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2.26 Associative Retrieval Processes in Episodic Memory

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> [Y]ou are wrong to say that we cannot move about in Time. For instance, if I am recalling an incident very vividly I go back to the instant of its occurrence: I become absent-minded, as you say. I jump back for a moment.
>
> H. G. Wells, *The Time Machine*, 1898

In the above quote from Wells' classic science-fiction novel, the protagonist compares his actual travels through time to the mental time travel one experiences through the act of reminiscence. During our childhood, many of us have fantasized about actual time travel. If we could only return to a previously experienced episode of our lives and re-experience that episode in light of our new found knowledge, perhaps that knowledge would lead us to act differently, or simply to appreciate that previous experience in new and different ways.

Although true time travel remains beyond our reach, the act of remembering is a form of time travel that we can exercise at will. Our power to remember previously experienced events can put us back in the approximate mental context of that earlier episode and allow us to interpret that episode in light of our current knowledge. In so doing, we also alter our memory of the episode in permanent ways, such that each remembering brings back not only the original encoding context, but also some elements of the context of previous rememberings.

In 1972, Endel Tulving coined the term episodic memory to refer to the form of memory that allows us to associate the many different types of information constituting an event into a spatiotemporal context and to later use the content of the event to retrieve its context. Episodic memory places us in the memory, marking the memory's position on our personal, autobiographical, timeline. Retrieval of episodic memories constitutes a form of time travel in which we recover the encoding context of the previously experienced event. Other important forms of memory, such as perceptual priming and semantic memory, do not have this feature.

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Episodic memory not only supports the vivid recollection of formative life events; it also enables us to remember where we parked our car in the morning, whether we took our medicine, and whom we met at a social engagement. Dramatic failures of these everyday aspects of episodic memory can result from damage to the medial temporal lobe of the brain (Spiers et al., 2001). More subtle impairments of episodic memory accompany the normal aging process (Salthouse, 1991; Kausler, 1994).

Ever since Ebbinghaus carried out his seminal studies in 1885, most laboratory studies of human memory have focused on episodic memory. In these experiments, lists of items[1] constitute sequences of mini-experiences presented in a controlled fashion. Subjects then attempt to recall or recognize the previously studied items under a variety of conditions designed to probe and challenge their memorial abilities.

2.26.1 Association and Context

Association has served as the core theoretical construct throughout the history of writings on memory. An association is not observed; rather, it is inferred from the tendency of one item to evoke another. Associations that come to mind quite naturally, like the association of king and queen or of bread and butter, relate to the meaning of the constituent items. This meaning develops through extensive experience, presumably involving the temporal co-occurrence of the items in many different situations. But associations can also be formed between nominally unrelated items in a single exposure. For example, when attending closely to a pair of items presented in temporal proximity (e.g., a name–face pair) we can quickly take hold of the association, at least temporarily. Sometimes, a salient new association may be encoded well enough after a single encounter that it can be recalled, or at least recognized, after a long delay.

The classic laboratory method for studying the encoding and retrieval of episodically formed associations is the paired-associate (or cued-recall) task. In this task, subjects study a list of randomly paired words, name–face pairs, or the like. Later, subjects are presented with one member of each studied pair as a cue to recall its mate. The paired-associate task has subjects explicitly learn associations among items. In the case of words, effective learning of the paired associates depends strongly on the formation of linguistic mediators, the use of imagery, or other strategies that involve elaboration of the meaning of the constituent items (for reviews, see, Paivio, 1971; Murdock, 1974; Crowder, 1976). One may ask whether strategies are strictly necessary for the formation of associations between contiguously presented items. We will return to this question at the end of the present chapter.

The idea of interitem association only takes us so far in thinking about episodic memory. To perform any episodic task one must have some means of distinguishing the current list from the rest of one's experience. For example, if we learn the association between the words *fountain* and *piano* in one setting, and then we later learn the association between *fountain* and *slipper* in another setting, how do we flexibly retrieve either *piano* or *slipper*, and how do we recall the setting in which the word was learned?

The idea that associations are learned not only among items, but also between items and their situational or temporal context was widely recognized in the first half of the twentieth century (Hollingsworth, 1928; Carr, 1931; McGeoch, 1932; Robinson, 1932). This idea formed the basis for Underwood's classic explanation of spontaneous recovery as described in his 1945 dissertation.

Despite its recognition among early memory scholars, the idea of context available at the time was too vague to find favor among the behavioristically oriented learning scholars who dominated in the post-war period (McGeoch and Irion, 1952). Whereas associations could be viewed as an experimentally determined increase in the probability of a stimulus evoking a response, context is not easily tied to experimental manipulations. To scholars of a strictly empirical orientation, the difficulty of controlling and manipulating context, especially internally generated context, greatly limited its utility as an explanatory construct. These scholars feared the admission of an ever-increasing array of hypothesized and unmeasurable mental constructs into the scientific vocabulary (e.g., Slamecka, 1987).

The notion of temporal context regained respectability in the memory literature after the appearance of Gordon Bower's temporal context model in 1972 (Bower, 1972; see also, Bower, 1967). The related notion of temporal coding processes was also emphasized by Tulving and Madigan (1970) in their influential review of the state of the field. According to Bower's model, contextual representations are composed of many features which fluctuate from moment

[1] Although Ebbinghaus used consonant-vowel-consonant (CVC) syllables as stimuli, most modern studies use words due to their relatively consistent interpretation and coding across participants.

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to moment, slowly drifting through a multidimensional feature space. Whereas previous investigators had noted the importance of temporal coding (e.g., Yntema and Trask, 1963), Bower's model, which drew heavily on the classic stimulus-sampling theory developed by William K. Estes (1955), placed the ideas of temporal coding and internally generated context on a sound theoretical footing. The Bower–Estes model provided the basis for more recent computational models of temporal context and its central role in episodic memory (Mensink and Raaijmakers, 1988; Howard and Kahana, 2002).

2.26.2 Associative Processes in Free Recall

The cognitive revolution of the 1960s brought a shift away from the paired-associate and serial learning tasks which had served as the major experimental approach to the study of human verbal memory until that time. The more cognitively oriented researchers were especially drawn to free recall. In the free recall task, subjects study a sequence of individually presented items. At test, they are simply asked to recall all of the items they can remember in any order they wish.[2] There is no experimenter-imposed structure on the nature of the recall process. By analyzing the order in which subjects recall list items, one can gain considerable insights into the memory processes operating under these relatively unconstrained conditions. In contrast, the paired-associate task imposes a strong, experimenter-defined, organization on the to-be-learned materials: subjects are aware that they must link the paired items at study and that they will later be asked to recall a specific target item in response to a given cue.

The scientific literature on free recall has followed two distinct strands. One strand of research focused on how subjects learn a list over the course of successive study-test trials. In a classic study, Tulving (1962) demonstrated that over repeated trials in which the input sequence is randomized, the sequences of recalled items becomes increasingly consistent from trial to trial. In learning lists of random words, subjects appeared to create a kind of organization of the materials, with the level of recall tracking the degree of organization (see Sternberg and Tulving, 1977, for a review of measures of subjective organization). Earlier work by Bousfield and colleagues (Bousfield, 1953; Bousfield et al., 1954) had shown that when subjects studied lists that included strong semantic associates, their sequence of recalls was organized semantically, a phenomenon termed category clustering. Tulving's work showed that organization was a far more general phenomenon, seen even in lists whose items lacked any obvious categorical or semantic organization. Tulving's work on organization and memory spawned several decades of work aimed at understanding the role of organization in the learning process (see Tulving, 1983, for a review).

The second strand of research on free recall focused on how subjects recalled a list after a single study trial. In his classic analysis of the serial position curve in free recall, Murdock (1962) reported the relation between list position and recall probability. On an immediate recall test, subjects exhibited a striking recency effect, recalling the last few items more frequently than items from earlier list positions. These recency items were typically the first items recalled in the sequence of responses (Deese and Kaufman, 1957; Nilsson et al., 1975). Among the earlier (prerecency) items, subjects exhibited superior recall for the first three or four list items than for items from the middle of the list (the primacy effect).

Murdock varied both list length and presentation rate, and found that both manipulations produced a dissociation between the level of recall of recency and prerecency items. Specifically, he found that increasing list length or speeding the presentation rate resulted in lower recall of early and middle items, but did not affect recall of the more recent items. In addition to list length and study time (presentation rate), other variables that boost recall of prerecency items have little or no effect on recency items. For example, lists of similar words are better recalled than unrelated words (Craik and Levy, 1970), and lists of common words are better recalled than lists of rare words (Sumby, 1963; Raymond, 1969; Ward et al., 2003).[3] In both of these cases, however, the enhanced recall is not seen for the recency items. In contrast, the recency effect is significantly greater for auditorally than for visually presented lists, while modality of presentation has no effect on prerecency items (Murdock and

[2] In 1894, E. A. Kirkpatrick published the first study using the free-recall method. This was the same year that Mary Calkins introduced the paired-associate technique. Because of the unconstrained nature of the free-recall technique, Ebbinghaus (1911) found it to be crude and superficial. However, interest in free recall surged following a series of influential studies published between 1953 and 1962 by Weston Bousfield, James Deese, Ben Murdock, Leo Postman, and Endel Tulving.

[3] In item recognition, normative word frequency has the opposite effect, with rare words being better recognized than common words (MacLeod and Kampe, 1996).

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Walker, 1969). Moreover, asking subjects to perform a brief unrelated distractor task at the end of the list (e.g., solving arithmetic problems for 15 s) greatly reduces the recency effect while having no adverse consequences on recall of prerecency items (Postman and Phillips, 1965; Glanzer and Cunitz, 1966). **Figure 1(a)** shows the effect of a brief distractor task on the serial position curve in free recall. These and other dissociations between recency and prerecency led many investigators to embrace the notion of distinct memory systems: a short-term store (STS) responsible for the recency effect, and a long-term store (LTS) responsible for the primacy effect and for the level of recall for prerecency items (Waugh and Norman, 1965; Atkinson and Shiffrin, 1968; Glanzer and Cunitz, 1966).

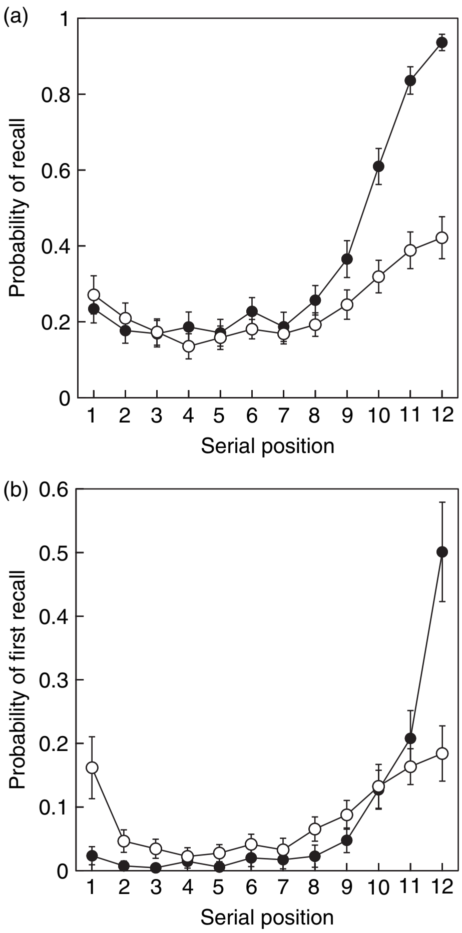

Figure 1 The recency effect in immediate and delayed free recall. After studying a list of 12 common words, subjects were either asked to recall items immediately (filled circles) or following a 15-s arithmetic distractor task (open circles). (a) Serial position curves. (b) Probability of first recall functions show the probability that the first recalled item was presented in a given serial position. These functions thus illustrate the relative tendency to begin recall with primacy or recency items. Data are from Howard MW and Kahana MJ (1999) Contextual variability and serial position effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 25: 923–941 (Experiment 1). Error bars denote 95% confidence intervals.

2.26.2.1 Retrieval Dynamics in Free Recall

Although traditional serial position-based analyses fueled much of the theoretical debate concerning the memory processing underlying free recall (and for that matter serial recall), such analyses discard information about sequential dependencies in retrieval, information which is crucial for understanding the structure of episodic memory storage, and the process of episodic memory retrieval. By measuring the order in which list items are recalled, we can decompose the retrieval process into a measure of how subjects initiate recall and a measure of how they make transitions among successively recalled items.

As mentioned above, subjects typically initiate recall with one of the final list items. This tendency can be quantified by measuring the probability with which subjects initiate recall at each serial position. **Figure 1(b)**, which shows the probability of first recall as a function of serial position, reveals a strong tendency for subjects to initiate recall with one of the final list items (Hogan, 1975; Laming, 1999). In delayed free recall, this tendency is markedly diminished (Howard and Kahana, 1999). By studying subjects' subsequent recall transitions, one can see that temporally defined, interitem associations exert a strong influence on output order and inter-response times in free recall. These associations are inferred from participants' tendency to successively recall items from nearby list positions. As shown in **Figure 2(a)**, the probability of recalling a word from serial position $i+\text{lag}$ immediately following a word from serial position i is a sharply decreasing function of $|\text{lag}|$. Positive values of lag correspond to forward recall transitions; negative values of lag correspond to backward recall transitions.[4] In calculating the conditional response probability as a

[4] For example, if the list had contained the subsequence '*absence hollow pupil*' and a participant recalled *hollow* then *pupil*, the recall of *pupil* would have a lag of +1. If, instead, the participant recalled *hollow* then *absence*, the recall of *absence* would have a lag of −1. In this case, the participant is moving backward in the list. *Absence* followed by *pupil* would yield a lag of +2.

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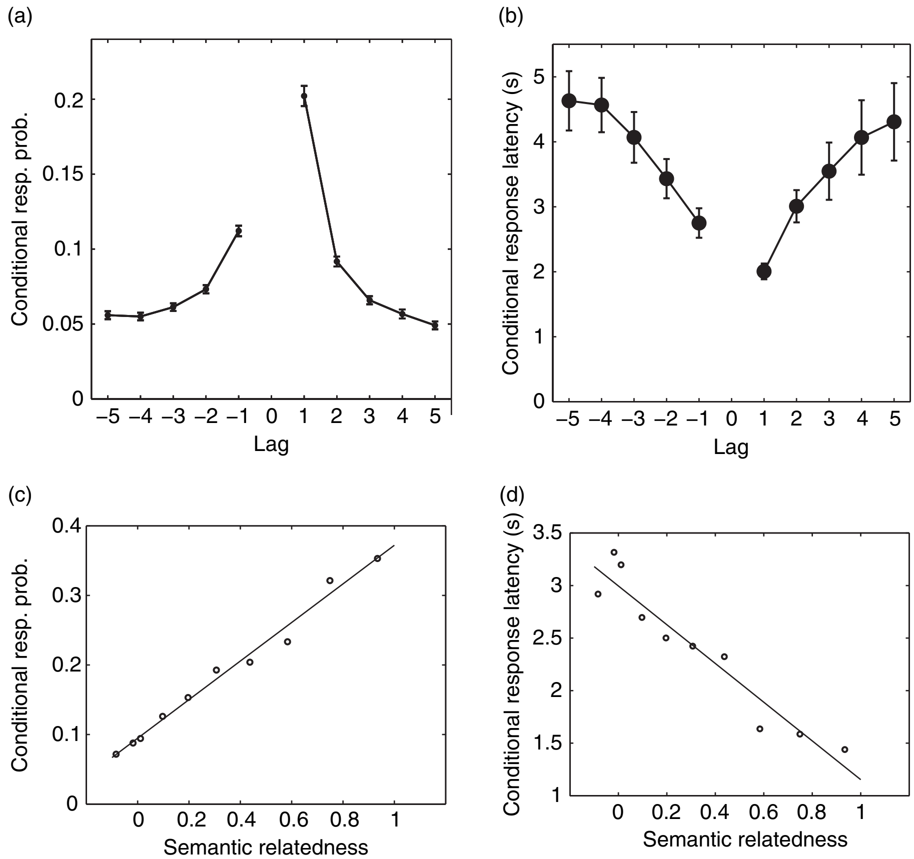

Figure 2 Associative processes in free recall: effects of temporal contiguity and semantic relatedness. (a) The conditional–response probability as a function of lag (or lag-CRP) shows the probability of recalling an item from serial position $i+\text{lag}$ immediately following an item from serial position i. This curve is based on data from 20 experimental conditions (Murdock BB (1962) The serial position effect of free recall. *J. Exp. Psychol.* 64: 482–488; Murdock BB and Okada R (1970) Interresponse times in single-trial free recall. *J. Verb. Learn. Verb. Behav.* 86: 263–267; Murdock BB and Metcalfe J (1978) Controlled rehearsal in single-trial free recall. *J. Verb. Learn. and Verb. Behav.* 17: 309–324; Roberts WA (1972) Free recall of word lists varying in length and rate of presentation: A test of total-time hypotheses. *J. Exp. Psychol.* 92: 365–372; Kahana MJ, Howard MW, Zaromb F, and Wingfield A (2002) Age dissociates recency and lag recency effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 28: 530–540; Howard MW and Kahana MJ (1999) Contextual variability and serial position effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 25: 923–941; Zaromb FM, Howard MW, Dolan ED, Sirotin YB, Tully M, Wingfield A, et al. (2006) Temporal associations and print-list intrutions in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 32(4), 792–804; Kimball DR and Bjork RA (2002) Influences of intentional and unintentional forgetting on false memories. *J. Exp. Psychol. Gen.* 131: 116–130; Kahana MJ and Howard MW (2005) Spacing and lag effects in free recall of pure lists. *Psychon. Bull. Rev.* 12: 159–164; Kahana MJ, Dolan ED, Sauder CL, and Wingfield A (2005a) Intrusions in episodic recall: Age differences in editing of overt responses. *J. Gerontol. Psychol. Sci.* 60: 92–97). (b) The conditional-response latency as a function of lag (or lag-CRL) shows the mean inter-response time between successive recalls of items from serial positions i and $i+\text{lag}$ (Howard MW and Kahana MJ (1999) Contextual variability and serial position effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 25: 923–941; Murdock BB and Okada R (1970) Interresponse times in single- trial free recall. *J. Verb. Learn. Verb. Behav.* 86: 263–267; Zaromb FM, Howard MW, Dolan ED, Sirotin YB, Tully M, Wingfield A, et al. (2006) Temporal associations and prior-list intrutions in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 32(4): 792–804; Kahana MJ, and Howard MW (2005) Spacing and lag effects in free recall of pure lists. *Psychon. Bull. Rev.* 12: 159–164). Error bars represent 95% confidence intervals across experiments. (c) The conditional-response probability as a function of semantic relatedness (semantic-CRP) reveals that subjects are more likely to recall items that are semantically related to the just-recalled item. Semantic-relatedness was measured using the word-association space technique (Steyvers M, Shiffrin RM, and Nelson DL (2004) Word association spaces for predicting semantic similarity effects in episodic memory. In: Healy AF (ed.) *Cognitive Psychology and its Applications: Festschrift in Honor of Lyle Bourne, Walter Kintsch, and Thomas Landauer*. Washington, DC: American Psychological Association). (d) The conditional-response latency as a function of semantic relatedness (semantic-CRL) shows that subject transitions are made more quickly when they are to related items.

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function of lag, or lag-CRP, we estimate the probability of a transition to a given lag by dividing the number of transitions to that lag by the number of opportunities to make a transition to that lag.

2.26.2.2 The Contiguity Effect

The analysis of retrieval transitions in free recall reveals a strong tendency for neighboring items to be recalled successively. We refer to this phenomenon, illustrating participants' reliance on temporal associations to guide recall, as the contiguity effect. As shown in **Figure 2(a)**, the contiguity effect exhibits a marked forward bias, with associations being stronger in the forward than in the backward direction. The basic form of the contiguity effect does not appear to depend on experimental manipulations. The lag-CRP functions are virtually identical across manipulations of presentation modality (visual vs. auditory), list length, and presentation rate (Kahana, 1996).

The contiguity effect also appears in the form of shorter inter-response times between recall of items from neighboring list positions. This can be seen in the conditional response latency (lag-CRL) function shown in **Figure 2(b)** (see Kahana and Loftus, 1999, for a further discussion of the accuracy–latency relation). The contiguity effect, as seen in both accuracy and latency data, may reflect a kind of mental time travel undertaken during memory search and retrieval. In recalling an item, the subject may 'travel back' to the time of its presentation, making it more likely that subsequent recalls will come from nearby serial positions.

2.26.2.3 The Semantic Proximity Effect

In free recall, participants do not rely solely on newly formed episodic associations; they also make use of their pre-existing semantic associations among list items. We can quantify subjects' use of semantic associations in free recall by computing the conditional probability of a recall transition as a function of an item's semantic relatedness to the just-recalled item (we term this function the semantic-CRP). This approach requires a measure of the semantic relatedness of arbitrary word pairs. To obtain such measures, we turn to computational models of semantic spaces. Landauer and Dumais (1997) developed latent semantic analysis (or LSA); this project involved the statistical analysis of a large text corpus, allowing them to derive a measure of word-relatedness from the tendency for words that share meaning to co-occur in paragraphs. Steyvers et al. (2004) developed a word association space (or WAS) based on the large University of South Florida word association database (Nelson et al., 2004). Both LSA and WAS provide measures of the semantic relatedness for a great many pairs of words in the English language. The measure is quantified as the cosine of the angle between the vectors representing the two words in a high-dimensional space. Completely unrelated words would have $\cos\theta \approx 0$, and strong associates would have $\cos\theta$ values between 0.4 and 1.0. For a more thorough treatment and discussion, see Howard et al. (2007).

The semantic-CRP shows that the stronger the semantic relation between two list words, the more likely it is that they would be successively recalled (**Figure 2(c)**). In addition, the stronger the semantic association between two successively recalled words, the shorter the inter-response time would be between the two words (**Figure 2(d)**). This analysis illustrates the powerful influence of semantic relatedness on recall of randomly chosen word lists. Even when lists lack any strong associates or any obvious categorical organization, recall transitions are driven by the relative semantic strengths among the stored items. Consistent with the findings of category clustering and subjective organization described above, the contiguity effect decreases, and the semantic-proximity effect increases, across learning trials in which the order of word presentation at study is randomized on each trial (Klein et al., 2005; Howard et al., 2007).

2.26.2.4 Normal Aging Affects Contiguity but Not Recency

It is well known that older adults perform more poorly on episodic memory tasks than their younger counterparts (Verhaeghen and Marcoen, 1993; Kausler, 1994). The age-related memory impairment is particularly marked in recall tasks that require subjects to use temporally defined associations, such as cued recall and free recall (Naveh-Benjamin, 2000; Wingfield and Kahana, 2002; Hoyer and Verhaeghen, 2006).

The analysis of retrieval transitions, as described above, can be used to directly assess subjects' reliance on temporal associations in free recall. Kahana et al. (2002) examined the difference between recency

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and contiguity effects in younger and older adults. Half of the subjects in each age group were given an immediate free recall test; the other half were given a delayed free recall test. As expected, younger adults recalled more words on both immediate and delayed tests, and the distractor task attenuated the recency effect for subjects in both age groups. The critical finding was that older adults exhibited a significantly diminished contiguity effect, as seen in their lag-CRP functions (Figure 3(b)). In contrast, younger and older adults initiated recall in the same manner; their probability of first recall functions were virtually identical both in the immediate and in the delayed free-recall conditions (Figure 3(a)). Although older adults exhibited a markedly reduced contiguity effect, their semantic-proximity effect was unimpaired (unpublished observation). These findings suggest that the mnemonic deficit observed for older adults is largely restricted to the ability to form and/or utilize temporally defined associations. This is consistent with previous reports of age-related deficits in the formation and retrieval of episodic associations (e.g., Naveh-Benjamin, 2000).

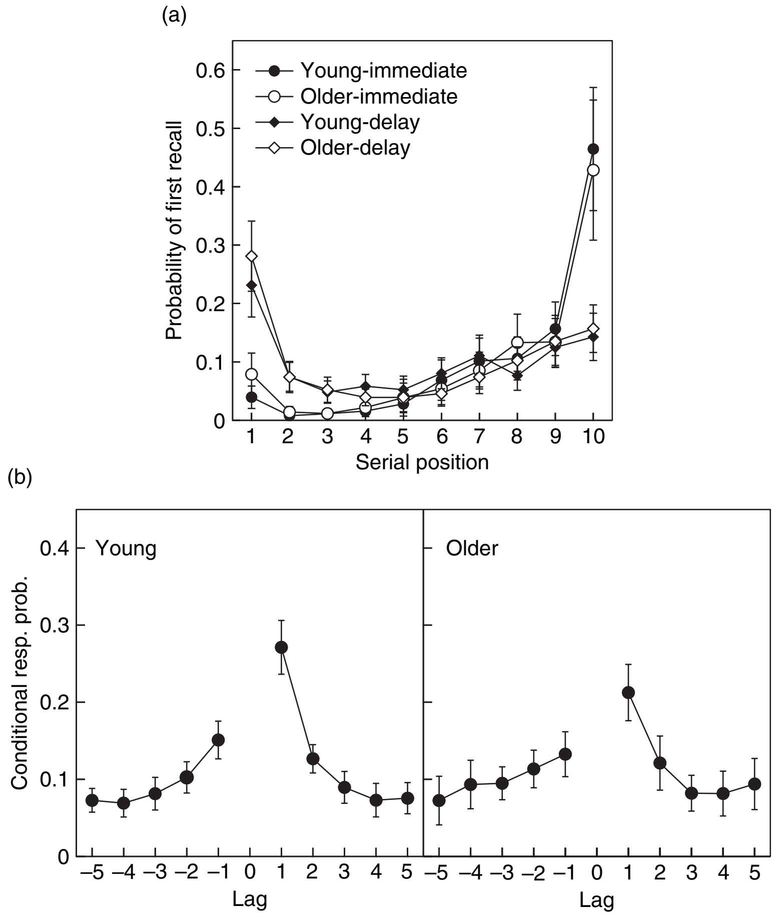

Figure 3 Selective effect of aging on associative processes in free recall. (a) Probability of first recall from immediate and delayed free recall for younger and older adults. Data taken from Kahana MJ, Howard MW, Zaromb F, and Wingfield A (2002) Age dissociates recency and lag recency effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.,* 28: 530–540. Figure reprinted with permission from Howard MW, Addis KA, Jing B, and Kahana MJ (2007) Semantic structure and episodic memory. In: McNamara D and Dennis S (eds.), *LSA: A Road Towards Meaning.* Hillsdale, NJ: Laurence Erlbaum and Associates. (b) Conditional response probability (CRP) for younger and older adults from the delayed condition of Kahana MJ, Howard MW, Zaromb F, and Wingfield A (2002) Age dissociates recency and lag recency effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn., 28*, 530–540.

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2.26.2.5 Long-Range Interitem Associations

Bjork and Whitten (1974) conducted an experiment which challenged the traditional STS-based account of recency effects in free recall. They were interested in seeing how well subjects could recall a list of word pairs under conditions designed to eliminate between-pair rehearsal. To eliminate between-pair rehearsal, they had subjects perform a difficult distractor task following the appearance of each pair, including the last one. Because the distractor was expected to displace any items in STS, Bjork and Whitten did not expect to find a recency effect. To their surprise, they found a strong recency effect, with the final few pairs being recalled better than pairs from the middle of the list. They called this the long-term recency effect. Their procedure, in which a distractor task is given following every item, including the last, is called continuous-distractor free recall. **Figure 4** illustrates the continuous-distractor free recall procedure alongside the more traditional immediate and delayed free recall procedures.

Condition	Recency
Immediate PEN CAR ROSE ··· BIRD ***	Yes
Delayed PEN CAR ROSE ··· BIRD [1+2=] ***	No
Continuous distractor PEN [6+2=] CAR [3+7=] ROSE [1+1=] ··· BIRD [2+5=] ***	Yes

Figure 4 Illustration of immediate, delayed, and continuous-distractor paradigms. The row of asterisks indicates the start of the recall period.

The long-term recency effect has now been replicated many times using both single words and word pairs, and across delays ranging from tenths of seconds (Neath, 1993) to days (Glenberg et al., 1983). The magnitude of the long-term recency effect depends critically on both the duration of the distractor given after the last word (the retention interval) and on the duration of the distractor intervening between list words (the interpresentation interval). For a given retention interval, increasing the interpresentation interval results in more recency and better recall of the final item.

Kahana (1996) interpreted the contiguity effect as evidence for associations formed in STS. If associations are formed between items that are active together in STS (as postulated by Glanzer, 1972; Raaijmakers and Shiffrin, 1980), then this would predict the contiguity effect because nearby items spend more time together in STS than remote items. However, because a long interitem distractor should displace items in STS, the contiguity effect should be significantly attenuated in continuous-distractor free recall.

Howard and Kahana (1999) tested this hypothesis by measuring the contiguity effect in continuous-distractor free recall. **Figure 5(a)** illustrates the contiguity effect for interpresentation intervals ranging from 0 s (standard delayed free recall) to 16 s. As can be seen, the contiguity effect was relatively constant across this range of interpresentation intervals. This result is quantified in **Figure 5(b)** by fitting a power function ($P = a|\text{lag}|^{-b}$) to each participant's lag-CRP curve and using the b parameter as an estimate of the contiguity effect (the a parameter determines the overall scale of

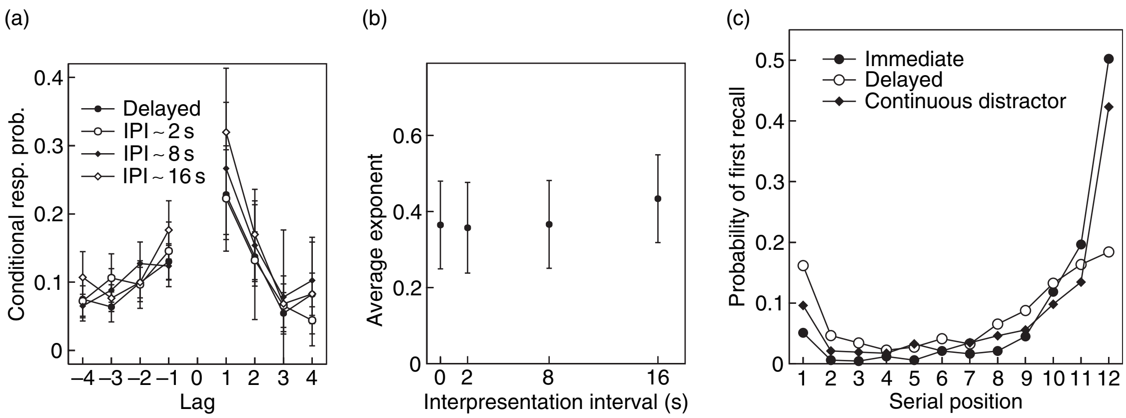

Figure 5 Long-range contiguity and recency effects. (a) Lag-CRP as a function of the length of the distractor task in continuous-distractor free recall. (b) To quantify the contiguity effect, power functions were fit to the lag-CRP curves for each participant in each condition. Error bars represent 95% confidence intervals. (c) The probability of first recall functions for immediate, delayed, and continuous-distractor free recall (Howard and Kahana, 1999).

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the function). Insofar as the contiguity effect is insensitive to the absolute delay between list items, it exhibits an approximate time-scale invariance. Although 16 s of a distractor had virtually no impact on the contiguity effect, the same amount of distractor activity presented at the end of the list was sufficient to eliminate the end-of-list recency effect (**Figure 5(c)**).

As shown in **Figure 5**, the contiguity effect persists even when the study items are separated by 16 s of a demanding distractor task. However, recent work shows that the contiguity effect is evident on even longer time scales. Howard et al. (2008) presented subjects with a series of lists for free recall. At the conclusion of the session, subjects were given a surprise final free recall test in which they were instructed to remember as many words as possible from the 48 study lists in any order. Howard et al. (2008) measured the contiguity effect in this final free recall period both for transitions within a list as well as between lists. They found that transitions between nearby lists were more frequent than transitions between lists that were farther apart in the experiment. This contiguity effect extended about ten lists, or several hundred seconds, extending the range over which contiguity effects are observed in free recall by a factor of ten. Moreover, this paradigm offers several potential advantages over continuous-distractor free recall. In continuous distractor free-recall, subjects have an incentive to try and rehearse items across the distractor intervals. Because the subject is only asked to recall the most recent list in the Howard et al. (2008) study, and intrusions from prior lists are scored as errors, there is no strategic reason for subjects to rehearse across lists in anticipation of the surprise final free recall test. In continuous-distractor free recall, the consistency of associations across delay intervals was inferred from observing lag-CRP curves across conditions that differed in their IPI. It is conceivable that this was due in part to different strategies across experimental conditions. In contrast, in the Howard et al. (2008) study, both within-and across-list associations were observed simultaneously during the final free recall period.

2.26.2.6 Interim Summary

We have shown how both temporal contiguity and semantic relatedness strongly predict the order and timing of subjects' responses in the free-recall task. The contiguity effect (**Figure 2(a, b)**) illustrates how episodic associations are graded, exhibiting power-function decay with increasing lag. Recall of an item has a tendency to evoke not only adjacent list items, but other nearby items as well. In addition, episodic associations appear to be asymmetrical, favoring retrieval of items in the forward order.

Whereas the previous two characteristics of episodic association can be accommodated within the view that neighboring items become associated when they cooccupy a short-term buffer (or working memory system), analyses of episodic association in continuous-distractor free recall show that the contiguity effect persists across time scales. That is, using a distractor task to temporally segregate list items does not disrupt the associative mechanism. Moreover, contiguity can even be observed in recall transitions among items studied as part of different lists, separated by several minutes. The tendency for an item to evoke a nearby item thus depends on the relative spacing, not the absolute spacing, of the list items.

A critical question for memory theory is whether the contiguity effect is specific to free recall, or whether similar associative processes operate in other memory tasks. It is possible that some of the phenomena described in the preceding section are a consequence of specific strategies that subjects use in the free-recall paradigm. In particular, by allowing participants to recall items in any order, we may be observing participants' biases in favoring particular kinds of transitions (e.g., forward over backward, adjacent over remote) rather than revealing the underlying associative structure. This criticism is blunted by our finding that the lag-CRP and lag-CRL functions vary little across experiments that differ significantly in their methodologies, even including the introduction of a long interitem distractor (see **Figure 5**). Nonetheless, it is important to take a broader look at the question of associative processes in episodic memory. In the next section, we show how associative processes can be seen in the pattern of subjects' errors in free recall, serial recall, and cued recall. We then examine the question of associative processes in item recognition. The final section of this chapter discusses these empirical data in terms of the major theories of associative processes in episodic memory.

2.26.3 Memory Errors Reveal Associative Processes

The study of the errors made in a variety of memory tasks shows that even when the memory system goes awry and produces a response that is incorrect in the context of a given experiment, the processes

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generating this error appear to be influenced by the same factors that guide correct responses. In this section, we consider how subjects' recall errors reveal characteristics of the associative processes operating in free recall, serial recall, probed recall, and cued recall tasks.

2.26.3.1 Prior-List Intrusions in Free Recall

It is well known that incorrect recalls (intrusions) often arise due to the semantic relations between studied and nonstudied items. For example, after studying a list of items that include the semantic associates of a critical word, participants often incorrectly recall that critical word even though it was not presented on the list (Deese, 1959; Roediger and McDermott, 1995; Roediger et al., 1998; Gallo and Roediger, 2002). Although semantic association is a major determinant of false recall, episodic memory processes also appear to play an important role. For example, in free recall of randomly arranged word lists, prior-list intrusions – incorrect recalls of words that were presented on an earlier list – are often more frequent than extralist intrusions – incorrect recalls of words that were not presented during the course of the experiment. This suggests that the recent study of an item increases the probability that it will be (incorrectly) recalled. Moreover, prior-list intrusions exhibit a strong recency effect, being most likely to come from the list immediately preceding the target list (Murdock, 1974; Zaromb et al., 2006); the number of prior-list intrusions coming from earlier lists decreases sharply (see **Figure 6(a)**).

In a recent study, Zaromb et al. (2006) asked whether contiguity-based associations would also tend to induce false recall. They conducted several free-recall experiments in which some items in a given list had also appeared on earlier lists. In all cases, participants were instructed to recall only the items from the most recently presented list. By creating lists that contained mixtures of novel items and items repeated from earlier lists, Zaromb et al. found that recalls of repeated items were more likely to be followed by prior-list intrusions than were recalls of novel items. This finding would emerge if temporal associations forged on prior lists compete with the associations formed in the current list, and if these older associations occasionally win in the competition. As further support for the role of contiguity-based associations, Zaromb et al. found that repetition-evoked prior-list intrusions came from the same prior lists as the repetitions themselves,

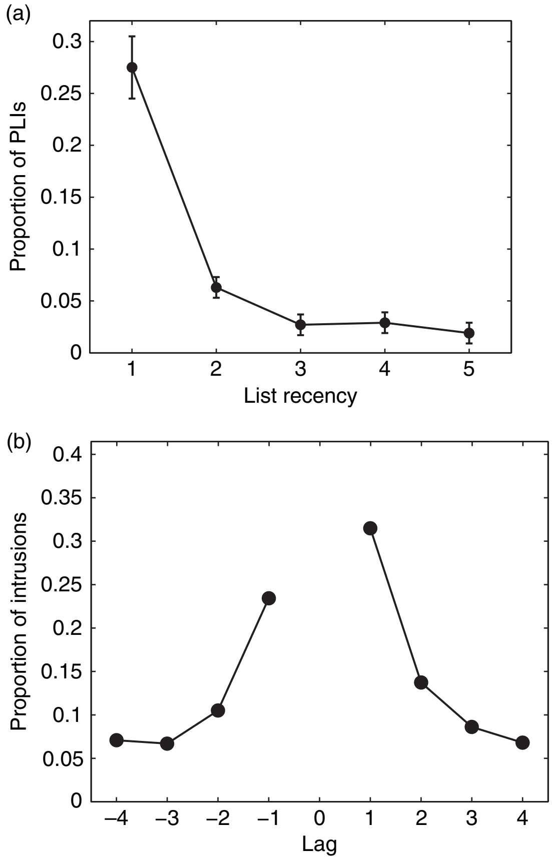

Figure 6 Effects of recency and contiguity on intrusions in free recall. (a) Prior-list intrusion (PLI) recency effect. Proportion of intrusions coming from one to five lists back. In calculating these PLI-recency functions for items originally presented one to five lists back, we excluded the first five trials from the analysis. That is because PLIs from five lists back could only occur on trials 6 and later. (b) Successive PLIs that came from the same original list tend also to come from neighboring positions in their original list. Thus, temporally defined associations influence PLIs in free recall (Zaromb et al., 2006).

and from positions near the repetitions in those lists. When subjects committed two same-list prior-list intrusions in succession, those intrusions tended to come from neighboring positions in their original list, exhibiting a temporal contiguity effect similar to that seen for correct recalls (see **Figure 6(b)**).

2.26.3.2 Intrusions in Serial and Probed Recall

We next consider the effect of contiguity on retrieval in serial-order memory. In a serial-recall task, participants are instructed to recall the list items in order of

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presentation, rather than in any order as in free recall. In requiring ordered recall, the serial-recall task demands that subjects store information not only about which items were on the list, but also about their order. Thus, the serial-recall task exerts greater control over the manner of encoding and retrieval than does free recall.

Although subjects can only make one correct response in a given output position, they can commit many different types of errors. The orderly pattern of subjects' errors in serial recall can teach us a great deal about the underlying processes. For example, it is well known that when recalling an item in the wrong position this item tends to be misplaced near the correct (target) position (e.g., Lee and Estes, 1977). This finding has also been documented extensively in reordering tasks, where subjects are given all of the target items and asked to place them in their correct studied order (e.g., Nairne, 1990a, 1990b).

The traditional method for measuring error gradients is to plot the probability of an item studied in serial position i being recalled in position $i +$ lag. This approach works especially well in reordering tasks where all the items are placed in some position. With longer lists, where only some of the items are recalled, it is especially important to correct for the availability of different lags, as we have done in our lag-CRP analysis of free recall. For these lag-CRP analyses, we compute the probability of recalling an item from position i in position $i +$ lag conditional on the possibility that an item could be placed in position $i +$ lag (for example, we make sure that the item from that position has not already been recalled). **Figure 7(a)** shows an analog of the lag-CRP derived from errors observed during serial recall (Kahana and Caplan, 2002). In addition to revealing the tendency for errors to come from nearby list positions, this curve shows a clear asymmetry effect, with errors in the forward direction being significantly more likely than errors in the backward direction.[5] Thus, the temporal gradient of errors in serial recall is strikingly similar to the temporal gradient of correct responses observed in free recall (see Klein et al., 2005, for a direct comparison of free recall and serial recall).

The analysis of errors in serial recall is complicated by the fact that each response depends on the sequence of prior responses (Giurintano, 1973). An alternative approach to measuring serial-order memory is to present subjects with a single item from a previously studied list and ask them to recall the item that preceded or followed the probe item (Murdock, 1968; Woodward and Murdock, 1968). Analysis of error gradients obtained in forward and backward probed recall provide an even cleaner test of the asymmetry effect observed in both free and serial recall. **Figure 7(b)** shows error gradients in a probed recall study reported by Kahana and Caplan (2002). The top panel shows that when subjects were given item i and asked to recall item $i + 1$, responses tended to come from nearby positions, with a forward bias ($i + 2$ is more likely than $i - 1$). The bottom panel of **Figure 7(b)** shows that when subjects were probed in the backward direction (i.e., given item i and asked to recall item $i - 1$), the same forward asymmetry was obtained (see also Raskin and Cook, 1937).

2.26.3.3 Intrusions in Paired-Associate Recall

The preceding section documented two characteristics of errors in serial recall and in probed recall of serial lists: (1) subjects' intrusions tend to be items studied near the position of the target item and (2) subjects' error gradients exhibit a forward asymmetry, with errors being more likely to be items following than items preceding the target item. The temporal gradient of retrieval transitions in free recall as seen in the lag-CRP, and the gradient of subjects' intralist intrusion errors in both serial and probed recall could reflect a common methodological aspect of these tasks. In both free and serial recall tasks, the to-be-learned items constitute an unbroken series such that storing and retrieving associations among neighboring items is useful for performing the task. An important exception to this is continuous-distractor free recall, in which list items are separated by a demanding distractor task. Nonetheless, even in continuous-distractor free recall, subjects may be motivated to make associations between neighboring items.

Paired associate memory provides an interesting contrast to both free and serial recall. In the standard paired-associate procedure, subjects are asked to learn a list of nonoverlapping pairs of words. Following this study phase, subjects are cued for recall of specific pairs (either in the forward or the backward order). Unlike free and serial recall, in which subjects must learn an entire list, subjects in the paired-associate task have no reason to learn associations other than those binding the items within

[5] As with the lag-CRP analysis of free recall, this analysis corrects for the number of available to-be-recalled items.

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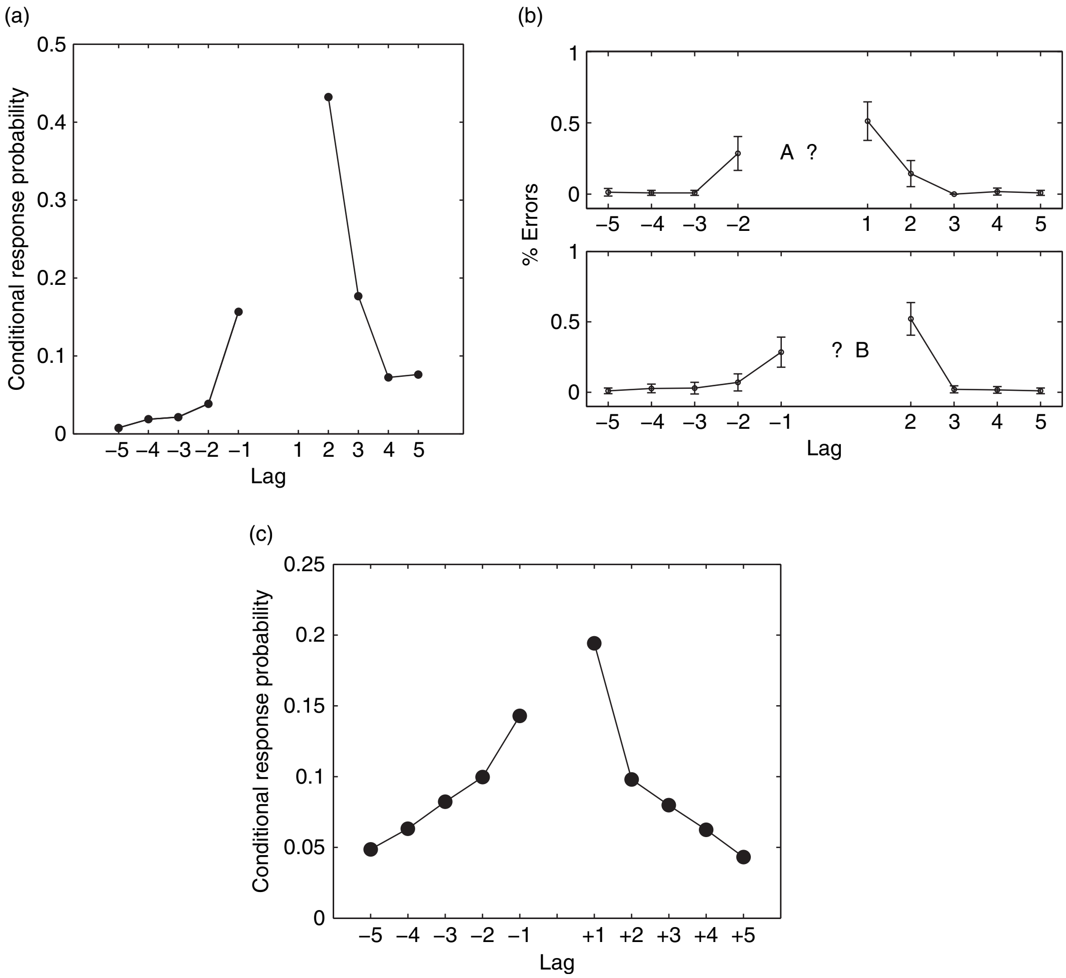

Figure 7 Intrusions reveal associative tendencies in serial-recall, probed-recall, and cued-recall tasks. (a) Lag-CRP analysis of errors in immediate serial recall. Correct responses (lag of +1) were excluded from this analysis. (b) Conditional error gradients in forward (top) and backward (bottom) probed recall; subjects are given item i as a cue for item $i+1$ (upper panel), or $i-1$ (lower panel), and they recall some other item $i+$ lag. Data are from Trial 1 of Kahana and Caplan's second experiment (Kahana MJ and Caplan JB (2002) Associative asymmetry in probed recall of serial lists. *Mem. Cognit.* 30: 841–849). (c) Following study of 12 randomly chosen noun-noun pairs, subjects were given a standard cued recall test. The probability of incorrectly recalling a word from pair-j in response to a cue word from pair-i decreased with increasing lag, measured in pairs. (Davis OC, Geller AS, Rizzuto DS, and Kahana MJ (2008) Temporal associative processes revealed by intrusions in paired-associate recall. *Psychon. Bull. Rev.* 15(1): 64–69).

each studied pair. Recall is strictly cued by the experimenter so there is no benefit to recalling any item other than the one being probed. Whereas associations in both free and serial recall have a strong forward bias, associations in paired-associate tasks are generally symmetric, with nearly identical recall rates for forward and backward probes (for reviews see Ekstrand, 1966; Kahana, 2002). This surprising result led Gestalt psychologists to propose an *associative symmetry hypothesis* (Köhler, 1947; Asch and Ebenholtz, 1962). According to this hypothesis, associations are learned by incorporating the representations of the constituent items into a new holistic representation. Formalized in computational models, this hypothesis implies that the strengths of forward and backward associations are approximately equal and highly correlated (Rizzuto and Kahana, 2001; Kahana, 2002; Caplan et al., 2006; Sommer et al., 2007).

In light of the distinct features of the paired-associate task, one may wonder whether subjects form temporal associations beyond those required to learn the pairings set forth in the experiment. Davis et al. (2008) addressed this question by examining subjects'

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pattern of intralist intrusions in paired associate recall. In a cued recall task, there are a number of types of errors a subject could make. Intralist intrusions are incorrect responses where the subject recalls an item from a different pair than the cue came from. Davis et al. (unpublished data) hypothesized that if a common associative process underlies all recall tasks, intralist intrusions would be more likely to come from neighboring list pairs. Consistent with CRP analyses from other paradigms, Davis et al. conditionalized the probability of committing an intrusion from a given lag on the availability of the pair at that lag. Although intralist intrusions constituted only 5% of subjects' responses, these intrusions exhibited a strong tendency to come from neighboring pairs. This can be seen in **Figure 7(c)**, which shows that the conditional probability of an intralist intrusion decreased monotonically with the number of pairs (lag) separating the intrusion from the probed item. This effect was not limited to an increased tendency to commit intrusions from adjacent pairs; even when adjacent pairs were excluded, a regression analysis demonstrated that the across-pair contiguity effect was highly reliable.

Because the order of test was randomized with respect to the order of study, there was no reason for subjects to adopt a strategy of learning interpair associations. Indeed, such a strategy would have been counterproductive insofar as it would induce high levels of associative interference between pairs (Primoff, 1938). As such, these findings of associative tendencies in subjects' intralist intrusions suggest that these temporally defined associations arise from a basic and most likely obligatory memory process that causes items studied in nearby list positions to become associatively connected.

This spectrum of findings reveals that free recall is not alone in providing evidence for the centrality of contiguity effects in human memory. All of the major recall paradigms – free recall, serial recall, and paired-associates learning – show graded effects of temporal contiguity; in many cases these effects are revealed in the patterns of errors made by subjects. Taken together, these findings allow us to glimpse the workings of a general-purpose 'engine of association' that is tapped by all of these varied tasks. Furthermore, the observation of long-range contiguity, both in free recall and in subjects' intrusions in paired-associate recall, challenges the view that intentional encoding is necessary for the formation of contiguity-based associations.

2.26.4 Associative Processes in Item Recognition

Theories of item recognition and cued recall typically assume that these two tasks are based on distinct and possibly independent sources of information (Murdock, 1982; Gillund and Shiffrin, 1984; Kahana et al., 2005b) According to these theories, item recognition relies on item-specific information, whereas recall tasks rely on associative (or relational) information (Humphreys, 1978; Hunt and McDaniel, 1993). This view is supported by experimental dissociations between item recognition and free recall (e.g., the word frequency effect; Kinsbourne and George, 1974) and by the finding that words that are recallable often cannot be recognized, and vice versa (e.g., Tulving and Thompson, 1973; Tulving and Wiseman, 1975).

Despite these differences between recall and recognition, both tasks assess memory for an event encoded within a temporal context. Given the ubiquitous character of the contiguity effect across all of the major recall paradigms, it is natural to ask whether contiguity exerts some influence on retrieval in item recognition, at least under conditions where subjects' recognition judgments are accompanied by a feeling of recollection. More specifically, one might hypothesize that recognizing an item as having been previously studied would partially reinstate the item's encoding context, which in turn might facilitate subsequent recognition of neighboring items.

To test this hypothesis, Schwartz et al. (2005) manipulated the serial lag between successive memory probes in an item recognition study that used landscape photos as stimuli. The recognition test was a sequence of test probes that included the old items from the list intermingled with an equal number of new items that served as lures. Subjects pressed one of six keys in response to each probe, rating their confidence that it was seen before from 1 (sure new) to 6 (sure old). A recognition test might include the subsequence of test probes $(\ldots O_{23}, N, O_{12}, O_7, N, N, O_{39}, \ldots)$, where N denotes a new item and O_x denotes an old item from position x in the study list. The lag between two successive old items $(\ldots O_i, O_j \ldots)$ is just the distance, $j - i$, between the items on their initial presentation.

Suppose that recognition of a test item, O_i, brings forth the mental state – or temporal context – that prevailed when O_i was first encoded. Suppose further

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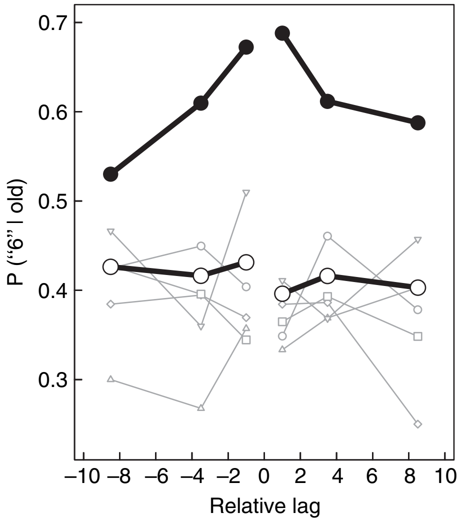

Figure 8 Contiguity effects in item recognition are specific to highest-confidence responses. Probability of a highest confidence (6) response to an old-item test probe as a joint function the relative lag of, and the response given to, the preceding old-item probe. Large filled circles represent 6 responses to the prior test probe. Open symbols represent one of the other five possible prior responses; downward-facing triangles, boxes, triangles, upward-facing diamonds, and circles represent responses 1–5 respectively. Large open circles collapse data over responses 1–5. Data are from Schwartz et al. (2005). Shadows of the past: Temporal retrieval effects in recognition memory. *Psychol. Sci.* 16: 898–904.

that this retrieved mental state contributes to the retrieval environment that determines subsequent recognition judgments. Then, if the very next test item is O_j, we would predict that memory for O_j should be enhanced when lag $= j - i$ is near zero.

The data in Figure 8 show that when two old items are tested successively, memory for the second is better if it was initially presented in temporal proximity to the first. This tendency, however, was wholly attributable to cases in which the first item received a highest-confidence response. These highest-confidence old responses may be considered to reflect successful recollection of specific attributes of the encoding episode, whereas lower-confidence old responses are assumed to reflect the familiarity of an item whose attributes are not recollected (Yonelinas, 1999; Sherman et al., 2003). Schwartz et al. (2005)'s observation of contiguity effects in item recognition suggests that recollection of an item not only retrieves detailed information about the item tested, but also retrieves information about the item's neighbors.

We have now seen that the contiguity effect appears in all of the major episodic memory paradigms, including free recall, serial recall, probed recall, paired-associates, and even item recognition. The ubiquitous nature of this phenomenon implores us to search for an explanation in terms of fundamental principles of memory function. This search is the topic of the next section.

2.26.5 Theories of Episodic Association

Four major theories have been proposed to account for associative processes in episodic memory: (1) associative chaining, (2) associations formed in working memory (or buffer theory), (3) hierarchical associations (or chunking theory), and (4) contextual retrieval theory. In this section, we examine the implications of each of these four theories for the key empirical findings concerning contiguity-based associations in episodic memory.

Chaining theory, which originates in the writings of the associationists (e.g., Herbart, 1834) and in the early experimental work of Ebbinghaus, (1885/1913), assumes that when the memorial representations of two items become simultaneously active, or become active in rapid succession, the items' representations become associated in the sense that activation of one will evoke the other. A key feature of chaining is that associations are formed on the basis of temporal contiguity at study and that an item's representation is assumed to remain active only until the occurrence of the next item in the list.

Buffer models elaborate the basic chaining idea to include a mechanism that maintains an item's representations in the system past its actual presentation, allowing direct interitem associations to be created between items that are presented further apart in time (remote associations). Whereas classic chaining models assume that only two items are simultaneously active, buffer models allow for a larger number of items to be maintained in an active state and provide rules that determine when an item enters and leaves the active state (i.e., the buffer; Raaijmakers and Shiffrin, 1981).

Hierarchical associative models are based on the idea that multiple items can become unitized into a higher-order, conjunctive, representation which is distinct from any of the constituent items. These models have been particularly useful in describing the process of serial learning and serial recall (Johnson, 1972; Martin and Noreen, 1974; Lee and Estes, 1977; Murdock, 1995b, 1997). They assume

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that associations between items are mediated by a higher-level (super-ordinate) representation.

Finally, contextual retrieval theory assumes that items are associated with a time-varying representation of spatiotemporal/situational context (Estes, 1955; Bower, 1972; Burgess and Hitch, 2005). Successively presented items are associated with this context representation, which then can be used as a cue to retrieve those item representations during the recall period. Importantly, associations arise when items retrieve their encoding context, which in turn cues neighboring items (Howard and Kahana, 2002).

Although we consider each of these major theories in turn, they are not mutually exclusive. In some cases, modern theories of episodic memory make use of more than one of the ideas presented above. For example, some modern buffer models also use a representation of temporal context to differentiate items on the current target list from items on previous lists (Mensink and Raaijmakers, 1988; Sirotin et al., 2005).

As we see it, any theory of associative memory retrieval needs to account for (at least) seven critical behavioral findings regarding temporal-associative processes. The first of these is the contiguity effect – the tendency for neighboring items to be recalled successively. The second critical finding is the asymmetry effect – the tendency for subjects to make transitions to items studied in subsequent list positions. This forward asymmetry is remarkably robust in free recall, being observed in every dataset that reports output order effects. The third critical finding is the long-range contiguity effect – the observation of contiguity effects in continuous-distraction free recall and in a final free-recall task. This finding illustrates how episodic associations are not limited to successively studied items, or even to items studied within a short time period. Rather, contiguity-based associations appear to span many intervening items. The fourth critical finding is that when items are repeated across lists, prior-list intrusions in free recall tend to come from serial positions close to the original presentation (Zaromb et al., 2006). This illustrates the tendency for associations formed on prior lists to influence memory for the current list. Fifth, the tendency for intrusions in serial-recall and probed-recall paradigms is to come from list positions close to the target item. This tendency also exhibits a forward asymmetry effect, where errors tend to be items from subsequent list positions. Sixth, the tendency is for intrusions in paired-associate paradigms to come from neighboring pairs. Although this effect exhibits some forward asymmetry, memory for the items within a pair is strikingly symmetric, with recall accuracy being nearly identical for forward and backward probes (Ekstrand, 1966; Kahana, 2002). Finally, the seventh critical finding is the observation of a contiguity effect in an item recognition task (though this effect appears to be limited to probe items that receive highest confidence old responses). In the sections below, we review the ability of the four major theories of episodic association to account for these findings.

In addition to the temporally defined associative processes reviewed above, a parallel set of findings concerns recency-sensitive processes in memory retrieval. Murdock (1974) summarizes the literature on primacy and recency effects in immediate recall and recognition tasks. Briefly, recency is the most prominent feature of the serial position curves obtained in free recall, paired-associate recall, probed recall, and item recognition. In serial recall, the primacy effect is more prominent than the recency effect. This is largely due to the fact that serial recall requires that subjects initiate recall at the start of the list. Although within-list recency effects in recall tasks are largely attenuated by an end-of-list distractor, recency returns in continuous-distractor free recall (Bjork and Whitten, 1974; Glenberg et al., 1980; Howard and Kahana, 1999). Recency is also observed over much longer time scales than the presentation of a single list, as evidenced by the observation that prior-list intrusions tend to come from recent lists (Murdock, 1974; Zaromb et al., 2006). Similarly, on a final free recall test, subjects are far more likely to recall items from recently studied lists (Craik, 1970; Tzeng, 1973; Glenberg et al., 1980; Howard et al., 2008). Thus, any theory of episodic memory must be able to accommodate recency across very long time scales. Whereas immediate recency effects have often been attributed to the operation of a short-term store, or buffer, longer-range recency effects are often attributed to a contextual coding process. A critical question is whether these recency effects have a common basis or whether they arise from distinct mechanisms (Greene and Crowder, 1984; Raaijmakers, 1993; Davelaar et al., 2005).

2.26.5.1 Chaining Theory

According to early conceptualizations of chaining theory, studying an item leads to the creation or strengthening of forward and backward connections

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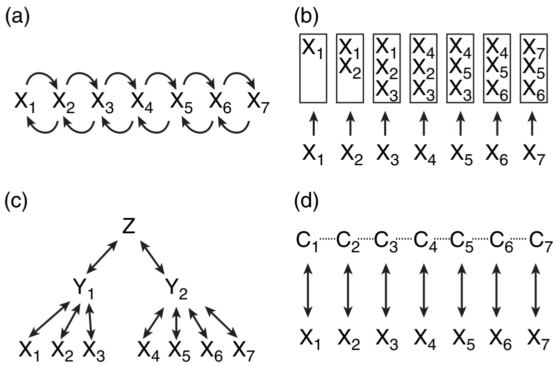

Figure 9 Illustration of the four types of memory models. (a) Chaining Theory. Each item is associated with its immediate neighbors. (b) Buffer Theory. Items are inserted into a fixed-capacity buffer and reside there until displaced. (c) Hierarchical Association Theory. Conjunctions of items are used to create higher-level representations, which are associated with the original items. (d) Contextual Retrieval Theory. A slowly changing context representation is associated with each of the items.

to the immediately preceding item, with associations being stronger in the forward direction (**Figure 9(a)**). As this classic version of chaining theory has often been associated with behaviorism and its rejection of mentalistic constructs, chaining has been a frequent source of ridicule at the hands of cognitively oriented theorists.

Modern chaining theories (e.g., Lewandowsky and Murdock, 1989; Chance and Kahana, 1997) improve on earlier conceptualizations in a number of critical ways. First, modern chaining theories represent each item as a collection of abstract features or attributes rather than as a single node. Second, associations are conceptualized as networks of connections between the processing units that represent the attribute values. These associative networks can be seen as representing a new entity rather than simply linking two preexisting knowledge structures. The associative retrieval process is thus able to recover a partial representation of an item and use that representation as a cue for subsequent recalls. In addition, the attribute representation of items provides a natural way of characterizing the similarities among item representations. By capturing the similarities among items, chaining models can simulate critical aspects of the behavioral data, such as the effect of semantic similarity on recall.

Lewandowsky and Murdock (1989) used the mathematical operations of convolution and correlation to simulate the chaining of associations among item representations in memory. This mathematical approach has also been used by Murdock and his colleagues to simulate data on free recall (Metcalfe and Murdock, 1981), paired associates, and item recognition (Murdock, 1982, 1992). Similar models have also been developed using Hebbian weight matrices to store associations (Humphreys et al., 1989; Rizzuto and Kahana, 2001; Kahana et al., 2005b).

Table 1 illustrates chaining theory's predictions regarding the seven critical findings reviewed above. It is not surprising that chaining theory predicts a contiguity effect in both immediate and delayed free recall (Kahana, 1996). Although most theories do not make explicit accounts of latency, it would be relatively straightforward to model the effect of contiguity on latency by using the strength of association to drive a diffusion model (e.g., Ratcliff, 1978).

Chaining theory is consistent with the idea that associations learned on earlier lists can induce subjects to commit intrusions when those earlier items are repeated in the target list. Further, when intrusions beget intrusions, chaining theory predicts that those intrusions should exhibit similar contiguity effects within the prior list that they came from (Zaromb et al., 2006). However, to accurately simulate the relatively modest interlist effects observed in the data, chaining theory must be augmented with a list context representation that is used to focus retrieval on the items in the target list (e.g., Sirotin et al., 2005).

Chaining theory can accommodate the forward asymmetry of the contiguity effect by differentially weighting the storage of forward and backward associations. This is not easily accomplished within the convolution-correlation formalism of Murdock and colleagues, but it can be easily implemented in a Hebbian matrix model (Pike, 1984; Kahana, 2002). Even so, employing differential weighting of forward and backward associations does little to explain the phenomenon.

The standard version of chaining theory assumes that associations are forged among neighboring items. One can extend the standard chaining model to produce the gradient of remote associations seen in the contiguity-effect in free recall by modeling the rehearsal process. When presented with an item for study, subjects often think about that item in relation to recently studied items. This rehearsal process will cause the functional order of study to differ from the nominal order of presentation (Brodie and Murdock, 1977; Tan and Ward, 2000), resulting in the remote

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Table 1 The ability of four major theories of association to account for contiguity phenomena across memory tasks.

Theory	Contiguity	Asymmetry	Long-range contiguity	Prior-list intrusions	Probed recall intrusions	Across-pair intrusions	Contiguity in item recognition
Chain	✓	*	×	✓	✓	✓	*
Buffer	✓	*	×	✓	✓	✓	*
Vertical	✓	*	×	✓	✓	*	*
Context	✓	✓	✓	✓	✓	✓	✓

The ✓ symbol means that the model can account for the data without modification. The * symbol means that the model requires some modification from the standard version to account for this data-point (see text for elaboration of each case). The × symbol means that the model is unable to account for this data-point.

associations of the kind seen in **Figure 2(a)**. The standard approach to modeling rehearsal in free recall is to assume that rehearsal is controlled by a working memory buffer that actively maintains (and rehearses) a small number of items (e.g., Raaijmakers and Shiffrin, 1980). We discuss the predictions of these so-called buffer models in the next subsection.

The more serious challenge to chaining theory comes from the observation of preserved long-range contiguity effects in free recall. It is hard to envision how chaining models would explain the approximate time-scale invariance of the contiguity effect, as shown in **Figure 5(b)**. Nearest-neighbor chaining theory, even when augmented with a rehearsal buffer and a list-context representation, would predict a diminished contiguity effect when subjects perform a demanding distractor task following each study item. For chaining theory to explain the long-range contiguity effect in continuous-distractor free recall, one would have to assume that remote associations extend through distractor intervals and even across entire lists. To explain the gradient of intrusions observed in recall of paired-associates (**Figure 7(c)**), one would need to assume that remote associations automatically link items that were studied in nonadjacent pairs.

The finding of associative effects in item recognition is also not easily explained by chaining theory, as it would require associations to be automatically formed between items even when there is no task demand to do so. If chained associations were automatically formed between neighboring items, and if compound cueing operates at retrieval (e.g., McKoon and Ratcliff, 1992), then chaining theory should be able to predict the associative effects seen in **Figure 8**.

It would be misleading to imply that chaining theory should be evaluated solely on the basis of the select phenomena highlighted in **Table 1**. In the domain of serial recall, where chaining theories have been most thoroughly investigated, the basic chaining model offers strikingly counterfactual predictions concerning subjects' recall errors, particularly in lists that incorporate repetitions of identical or similar items (Ranschburg, 1902; Lashley, 1951; Crowder and Melton, 1965; Crowder, 1968; Henson et al., 1996; Henson, 1998; Kahana and Jacobs, 2000).

2.26.5.2 Working Memory Buffers and Dual Store Theory

Chaining theory makes the implicit assumption that the just-presented item is somehow maintained long enough to become associated with the current item. In essence, the just-presented item must be maintained in some type of working memory buffer. Dual-store memory models, such as the Atkinson–Shiffrin model and its more modern descendant, the SAM retrieval model, elevate the working memory buffer to a far more prominent role (Raaijmakers and Shiffrin, 1980; Sirotin et al., 2005). These models assume a working memory buffer that is capable of holding multiple items during list presentation. Any items residing in the buffer at the time of test may be recalled without a lengthy search process. Moreover, the rules that determine how items enter and leave the buffer can be designed to simulate the process of strategic rehearsal, thus enabling the models to account for aspects of free-recall data that are believed to depend on the pattern of rehearsals that occur during list presentation (Rundus, 1971; Brodie and Murdock, 1977; Tan and Ward, 2000; Laming, 2006). The critical assumption for our purposes is that items that are co-resident in the buffer become associated, and the size of the buffer determines the range of remote associations among items (see **Figure 9(b)**).

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The SAM retrieval model, and its latest variant, eSAM, offers the most comprehensive model of free recall currently available (Raaijmakers and Shiffrin, 1980; Sirotin et al., 2005). The model's ability to explain a wide range of data, including findings concerning semantic organization effects, comes at the expense of a greater number of assumptions and mechanisms that are built into the model. For example, the eSAM model incorporates associations between items that share time in the buffer (essentially chaining) as well as associations between a time-varying list context signal and items. These associations reside in an episodic memory matrix that is distinct from a semantic memory matrix which is also used in retrieval. eSAM (and SAM) include a dynamical probabilistic recall process which keeps track of which items have already been recalled given a particular set of cues. Finally, a postretrieval recognition test is used to determine whether a retrieved item should be recalled or rejected due to its weak strength to the current list context.

It is important to note that buffer models such as those described by Davelaar et al. (2005) and Sirotin et al. (2005) have been shown to account for a very wide range of recall phenomena. For example, buffer models provide a natural explanation for the striking recency effect observed in immediate free recall and its marked attenuation following a brief interval of distracting activity. Because retrieval of items remaining in the buffer produces the recency effect in immediate recall tasks, buffer-based models can also neatly explain the numerous dissociations between recall of recency and prerecency items, as well as dissociations between immediate and continuous distractor free recall (Davelaar et al., 2005). Although they cannot easily account for long-range contiguity effects, buffer models still represent an important benchmark in the episodic memory literature.

2.26.5.3 Hierarchical Association Theory

Hierarchical models of association (e.g., Johnson, 1972; Lee and Estes, 1977; Murdock, 1995a, 1997; Anderson and Matessa, 1997; Anderson et al., 1998) attempt to explain how subjects unitize (or chunk) groups of items to create new conjunctive representations in memory. Whereas both chaining and buffer models define associations as directly linking neighboring items, hierarchical models assume that associations are mediated by a superordinate representation that provides access to two or more neighboring items. An item can be used to retrieve the superordinate representation (or chunk) which in turn can retrieve the other items associated with it. This kind of hierarchical associative structure is illustrated in **Figure 9(c)**.

Hierarchical theories of association have been largely motivated by the observation that practiced subjects tend to rhythmically group items during serial learning (e.g., Müller and Pilzecker, 1900). Because it is difficult to study subjects' grouping strategies in an unconstrained learning situation, researchers have devised methods to encourage specific grouping strategies whose consequences can be reliably measured. Such experimenter-imposed grouping is typically achieved by inserting pauses at regular intervals during list presentation.

There are four major consequences of experimenter-imposed grouping. First, consistent grouping leads to better serial recall, with the highest levels of recall observed for group sizes of three or four items (Wickelgren, 1967). Second, the grouping effect is largest for auditorally presented lists (Ryan, 1969). Third, grouping leads subjects to recall items in the correct within-group position but in the wrong group (Johnson, 1972; Brown et al., 2000). Fourth, subjects inter-response times during recall are longer at group boundaries (Maybery et al., 2002). These and related findings inspired the development of hierarchical associative models which have been applied with great success to data on serial recall (e.g., Estes, 1972; Lee and Estes, 1977; Murdock, 1993, 1997).

Hierarchical, or vertical, associations can be used to create representations that bridge time, which would help to explain some of the critical findings listed in **Table 1**. If the model is able to make a higher-level bridging representation associating successively presented items, then it can capture the contiguity effect. It is less clear whether a model like this can capture the asymmetry effect (Murdock, 1995b). Long-range contiguity effects pose a greater challenge, as they would require hierarchical representations to be robust to distraction, and to keep building up across lists. Hierarchical associations may be able to capture the contiguity effect in recognition, but this would require that the hierarchical representations are formed when there is no task demand to do so.

The preceding discussion refers to a type of hierarchical representation that bridges representations that are separated in time; however, another class of

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hierarchical models forms higher-level representations that bridge various simultaneously active lower-level representations. In particular, the connectionist model of episodic memory introduced by McClelland et al. (1995), and further developed by Norman and O'Reilly (2003) posits that the hippocampus serves as the locus of a higher-level representation that represents the conjunction of all of the features activated in the various cortical areas that project to it. This hippocampally based episodic representation is associated with all of these lower-level features such that the later activation of a subset of those features allows the episodic representation to be retrieved; it then projects out to the cortical areas and reactivates the full set of originally active features.

2.26.5.4 Contextual Retrieval Theory

The effective use of memory depends on our ability to focus retrieval on those memories learned within a given spatiotemporal context (e.g., Carr, 1931; McGeoch, 1932). According to temporal-context models, the memory system associates each studied item with the contextual features present at the time of encoding. At the time of test, the current state of context is a good retrieval cue for recently studied memories (Bower, 1972; Howard and Kahana, 2002). Because retrieval results from a competition among activated memory traces, one observes recency both in immediate and in continuous-distractor free recall (Bjork and Whitten, 1974; Crowder, 1976; Howard and Kahana, 1999).

Howard and Kahana (2002) proposed an extension of the classic Estes-Bower context theory that was designed to explain the observation of long-range contiguity effects. According to their temporal context model (TCM), recall of an item results in a partial reinstatement of the context that was present when that item was studied. This retrieved context then serves as a retrieval cue for other items with a similar context at study, which are most likely to be items from nearby serial positions, thus yielding the contiguity effect.

TCM provides a natural explanation for the robust contiguity effects found in continuous-distractor free recall, as retrieval transitions are driven by the relative similarity between the temporal contexts of different list items. As long as a similar duration of distracting activity separates each item from its neighbors, TCM predicts that the transitions among neighboring list items will be largely independent of the absolute temporal separation of the items in the list.

According to TCM, context is a vector that changes gradually as a result of items being activated in semantic memory. TCM provides a formal mathematical model of how temporal context evolves as a consequence of item encoding and retrieval. It also describes an associative architecture, implemented as a neural network, that links both items to context and context to items.

A given state of temporal context will cue recall items via the context-to-item associative network. Consistent with Tulving's notion of encoding specificity (Tulving, 1983), the optimal cue for an item is the context in which it was encoded. Because context changes gradually, the state of context at the time of test will overlap most strongly with the contexts associated with recent items. This gives rise to the recency effect seen in all episodic memory tasks. Primacy is accommodated within TCM by assuming that early list items receive more rehearsals and/or increased attentional resources (Brodie and Murdock, 1977; Tan and Ward, 2000).

Just as contextual states can retrieve items in semantic memory, so too can items retrieve their associated contextual states. In TCM, it is this process of contextual reactivation that drives the evolution of the context vector itself. Contiguity effects arise because the retrieved contextual states overlap with the encoding context of nearby items. For a more complete treatment, the reader is referred to Howard and Kahana (2002) and Howard et al. (2006). For a discussion of a potential mapping between TCM and the structure and function of the medial temporal lobe, see Howard et al. (2005).

According to TCM, 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 pre-experimental contextual states associated with the item. Because the pre-experimental contextual states 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 pre-experimental contextual states). The combination of these two components produces the forward asymmetry seen in the contiguity effect (**Figure 2(a)**).

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Retrieved context is one way that contiguity effects could arise across wide-ranging time scales, such as those observed in continuous-distractor free recall, final free recall, and recall of paired-associates. Dennis and Humphreys (2001) suggested that temporal context may underlie recognition judgments as well. In this case, one might predict that high confidence yes responses reflect successful retrieval of context. The contiguity effect seen in item recognition (**Figure 8**) could arise if the retrieved contextual representation of an item combined with the subsequent test probe.

2.26.6 Conclusions and Open Questions

The evidence we have reviewed shows how retrieval of episodic memories is a cue-dependent process that reflects the temporal contiguity and the semantic relatedness of the cue and the target items. Analyses of retrieval transitions in free recall demonstrate that both temporal and semantic factors have a dramatic effect on retrieval. Although subjects may recall items in any order they wish, the recall of a given item is predictable on the basis of its semantic relatedness and temporal contiguity to the just recalled item.

The contiguity effect, as seen in **Figure 2(a)**, exhibits a strong forward asymmetry, with recall transitions being nearly twice as likely in the forward than in the backward direction. This tendency to make forward transitions contrasts with the overall tendency to begin recall at the end of the list (Kahana, 1996). Contiguity and asymmetry are ubiquitious in free recall. The basic lag-CRP and lag-CRL curves have the same form for lists of different lengths and presentation rates, for different presentation modalities, for different word frequencies, etc. Although reduced for older adults, the contiguity and asymmetry effects have the same basic form across age groups.

The contiguity effect is not limited to free recall; rather, it is a nearly universal characteristic of retrieval in episodic memory. Contiguity is seen in the pattern of correct recalls, inter-response times, and intrusions in free recall, and in the memory errors seen in probed recall, serial recall, and paired-associate recall. Even in item recognition, contiguity appears when subjects respond with high confidence.

One of the most striking and theoretically significant features of the contiguity effect is its persistence across time scales. In free recall, the contiguity effect is not reduced when list items are separated by 16 s of distractor activity. In recall of paired associates, contiguity appears in subjects' tendency to recall items from nearby pairs, thus demonstrating that contiguity does not depend on subjects intention to learn the association between neighboring items.

Four major theories have been proposed to explain episodic associations: Chaining theory, buffer theory, hierarchical association theory, and retrieved context theory. Whereas all of these theories can account for the basic contiguity effect, retrieved context theory offers the only adequate account of the long-range contiguity effect. Retrieved context theories, such as TCM, provide a basis for synthesizing the associative effects observed across all of the major episodic recall and recognition paradigms. In TCM, associative effects appear because retrieved context of a given item overlaps with the encoding context of nearby items. This approach constitutes a departure from traditional accounts of association, such as those assuming direct interitem associations (chaining or buffer theory) or those that assume hierarchial associative structures.

Although the presence of contiguity across time scales supports the contextual retrieval account of episodic association, it does not preclude the operation of other factors as suggested by the alternative theories. For example, it is possible to envision a hierarchical associative model or a buffer-based associative model that also includes a contextual retrieval mechanism.

Despite the enormous strides in our understanding of episodic association, a number of intriguing puzzles remain to be solved. One unsolved puzzle concerns the asymmetric nature of episodic associations. Although the forward asymmetry is a striking feature of associations in free recall, serial recall, and probed recall, the data do not reveal striking asymmetries in all episodic tasks. Moreover, recall of individual 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 (Kahana, 2002).

Perhaps the most important of these puzzles is the question of how the rich structure of semantic associations in human memory could arise simply due to the repeated presentation of related items in temporal proximity. Computational models of semantic memory, such as LSA (Landauer and Dumais, 1997) and the topics model (Griffiths and Steyvers, 2002, 2003) provide some clues as to how such a reconciliation might be possible. LSA and the topics model

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extract information about the temporal contexts in which words appear to estimate their meaning. Specifically, in these models, temporal context is defined as a passage of text. The hyperspace analog of language (HAL, Lund and Burgess, 1996) and BEAGLE (Jones and Mewhort, 2007) models define temporal context as a sliding window of a fixed number of words. This suggests the possibility of a unification of computational models of semantic memory and models of episodic memory based on contextual retrieval (Dennis and Humphreys, 2001; Howard and Kahana, 2002), in that each process may rely on the presence of a slowly-drifting source of contextual information.

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References

Anderson JR and Matessa M (1997) A production system theory of serial memory. *Psychol. Rev.* 104: 728–748.

Anderson JR, Bothell D, Lebiere C, and Matessa M (1998) An integrated theory of list memory. *J. Mem. Lang.* 38: 341–380.

Asch SE and Ebenholtz SM (1962) The principle of associative symmetry. *Proc. Am. Philos. Soc.* 106: 135–163.

Atkinson RC and Shiffrin RM (1968) Human memory: A proposed system and its control processes. In: Spence KW and Spence JT (eds.) *The Psychology of Learning and Motivation,* Vol. 2, pp. 89–105. New York: Academic Press.

Bjork RA and Whitten WB (1974) Recency-sensitive retrieval processes in long-term free recall. *Cogn. Psychol.* 6: 173–189.

Bousfield WA (1953) The occurrence of clustering in the recall of randomly arranged associates. *J. Gen. Psychol.* 49: 229–240.

Bousfield WA, Sedgewick CH, and Cohen BH (1954) Certain temporal characteristics of the recall of verbal associates. *Am. J. Psychol.* 67: 111–118.

Bower G (1967) A multicomponent theory of the memory trace. In: Spence KW and Spence JT (eds.) *The Psychology of Learning and Motivation: Advances in Research and Theory,* Vol. 1, pp. 229–325. New York: Academic Press.

Bower GH (1972) Stimulus-sampling theory of encoding variability. In: Melton AW and Martin E (eds.) *Coding Processes in Human Memory*, pp. 85–121. New York: John Wiley and Sons.

Brodie DA and Murdock BB (1977) Effects of presentation time on nominal and functional serial position curves in free recall. *J. Verb. Learn. Verb. Behav.,* 16: 185–200.

Brown GDA, Preece T, and Hulme C (2000) Oscillator-based memory for serial order. *Psychol. Rev.,* 107(1): 127–181.

Burgess N and Hitch G (2005) Computational models of working memory: putting long-term memory into context. *tics,* 9: 535–41.

Caplan JB, Glaholt M, and McIntosh AR (2006) Linking associative and list memory: pairs versus triples. *J. Exp. Psychol. Learn. Mem. Cogn.* 32: 1244–1265.

Carr HA (1931) The laws of association. *Psychol. Rev.* 38: 212–228.

Chance FS and Kahana MJ (1997) Testing the role of associative interference and compound cues in sequence memory. In: Bower J. (ed.) *Computational Neuroscience: Trends in Research*, pp. 599–603. New York: Plenum Press.

Craik FIM (1970) The fate of primary memory items in free recall. *J. Verb. Learn. Verb. Behav.,* 9: 658–664.

Craik FIM and Levy BA (1970) Semantic and acoustic information in primary memory. *J. Exp. Psychol.* 86: 77–82.

Crowder RG (1968) Intraserial repetition effects in immediate memory. *J. Verb. Learn. Verb. Behav.,* 7: 446–451.

Crowder RG (1976) *Principles of Learning and Memory*. Hillsdale, NJ: Lawrence Erlbaum and Associates.

Crowder RG and Melton AW (1965) The Ranschburg phenomenon: Failures of immediate recall correlated with repetition of elements within a stimulus. *Psychon. Sci.* 2: 295–296.

Davelaar EJ, Goshen-Gottstein Y, Ashkenazi A, Haarmann HJ, and Usher M (2005) The demise of short-term memory revisited: Empirical and computational investigations of recency effects. *Psychol. Rev.* 112: 3–42.

Davis OC, Geller AS, Rizzuto DS, and Kahana MJ (2008) Temporal associative processes revealed by intrusions in paired-associate recall. *Psychon. Bull. Rev.* 15(1): 64–69.

Deese J (1959) On the prediction of occurrence of particular verbal intrusions in immediate recall. *J. Exp. Psychol.* 58: 17–22.

Deese J and Kaufman RA (1957) Serial effects in recall of unorganized and sequentially organized verbal material. *J. Exp. Psychol.* 54: 180–187.

Dennis S and Humphreys MS (2001) A context noise model of episodic word recognition. *Psychol. Rev.* 108: 452–478.

Ebbinghaus H (1885/1913) *On Memory: A Contribution to Experimental Psychology*. New York: Teachers College, Columbia University.

Ekstrand BR (1966) Backward associations. *Psychol. Bull.* 65: 50–64.

Estes WK (1955) Statistical theory of spontaneous recovery and regression. *Psychol. Rev.* 62: 145–154.

Estes WK (1972) An associative basis for coding and organization in memory. In: Melton AW and Martin E (eds.) *Coding Processes in Human Memory*, pp. 161–190. Washington, DC: Winston.

Gallo DA and Roediger HL (2002) Variability among word lists in eliciting memory illusions: Evidence for associative activation and monitoring. *J. Mem. Lang.* 47: 469–497.

Gillund G and Shiffrin RM (1984) A retrieval model for both recognition and recall. *Psychol. Rev.* 91: 1–67.

Giurintano SL (1973) Serial learning process: test of chaining, position, and dual process hypotheses. *J. Exp. Psychol.* 97(2): 154–157.

Glanzer M (1972) Storage mechanisms in recall. In: Spence KW. and Spence JT. (eds.) *The Psychology of Learning and Motivation*, pp. 129–193. New York: Academic Press.

Glanzer M and Cunitz AR (1966) Two storage mechanisms in free recall. *J. Verb. Learn. Verb. Behav.* 5: 351–360.

Glenberg AM, Bradley MM, Stevenson JA, Kraus TA, Tkachuk MJ, and Gretz AL (1980) A two-process account of long-term serial position effects. *J. Exp. Psychol. Learn. Mem. Cogn.* 6: 355–369.

Glenberg AM, Bradley MM, Kraus TA, and Renzaglia GJ (1983) Studies of the long-term recency effect: Support for a contextually guided retrieval theory. *J. Exp. Psychol. Learn. Mem. Cogn.* 12: 413–418.

Greene RL and Crowder RG (1984) Effects of semantic similarity on long-term recency. *Am. J. Psychol.* 97: 441–449.

Author's personal copy

Griffiths T and Steyvers M (2002) A probabilistic approach to semantic representation. *Proceedings of the 24th Annual Conference of the Cognitive Science Society*.

Griffiths T and Steyvers M (2003) Prediction and semantic association. In: Halmberg KJ and Steyvers M (eds.) *Advances in Neural Information Processing Systems, 15*, pp. 11–18. Cambridge, MA: MIT Press.

Henson RNA (1998) Item repetition in short-term memory: Ranschburg repeated. *J. Exp. Psychol. Learn. Mem. Cogn.* 24: 1162–1181.

Henson RNA, Norris DG, Page MPA, and Baddeley AD (1996) Unchained memory: Error patterns rule out chaining models of immediate serial recall. *Q. J. Exp. Psychol.* 49A: 80–115.

Herbart JF (1834) Lehrbuch zur Psychologie. In: Kehrbach K (ed.) pp. 376–377. Konigsberg: August Wilhelm Unzer.

Hogan RM (1975) Interitem encoding and directed search in free recall. *Mem. Cognit.* 3: 197–209.

Hollingsworth HL (1928) *Psychology: Its Facts and Principles*. D. Appleton and Company.

Howard MW and Kahana MJ (1999) Contextual variability and serial position effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 25: 923–941.

Howard MW and Kahana MJ (2002) A distributed representation of temporal context. *J. Math. Psychol.* 46: 269–299.

Howard MW, Fotedar MS, Datey AV, and Hasselmo ME (2005) The temporal context model in spatial navigation and relational learning: Toward a common explanation of medial temporal lobe function across domains. *Psychol. Rev.* 112(1): 75–116.

Howard MW, Kahana MJ, and Wingfield A (2006) Aging and contextual binding: modeling recency and lag recency effects with the temporal context model. *Psychon. Bull. Rev.* 13: 439–445.

Howard MW, Addis KA, Jing B, and Kahana MJ (2007) Semantic structure and episodic memory. Invited chapter for *LSA*: *A Road Towards Meaning*, T. Landauer, D. McNamara, S. Dennis, and W. Kintsch (eds), Laurence Erlbaum, pp. 121–141.

Howard MW, Youker TE, and Venkatadass V (2008) The persistence of memory: Contiguity effect across several minutes. *Psychon. Bull Rev.* 15: 58–63.

Hoyer WJ and Verhaeghen P (2006) Memory aging. In: Birren JE and Schaie KW (eds.) *Handbook of the Psychology of Aging (6th edition)*, pp. 209–232. San Diego: Elsevier.

Humphreys MS (1978) Item and relational information: A case for context independent retrieval. *J. Verb. Learn. Verb. Behav.* 17: 175–187.

Humphreys MS, Bain JD, and Pike R (1989) Different ways to cue a coherent memory system: A theory for episodic, semantic, and procedural tasks. *Psychol. Rev.* 96: 208–233.

Hunt RR and McDaniel MA (1993) The enigma of organization and distinctiveness. *J. Mem. Lang.* 32(4): 421–445 Aug.

Johnson NF (1972) Organization and the concept of a memory code. In: Melton AW. and Martin E. (eds.) *Coding Processes in Human Memory*, pp. 125–159. Washington, DC: Winston.

Jones MN and Mewhort DJK (2007) Representing word meaning and order information in a composite holographic lexicon. *Psychol. Rev.* 114: 1–37.

Kahana MJ (1996) Associative retrieval processes in free recall. *Mem. Cognit.* 24: 103–109.

Kahana MJ (2002) Associative symmetry and memory theory. *Mem. Cognit.* 30: 823–840.

Kahana MJ and Caplan JB (2002) Associative asymmetry in probed recall of serial lists. *Mem. Cognit.* 30: 841–849.

Kahana MJ and Howard MW (2005) Spacing and lag effects in free recall of pure lists. *Psychon. Bull. Rev.* 12: 159–164.

Kahana MJ and Jacobs J (2000) Inter-response times in serial recall: Effects of intraserial repetition. *J. Exp. Psychol. Learn. Mem. Cogn.* 26: 1188–1197.

Kahana MJ and Loftus G (1999) Response time versus accuracy in human memory. In: Sternberg RJ (ed.) *The Nature of Cognition*, pp. 322–384. Cambridge, MA: MIT Press.

Kahana MJ, Howard MW, Zaromb F, and Wingfield A (2002) Age dissociates recency and lag recency effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 28: 530–540.

Kahana MJ, Dolan ED, Sauder CL, and Wingfield A (2005a) Intrusions in episodic recall: Age differences in editing of overt responses. *J. Gerontol. Psychol. Sci.* 60: 92–97.

Kahana MJ, Rizzuto DS, and Schneider A (2005b) Theoretical correlations and measured correlations: Relating recognition and recall in four distributed memory models. *J. Exp. Psychol. Learn. Mem. Cogn.* 31: 933–953.

Kausler DH (1994) *Learning and memory in normal aging*. San Diego, CA: Academic Press.

Kimball DR and Bjork RA (2002) Influences of intentional and unintentional forgetting on false memories. *J. Exp. Psychol. Gen.* 131: 116–130.

Kinsbourne M and George J (1974) The mechanism of the word-frequency effect on recognition memory. *J. Verb. Learn. Verb. Behav.* 13: 63–69.

Kirkpatrick EA (1894 November) An experimental study of memory. *Psychol. Rev.* 1(6:): 602–609.

Klein KA, Addis KM, and Kahana MJ (2005) A comparative analysis of serial and free recall. *Mem. Cognit.* 33: 833–839.

Köhler W (1947) *Gestalt Psychology*. New York: Liveright.

Laming D (1999) Testing the idea of distinct storage mechanisms in memory. *Int. J. Psychol.* 34: 419–426.

Laming D (2006) Predicting free recalls. *J. Exp. Psychol. Learn. Mem. Cogn.* 32(5): 1146–1163.

Landauer TK and Dumais ST (1997) Solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychol. Rev.* 104: 211–240.

Lashley KS (1951) The problem of serial order in behavior. In: Jeffress LA (ed.) *Cerebral Mechanisms in Behavior*, pp. 112–136. New York: Wiley.

Lee CL and Estes WK (1977) Order and position in primary memory for letter strings. *J. Verb. Learn. Verb. Behav.* 16: 395–418.

Lewandowsky S and Murdock BB (1989) Memory for serial order. *Psychol. Rev.* 96: 25–57.

Loftus GR and Masson MEJ (1994) Using confidence intervals in within-subject designs. *Psychon. Bull. Rev.* 1: 476–490.

Lund K and Burgess C (1996) Producing high-dimensional semantic spaces from lexical co-occurrence. *Behav. Res. Methods Instrum. Comput.* 28(2): 203–208.

MacLeod CM and Kampe K (1996) Word frequency effects on recall, recognition, and word fragment completion tests. *J. Exp. Psychol.* 22(1): 132–142.

Martin E and Noreen DL (1974) Serial learning: Identification of subjective subsequences. *Cognit. Psychol.* 6: 421–435.

Maybery MT, Parmentier FBR, and Jones DM (2002) Grouping of list items reflected in the timing of recall: implications for models of serial verbal memory. *J. Mem. Lang.* 47: 360–385.

McClelland JL, McNaughton BL, and O'Reilly RC (1995) Why there are complementary learning systems in the hippocampus and neocortex: insights from the successes and failures of connectionist models of learning and memory. *Psychol. Rev.* 102(3): 419–57.

McGeoch JA (1932) Forgetting and the law of disuse. *Psychol. Rev.* 39: 352–70.

McGeoch JA and Irion AL (1952) *The Psychology of Human Learning*. 2nd edition. New York: Longmans, Green and Co.

McKoon G and Ratcliff R (1992) Spreading activation versus compound cue accounts of priming: Mediated priming revisited. *J. Exp. Psychol. Learn. Mem. Cogn.* 18: 1155–1172.

Mensink G-JM and Raaijmakers JGW (1988) A model for interference and forgetting. *Psychol. Rev.* 95: 434–455.

Author's personal copy

Metcalfe J and Murdock BB (1981) An encoding and retrieval model of single-trial free recall. *J. Verb. Learn. Verb. Behav.* 20: 161–189.
Müller GE and Pilzecker A (1900) Experimental contributions to memory theory. *Z. Psychol. Eganzungs.* 1: 1–300.
Murdock BB (1962) The serial position effect of free recall. *J. Exp. Psychol.* 64: 482–488.
Murdock BB (1968) Serial order effects in short-term memory. *J. Exp. Psychol. Monogr. Suppl.* 76: 1–15.
Murdock BB (1974) *Human Memory: Theory and Data*. Potomac, MD: Lawrence Erlbaum and Associates.
Murdock BB (1982) A theory for the storage and retrieval of item and associative information. *Psychol. Rev.* 89: 609–626.
Murdock BB (1992) Item and associative information in a distributed memory model. *J. Math. Psychol.* 36: 68–99.
Murdock BB (1993) TODAM2: A model for the storage and retrieval of item, associative, and serial-order information. *Psychol. Rev.* 100: 183–203.
Murdock BB (1995a) Developing TODAM: Three models for serial-order information. *Mem. Cognit.* 23: 631–645.
Murdock BB (1995b) Similarity in a distributed memory model. *J. Math. Psychol.* 39: 251–264.
Murdock BB (1997) Context and mediators in a theory of distributed associative memory (TODAM2). *Psychol. Rev.* 104: 839–862.
Murdock BB and Metcalfe J (1978) Controlled rehearsal in single- trial free recall. *J. Verb. Learn. Verb. Behav.* 17: 309–324.
Murdock BB and Okada R (1970) Interresponse times in single-trial free recall. *J. Verb. Learn. Verb. Behav.* 86: 263–267.
Murdock BB and Walker KD (1969) Modality effects in free recall. *J. Verb. Learn. Verb. Behav.* 8: 665–676.
Nairne JS (1990a) A feature model of immediate memory. *Mem. Cognit.* 18: 251–269.
Nairne JS (1990b) Similarity and long-term memory for order. *J. Mem. Lang.* 29: 733–746.
Naveh-Benjamin M (2000) Adult-age differences in memory performance: Tests of an associative deficit hypothesis. *J. Exp. Psychol. Learn. Mem. Cogn.* 26: 1170–1187.
Neath I (1993) Contextual and distinctive processes and the serial position function. *J. Mem. Lang.* 32: 820–840.
Nelson DL, McEvoy CL, and Schreiber TA (2004) The University of South Florida free association, rhyme, and word fragment norms. *Behav. Res. Methods Instrum. Comput.* 36(3): 402–407.
Nilsson LG, Wright E, and Murdock BB (1975) The effects of visual presentation method on single-trial free recall. *Mem. Cognit.* 3: 427–433.
Norman KA and O'Reilly RC (2003) Modeling hippocampal and neocortical contributions to recognition memory: A complementary learning systems approach. *Psychol. Rev.* 110: 611–646.
Paivio A (1971) *Imagery and Verbal Processes*. New York: Holt, Rinehart, and Winston.
Pike R (1984) Comparison of convolution and matrix distributed memory systems for associative recall and recognition. *Psychol. Rev.* 91: 281–294.
Postman L and Phillips LW (1965) Short-term temporal changes in free recall. *Q. J. Exp. Psychol.* 17: 132–138.
Primoff E (1938) Backward and forward associations as an organizing act in serial and in paired-associate learning. *J. Psychol.* 5: 375–395.
Raaijmakers JGW (1993) The story of the two-store model of memory: Past criticisms, current status, and future directions. In: Meyer D. and Kornblum S. (eds.) *Attention and Performance xiv*, pp. 467–488. Cambridge MA: MIT Press.
Raaijmakers JGW and Shiffrin RM (1980) SAM: A theory of probabilistic search of associative memory. In: Bower GH (ed.) *The Psychology of Learning and Motivation: Advances in Research and Theory,* Vol. 14, pp. 207–262. New York: Academic Press.
Raaijmakers JGW and Shiffrin RM (1981) Search of associative memory. *Psychol. Rev.* 88: 93–134.
Ranschburg P (1902) Uber hemmung gleichzeitiger reizwirkungen. *Z. Psychol. Physiol. Sinnesorgane* 30: 39–86.
Raskin E and Cook SW (1937) The strength and direction of associations formed in the learning of nonsense syllables. *J. Exp. Psychol.* 20: 381–395.
Ratcliff R (1978) A theory of memory retrieval. *Psychol. Rev.* 85: 59–108.
Raymond BJ (1969) Short-term storage and long-term storage in free recall. *J. Verb. Learn. Verb. Behav.* 8: 567–574.
Rizzuto DS and Kahana MJ (2001) An autoassociative neural network model of paired-associate learning. *Neural Comput.* 13: 2075–2092.
Roberts WA (1972) Free recall of word lists varying in length and rate of presentation: A test of total-time hypotheses. *J. Exp. Psychol.* 92: 365–372.
Robinson ES (1932) *Association Theory Today; an Essay in Systematic Psychology*. New York: The Century Co.
Roediger HL and McDermott KB (1995) Creating false memories: Remembering words not presented in lists. *J. Exp. Psychol. Learn. Mem. Cogn.* 21: 803–814.
Roediger HL, McDermott KB, and Robinson KJ (1998) The role of associative processes in creating false memories. In: Conway M., Gathercole SE., and Cornoldi C. (eds.) *Theories of Memory,* vol. ii, pp. 230–241. New York: Psychology Press.
Rundus D (1971) An analysis of rehearsal processes in free recall. *J. Exp. Psychol.* 89: 63–77.
Ryan J (1969) Grouping and short-term memory: Different means and patterns of grouping. *Q. J. Exp. Psychol.* 21: 137–147.
Salthouse TA (1991) *Theoretical Perspectives on Cognitive Aging*. Hillsdale, NJ: Lawrence Erlbaum and Associates.
Schwartz G, Howard MW, Jing B, and Kahana MJ (2005) Shadows of the past: Temporal retrieval effects in recognition memory. *Psychol. Sci.* 16: 898–904.
Sherman SJ, Atri A, Hasselmo ME, Stern CE, and Howard MW (2003) Scopolamine impairs human recognition memory: Data and modeling. *Behav. Neurosci.* 117: 526–539.
Sirotin YB, Kimball DR, and Kahana MJ (2005) Going beyond a single list: Modeling the effects of prior experience on episodic free recall. *Psychon. Bull. Rev.* 12(5): 787–805.
Slamecka NJ (1987) The law of frequency. In: Gorfein DS and Hoffman RR (eds.) *Memory and Learning: The Ebbinghaus Centennial Conference*, pp. 105–128. Hillsdale, NJ: Lawrence Erlbaum and Associates.
Sommer T, Rose M, and Büchel C (2007) Associative symmetry versus independent associations in the memory for object-location associations. *J. Exp. Psychol. Learn. Mem. Cogn.* 33: 90–106.
Spiers HJ, Maguire EA, and Burgess N (2001) Hippocampal amnesia. *Neurocase* 7: 357–382.
Sternberg RJ and Tulving E (1977) The measurement of subjective organization in free recall. *Psychol. Bull.* 84(3): 539–556.
Steyvers M, Shiffrin RM, and Nelson DL (2004) Word association spaces for predicting semantic similarity effects in episodic memory. In: Healy AF (ed.) *Cognitive Psychology and its Applications: Festschrift in honor of Lyle Bourne, Walter Kintsch, and Thomas Landauer*, Washington, DC: American Psychological Association.
Sumby WH (1963) Word frequency and serial position effects. *J. Verb. Learn. Verb. Behav.* 1: 443–450.
Tan L and Ward G (2000) A recency-based account of the primary effect in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 26: 1589–1626.

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Tulving E (1962) Subjective organization in free recall of ''unrelated'' words. *Psychol. Rev.* 69(4): 344–354.
Tulving E (1972) Episodic and semantic memory. In: Tulving E. and Donaldson W. (eds.) *Organization of Memory*, pp. 381–403. New York: Academic Press.
Tulving E (1983) *Elements of Episodic Memory*. New York: Oxford.
Tulving E and Madigan SA (1970) Memory and verbal learning. *Annu. Rev. Psychol.* 21: 437–484.
Tulving E and Thompson DM (1973) Encoding specificity and retrieval processes in episodic memory. *Psychol. Rev.* 80: 352–373.
Tulving E and Wiseman S (1975) Relation between recognition and recognition failure of recallable words. *Bull. Psychon. Soc.* 6: 79–82.
Tzeng OJL (1973) Positive recency in delayed free recall. *J. Verb. Learn. Verb. Behav.* 12: 436–439.
Underwood BJ (1945) The effect of successive interpolations and proactive inhibition. *Psychol. Monogr.* 59: v+33.
Verhaeghen P and Marcoen A (1993) Memory aging as a general phenomenon: episodic recall of older adults is a function of episodic recall of young adults. *Psychol. Aging* 8(3): 380–8.
Ward G, Woodward G, Stevens A, and Stinson C (2003) Using overt rehearsals to explain word frequency effects in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 29: 186–210.
Waugh NC and Norman D (1965) Primary memory. *Psychol. Rev.* 72: 89–104.
Wickelgren WA (1967) Rehearsal grouping and hierarchical organization of serial position cues in short-term memory. *Q. J. Exp. Psychol.* 19: 97–102.
Wingfield A and Kahana MJ (2002) The dynamics of memory retrieval in older adults. *Can. J. Exp. Psychol.* 56: 187–199.
Woodward A and Murdock BB (1968) Positional and sequential probes in serial learning. *Can. J. Psychol.* 22: 131–138.
Yntema DB and Trask FP (1963) Recall as a search process. *J. Verb. Learn. Verb. Behav.* 2: 65–74.
Yonelinas AP (1999) The contribution of recollection and familiarity to recognition and source-memory judgments: a formal dual-process model and an analysis of receiver operating characteristics. *J. Exp. Psychol. Learn. Mem. Cogn.* 25(6): 1415–34.
Zaromb FM, Howard MW, Dolan ED, Sirotin YB, Tully M, Wingfield A, et al. (2006) Temporal associations and prior-list intrusions in free recall. *J. Exp. Psychol. Learn. Mem. Cogn.* 32(4): 792–804.