations, it is assumed that the items are being strengthened, leading to higher recovery probabilities and more overall items being recalled. However, other manipulations lead to changes in both N and λ (i.e., list length, proactive interference, retroactive interference, directed forgetting, spaced repetitions), suggesting that the overall search set is being increased. In some of the latter situations, the search set is being increased because more target items are being included in the search set (e.g., list length and spaced repetitions), leading to increases in both the number of items recalled and recall latency. In other situations, the search set is being increased, because more irrelevant items (intrusions) are being included in the search set (e.g., proactive interference, retroactive interference, and directed forgetting), leading to decreases in the number of items recalled and increases in recall latency. Thus, within a very simple random search model, N and λ vary in theoretically meaningful ways, with some manipulations influencing N (with no change to λ), suggesting changes in absolute strength (and recovery), and other manipulations influencing both N and λ, suggesting changes in the size of the search set (and relative strength). Overall, the present results add to prior research by demonstrating the utility of examining recall latency and the dynamics of recall to better understand encoding and retrieval processes that lead to successful remembering. Future work should continue to examine conditions under which N and λ vary in theoretically meaningful ways.

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