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A Spacing Account of Negative Recency in Final Free Recall

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The well-known recency effect in immediate free recall reverses when subjects attempt to recall items studied and tested on a series of prior lists, as in the final-free-recall procedure (Craik, 1970). In this case, the last few items on each list are actually remembered less well than are the midlist items. Because dual-store theories of recall naturally predict negative recency, this phenomenon has long been cited as evidence favoring these models. In a final-free-recall study, we replicate the negative-recency effect for the within-list serial position curve and the positive-recency effect for the between-list serial position curve. Whereas we find prominent negative recency for items recalled early in the initial recall period, this effect is markedly reduced for items recalled later in the recall period. When considering initial recall as a second presentation of studied items, we find that the probability of final free recall increases as the number of items between initial presentation and initial recall increases. These results suggest that negative recency may reflect the beneficial effects of spaced practice, in which end-of-list items recalled early constitute massed repetitions and end-of-list items recalled late are spaced repetitions. To help distinguish between the spacing account and the prevailing dual-store, rehearsal-based account, we examined negative recency in continual-distractor free recall. Contrary to the dual-store account, but in accord with the spacing account, we find robust negative recency in continual-distractor free recall, which is greater for those items recalled early in output.

Keywords: spacing effect, testing effect, recency effect, free recall

The prominent recency effect observed in free recall is sharply attenuated when the experiment requires subjects to perform an attentionally demanding distractor task between study and recall. This well-known fact about human memory (e.g., Glanzer & Cunitz, 1966; Postman & Phillips, 1965) has been interpreted as showing that the retrieval cue or memory process that favors recall of recent experiences is easily disrupted, even by unrelated cognitive activity. By this view, one would expect that for a sufficiently long retention interval, final list items would completely lose their recency advantage, being recalled at the same rates as midlist items. However, when a list of items is initially recalled and then tested again after a very long delay, as in the final-free-recall procedure, memory for the final list items is actually worse than memory for earlier list items (Craik, 1970).[1] This so-called negative-recency effect has been interpreted as evidence for a strategic rehearsal process that favors early and middle-list items, giving those items a long-term memory advantage (Rundus, 1971; Tan & Ward, 2000). Because the last few items have fewer opportunities for rehearsal, removing the recency cue that favors those items, or "removing" them from working memory, reveals that they were actually encoded less effectively in memory than were items from the middle of the study list. As such, memory theorists have often cited the negative-recency effect as an important source of evidence for rehearsal-based models of recall (Crowder, 1976).

Whereas this account of a rehearsal-based, short-term store (STS) dominates past literature, in this paper, we focus on an intriguing alternative explanation, as raised in Craik (1970). Specifically, Craik suggested that because recalling an item after its initial presentation would act as a further encoding event, the distance or spacing between the initial encoding and the initial recall of an item could affect the probability of its subsequent retrieval on a final recall test. Given that recall probability increases with the spacing of item presentations (e.g., Melton, 1970; Madigan, 1969), final free recall of recency items may suffer relative to nonrecency items because of the relative proximity between encoding and initial recall. Although Craik raised this as an alternative account, neither he nor subsequent researchers have tested this spacing account of negative recency. Instead, the field

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[1] Negative recency has also been observed in serial and cued recall tasks (Cohen, 1970; McCabe & Madigan, 1971).

has embraced the interpretation of negative recency as reflecting a failure to transfer terminal list items from short-term to long-term memory. Here we reexamine the negative-recency effect in final free recall in an effort to distinguish between the STS, rehearsal-based account and the alternative spacing account, in which spacing is measured between initial encoding and initial recall.

We analyze final free-recall data collected as part of the Penn Electrophysiology of Encoding and Retrieval Study (PEERS). Subjects recruited to PEERS took part in three subsequently administered multisession experiments, comprising a total of 20 experimental sessions (of the 171 participants who completed the seven sessions of Experiment 1, 158 also completed six sessions of Experiment 2, and 151 completed the remaining sessions of Experiment 3). Subjects in these experiments studied and then freely recalled lists of 16 common words under various conditions (immediate free recall in Experiments 1 and 3; immediate, delayed, and continual-distractor free recall [CDFR] in Experiment 2). During half of the experimental sessions, subjects were also given a final-free-recall test, and the present paper is the first to report on these data. Experiment 3 differed from Experiment 1 in that a subset of subjects were asked to verbalize all words that came to mind during recall (externalized free-recall methods; Kahana, Dolan, Sauder, & Wingfield, 2005; Zaromb et al., 2006). Because intrusions are not a focus of the present study, and because the externalized recall procedure had no reliable effect on correct recall rates (Lohnas, Polyn, & Kahana, 2015), we aggregated final-free-recall data from Experiments 1 and 3.

Here we asked whether the spacing between a word's initial study and recall predicts negative recency on a delayed, final recall test. By analyzing the continual-distractor conditions in Experiment 2, we further examine the extent to which negative recency depends on rehearsal strategies that should be disrupted as subjects perform a demanding distractor task between successive, studied list items.

Method

Each session of Experiments 1 and 3 consisted of 16 lists of 16 words presented individually on a computer screen. As noted earlier, each study list was followed by an immediate free-recall test, and in a random half of the experimental sessions, a final-free-recall test followed the final (16th) immediate recall task. On each study list, words were either presented concurrently with a task cue, indicating one of two judgments (size or animacy) that the subject should make for that word, or with no encoding task, although the manipulation of encoding task was not considered here. There were three conditions: no-task lists (subjects did not have to perform judgments with the presented items), single-task lists (all items were presented with the same task), and task-shift lists (both types of judgments were used in a list, although each item was presented with only one judgment type). Because the encoding task had minimal effects on both recall accuracy and various measures of recall dynamics, we aggregated data across these conditions for the present report. We found nearly identical negative-recency effects for words in each of the encoding conditions.

Each word was drawn from a pool of 1,638 words that is available for download from the senior author's website. Earlier PEERS publications report details of list construction and the timing of item presentations. In brief, items were on the screen for 3 sec followed by a 1-sec, jittered interstimulus interval. If the word was associated with a task, then subjects indicated their response via a keypress. After the last item in the list, there was a 1,200- to 1,400-msec jittered delay, after which, a tone sounded, a row of asterisks appeared, and the subject was given 75 sec to attempt to vocally recall the just-presented items in any order. After the immediate free-recall test from the last list, subjects were shown an instruction screen for final free recall, informing them to recall all of the items from the preceding lists in any order. After a 5-sec delay, a tone sounded and a row of asterisks appeared. Subjects had 5 min to recall any item from the preceding lists. The audio recordings for both the immediate and final-free-recall tests were annotated offline using the laboratory's TotalRecall software to determine the precise sequence of recalls, including intrusions and the determination of interresponse times.

Experiment 2 was identical to Experiment 1 except for the manipulations described here. Subjects performed distractor intervals of varying duration. In each distractor interval, subjects solved math problems of the form $A + B + C = ?$, where A, B, and C were positive, single-digit integers, although the answer could be one or two digits. When a math problem was presented on the screen, the subject typed the sum as quickly as possible. The task was self-paced, such that a subject may have been presented with but not responded to a problem at the end of the distractor interval.

Subjects were given a monetary bonus based on the speed and accuracy of their responses. For the distractor intervals in the first two lists, one list had a distractor period after the last word presentation for 8 sec and the other had an 8-sec distractor period before and after each word presentation. In the remaining 10 lists, subjects performed free recall with five possible time durations for the between-item and end-of-list distractor tasks, such that 2 lists had each of the five conditions. As listed here, the first number indicates the between-item distractor duration and the second number indicates the end-of-list distractor, both in seconds: 0–0, 0–8, 0–16, 8–8, and 16–16. A 0-sec distractor refers to the typical, nonfilled duration intervals as described for Experiments 1 and 3.

For a more complete description of the methods used in Experiments 1–3, we refer the reader to earlier PEERS publications (Healey, Crutchley, & Kahana, 2014; Healey & Kahana, 2014, 2016; Lohnas & Kahana, 2013, 2014a; Lohnas et al., 2015; Long, Burke, & Kahana, 2014; Long, Danoff, & Kahana, 2015; Long & Kahana, 2017; Weidemann & Kahana, 2016). All raw data from the PEERS studies may be freely obtained from the senior author's web page (http://memory.psych.upenn.edu).

Results

We first examined final-free-recall data collected after the 16 immediate free recall (IFR) lists in each session of Experiments 1 and 3. Because retrieval of an item produces learning, we considered final free recall separately for those items that subjects did, and did not, initially recall during their IFR lists (cf. Craik, 1970). To test the hypothesis that spacing between encoding and retrieval influences final free recall, we partitioned the initially recalled items into those recalled in early and late output positions, defining early and late as the first half and last half of outputs, respectively.

This partitioning resulted in three classes of items: not-initially recalled, recalled early, and recalled late.

Figure 1 shows the probability of final free recall as a function of recency of encoding, considering both the list that each item came from and the item's serial position within that list, for a total of 256 (16 × 16) possible positions. To compute the probability of final recall separately for early and late recalls, we incremented a counter for each subject at each of the 256 presentation positions for items that were initially recalled early versus late. This counter then allowed us to normalize the final recall probabilities based on the fate of the items on their initial recall test.

Figure 1 illustrates three major effects in final free recall. First, subjects recall more items from recent than from remote lists. Second, subjects rarely recall items that they failed to recall in IFR. Third, we find a pronounced negative-recency effect that is seen primarily in recall of items that were recalled in early output positions during IFR. This negative-recency effect is attenuated for items recalled in late output positions. To provide a clearer picture of the interaction between negative recency and item type, we aggregated the data across all 16 lists to depict the overall serial position curves in Figure 2A. Here, one sees that the negative-recency effect is almost completely eliminated when the analysis is restricted to either not-recalled items or items recalled late in the recall period.

Dual-store models of memory search (e.g., Sirotin, Kimball, & Kahana, 2005; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Lehman & Malmberg, 2013) predict that end-of-list items suffer on a final recall test because they have fewer rehearsal opportunities. In the case of the Search of Associative Memory (SAM) model, as terminal list items arrive in STS, they probabilistically displace earlier list items. Thus, at the time of test, terminal list items predominate STS and will generally get recalled at the start of the recall period (i.e., first half of recalls). Because terminal items spend a shorter period of time in STS than do earlier list items, they have weaker long-term store (LTS) associations; thus, they are harder to recall on a final-free-recall test. This accounts for the overall negative-recency effect evident in Figure 2.

Although SAM predicts that subjects begin their recall by reporting items still active in STS, there is presumably variability in the persistence of items in STS that reflects overall goodness of memory encoding. To the extent that the durability of traces in STS also reflects effective storage of associations in LTS, we would expect that terminal items recalled early in output had greater durability in STS and greater associative strength in LTS. As such, terminal items recalled early in output should have a privileged status in LTS. However, the comparison between terminal items recalled early and late is complicated by the fact that those items may differ in other ways that are not related to their durability in STS. Because we do not observe whether terminal items that are recalled early would also have been recalled late, it is possible that some of those items remained in STS because of factors unrelated to their durability in LTS. Items recalled late in output should be weaker than those early recalled items that benefited from favorable LTS encoding but stronger than those early recalled items that benefited from stochastic factors unrelated to their LTS encoding strength. Of course, retrieval from LTS will also reflect both information that overlaps with STS durability as well as factors related to retrieval dynamics, such as having just recalled a semantic or temporal associate of the target item. Our finding that negative recency appears most strongly for terminal items recalled early in output is hard to reconcile with the classic dual-store interpretation. This is because durability in STS should be positively associated with the strength of LTS associations. However, an alternative interpretation is that later recalled terminal items have strong LTS representations but somehow dropped out of STS for other reasons.

Here we consider an alternative interpretation of negative recency that is based on the joint effects of output encoding and spaced repetitions. It is well known that recalling an item strengthens later memory for that item, often more strongly than intentionally studying that item for a later test (Roediger, Putnam, & Smith, 2011). It is also well known that spaced repetitions lead to better long-term retention than massed repetitions, with the beneficial effects of spacing repetitions often extending out to 20 or more intervening items (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Lohnas & Kahana, 2014b). If one considers the study of an item and its subsequent recall as repetitions of the same item, then spacing these repetitions would lead to superior recall, just as in the case of spaced study items. This idea is not original to the

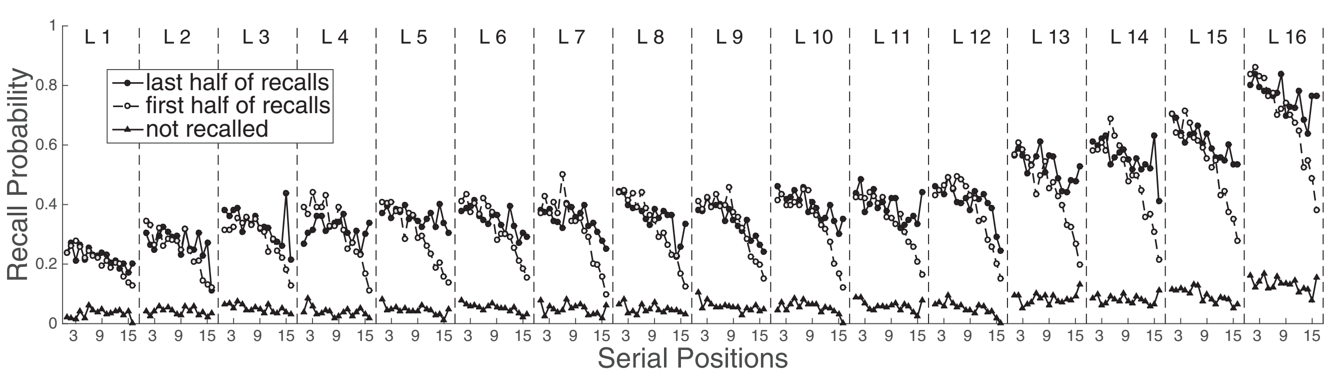

Figure 1. Final free recall as a function of recency of encoding. We consider three classes of items: those recalled in early output positions in IFR, those recalled in late output positions in IFR, and items that were not recalled in IFR but were recalled during final free recall. We observe a positive long-term recency effect across lists and a negative-recency effect within lists. The negative-recency effect appears greatest for the items recalled in early output positions.

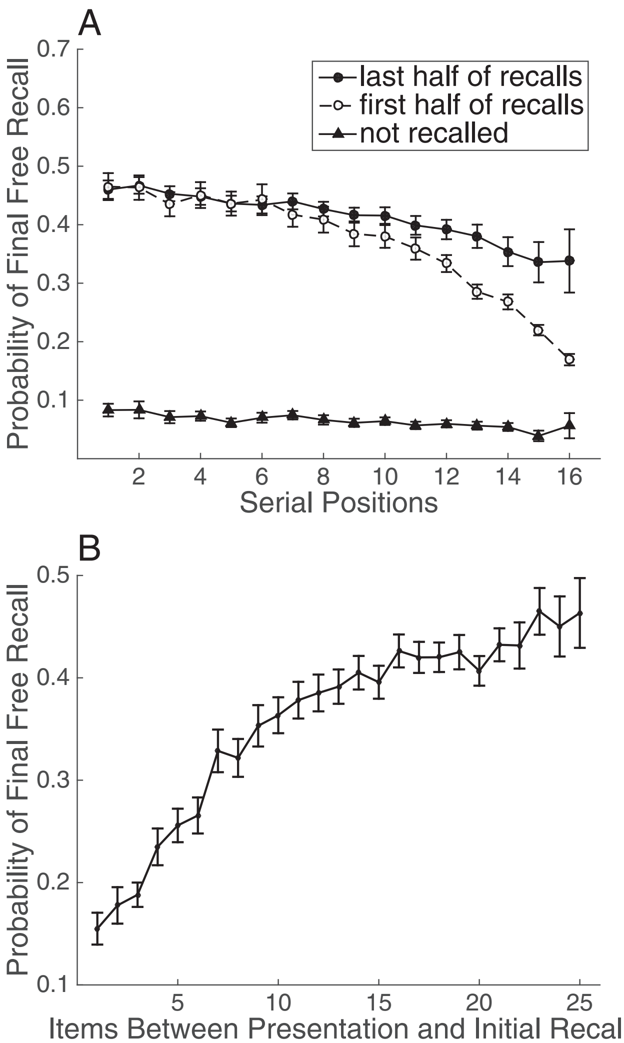

Figure 2. Negative recency in final free recall. (A) Within-list serial position curve. All 16 lists of Figure 1 are averaged together. The negative-recency effect persists for the first half of recall condition but is not present for the last half and not-recalled conditions. (B) Probability of final free recall as a function of the spacing between initial presentation and recall. As the number of items between the initial presentation and the initial recall of a word increases, the probability of recalling that item during final free recall increases. Error bars reflect Loftus Masson standard error of the mean.

present paper; it was offered by Craik (1970) as an alternative explanation in his classic article.

To test the spacing account, we examined the probability of recalling an item during final free recall as a function of the spacing (i.e., number of intervening items) between initial presentation and recall of the items. If learning takes place during recall, as suggested by a vast body of previous evidence (e.g., Izawa, 1966; Carrier & Pashler, 1992; Karpicke & Roediger, 2008), then the encoding and initial recall of an item constitutes two learning trials for which the traces are assessed in final free recall. If one further assumes that spaced practice leads to superior delayed recall as compared with massed practice (e.g., Karpicke & Roediger, 2008), then the negative recency in final free recall is just a manifestation of the spacing effect. End-of-list items will on average have shorter spacings than early list items, and those end-of-list items that are recalled early should have the shortest spacings of all. Figure 2B shows how final-free-recall performance rises monotonically with the spacing between an item during study and at initial recall, as suggested by the analogy with the spacing effect.[2] To assess the reliability of this effect, we computed the correlation between spacing and recall probability separately for each subject. Consistent with the spacing account, the distribution of correlation coefficients was significantly positive (mean correlation = 0.45, $t(169) = 24.02$, $p < .0001$).

To adjudicate between the spacing account and the rehearsal account of negative recency, we examined data from the delayed free recall (DFR) and CDFR conditions of Experiment 2. CDFR substantially curtails interitem rehearsal by having subjects perform a demanding distractor task after the presentation of each study item. Researchers have used CDFR extensively to test rehearsal accounts of recency and contiguity in free recall; indeed, this paradigm has been used specifically to examine the role of rehearsal in producing the negative-recency effect in final free recall. Given that previous studies (Bjork & Whitten, 1974; Tzeng, 1973) found mixed results, we reexamined the negative-recency effect in final free recall after both CDFR lists and DFR lists in which there was no interitem distractor.

To test the rehearsal-based account of negative recency, we compared this effect across IFR, DFR, and CDFR conditions. According to the rehearsal-based account, negative recency arises because final-list items receive fewer rehearsals than midlist items, and as such, the recency items have weaker associative representations in long-term memory. In CDFR, we would expect to see a significant disruption in interitem rehearsals as subjects in this task perform a demanding distractor task after each item presentation. As a result, we would predict substantially reduced negative recency in this condition. In IFR and DFR, subjects have similar rehearsal opportunities over the course of list presentation. However, neither group would be expected to allocate significant rehearsal to end-of-list items, either because the recall period will have begun (in IFR) or because rehearsal should be suppressed by the end-of-list distractor task (in DFR). In sum, the rehearsal account predicts reduced negative recency in CDFR and similar negative recency in IFR and DFR.

The spacing account also makes differential predictions regarding negative recency across the three distractor conditions. In IFR, those end-of-list items that subjects recall early in output have short study-test lags and consequently poor long-term retention, as seen in final free recall. In CDFR, subjects perform a demanding distractor task between items and at the end of the list, thereby increasing study-test lags for all items. Although the distractors

[2] The spacing final free-recall analysis was restricted to items recalled during the initial study-test lists. Thus, a subject who recalled the sequence of items from list positions 16, 15, 12, 1, and 3 would have "repeated" those items at spacings of 0, 2, 6, 18, and 16 items, respectively. For any item recalled on the initial study-test lists, we calculated the probability of final recall as a function of item spacing by dividing the number of recalled items with a given spacing by the number of possible recalls that had that spacing (the latter calculation is unique to each subject session because it is determined by the particular history of recalls on the initial study-test lists).

should degrade overall recall performance on the initial CDFR test (and they do), successfully recalled items should enjoy a spacing advantage on the final-free-recall test. Because the interitem distractor tasks preserve the relative spacings for all items, the overall negative-recency effect is predicted to be invariant to this manipulation. In DFR, the distractor task also increases the study-test lag for all items, but the absence of the interitem distractors results in a smaller spacing advantage for earlier list items and thus a reduction in the negative-recency effect. The logic here bears a resemblance to the analysis of recency effects in these three conditions. The retention-interval distractor task in both DFR and CDFR makes it harder to remember recent list items; however, the additional interitem distractors in CDFR rescues the recency effect in that condition by reducing interference from the weakened earlier list items.

For each subject, and in each condition, we quantified negative recency by the slope of a regression line fit to recall probabilities for the last seven serial positions. Figure 3 compares the negative-recency effect in each of the three distractor conditions and for each of the three initial-recall item categories: early recalls, late recalls, and nonrecalled items. Here we can see that negative recency was greater in the first half of recalls as compared with the last half of recalls in both IFR and CDFR conditions; however, this effect was significantly reduced in DFR. In CDFR, despite having to perform a demanding distractor task between study-item presentations, subjects exhibited a marked reduction in negative recency for those items that were initially recalled in later output positions as compared with those in earlier output positions (paired-sample $t(142) = 3.027$, $p < .005$). This finding argues against a rehearsal-based explanation of negative recency. Rather, the data appear more consistent with the interpretation that negative recency reflects poorer memory for items recalled soon after study because these items are akin to massed items in a spaced-practice manipulation. In DFR, items recalled at the beginning of the recall phase benefit most from the spacing provided by the distractor task, and as such, one would predict a reduction in the negative-recency effect for early recalls in this condition. Indeed, that is what is shown in our DFR data exhibited in Figure 3.

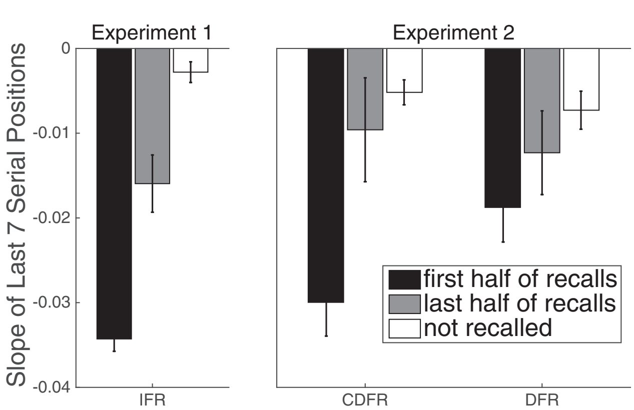

Figure 3. Negative recency in IFR, CDFR, and DFR. Left panel shows data from IFR (Experiment 1) and right panel shows data from CDFR and DFR conditions of Experiment 2. The magnitude of recency is measured by the slope of the last seven serial positions from the final-free-recall serial position curve for each subject. Error bars reflect ±1 *SEM*.

Comparing the slope of the recency effect across CDFR and DFR reveals a small but reliable decrease in negative recency (slope) in the DFR condition (paired-sample $t(142) = 2.058$, $p = .041$).

Conclusion

Investigations of serial position effects in free and serial recall tasks fueled the rise of rehearsal-based accounts of human memory and in particular helped to popularize memory models with two interacting storage systems: a short-term rehearsal buffer and a long-term associative memory. Although subsequent work has shown that continuous-memory models could more parsimonuously explain serial position effects and the dynamics of recall (Kahana, 2012), the negative-recency effect has remained a strong pillar of dual-store theory. This phenomenon particularly stood out because it was an unexpected prediction of early rehearsal-based memory models seemingly without precedent in the extensive earlier literature on free recall. Indeed, negative recency seemed so counterintuitive that it was not clear how it could arise from "standard" mechanisms.

However, recent years have seen a renewed focus on the importance of testing and recall as a memory modulator (McDermott, Arnold, & Nelson, 2014). Although this was long recognized by scholars of memory, it was widely neglected by both experimentalists and theorists until the dramatic demonstrations by Roediger and colleagues showing how testing effects can be even more potent than study in supporting long-term retention and access to previously experienced items and events (Karpicke & Roediger, 2008). Furthermore, the spacing effect, first reported in the late 19th century, has joined center stage with the testing effect as a potent modulator of memory encoding. Here we have shown how testing and spacing mechanisms, taken together, provide a very natural explanation of the negative-recency effect in free recall. This idea, first suggested in Craik's classic paper as an alternative account to rehearsal-based models, had been neglected in the intervening years. The spacing account makes a very specific set of predictions concerning the effects of early and late initial recall on the probability of final recall. Using a very large data set from the PEERS study, we were able to test and confirm these predictions. Furthermore, the spacing account makes novel predictions about how the differential negative recency of early and late initial recalls should vary with distractor manipulations as in delayed and continual-distractor tasks. Data from Experiment 2 confirm the predictions of the spacing-testing account of negative recency. Although we cannot entirely dismiss the role of rehearsal in these data, we cannot see any straightforward way that these findings would emerge from dual-store or rehearsal-based models.

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