2.11 Memory Search☆

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At our dinner table each evening my wife and I ask our children to tell us what happened to them at school that day; our older ones sometimes ask us to tell them stories from our day at work. Answering these questions requires that we each search our memories for the day's events and evaluate each memory's interest value for the dinner table conversation. Our search must target those memories that belong to a particular context, usually defined by the time and place in which the event occurred.

In the psychological laboratory, this task is referred to as *free recall* and is studied by first having subjects experience a series of items. Then, either immediately or after some delay, subjects attempt to recall as many items as they can remember irrespective of the items' order of presentation. Unlike other memory tasks, free recall does not provide a specific retrieval cue for each target item.

The free recall task, first introduced to the scientific literature by Kirkpatrick (1894), did not enter into mainstream use until popularized by prominent postwar experimental psychologists such as Endel Tulving, Ben Murdock, Gus Craik, and Murray Glanzer. In the hands of these scholars, free recall was shown to inform several major theoretical issues facing the cognitive analysis of learning and memory, including the possibility that specialized retrieval processes support access to very recent memories [those hypothesized to be in a short-term store; Glanzer (1972); Murdock (1967)], and the idea that long-term retention depends on organizational processes that evolve over the course of learning (Tulving, 1968).

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2.11.1 Recency and Primacy

By virtue of presenting each list item individually, we can ask how the serial position of an item affects its likelihood of being recalled. This leads us to the classic serial position analysis of free recall, which illustrates the principles of primacy and recency. When memory is tested immediately following the presentation of the final list item (immediate free recall, or IFR), subjects are much more likely to recall the last few items in the list than they are to recall earlier list items (the *recency effect*). When memory is tested following a filled retention interval (RI) (delayed free recall, or DFR), the recency effect is sharply attenuated. When a period of distracting activity not only follows the last studied item, but also follows every other item in a list (continual distractor free recall, or CDFR), the recency effect is restored. **Fig. 1** shows the serial position effects in IFR, DFR, and CDFR. These findings illustrate both the fragile nature of recency, in that it can be disrupted by a very brief filled delay (Postman and Phillips, 1965; Glanzer and Cunitz, 1966), and also the persistence of recency across longer time periods so long as the relative spacing of the items is maintained (Bjork and Whitten, 1974; Howard and Kahana, 1999).

The recency effect's vulnerability to a period of mental distraction contrasts with its resilience in the face of other manipulations that affect recall of early- and middle-list items. Consider, for example, the effect of varying the rate of item presentation. Subjects recall a larger proportion of early- and middle-list items when they are presented at a slow, as compared with a fast, rate. Yet, the rate of item presentation has little or no effect on recall of the last few recency items (Murdock, 1962). As another example, increasing the length of the study list from 20 to 40 items yields a marked reduction in recall of early- and middle-list items, but has no effect on recall of recency items (Murdock, 1962). Yet another experimental dissociation between recall of recency and prerecency items was reported by Craik and Levy (1970). They found that lists of semantically related items were better recalled than lists of unrelated items, but this effect was limited to the prerecency serial positions.

Dissociations between recall of recency and prerecency items, including those reported above, provided one important line of support for dual-store memory models (Atkinson and Shiffrin, 1968; Raaijmakers and Shiffrin, 1981). According to these models, recall of recency items reflects output of items that are maintained by rehearsal in a short-term store or buffer. By contrast, recall of prerecency items reflects search of a semantically organized long-term memory system.

To the extent that recency in free recall arises from accessibility of items in short-term store, one should see a marked reduction in recency in CDFR. The finding of recency in CDFR, termed the long-term recency effect (see **Fig. 1**), has thus proven to be a major challenge to dual-store theories. One way that dual-store theorists have responded to this challenge is by suggesting that separate mechanisms give rise to immediate and long-term recency (Davelaar et al., 2005).

The serial position analysis of free recall also illustrates the superiority of memory for the earliest list items, known as the *primacy effect*, a phenomenon that is readily apparent in both IFR and DFR, but attenuated in CDFR. The classic explanation for the primacy effect is that subjects, who are highly motivated to recall as many items as possible, will use the time following each item presentation to think back to earlier list items, a process termed *rehearsal*. When experimental conditions promote the opportunities for rehearsal, such as by giving subjects a long pause between successive items, the primacy effect is greatly enhanced. Similarly, when experimental conditions discourage rehearsal, such as in CDFR, or when subjects encode items without realizing that they will be given a subsequent memory test, primacy effects are greatly reduced (Kahana, 2012). Much of the work that has uncovered the importance of rehearsal in free recall comes from experiments that utilize the *overt rehearsal technique* in which subjects are asked to say, out loud, everything that comes into their minds as they try to memorize the words on the study list (Rundus, 1971; Brodie and Murdock, 1977; Tan and Ward, 2000). Studies using this method indicate that primacy items receive the greatest number of rehearsals and that subjects often continue to rehearse the primacy items until the end of the list. These studies also show that the number of rehearsals an item receives strongly correlates with that item's eventual recall.

2.11.2 Recall Dynamics

The serial position analysis of free recall provides a seductively simplistic view of a complex and dynamic retrieval process. Ultimately, what determines each point in the serial position curve is not a single probe of memory strength but rather the aggregation of probabilities over multiple successive recall attempts; each of these prior attempt being influenced by the set of prior retrievals and the associative structures both within the target list, and between the target list items and the previously experienced items stored in memory. Let us revisit the example of a dinner table conversation at which children attempt to freely recall events from their school day. First, they must think of some event to recount, a process that we will term *initiation*. Then, having accessed part of an experience, they need to search their memory for the elements of that experience which they will recall in succession. This stage is studied by measuring the statistical dependencies between retrieval transitions and by relating those dependencies to the attributes of the items being recalled. Finally, the children must eventually terminate their recall, either because they have run out of time (it is someone else's turn) or because they have exhausted the elements they are able to or wish to recall. Although termination is marked by a failure to continue making transitions, we consider it a distinct stage because of the different mechanisms that can lead to recall termination, as we discuss below. Although the laboratory free recall task differs from our real-life example in many important ways, the same three stages of initiation, transition, and termination characterize recall both in the laboratory and in everyday life. Below, we summarize some of the major findings concerning recall initiation, recall transitions, and recall termination. In subsequent sections, we use the analysis of recall dynamics to help inform our understanding of false recall, multi-trial organization of recall, and several other phenomena.

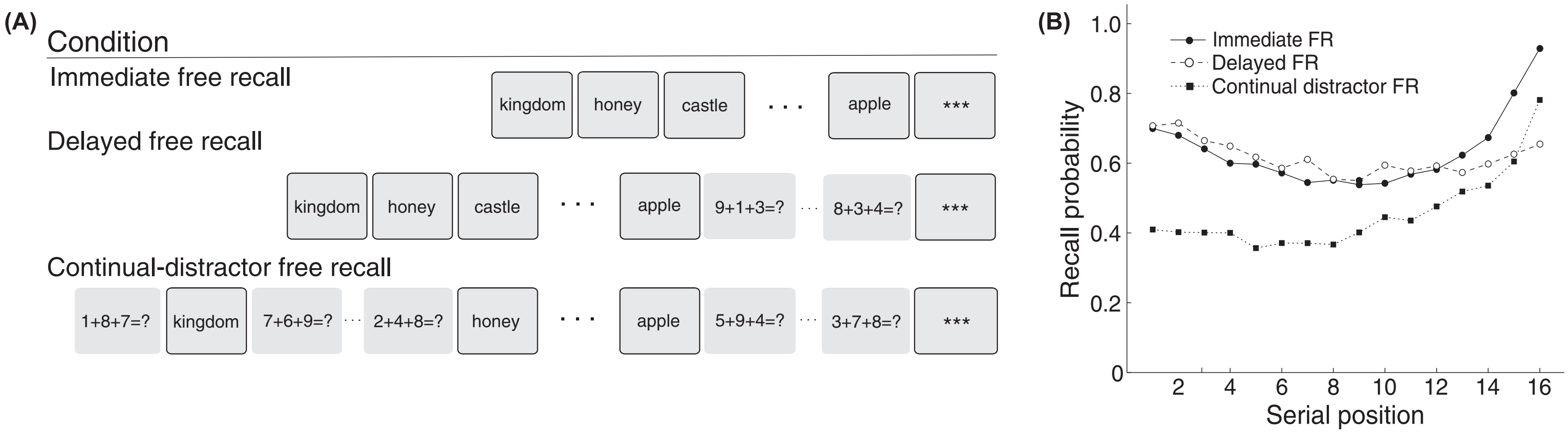

Figure 1 Serial position effects in immediate, delayed, and continual distractor free recall. (A) Illustration of presentation schedules in each of the three conditions. Arithmetic problems fill the distractor intervals. (B) Recency appears in both immediate and continual distractor free recall, but is sharply attenuated in delayed recall. Modest primacy is seen in both immediate and delayed tests. Primacy is likely attenuated in continual distractor free recall because the distractor task disrupts rehearsal. *FR*, free recall.

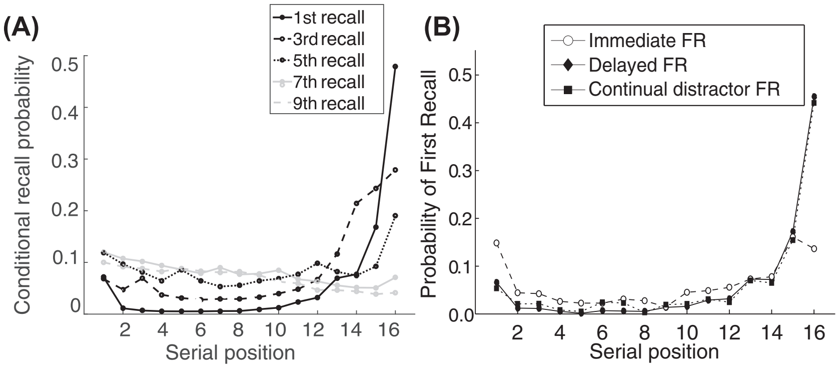

Figure 2 Recall initiation. (A) The probability of recalling a list item from each serial position in output positions 1, 3, 5, 7, and 9, conditional on serial position availability as computed on a trial by trial basis. (B) Probability of first recall (PFR) in immediate, delayed, and continual distractor free recall. *FR*, free recall. Data from Healey, M.K., Crutchley, P., Kahana, M.J., 2014. Individual differences in memory search and their relation to intelligence. J. Exp. Psychol. Gen. 143 (4), 1553–1569. http://dx.doi.org/10.1037/a0036306.

2.11.2.1 Initiation

Assuming that someone is going to recall at least one item, we can compute the probability that the first recalled item came from each serial position. As observed by Deese and Kaufman (1957) and Hogan (1975), subjects in IFR tasks exhibit a pronounced tendency to begin recall with one of the most recently studied items. This may be seen in **Fig. 2**A, which shows that the probability of first response is greatest for the final list item in IFR.[1] An immediate question that arises is whether subsequently recalled items are drawn from the same distribution as the first response. In other words, what is the probability of the second response coming from each serial position, conditional on the availability of a response at that serial position (this conditionalization is important as we know that neurologically intact individuals rarely repeat recalled items)? As may be seen in **Fig. 2**A, the probability distribution across serial positions changes markedly as a function of output position. Specifically, the strong tendency to sample recent items fades rapidly across multiple retrieval attempts. The reason for this change will be illuminated when we consider the dynamics of recall transitions in the next section.

Subjects' tendency to begin recall at the end of the list has been strongly linked to the *recency effect*, which is the increased probability of recalling items from the end of the list (Howard and Kahana, 1999; Healey and Kahana, 2014). The striking recency effect seen in the distribution of first recall probabilities function is greatly reduced in DFR, as shown in **Fig. 2**B. However, when distractors are interpolated between list items to equate the relative times between study items, and between the final study item and the test period, we see a recovery of the probability of initiating with the final list item almost to the same level as seen in IFR. In addition to the recency effect, one also observes a *primacy effect* in the probability of first recall (PFR), indicating that subjects are more likely to begin recall at the start of the list than at one of the middle serial positions (**Fig. 2**A and B).

The striking similarity of the PFR curves in IFR and CDFR shows that recency is determined by the relative, rather than the absolute, times between item presentations. In the language of the continual distractor task, recency depends on the relative durations of the filled *retention interval* (the delay after the final list item) and the filled *interpresentation interval* (IPI; the delay between the words on the list). For a given RI, increasing the IPI results in more recency and better absolute recall of the last item on the list. This is true of the recency effect seen in the overall serial position curve, as well as in the tendency to initiate recall with final list items. This dependence of recency on the relative, rather than the absolute, spacing of items has been taken as critical evidence against models that ascribe recency to the operation of a limited capacity short-term memory system (Howard and Kahana, 1999; Sederberg et al., 2008).

2.11.2.2 Transitions

Because the order of recall reflects the order in which items come to mind, recall transitions can help to reveal the organization of memory. Consider a subject who has just studied a 12-item list, comprised of the words: KINGDOM, HONEY CASTLE, APPLE, MONKEY, LILY, BUSHEL, ISLAND, JEWEL, EAGLE, FARMER, DIAMOND.

Then, upon an immediate recall test, the subject recalled DIAMOND, JEWEL, EAGLE, KINGDOM, CASTLE, and HONEY. Consistent with data on the recency effect, this subject initiated recall with the final list item. From DIAMOND, their first transition was to JEWEL, which is a strong semantic associate, and their next recall transition was to the contiguously presented item EAGLE. That people would transition in their recalls between items that are similar in meaning or neighboring in their list positions would

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[1] To calculate the probability of first recall, one tallies the number of times the first recall came from a certain serial position in the presented word list and then divides the tally by the number of times the first recall could have come from that serial position.

not have surprised Aristotle and other sages who maintained that similarity and contiguity were the two primary laws of association (Kahana, 2012).

Temporal Contiguity. Conditional probability analysis is a useful tool for quantifying and visualizing the predictability of the recall sequence on the basis of the similarity relations among items, either in time of occurrence, in meaning, or in another attribute of the experienced items. Kahana (1996) applied this method to quantify the effect of temporal contiguity on recall transitions. Specifically, this paper addressed how the probability of transitioning from an item studied in serial position i to an item studied in serial position j depends on the $lag = j-i$ between the items.[2] This measure is called the *conditional response probability as a function of lag*, or *lag-CRP*. **Fig. 3** shows lag-CRP functions obtained in IFR, DFR, and CDFR. In this figure, positive values of lag correspond to forward recalls; negative values of lag correspond to backward recalls. Large absolute values of lag correspond to words spaced widely in the list; small absolute values correspond to words spaced closely together in the list.

The lag-CRP function has two invariant characteristics. First, the function decreases systematically as absolute lag increases, approaching an asymptotic value at moderate lags; the asymptotic value depends almost exclusively on list length, with lower asymptotic values for longer lists. Second, for small absolute lags, the function is consistently asymmetric, with an approximately 3:2 ratio favoring forward recall over backward recall transitions. Although the contiguity effect is monotonically decreasing for lags ranging from one to five items, transitions to start- and end-of-list items can be more frequent than transitions to items of intermediate lag, especially for the first few output positions (Farrell and Lewandowsky, 2008). This effect is consistent with the idea that primacy and recency effects can provide a persistent boost to early- and end-of-list items (Polyn et al., 2009; Howard et al., 2009).[3]

Another striking feature of the lag-CRP is the persistence of contiguity across timescales (Howard and Kahana, 1999). Although one might reasonably expect that requiring subjects to perform a demanding arithmetic task between items would sharply disrupt a subject's tendency to transition among neighboring items at retrieval, the data show otherwise; contiguity is preserved despite the disruption of the encoding process. As shown in **Fig. 1**, the same 16 s of distractor activity was sufficient to sharply attenuate the recency effect in the same experiment.

Semantic Similarity. Whereas the contiguity effect illustrates the temporal organization of memories, it is also well known that subjects also make use of preexisting semantic associations among list items (Romney et al., 1993; Howard and Kahana, 2002b). This can be seen in people's tendency to make recall transitions among semantically related items, even in random word lists that lack obvious semantic associates. This *semantic similarity effect* can be seen in **Fig. 4**, which shows how the probability of making a recall transition among two items increases with their semantic relatedness. This effect is evident even at low levels of semantic similarity when lists lack any strong associates or any obvious categorical organization, providing evidence that recall transitions are driven by the relative semantic strengths among the stored items (Howard and Kahana, 2002a; Howard et al., 2007; Long and Kahana, 2016).

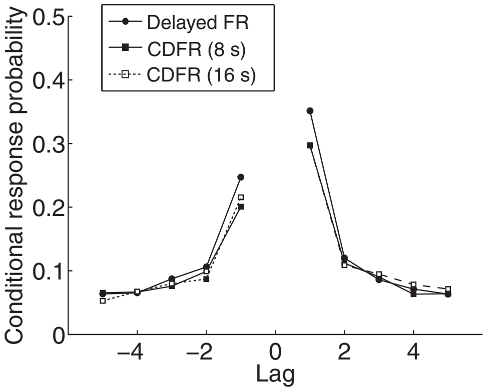

Figure 3 Contiguity in immediate, delayed, and continual distractor free recall (CDFR). The conditional response probability as a function of lag exhibits a strong contiguity effect in both delayed free recall and CDFR. The three CDFR conditions varied the interpresentation interval during which subjects performed an arithmetic distractor task between list items, as noted in the legend. *FR*, free recall.

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[2] To compute these probabilities, one divides the frequency of transitions to a given lag by the possible transitions to that lag, excluding transitions that are outside of the bounds of the list or transitions to already recalled items. One can also do more sophisticated corrections for autocorrelations in goodness of encoding, as discussed more fully in Healey et al., (2017).

[3] In immediate free recall, the lag-CRP exhibits a stronger contiguity effect for the first few recall transitions than for later recall transitions. This reflects bleed-in from the recency effect, where the last two or three study items tend to be recalled as a cluster prior to recall of other items. The lag-CRP function remains stable across later output positions, thus reflecting the general tendency to make transitions between neighboring items throughout recall. In delayed free recall, recency is reduced or eliminated, and the lag-CRP remains stable across all output positions.

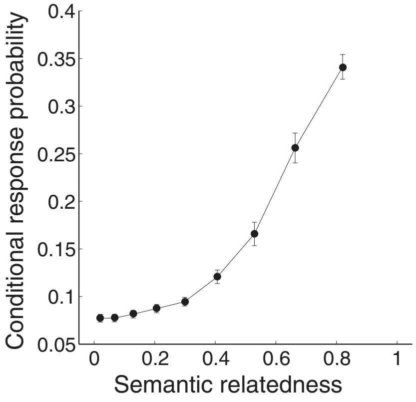

Figure 4 Semantic relatedness predicts output order in free recall. Subjects are more likely to recall items that are semantically related to the just-recalled item. Semantic relatedness was measured using latent semantic analysis. A word has a semantic relatedness of 1 with itself and a semantic relatedness of 0 with completely unrelated items. Error bars are 95% confidence intervals. Data from Miller, J.F., Weidemann, C.T., Kahana, M.J., 2012. Recall termination in free recall. Mem. Cogn. 40, 540–550.

2.11.2.3 Termination

Subjects terminate their recall for one of three reasons: because their time has run out, because they cannot think of any other items that were on the list, or because they have finished recalling all of the items. Understanding recall termination is particularly important, because whatever accounts for termination determines the total number of items that are ultimately recalled. Although previous research has revealed a great deal about how people initiate recall and how they transition between successively recalled items, less is known about the conditions that determine recall termination.

The first challenge in studying recall termination is in determining whether a subject is done recalling items. One can determine this either by asking subjects to indicate when they cannot recall any further items or by simply looking at the last item they recall within a fixed recall period. Given that most free recall studies give subjects a relatively long fixed interval (usually 2 min) to recall as many items as they can, the second approach allows one to consider a much wider range of data.

Miller et al. (2012) defined recall termination as occurring when the time between the last recalled item and the end of the fixed recall period was both longer than all of the IRTs on the current trial and exceeded a criterion of 12 s. This value was chosen to exceed the mean exit latency of 10 s reported by Dougherty and Harbison (2007) in an open-ended retrieval period where subjects pressed a button to indicate that they could not recall any more items.

Miller et al. examined how recall termination varied with output position and as a function of the nature of the last recalled item. Fig. 5 shows the conditional probability of recall termination following correct responses and intrusion errors as a function of output position during recall. In particular, Miller et al. considered two major types of intrusions: prior-list intrusions (PLIs), which refer to recall of items presented on a prior list but not on the target list, and extralist intrusions (ELIs), which refer to incorrect recall of an item that was not presented on any of the experimental lists. The probability of stopping is very low for the first few responses, but it rises as recall proceeds. Subjects are more likely to terminate recall following an intrusion (either a PLI or an ELI) than following a correct recall. This pattern holds true at all stages of the recall process, from early- to late-output positions.

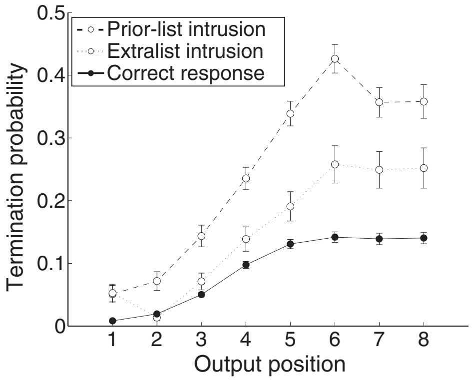

Figure 5 Probability of stopping recall. Probability of a response being the final response in a recall sequence for correct recalls, prior-list intrusions (PLIs), and extralist intrusions (ELIs) as a function of output position. Error bars represent ±*SEM*. Data from Data from Miller, J.F., Weidemann, C.T., Kahana, M.J., 2012. Recall termination in free recall. Mem. Cogn. 40, 540–550.

Assuming that additional list items remain to be recalled at the end of the recall period, and that the subject had ample time to retrieve those items, we may wonder why recall stopped at this particular point. One possibility is that the remaining items were simply not encoded well during the study phase. Perhaps the subject was so intensively thinking about some items that he or she effectively ignored the other items. Another possibility is that the nonrecalled items were encoded sufficiently to support recall under some conditions, but that the current retrieval cue is not effective in targeting those items. The analysis of recall transitions suggests how the latter might happen. Suppose that the last three recalled items were from list positions 3, 2, and 1, respectively. In this case, the last recalled item is a strong retrieval cue for items 2 and 3. However, since those items were already recalled, the last recalled item is not a very good retrieval cue, and recall is more likely to terminate. Alternatively, suppose that our subject recalled an item that appeared on a prior list but not on the current list (a PLI). In this case, we would expect a high probability that a subject would stop recalling because the just-recalled item is a very poor retrieval cue for any of the items on the target list. This is exactly what we have seen in **Fig. 5** and in data reported by Zaromb et al. (2006). This analysis suggests that subjects can sometimes find themselves in a mental cul-de-sac where the recently recalled items are poor cues for the remaining target items.

2.11.3 Organizational Processes

The previous section illustrated how recall transitions provide important clues to the organization of memory. The contiguity effect indicates that items studied in temporally contiguous positions tend to be clustered together in the recall sequence. Similarly, the semantic similarity effect illustrates that items that share semantic attributes tend to be clustered together in recall. Although we have emphasized contiguity- and similarity-based clustering, one can observe clustering for a wide array of other attributes. Below, we discuss three additional forms of organization in free recall: task clustering, spatial clustering, and affective clustering.

2.11.3.1 Task Clustering

Polyn et al. (2009) had subjects study lists in which items were encoded using two different tasks: as each word appeared, subjects were cued either to judge whether the item would fit into a shoebox or to judge whether the item is living or not living. During recall, items studied using the same encoding task tended to be clustered together. This can be seen in **Fig. 6**, which shows the interaction between *temporal clustering* (i.e., contiguity) and *task clustering*. The encoding tasks used in this experiment may be thought of as providing a context for each studied item, either adding additional attributes concerning size or animacy to the representation of each learned item, or biasing the meaning of each item based on the task being performed. Polyn et al. (2009) showed that the degree of task and semantic clustering interacts with temporal clustering insofar as similarity-based clustering (based on semantic or task similarity) is greater for contiguously presented items (Howard and Kahana, 2002b; Polyn et al., 2009).

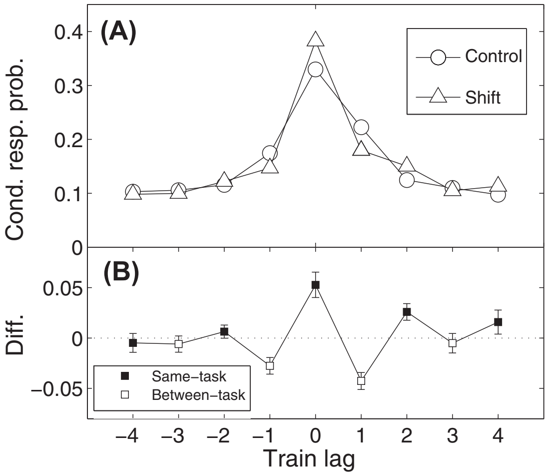

Figure 6 Interaction between task and temporal clustering. During switch lists, subjects made size or animacy judgments on trains of 2–6 sequentially studied items and were then given an immediate free recall test (Polyn et al., 2009). In other control list, all items were studied using the same orienting task (size or animacy judgments). Panel (A) shows an analysis of contiguity based on the number of trains (rather than the number of items) separating the two recalled items. A train lag of zero corresponds to recall of two items studied within the same train; a lag of ±1 corresponds to recall transitions between items studied in adjacent trains. The control curve is based on data from control lists, with items relabeled based on the same positions in the switch lists. (B) The difference in conditional probabilities between the relabeled control and the task shift conditions highlights a strong interaction between task and temporal clustering, with contiguity being enhanced when the transition is between items studied under the same encoding task.

This demonstration of task clustering is reminiscent of earlier work by Murdock and Walker (1969) who had subjects study lists in which some items were presented visually and others were presented auditorally. They found that subjects' responses were clustered according to the modality in which the items were encoded (i.e., visually presented items tended to be recalled together). In another early study, Hintzman et al. (1972) had subjects study lists in which some items were presented in a male voice and other items were presented in a female voice. They found that responses were clustered according to the gender by which the item was spoken.

2.11.3.2 Spatial Clustering

Just as the task characteristics or source characteristics of a judgment task can serve as context for a set of studied items, the spatial attributes of an environment can serve as context for material experienced within that environment (Smith, 1988). To elucidate the joint contributions of temporal and spatial information to memory search, Miller et al. (2013) asked subjects to play the role of a delivery person in a 3D-rendered virtual town (**Fig. 7**A and B). In a first phase of this experiment, subjects became familiar with the town layout, as well as the locations of the stores, by navigating to each of the target stores in succession. Subjects then began a series of "Delivery Days," each of which involved delivering a series of 12 objects, 1 to each of 12 stores. At the end of the delivery day, the screen went blank and the subjects were cued to freely recall all of the delivered objects. During each delivery day, subjects were cued to navigate to a series of randomly chosen, trial-unique, stores, and upon arrival at each store they were informed of the identity of the object they had delivered. After the final delivery day, subjects were asked to freely recall all of stores in the town (this was an additional probe of spatial memory). Miller et al. (2013) observed significant temporal clustering for the recalled items, significant spatial clustering for the recalled stores, and significant spatial clustering in the order of recalled items themselves (**Fig. 7**C). This latter effect provides insight into how memories are organized within a spatiotemporal context by demonstrating spatial organization of nonspatial memories embedded in a spatial context.

2.11.3.3 Affective Clustering

If emotional features are integrated with context and used as a retrieval cue, then recall outputs should be clustered by affective (emotional) valence. To explore whether subjects emotionally cluster their retrievals during recall, Long et al. (2015) calculated the likelihood of transitioning between words as a function of their emotional or affective valence. As shown in **Fig. 8**, subjects were more likely to transition between same-valence items than different-valence items.

Because similarities among same-valence words are likely greater than among words from different valence classes, it is important to rule out this potential confound. Long et al. showed that even after controlling for semantic similarity, subjects exhibited reliable affective clustering of their recalls. This finding further supports the idea that the affective attributes of remembered items contribute to the organizational processes during recall.

2.11.3.4 Moderators of Recall Organization

Both the contiguity effect and the semantic similarity effect have been documented in many diverse experiments. Successively recalled items are far more likely to come from nearby serial positions than from remote serial positions, regardless of whether items are presented visually or auditorally, whether they are presented quickly or slowly, whether people study long or short lists, whether people are encouraged to rehearse, or whether rehearsal is disrupted (for a review, see Healey et al., 2017). The semantic proximity

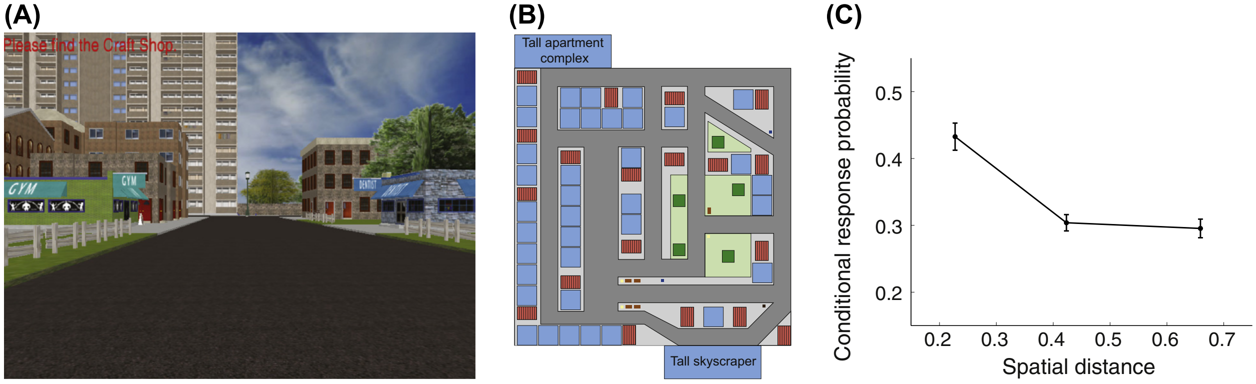

Figure 7 Spatial clustering in free recall of objects delivered in a virtual town. (A) View that a subject may see when navigating through the virtual town. (B) Overhead map of the town. (C) Objects that were delivered to nearby locations tend to cluster during recall, as seen in the conditional response probability as a function of spatial distance within the town. Data from Miller, J.F., Lazarus, E., Polyn, S.M., Kahana, M.J., 2013. Spatial clustering during memory search. J. Exp. Psychol. Learn. Mem. Cogn. 39 (3), 773–781.

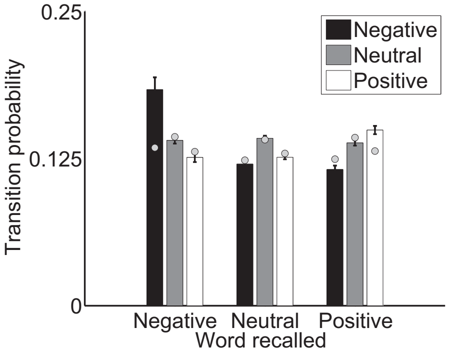

Figure 8 Affective Clustering. Following recall of an affectively positive or negative word, subjects are more likely to make transition to a word from the same affective valence category (black, negative; gray, neutral; white, positive). Error bars are standard error of the mean. *Gray dots* are the expected transition value derived from permuting the recall order within every list, session, and subject. Data from Long, N.M., Danoff, M.S., Kahana, M.J., October 2015. Recall dynamics reveal the retrieval of emotional context. Psychon. Bull. Rev. 22 (5), 1328–1333.

effect is similarly robust to numerous experimental manipulations (Howard and Kahana, 2002b; Polyn et al., 2009; Sederberg et al., 2010; Healey and Kahana, 2016; Long and Kahana, 2016). Here, we consider the interaction between semantic and temporal organization and discuss the effects of practice on both of these variables. Later we will consider the effects of aging and individual differences, which are two other moderators of the effects of recall organization.

Interactions between semantic and temporal clustering. The presence of strong semantic associations among list items could mitigate the need to rely on temporal associations to guide recalls. Yet, the contiguity effect is seen even when every item is drawn from the same semantic category (Miller et al., 2013), which should provide very strong semantic cues. McCluey et al. (2016) directly assessed the influence of such strong cues by having subjects study lists in which each item was drawn from the same category or each item was drawn from a different category. As shown in **Fig. 9**, although contiguity was modestly reduced in the same-category lists, it was still substantial and robust. That is, even when subjects have strong semantic associations to rely on, temporal associations among words still powerfully influence recall order.

Temporal and semantic associations can either be mutually supportive or competitive. Healey et al., (2017) compared the contiguity effect for transition types: (1) those in which there was a highly similar item studied in a neighboring list position, (2) those in which there was a highly similar item studied only in a remote list position, and (3) those in which there was no similar item present on the list. Each list in their study was constructed so that it had two pairs of high similarity words such that members of one pair were presented in adjacent serial positions and the members of the other pair were separated by at least two other items. As seen in **Fig. 9**, the presence of a strong associate modulated the lag-CRP in a systematic way, making it steeper when the associate was available at a near lag and making it shallower when the associate was available at a distant lag.

Practice effects. If contiguity arises from basic memory mechanisms, it should be evident on the very first list that an experimentally naïve subject attempts to recall, and it should persist over the course of practice while performing the recall task. Healey et al. (2017) examined contiguity in the first and last list recalled from an experiment in which subjects performed IFR on 12 different study-test lists each comprising 16 common nouns (see **Fig. 10**A). Contiguity was clearly present on list 1, but became steeper by list 12. Healey et al. further examined the change in the contiguity effect across a 24-session free recall experiment in which subjects

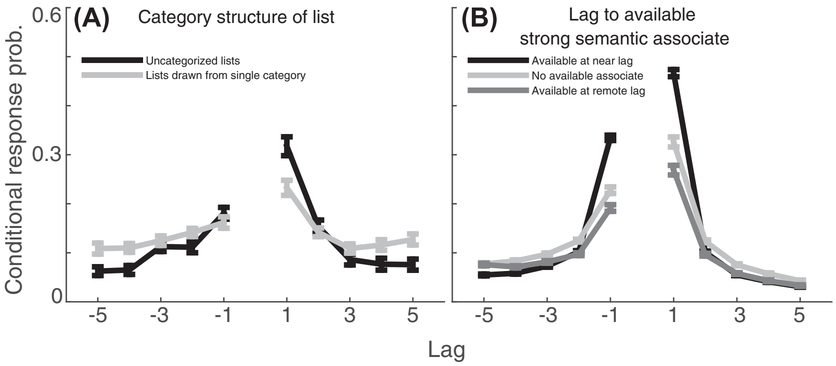

Figure 9 Interactions between semantic and temporal organization. (A) Contiguity in recall of uncategorized lists versus lists drawn from a single category in McCluey et al. (2016). (B) Transitions originating from items that had a strong associate available only at *lags* > 5 versus items that had a strong associate available at *lags* ≤ 2 versus items that had no strong associates available. Error bars represent $\pm$*SEM*. Adapted from Healey, M.K., Long, N.M., Kahana, M.J., 2017. Contiguity in Episodic Memory (submitted).

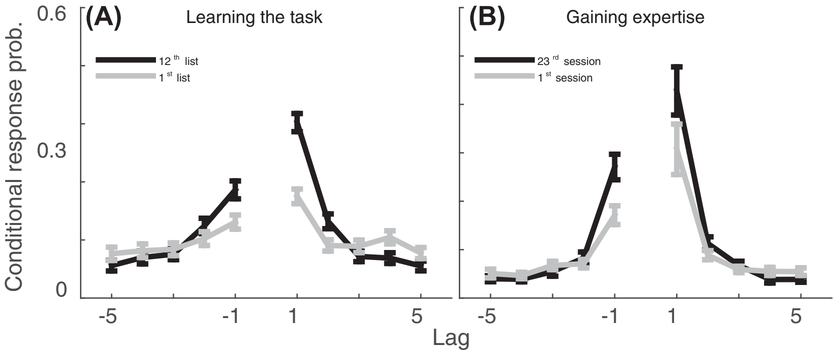

Figure 10 Changes in contiguity with practice. (A) Contiguity on list 1 versus 12 of the first task of a 24-session free recall experiment. (B) Contiguity on the 1st versus 24th session of the same experiment. Contiguity increases markedly with practice doing the task. Error bars represent ±*SEM*. Adapted from Healey, M.K., Long, N.M., Kahana, M.J., 2017. Contiguity in Episodic Memory (submitted).

performed DFR on lists of 24 items. Here, too, the contiguity effect is pronounced on both the first and last session and appears to increase with training (see **Fig. 10**B).

Compound cueing. Following recall of a given item, *j*, subjects tend to recall another item, *k*, whose temporal, semantic, spatial, source, and affective attributes are similar to those of item *j*. In all of the preceding analyses of recall transitions, we only considered the role of the single prior item *j* in predicting the nature of the transition to item *k*. Lohnas and Kahana (2014a) asked whether multiple prior items serve as part of the retrieval cue for the next recalled item. For example, perhaps the cue for item *k* would include two (or more) preceding items, *i* and *j*. This idea of compound cueing has substantial roots in the literature on human memory, going back to early theories of remote associations (e.g., Herbart, 1834). The idea of compound cueing has been employed in earlier research on serial and probed recall (Kahana and Caplan, 2002), associative recognition (Clark and Shiffrin, 1987), priming (Ratcliff and McKoon, 1988; Dosher and Rosedale, 1989), perceptual learning (Cohen and Sekuler, 2010), implicit learning (Jimenez et al., 1996), and false memory (Kimball et al., 2007). Lohnas and Kahana (2014a) showed that in free recall, the contiguity effect measured for transitions between successively recalled items *j* and *k* increased when the lag between the previously recalled items *i* and *j* was short. In other words, following recall of two temporally clustered items, the next recalled item is more likely to also be temporally clustered. They showed that this result was consistent with theories in which the cue for recall is not simply the just-recalled item, but the context defined by multiple prior recalls, as suggested by retrieved context theories of recall (Sederberg et al., 2008; Polyn et al., 2009; Lohnas et al., 2015b). Other theories, such as those based on chunking (Farrell, 2012), would likely make similar predictions.

Individual differences. The contiguity effect in free recall has been shown to be related to subjects' overall ability to recall list items. For example, older adults, who recall significantly fewer correct items than younger adults, exhibit reduced contiguity (Kahana et al., 2002). In contrast to their deficits in contiguity, older adults exhibit intact semantic clustering (Healey and Kahana, 2016). For a more complete picture of the age-related changes in memory performance, please see the chapter on *Memory and Aging* by C. Dodson, in this volume.

The magnitude of the contiguity effect correlates positively with both overall recall performance and psychometric intelligence measures (see **Fig. 11** from Healey et al. 2017). Temporal contiguity thus constitutes an aspect of recall organization that reliably

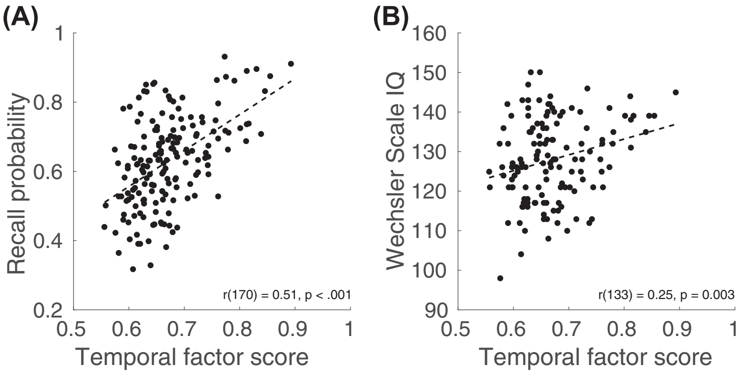

Figure 11 Individual differences in contiguity predict memory performance and the Wechsler Intelligence Scale (A) The correlation between temporal factor scores and overall recall probability. Temporal factor scores give the average percentile ranking the temporal lag of each actual transition with respect to the lags of all transitions that were possible at that time. (B) The correlation between temporal factor scores and intelligence as measured by the Wechsler Adult Intelligence Scale IV.

differs among individuals, and these individual differences appear to predict variation in overall memory performance and intelligence more strongly than other factors, such as primacy, recency, and semantic clustering (Healey et al., 2014).

Associative Asymmetry. An interesting feature of the contiguity effect is the strong forward asymmetry, with recall transitions being nearly twice as likely in the forward than in the backward direction. This more pronounced tendency to make forward transitions is also seen in ordered (serial) recall and in the pattern of errors observed when subjects are given a single list item as a probe to recall its successor (Kahana and Caplan, 2002; Caplan et al., 2006). However, the forward asymmetry effect in free recall contrasts with the finding that recall of paired associates is almost perfectly symmetrical, with subjects exhibiting nearly identical rates of forward and backward recall and with forward and backward recall being highly correlated at the level of individual pairs (Asch and Ebenholtz, 1962; Ekstrand, 1966; Kahana, 2002). It may be that temporally segregated word pairs (as in paired-associate memory tasks) are more likely to be encoded as separate meaning units than neighboring words in a list. Associative symmetry may thus be a property of well-integrated pairs that are broken due to the interference among items from different list positions (Caplan et al., 2006).

Encoding Manipulations. Here, we consider the question of encoding processes as a moderator of the contiguity effect. Nearly all studies to date have used intentional encoding instructions, so unfortunately, little is known about recall dynamics under conditions of incidental encoding. The one published study that used incidental encoding conditions (Nairne and Pandeirada, 2016) failed to observe reliable contiguity-based clustering. Because analyses of contiguity-based clustering rely on estimating conditional probabilities, they require far more data than traditional serial position–based or output position–based analyses. As such, it is hard to reject the hypothesis that incidental learning gives rise to a small, but significant, degree of temporal clustering.

Other studies (e.g., Long and Kahana, 2016) that have manipulated the type of intentional encoding have shown that temporal clustering is attenuated under conditions that focus attention on the semantic attributes of to-be-learned items. This is illustrated in **Fig. 12**, which shows how the contiguity affect is reduced when subjects were asked to judge the size or animacy of each studied item. This result could arise from any process that focuses attention on item-specific attributes and away from contextual or associative information that helps to bind items with their neighbors. Alternatively, the encoding task itself may consume resources that otherwise support associative memory encoding.

2.11.4 Recall Errors and False Memory

Recently, a great deal of attention has focused on the phenomenon of false memory: mistaken memory for an event that never occurred or that occurred but not as remembered. In the case of free recall, false memory may be said to occur whenever a subject recalls an item that was not on the study list. When making such intrusions, subjects are sometimes highly confident that the item they incorrectly recalled was presented as part of the study list.

The same memory processes that give rise to correct recalls could also give rise to errors (Schacter, 1999). Previously, we have seen how recency, temporal contiguity, and semantic similarity predict recall initiation and transitions. Here, we consider how these three variables influence intrusion errors in free recall.

2.11.4.1 Recency

Many of the intrusions that subjects commit during free recall are items that had been presented on earlier lists. These PLIs could have come from one, two, three, or more lists back. **Fig. 13**A shows the proportion of PLIs coming from lists of varying recency up to 10 lists back. For these analyses we only consider lists 11 and later, so that PLIs are available from all preceding lists in the analysis. The PLI-recency effect is similar in both IFR and DFR, as well as for younger and older adults, although older adults make a larger absolute number of intrusions than younger adults do (Zaromb et al., 2006).

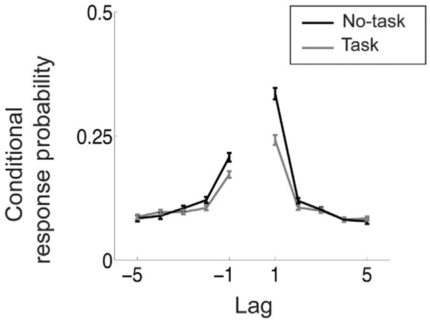

Figure 12 Lag contiguity as a function of encoding task. The lag contiguity analysis shows that subjects are more likely to make transitions between study neighbors, those items separated by a lag of ±1, than b lists. Error bars are ±1 SEM. Long and Kahana (2016).

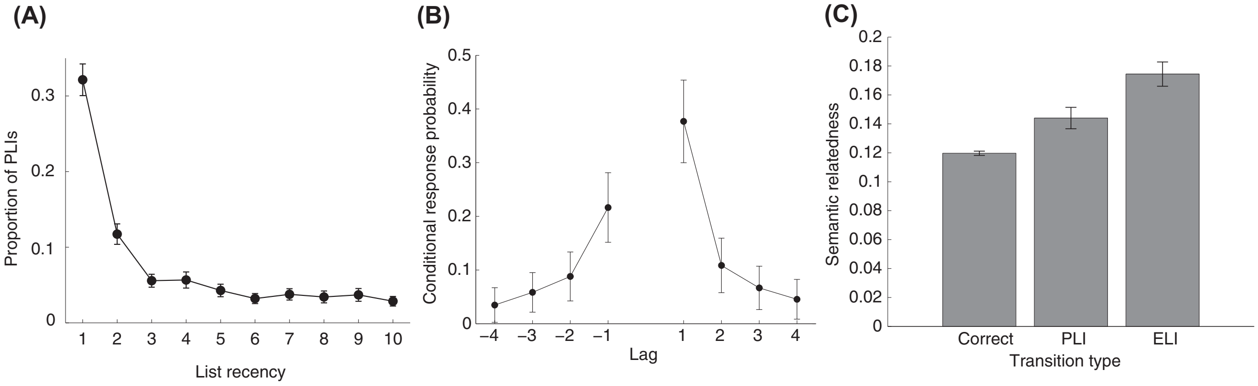

Figure 13 Recency, Contiguity, and Similarity Influence Recall Errors. (A) Proportion of prior-list intrusions (PLIs) coming from lists presented from 1 to 10 lists back. Because PLIs from 10 lists back can only occur on list 11 and later, we excluded the first 10 lists from these analyses. (B) Successive PLIs that came from the same original list tend also to come from neighboring serial positions. (C) Semantic relatedness values (measured using latent semantic analysis) for making transitions from a correct list item to either another correct item, a PLI or an extralist intrusion (ELI). Error bars represent 95% confidence intervals. Data from Miller, J.F., Weidemann, C.T., Kahana, M.J., 2012. Recall termination in free recall. Mem. Cogn. 40, 540–550 free recall database.

2.11.4.2 Temporal Contiguity

The temporal contiguity effect helps to focus memory search on those items that share a particular temporal context, such as that of a target list. Although this should support retrieval of target items, it can also explain how a single recall error can lead to further errors or recall termination. Specifically, if subjects recall an item associated with an incorrect context, such as would be the case for PLIs, then the contiguity effect should bias the next recall to the inappropriate prior list. To exploit this hypothesized mechanism for generating intrusions, Zaromb et al. (2006) gave subjects lists that contained mixtures of novel items and items repeated from earlier lists. They hypothesized that recalling a repeated item would tend to elicit PLIs because these items would harbor associations not only with their neighbors on the current target list, but also with their neighbors on their earlier presentation list. As predicted, they found that subjects had a significantly higher rate of committing PLIs following repeated than following once-presented items. More generally, one would predict that in any standard free recall experiment (without repeated items across lists), recall of a PLI would be followed by another PLI, and moreover that the other PLI would tend to come from a neighboring position in the prior list (a PLI contiguity effect). This prediction is borne out in the data, as shown in **Fig. 13**B.

2.11.4.3 Semantic Similarity

Assuming that prior-list items compete with current-list items for recall and that semantic information is an important retrieval cue, we would expect PLIs to have greater semantic relatedness to the just-recalled word than do correct recalls. Zaromb et al. (2006) sought to test this idea. To do so, they first needed a way of computing the similarities among all possible words used in their experiment. Pioneering work by Landauer and Dumais (1997) provided one solution to this problem. They used the cooccurrence of words in paragraphs to find a high-dimensional geometric representation of every word in the English language. Using their approach, termed, latent semantic analysis, one can derive a vector representation of every word. Similarities among words can be computed by calculating the cos θ between any two "word" vectors. This measure is just like a correlation, being 0 for unrelated items and close to 1.0 for synonyms. Zaromb et al. found that subjects exhibit a strong tendency to commit PLIs whose recall-transition similarity values are, on average, higher than those for correct recall transitions (**Fig. 13**C).

2.11.4.4 False Memory Paradigm

One popular method for studying false memory is the Deese–Roediger–McDermott (DRM) procedure in which subjects study lists of items that are semantically associated with a nonpresented critical word (Deese, 1959; Roediger and McDermott, 1995). When asked to recall these words, subjects find that they will often recall the critical word, even though it was not presented (see Brainerd and Reyna, 2005; Gallo, 2006; Roediger et al., 2001 for reviews). The finding that semantic proximity helps govern the dynamics of correct responses in free recall, as shown in **Fig. 13**C, suggests a possible mechanism for producing high levels of false recall in the DRM paradigm.

Although intrusions of the critical word during recall occur quite frequently in the DRM paradigm, intrusions of other words—including PLIs and ELIs—occur much less frequently (Kimball et al., 2007). The dual findings of a high rate of critical word intrusions and relatively low rates of other intrusions constitute an important puzzle for theories of memory. Theories of this phenomenon have either suggested that the critical nonstudied word becomes activated at study due to its associations to the studied items or that semantic cueing from multiple items during retrieval conspire to raise the level of intrusions of the critical item. There is ample evidence for both of these theories, and formal models that employ both mechanisms have been able to explain a wide range of results obtained from DRM studies (Kimball et al., 2007).

2.11.5 Repetition Effects

Repetition is an essential ingredient of learning and one that has been studied extensively in the free recall task. Here, we consider both repetition of items within a single list (intraserial repetition) and repetition of items across lists (multitrial recall). Although repetition usually refers to repeated encoding events, it can also refer to the role of recall itself as a repeated learning event, a topic that has returned to the center stage of memory research in recent years. We begin by discussing a classic study of the learning process carried out by Endel Tulving in 1962.

2.11.5.1 Subjective Organization

In studying the learning process in multitrial free recall, Tulving (1962) noticed that the sequence in which subjects recalled list items became increasingly consistent over repeated trials, even though the items were presented in a different and randomly determined order on each trial. Tulving quantified this tendency by showing that the correlation between the order of subjects' recalls increased across successive study–test trials. One interpretation of this finding is that over repeated trials, subjects created an organized representation of the list in memory. Because the organization was quite variable across subjects, Tulving referred to this finding as *subjective organization*. Tulving's demonstration of subjective organization in free recall of *random* word lists had a greater impact on the scientific community than did earlier demonstrations that semantic similarity strongly influences the order in which we recall lists of items. This was because Tulving's demonstration suggested that subjects not only use the organization present in the material, but that they also impose their own organization as a key dimension of the learning process. The appeal of organization theory led some researchers to reject associationistic models of free recall. As Tulving (1968) noted, "It looks as if the conceptual analyses of free recall have been developed not just in isolation, but almost in defiance of the traditional S[timulus]-R[esponse] models of behavior."

Klein et al. (2005) analyzed recall dynamics and subjective organization in two variants of a multitrial free recall task. In the *FR-varied* condition, subjects performed free recall on a list of words that was presented in a different random order on each of five study–test trials. In the *FR-constant* condition, the list was repeated in the same order on each trial. Across both conditions, the degree of subjective organization, as measured by *pair frequency*,[4] and the number of words recalled increased across successive study–test trials (**Fig. 14**).

We can also examine how the dynamics of recall changes across multiple study–test trials of the same list, and in particular, in terms of the contiguity effect and the semantic proximity effect. In the FR-constant condition, contiguity-based associations are reinforced across successive study–test trials, whereas in the FR-varied condition, contiguity-based associations vary from trial to trial, producing associative competition among items.

Klein et al. found a strong contiguity effect in all conditions and on all trials. As shown in **Fig. 14**A, the contiguity effect (as seen in the degree of temporal clustering[5]) decreased over trials in the FR-varied condition and increased over trials in the FR-constant condition. The opposite pattern was true of semantic associations: semantic clustering increased over trials in the FR-varied condition, but remains relatively flat in the FR-constant condition. Although the contiguity effect decreased significantly over learning trials in the FR-varied condition, it should be noted that lag was calculated based on the most recent list presentation. If the order of subjects' recalls reflects both the order of presentation on the most recent list and also the orders on earlier lists, then the contiguity effect as defined based on the most recent list should decrease over trials. Klein et al.'s study shows how associative information from prior study and test trials strongly influences the way people recall items on the current list. The finding that, even in random word lists, semantic clustering increases with trials in the FR-varied condition helps to explain the phenomenon of subjective organization in terms of basic associative processes (Tulving, 1966; Schwartz and Humphreys, 1973).

2.11.5.2 Intraserial Repetition and Spacing

Here, we consider the problem of intraserial repetition in free recall. Repeating a target item within a list will increase its chance of being recalled simply because there are now multiple retrieval routes to the target. Or, stated another way, there are now multiple, identical targets in memory, and you only need to find one of them to get credit for recalling the target item. However, the beneficial

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[4] Among the numerous methods that have been proposed to measure subjective organization, *pair frequency* has been lauded for its simplicity and good statistical properties (Sternberg and Tulving, 1977). Pair frequency is defined as the number of observed intertrial repetitions of word pairs minus the number of intertrial repetitions of word pairs expected to occur by chance. An intertrial repetition is defined as a pair of studied words that were recalled successively on trials t and $t+1$. Such pairs are considered repetitions even if the order of recall differs across trials (e.g., if the subject recalls …, *key*, *rose*, … on Trial 4 and then recalls …, *rose*, *key*, … on Trial 5).

[5] It is often convenient to quantify clustering effects with a single number. Polyn et al. (2009) introduced a percentile-based measure for this purpose. This measure produces a percentile rank for each recall transition, which reflects the temporal proximity or attribute similarity of the two recalled items in the study list, taking into account that already-recalled items are no longer available for recall. Subjects who exhibit strong temporal or semantic organization produce high temporal and semantic clustering scores. By quantifying each form of clustering, one can more easily determine whether the different types of clustering interact with one another or with experimental variables.

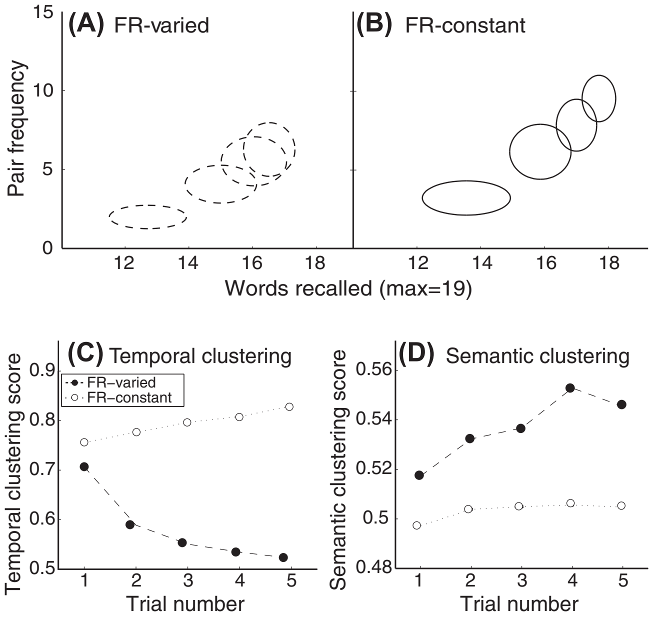

Figure 14 The relations between organization, learning, and recall dynamics. In a multitrial free recall experiment, subjects studied lists whose order of presentation was either (A) permuted pseudorandomly on each trial (FR-varied condition) or (B) kept constant across trials (FR-constant condition). Pair frequency indicates the consistency of recalls across repeated trials (see text). *Ellipses* indicate regions of 95% confidence in the data. (C and D) When list order was randomized at the start of each learning trial (FR-varied condition), temporal clustering of recalls decreased over trials and semantic clustering increased. When list order was kept constant on each trial (FR-constant condition), temporal clustering increased slowly over trials, and semantic clustering remained relatively constant. Reanalysis of data from Klein, K.A., Addis, K.M., Kahana, M.J., 2005. A comparative analysis of serial and free recall. Mem. Cogn. 33, 833–839, carried out by L. Lohnas.

mnemonic effects of repetition depend critically on how those repetitions are spacing within a list. Specifically, spacing the repetitions within a target list leads to substantial mnemonic gains over repeating items in massed fashion. Although documented in a wide range of memory tasks, the spacing effect is particularly strong in free recall, where the probability of recalling a repeated word often increases monotonically to spacings of 20 or more items (Cepeda et al., 2006; Delaney et al., 2010; Donovan and Radosevich, 1999; Madigan, 1969; Melton, 1970).

Fig. 15 reproduces data from a classic study by Madigan (1969). Subjects studied lists containing a mixture of once-presented (1P) and twice-presented (2P) items. The 2P items were either presented successively (spacing = 0) or with varying numbers of items separating the repetitions (2, 4, 8, 20, or 40). As shown in Fig. 15, increased separation of the 2P items improved their recall. Underwood (1970) showed that the spacing effect in free recall is obtained for both slow and fast presentation rates, for auditory and visual presentation modalities, and for items that came from different linguistic classes (nouns, verbs, etc.).

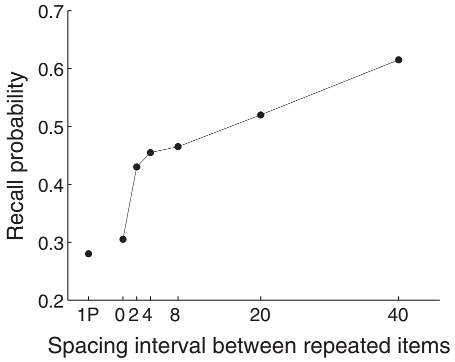

Figure 15 The effect of spacing repetitions in free recall. Increasing the spacing between repeated items increases the magnitude of the repetition effect. 1P indicates once-presented item. Data from Madigan, S.A., 1969. Intraserial repetition and coding processes in free recall. J. Verbal Learn. Verbal Behav. 8, 828–835.

The finding of a spacing effect in free recall can be seen as following from the effect of temporal contiguity. Whereas each massed 2P item will be associated with at most two distinct list items (e.g., APPLE, BUSHEL, BUSHEL, CASTLE), each spaced 2P item may be associated with up to four distinct items (e.g., APPLE, BUSHEL, CASTLE, DIAMOND, BUSHEL, EAGLE). Appealing as this account may sound, it turns out that such associative or contextual variability only accounts for a small proportion of the beneficial effects of spacing on recall performance (Lohnas and Kahana, 2014b). The larger share of the effect appears to come from a study-phase retrieval process wherein the repetition of an item retrieves information about the item's earlier occurrences and this information in turn becomes part of the cue for the current instance of the repeated item. This particular account leads to the novel prediction that subjects are more likely to successively recall items that follow a shared repeated item (e.g., items from positions $i + 1$, $j + 1$) because both items are associated with the context of the repeated item presented at positions i and j. Lohnas et al. (2015) tested and experimentally verified this prediction.

2.11.6 Interresponse Time Analysis

When recording vocal or typed responses, it is straightforward to measure the time between successive recalls or interresponse times (IRTs). Like other measures of response time, the distribution of IRTs is marked by a sharp leading edge and a very heavy tail (see **Fig. 16**A that shows the distribution of IRTs for both correct-to-correct and correct-to-incorrect responses). The shape of these distributions has been used to evaluate various theories of memory search (Wixted and Rohrer, 1993, 1994).

In 1970, Ben Murdock and Ron Okada showed that IRTs between successive recalls increase steadily throughout the recall period, growing as an exponential function of the number of items recalled. This increase in IRTs is highly predictive of recall termination—following an IRT of >10 s, people rarely recall further items. **Fig. 16**B shows a replication of Murdock and Okada's analysis based on data from DFR. These curves indicate that the time between successive responses is a reliable predictor of when subjects will stop recalling. **Fig. 16**C shows a similar increase in IRTs with output position for transitions between correct responses and intrusions (either PLIs or ELIs).

Given that recall transitions are strongly influenced by both semantic similarity and temporal contiguity, one might expect these variables to also affect IRTs. **Fig. 17** shows how IRTs increase as a function of both semantic similarity and temporal contiguity. Here, we can see that, controlling for output position, both of these variables exhibit a strong effect on IRTs, with responses being fastest when transitioning between items that were both contiguously studied and also semantically related to one another.

2.11.7 Ingredients of a Successful Model of Memory Search

Theorists have developed a variety of models to account for subsets of the aforementioned data. Whereas earlier reviews have focused on comparing the distinct predictions of different models (Kahana et al., 2007), there has now been sufficient convergence among models that it is possible to identify a set of key ingredients that any model is likely to require if it is to explain the core features of the data. Below I discuss each of these ingredients and the way they have been employed in various models of memory search to explain the core behavioral data. Finally, I will briefly describe several other model mechanisms that although debated in the literature may ultimately prove essential for explaining certain recall phenomenal.

2.11.7.1 Cue-Dependent Retrieval

Analyses of recall transitions provide strong evidence for the cue-dependent nature of memory retrieval. Following recall of a given item, subjects show a pronounced tendency to recall items that were studied in nearby list positions (e.g., the temporal contiguity effect). In addition, recall transitions are highly predictable based on the shared semantic, affective, or spatial attributes of studied items (among others). These tendencies cannot be accounted for by temporal autocorrelations in variables that affect goodness of encoding (Healey et al., 2016).

The cue-dependent nature of memory retrieval was emphasized in the classic chaining theory of Ebbinghaus and carried forward into more modern theories of both serial and free recall (see Kahana, 2012 for a review). Nearly all models being actively developed to explain data on memory search assume cue-dependent retrieval (Kahana et al., 2007).

Dual-store memory models assume that a working memory buffer (or short-term store) can hold a limited number of items which may be accessed, manipulated, and retrieved at any given moment (e.g., Atkinson and Shiffrin, 1968; Raaijmakers and Shiffrin, 1980; Sirotin et al., 2005; Kimball et al., 2007). These models further assume that items that are coresident in the short-term buffer become associated with one another and with contextual information present at the time of item processing. These long-term memory associations subsequently enable subjects to search their memories in a cue-dependent manner; both context and item information from previously recalled items serve as a cue for the next retrieval attempt.

According to retrieved context models, recall of an item retrieves its associated contextual representations, which in turn serve to cue subsequent retrievals (e.g., Lohnas et al., 2015a; Healey and Kahana, 2016). Because contextual information is both temporally autocorrelated and includes information on the representational similarities among items, this cue-dependent retrieval process gives rise to the temporal and semantic clustering effects described above.

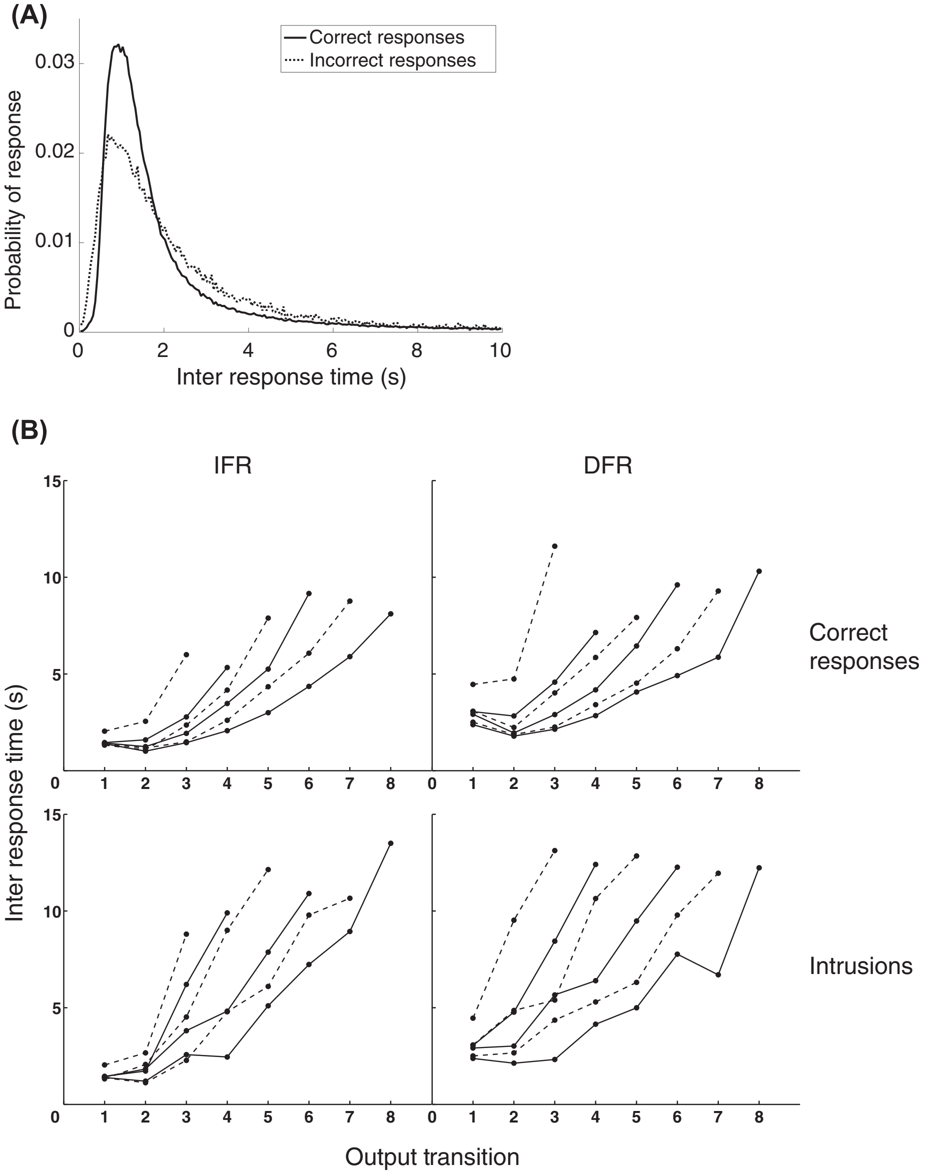

Figure 16 Interresponse times (IRTs) in free recall. (A) IRT distributions for correct-to-correct transition and correct-to-incorrect transition. Each distribution has a sharp leading edge and a heavy tail whose shape has been used in testing theories of memory search (e.g., Wixted and Rohrer, 1993, 1994). (B) IRT as a joint function of output position and total number of item recalls on a given trial (each line corresponds to trials on which 5, 7, 9, 11, and 13 items were recalled; the time between the recall signal and the first recall is not shown). The two panels show data for transitions between correct responses and for transitions between correct responses and intrusions. Data from Experiment 4 of the PEERS study Healey, M.K., Long, N.M., Kahana, M.J., 2017. Contiguity in Episodic Memory (submitted).

2.11.7.2 Representational and Contextual Similarity

In many respects, memory is like perception with the added dimension of time. In both cases, representational similarity is a key stimulus variable that can both enhance or degrade performance depending on task demands. Nearly all memory models implement some form of representational and contextual similarity. In some models, items are explicitly modeled as vectors of attributes over which a similarity function may be defined based on the geometric distances among item representations. These distance-based similarity measures, in turn, predict both associative interference and facilitation effects. In other models, items are assumed to be independent representations whose similarities are mediated by associative strengths based on cooccurrence history, among other variables.

It has long been recognized that items are not encoded in isolation of background cognitive elements (e.g., Carr, 1931; Estes, 1959). Indeed, similarity of background contextual information has been shown to be an important variable in nearly all memory paradigms (Kahana, 2012). Such contextual similarity can both represent external features of the environment, such as spatial

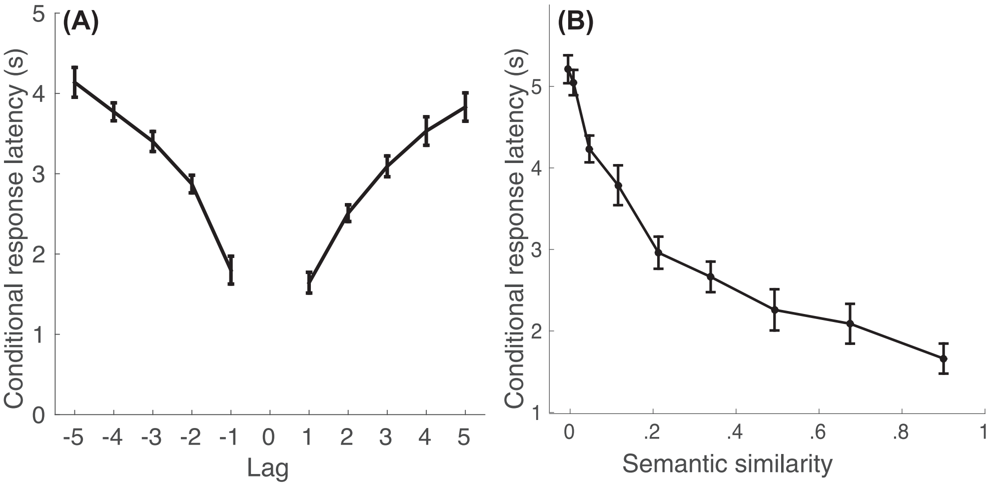

Figure 17 Contiguity and similarity effects on interresponse times (IRTs). (A) Contiguity effect is seen in faster IRTs between recall of an item from serial positions *i* and *i* + lag when *lag* is small. (B) Semantic similarity effect seen in faster IRTs between items with more similar semantic representations.

location or other background perceptual features, as well as internal variables, including mood or pharmacological state (McGeoch, 1932).

Nearly all models of memory have come to include some representation of context to help focus memory search on the target list. In some models, context is modeled as changing between lists, whereas in other models it is assumed to change from item to item. Models that employ list context primarily use this representation to enable subjects to focus retrieval on a target list (e.g., Sirotin et al., 2005; Kimball et al., 2007; Davelaar et al., 2005), whereas other models use contextual similarity between items to help explain the phenomenon of temporal contiguity and its persistence across filled periods of distracting activity (Howard and Kahana, 2002a; Lohnas et al., 2015a).

2.11.7.3 Stopping Criterion

Memory search does not go on indefinitely. At a certain point, people stop recalling either because they run out of time or they cannot easily recall additional items. Although this may not be the most glamorous aspect of a retrieval model, it is a critical component that cannot be ignored. The dual-store search models developed by Raaijmakers and Shiffrin (1980) and extended by others (Sirotin et al., 2005; Kimball et al., 2007) posit that memory search terminates after a certain number of retrieval failures. A similar stopping rule is employed in Farrell's chunking model of serial and free recall (Farrell, 2012), as well as by other models. Retrieved context models that use a competitive leaky accumulator to generate IRTs terminate recall when the retrieval period ends (e.g., Sederberg et al., 2008; Polyn et al., 2009; Lohnas et al., 2015a). Without a stopping rule, models of memory search would not be able to explain how overall recall probability varies as a function of experimental manipulations.

2.11.7.4 Suppression of Previously Recalled Items

In recalling a list of words, subjects rarely repeat items that they have already recalled. Given that subjects are most likely to recall those items that possess strong retrieval cues (and which were encoded well), it is perhaps surprising that repetitions appear so infrequently in the recall data from healthy subjects. Without some way of suppressing retrieval of already recalled items, many models would repeatedly sample the same items over and over again, exhibiting the kind of perseveration seen occasionally in patients with frontal lobe lesions. Whereas many recall models have simply excluded repetitions as candidate items for recall (e.g., Sirotin et al., 2005; Sederberg et al., 2008; Farrell, 2012), some other recent models (e.g., Lewandowsky and Farrell, 2008; Lohnas et al., 2015a; Healey and Kahana, 2016) assume recalling an item temporarily increases its recall threshold, making subjects less likely to recall that item for a period of time. This suppression effect gradually dissipates, allowing subjects to repeat a previously recalled item following the recall of several other nonrepeated items, as seen in the data.

2.11.7.5 Asymmetric Associative Mechanism

The contiguity effect exhibits a striking forward asymmetry, with recall transitions being nearly twice as likely in the forward than in the backward direction. This forward bias in retrieval is not a natural consequence of most assumptions about the associative processes that bind items, but it is a key feature of data on recall transitions. Whereas asymmetry effects are substantial in free recall, other associative tasks exhibit more symmetric transition probabilities (Kahana, 2002; Kahana and Caplan, 2002).

Several models of free recall have been adapted to explain this asymmetry. In both chaining and dual-store models, researchers have employed a scaling factor to make forward associations stronger than backward associations (Sirotin et al., 2005; Solway et al., 2010). Some chaining models assume that only forward associations are stored and that backward associations arise from rehearsal processes (Laming, 2010). Chunking models naturally predict asymmetric retrieval because retrieval of a chunk is assumed to produce forward serial recall of the items within the chunk (Farrell, 2012).

According to retrieved context models, the forward bias in the contiguity effect arises because recall of an item retrieves both the context stored during list presentation (which is similar to both the prior and subsequent list items) and the preexperimental contextual states associated with the item. Because the preexperimental contextual state associated with an item is added to the context vector at the time of the item's encoding, that part of the retrieved context is similar to the contextual states associated with subsequent list items but not prior-list items. Thus, the context retrieved by an item includes a symmetric component (the contextual state associated during list presentation) and an asymmetrical component (the preexperimental contextual states). The combination of these two components produces the forward asymmetry seen in the contiguity effect.

2.11.7.6 Potential Ingredients

The foregoing list of ingredients was by no means intended to be comprehensive. Memory search is a highly complex process and it is likely that a successful model will include additional ingredients beyond those listed above. Clearly, the models we have already discussed differ from one another in important ways, and some of those differences pertain to whether they include the ingredients listed below.

Perhaps the most widely debated theoretical mechanism in models of memory search is that of a phonological short-term memory buffer. The exact nature of such a buffer varies from model to model, but a common feature of buffer models is that they impose a specific timescale on both the recency and the contiguity effect owing to the size of the buffer. These models are thus challenged by data on the persistence of both recency and contiguity across timescales. On the other hand, these models can neatly account for experimental dissociations between recency and contiguity measured at different timescales. One can easily imagine a model in which recency and contiguity are partially accounted for by the operation of a phonological buffer. In such a hybrid model, contextual dynamics may produce both recency and contiguity to some extent, but phonologically based rehearsal processes may enhance one or both of these effects.

Another potential ingredient is linguistic organization, or other types of chunking or grouping processes. Clearly subjects report using these strategies, and it would be strange if such strategic activities did not impact retrieval dynamics. On the other hand, models that do not include these mechanisms provide a fairly comprehensive account for temporal clustering effects, although some grouping effects seem to require additional assumptions (Farrell, 2012).

Finally, several recent models have advanced the idea that variability in memory encoding is not simply a result of stochastic variation in attention or learning parameters, but that the memory system uses prediction to control the learning of new information and the way in which memories are organized into specific "events" (e.g., Gershman et al., 2012). This work provides great promise in linking models of reinforcement learning and models of episodic memory, and moreover extended the explanatory scope of memory search models way beyond the confines of laboratory list memory tasks. In particular, these models will allow theorists to make specific predictions about how subjects recall naturally occurring events, such as narratives and films.

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