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Associative Retrieval Processes in Episodic Memory

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Abstract

Association and context constitute two of the central ideas in the history of episodic memory research. Following a brief discussion of the history of these ideas, we review data that demonstrate the complementary roles of temporal contiguity and semantic relatedness in determining the order in which subjects recall lists of items and the timing of their successive recalls. These analyses reveal that temporal contiguity effects persist over very long time scales, a result that challenges traditional psychological and neuroscientific models of association. The form of the temporal contiguity effect is conserved across all of the major recall tasks and even appears in item recognition when subjects respond with high confidence. The near-universal form of the contiguity effect and its appearance at diverse time scales is shown to place tight constraints on the major theories of association.

> [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

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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 spatio-temporal 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.

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, Maguire, & Burgess, 2001). More subtle impairments of episodic memory accompany the normal aging process (Kausler, 1994; Salthouse, 1991).

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.

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, usually 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, or a hotel room number) 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

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

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, Crowder, 1976; Murdock, 1974; Paivio, 1971). 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 (Carr, 1931; Hollingsworth, 1928; McGeoch, 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 & 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. 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 to moment, slowly drifting through a multidimensional feature space. Whereas previous investigators had noted the importance of temporal coding (e.g., Yntema & 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 & Raaijmakers, 1988; Howard & Kahana, 2002).

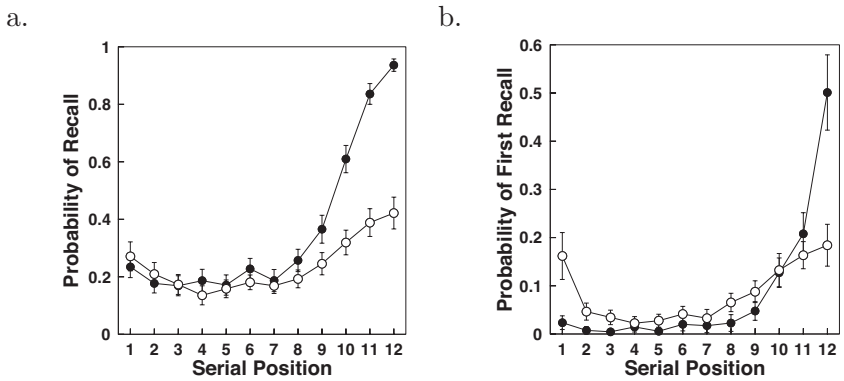

Figure 1. **The recency effect in immediate and delayed free recall.** After studying a list of 12 common words, subjects were either asked to recall items immediately (filled circles) or following a 15 second arithmetic distractor task (open circles). **a.** Serial position curves. **b.** Probability 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 & Kahana (1999, Experiment 1). Error bars denote 95% confidence intervals.

Associative Processes in Free Recall

The "cognitive revolution" of the 1960's 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 & Tulving, 1977, for a review of measures of subjective organization). Earlier

[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.

work by Bousfield and colleagues (Bousfield, 1953; Bousfield, Sedgewick, & Cohen, 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 significant efforts over a 20+ year period 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) quantified the relation between list position and recall probability. On an immediate recall test, subjects nearly always began by recalling items from the end of the list (the recency effect) (cf., Nilsson, Wright, & Murdock, 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 & Levy, 1970), and lists of common words are better recalled than lists of rare words (Raymond, 1969; Sumby, 1963; Ward, Woodward, Stevens, & Stinson, 2003).[3] In both of these cases, however, the improved 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 & 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 sec.) greatly reduces the recency effect while having no adverse consequences on recall of prerecency items (Glanzer & Cunitz, 1966; Postman & Phillips, 1965). Figure 1a 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 the level of recall for items from asymptotic serial positions (Atkinson & Shiffrin, 1968; Glanzer & Cunitz, 1966; Waugh & Norman, 1965).

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

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

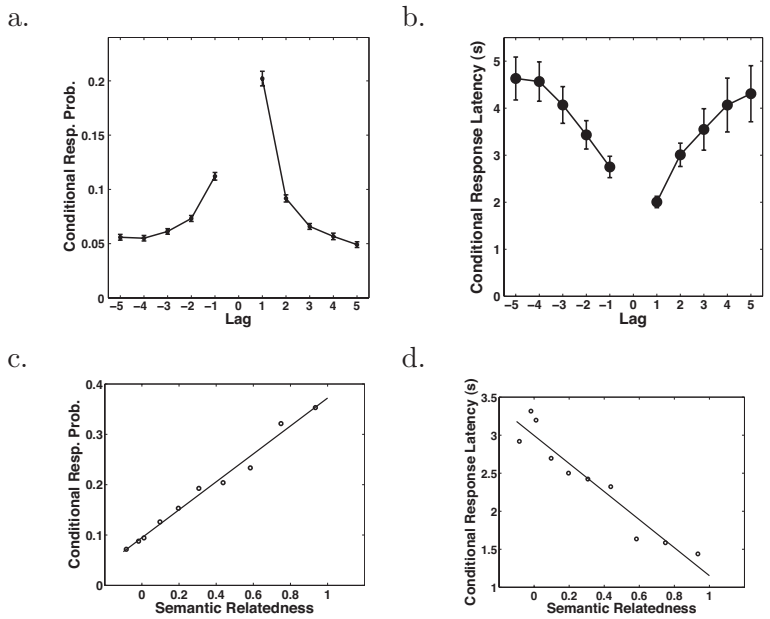

Figure 2. **Associative Processes in Free Recall: Effects of temporal contiguity and semantic relatedness. a.** The conditional–response probability as a function of lag (or lag-CRP) shows the probability of recalling an item from serial position $i+\text{lag}$ immediately following an item from serial position i. This curve is based on data from 20 experimental conditions (Murdock, 1962; Murdock & Okada, 1970; Murdock & Metcalfe, 1978; Roberts, 1972; Kahana et al., 2002; Howard & Kahana, 1999; Zaromb et al., 2006; Kimball & Bjork, 2002; Kahana & Howard, 2005; Kahana et al., 2005). **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 & Kahana, 1999; Murdock & Okada, 1970; Zaromb et al., 2006; Kahana & Howard, 2005). **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 et al., 2004). **d.** The conditional–response latency as a function of semantic relatedness (semantic-CRL) shows that subjects transitions are made more quickly when they are to related items. Error bars represent 95% confidence intervals across experiments.

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 1b, 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 & Kahana, 1999). By studying subjects' subsequent recall transitions, one can see that temporally-defined, inter-item 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 2a, 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 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 transitions to that lag.

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 2a, 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 2b (see Kahana & 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 "jump back" into the list, making it more likely that subsequent recalls will come from nearby serial positions.

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

[4]For example, if the list had contained the sub-sequence "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.

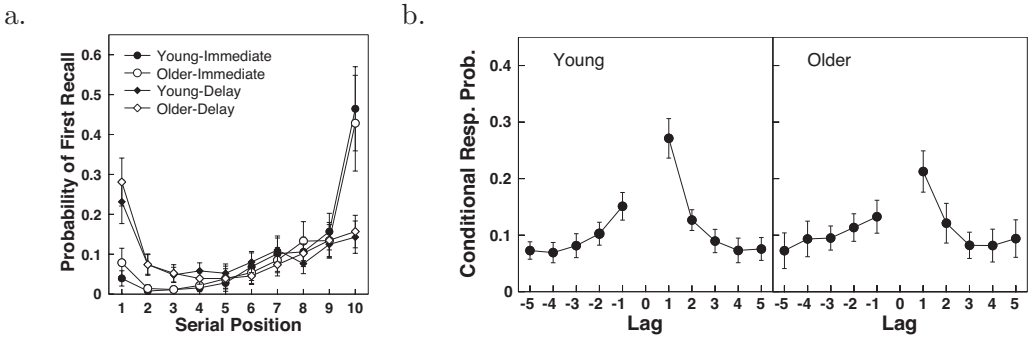

Figure 3. **Selective effect of aging on associative processes in free recall. a.** Probability of first recall from immediate and delayed free recall for younger and older adults. Data taken from Kahana, et al. (2002). Figure reprinted with permission from Howard, Kahana and Wingfield (in press). **b.** Conditional response probability (CRP) for younger and older adults from the delayed condition of Kahana, et al. (2002).

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 recent developments in 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, Shiffrin, and Nelson (2004) developed a *Word Association Space* (or WAS) based on the large University of South Florida word association database (Nelson, McEvoy, & Schreiber, 2004). Both LSA and WAS provide measures of the semantic relatedness for almost any pair 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, Addis, Jing, and Kahana (in press).

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 2c). In addition, the stronger the semantic association between two successively recalled words, the shorter the inter-response time was between the two words (Figure 2d). 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 (Howard et al., in press; Klein, Addis, & Kahana, 2005).

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 (Kausler, 1994; Verhaeghen & Marcoen, 1993). 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; Hoyer & Verhaeghen, 2006; Wingfield & Kahana, 2002)

The analysis of retrieval transitions, as described above, can be used to directly assess subject's reliance on temporal associations in free recall. Kahana, Howard, Zaromb, and Wingfield (2002) examined the difference between recency and contiguity effects in young 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 3b). In contrast, young 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 3a). This suggests that the older adults had unimpaired access to the most recently encoded items, but were less able to use, form and/or utilize temporally-defined associations to cue recall of temporally proximate list items.[5] This finding is consistent with previous reports of age-related deficits in the formation and retrieval of episodic associations (Naveh-Benjamin, 2000).

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.

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, Bradley, Kraus, & Renzaglia, 1983). The magnitude of the long-term recency effect depends critically on 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.

[5] Although older adults exhibited a markedly reduced contiguity effect, their semantic-proximity effect was unimpaired (unpublished observation).

Condition	Recency
Immediate PEN CAR ROSE $\cdots$ BIRD ***	Yes
Delayed PEN CAR ROSE $\cdots$ BIRD $\boxed{1+2=}$ ***	No
Continuous Distractor PEN $\boxed{6+2=}$ CAR $\boxed{3+7=}$ ROSE $\boxed{1+1=}$ $\cdots$ BIRD $\boxed{2+5=}$ ***	Yes

Figure 4. **Illustration of Immediate, Delayed, and Continuous-distractor Paradigms.**

Kahana (1996) interpreted the contiguity effect as evidence for associations formed in STS. If STS is the locus for episodically-formed associations (as postulated by Atkinson & Shiffrin, 1968; Glanzer, 1972; Raaijmakers & 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 5a illustrates the contiguity effect for interpresentation intervals ranging from 0s (standard delayed free recall) to 16s. As can be seen, the contiguity effect was relatively constant across this range of interpresentation intervals. This result is quantified in Figure 5b 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. Insofar as the contiguity effect is insensitive to the absolute delay between list items, it exhibits an approximate time-scale invariance. Although 16s 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 5a).

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 this effect is evident on much longer time scales. Howard, Youker, and Venkatadass (submitted) 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. (submitted) 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 *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 by a factor of $\sim$40 the range over which contiguity effects are observed in free recall. Moreover, this paradigm offers several potential advantages over continuous-distractor free recall. Because the subject is only asked to recall the most recent list, and intrusions from prior lists

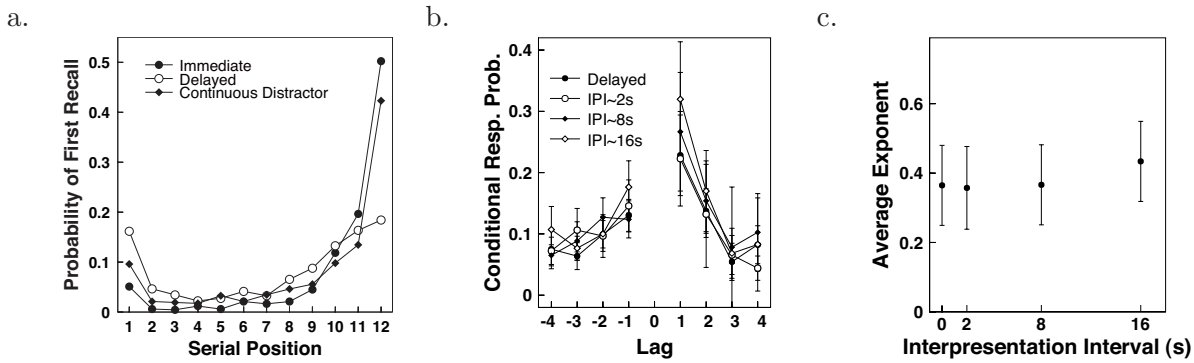

Figure 5. **Long-range recency and contiguity effects**. **a.** The probability of first recall functions for immediate, delayed, and continuous-distractor free recall (Howard and Kahana, 1999). **b.** Lag-CRP as a function of the length of the distractor task in continuous-distractor free recall. **c.** 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.

are scored as errors, there is no strategic reason for subjects to rehearse across lists in anticipation of the surprise final free recall test. Moreover, both within- and across-list associations were observed simultaneously during the final free recall period, rather than across conditions as in the continuous-distractor free recall experiment.

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 2a,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

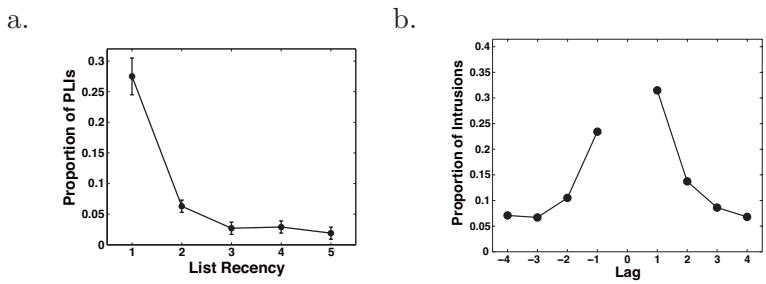

Figure 6. **Effects of Recency and Contiguity on Intrusions in Free Recall. a.** Prior-list intrusion (PLI) Recency Effect. Proportion of intrusions coming from 1 to 5 lists back. In calculating these PLI-recency functions for items originally presented 1 to 5 lists back we excluded the first 5 trials from the analysis. That is because PLIs from 5 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).

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.

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 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.

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; Gallo & Roediger, 2002; Roediger & McDermott, 1995; Roediger et al., 1998). 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 are often more frequent than extralist intrusions, suggesting 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 6a).

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, and from positions near to 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 6b).

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 presentation, rather than in any order. In requiring ordered recall, the serial recall tasks 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 to the correct (target) position (e.g., Lee & 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, 1992).

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 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 7a shows a lag-CRP derived from serial recall data (Kahana & 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

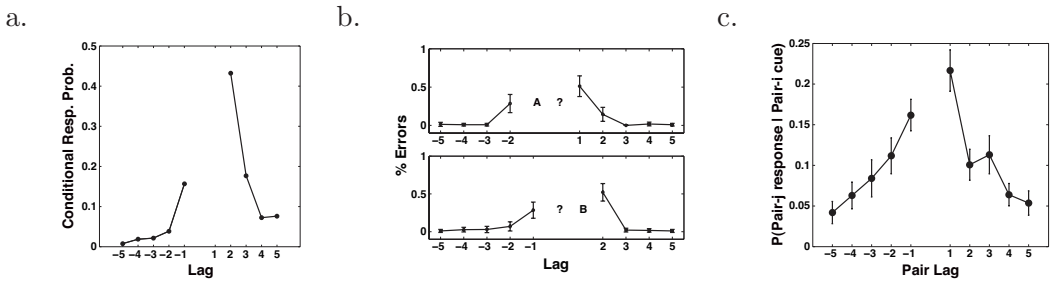

Figure 7. **Intrusions reveal associative tendencies in serial-recall, probed-recall, and cued-recall tasks. a.** Lag-CRP analysis of errors in immediate serial recall. Correct responses (lag of +1) were excluded from this analysis. **b.** Conditional error gradients in forward (top) and backward (bottom) 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 $i+\text{lag}$. Data are from Trial 1 Kahana and Caplan (2002)'s second experiment. **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, Geller, Rizzuto and Kahana, 2006).

likely than errors in the backward direction.[6] 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 & 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 7b shows error gradients in a probed recall study reported by Kahana and Caplan (2002). 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 $i-1$). Figure 7c 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 & Cook, 1937).

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,

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

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 transitions 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 non-overlapping 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 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* (Asch & Ebenholtz, 1962; Köhler, 1947). 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 (Caplan, Glaholt, & McIntosh, in press; Kahana, 2002; Rizzuto & Kahana, 2001; Sommer, Rose, & Büchel, in press).

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, Rizzuto, Geller, and Kahana (n.d.) addressed this question by examining subjects pattern of intralist intrusions in paired associate recall. They hypothesized that if a common associative process underlies all recall tasks, intralist intrusions would be more likely to come from neighboring list pairs.

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 7c 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 (in this analysis, Davis et al. conditionalize the probability of committing an intrusion from a given lag on the availability of pairs at that lag). 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 show 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.

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 (Gillund & Shiffrin, 1984; Kahana, Rizzuto, & Schneider, 2005; Murdock, 1982) According to these theories, item recognition relies on item-specific information whereas recall tasks rely on associative (or relational) information (Humphreys, 1978; Hunt & 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 & Thompson, 1973; Tulving & 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, Howard, Jing, and Kahana (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 sub-sequence 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 that prevailed when O_i was first encoded. Suppose further 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.

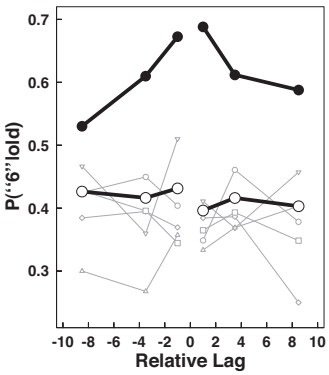

Figure 8. **Contiguity effects in item recognition are specific to highest-confidence responses.** Probability of a highest confidence ("6") response to an old-item test probe as a joint function the relative lag of, and the response given to, the preceding old-item probe. Large filled circles represent "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".

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 (Sherman, Atri, Hasselmo, Stern, & Howard, 2003; Yonelinas, 1999). 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 ubuiquitous nature of this phenomenon implores us to search for an explanation in terms of deep principles of memory function. This search is the topic of the next section.

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

Theory	Contiguity	Asymmetry	Long-range Contiguity	Prior-list Intrusions	Probed Recall Intrusions	Across-pair Intrusions	Contiguity in Item Recognition
Chain.	$\surd$	$*$	$\times$	$\surd$	$\surd$	$\surd$	$*$
Buffer	$\surd$	$*$	$\times$	$\surd$	$\surd$	$\surd$	$*$
Vertical	$\surd$	$*$	$\times$	$\surd$	$\surd$	$*$	$*$
Context	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$

Table 1. The $\surd$ 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 $\times$ symbol means that the model is unable to account for this data-point.

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 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).

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; Lee & Estes, 1977; Martin & Noreen, 1974; Murdock, 1995b, 1997). They assume 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). 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 & 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 & Raaijmakers, 1988; Sirotin, Kimball, & Kahana, 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 nearby serial positions 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 to come from nearby list positions from the target item. This tendency also exhibits a forward asymmetry effect, where errors tend to be items from subsequent list positions. Sixth, the tendency 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 concern 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 because the task requires subjects to 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 (often to full strength) in continuous distractor free recall (Bjork & Whitten, 1974; Glenberg et al., 1980; Howard & 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 (Tzeng, 1973; Glenberg et al., 1980; Craik, 1970; Howard et al., submitted). 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 (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Greene & Crowder, 1984; Raaijmakers, 1993).

Chaining theory

According to early conceptualizations of chaining theory, studying an item leads to the creation or strengthening of forward and backward connections to the immediately preceding item, with associations being stronger in the forward direction (Figure 9a). 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 & Murdock, 1989) 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 pre-existing 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 repesentations in memory. This mathematical approach has also be used by Murdock and his colleagues to simulate data on free recall (Metcalfe & Murdock, 1981), paired associates, and item recognition (Murdock, 1992). Similar models have also been developed using "Hebbian" weight matrices to store associations (Humphreys, Bain, & Pike, 1989; Rizzuto & Kahana, 2001; Kahana, Rizzuto, & Schneider, 2005).

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 don't 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 and further that when intrusions beget intrusions, 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 & Murdock, 1977; Tan & Ward, 2000), resulting in the remote associations of the kind seen in Figure 2a. 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 & 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 5c. 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 7c) one would need to assume that remote associations automatically connect items in distinct pairs, and that the remote association process extends across at least three or four intervening pairs.

The finding of associative effects in item recognition is also not easily explained by chaining theory as it requires 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 & Ratcliff, 1992), then chaining theory can 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 selective 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 & Melton, 1965; Crowder, 1968; Henson, Norris, Page, & Baddeley, 1996; Henson, 1998; Kahana & Jacobs, 2000).

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 (Murdock & Oddson, in press). 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 & 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 recall data that are believed to depend on the pattern of rehearsals that occur during list presentation (Rundus, 1971; Brodie & Murdock, 1977; Tan & Ward, 2000). 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 9b).

The SAM retrieval model, and its latest variant, eSAM, offers the most comprehensive model of free recall currently available (Raaijmakers & 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 items and a time-varying list context signal. 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 post-retrieval 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.

Davelaar et al. (2005) proposed an even more sophisticated version of the basic buffer model which implements the buffer as a dynamical system in which the individual buffer items compete with each other to stay active; Lisman and Idiart (1995) also proposed a neural implementation of the basic buffer idea; Murdock and Oddson (in press) implement working memory within the convolution-correlation distributed memory framework (Murdock, 1982, 1997). In essence, however, all of these models embody the chaining assumption that neighboring items become bidirectionally associated, and that formation of these interitem associations depends critically on the items being processed within a confined temporal window. Thus, these models inherit both the success of chaining theory in accounting for the phenomena listed in Table 1, and also the failure of chaining theory to predict long-range associative tendencies in continuous distractor free recall, final free recall and paired-associate memory.

It is important to note that buffer models such as those described by Sirotin et al. (2005) and Davelaar 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.

Hierarchical Association Theory

Hierarchical models of association (e.g., Anderson & Matessa, 1997; Anderson, Bothell, Lebiere, & Matessa, 1998; Johnson, 1972; Lee & Estes, 1977; Murdock, 1995a, 1997) 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 9c.

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

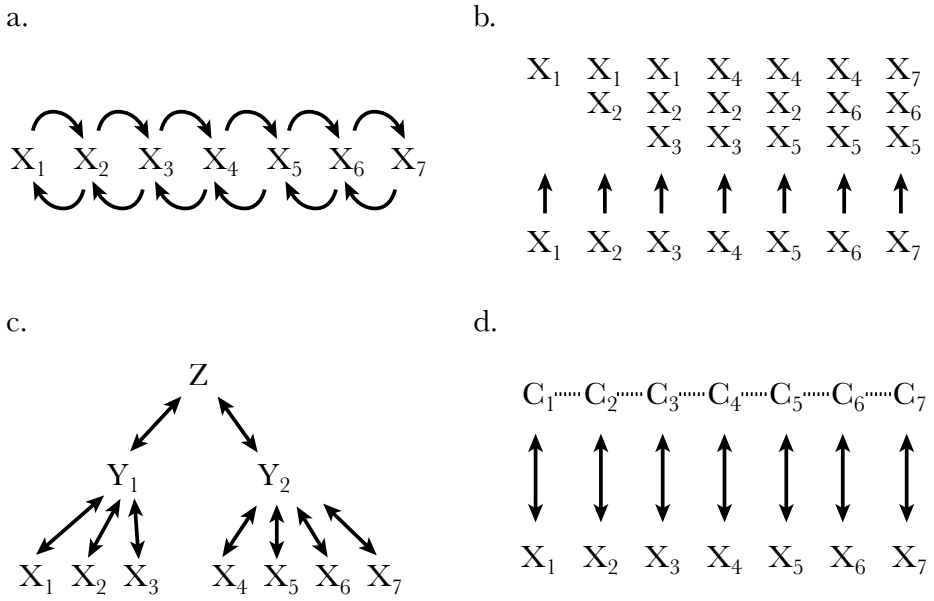

Figure 9. **Illustration of the four types of memory models. a.** *Chaining Theory.* Each item is associated with its immediate neighbors. **b.** *Buffer Theory.* Items are inserted into a fixed-capacity buffer and reside there until displaced. **c.** *Hierarchical Association Theory.* Conjunctions of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

& 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 highest levels of recall observed for group sizes of 3 or 4 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, Preece, & Hulme, 2000). Fourth, subjects IRTs during recall are longer at group boundaries (Maybery, Parmentier, & Jones, 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 & Estes, 1977; Murdock, 1993, 1997).

Hierarchical, or vertical, associations can be used to create representations that bridge time, which 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 foregoing text refers to a type of hierarchical representation that bridges representations that are separated in time; however, another class of 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, McNaughton, and O'Reilly (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 all of 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.

Contextual retrieval

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 & 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 & Whitten, 1974; Crowder, 1976; Howard & 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 (Tan & Ward, 2000; Howard et al., 2006).

Just as contextual states can retrieve items in semantic memory, so too, items can 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).

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 state associated with an item is added to the context vector at the time of the item's encoding, that part of the retrieved context is similar to the contextual states associated with subsequent list items but not prior list items. Thus, the context retrieved by an item includes a symmetric component (the contextual state associated during list presentation) and an asymmetrical component (the pre-experimental contextual states). The combination of these two components produces the forward asymmetry seen in the contiguity effect (Figure 2a).

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.

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 relationedness of the cue and the target items. The role of both temporal and semantic factors in retrieval appears strikingly in the analysis of retrieval transitions in free recall. Although subjects may recall items in any order they wish, the recall of a given item is predicatable on the basis of its semantic relatedness and temporal contiguity to the just recalled item.

The contiguity effect, as seen in Figures 2a, 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 has 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 contiguity effect is its persistence across time scales. In free recall, the contiguity effect is not reduced when list items are separated by 16 seconds 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 atlernative 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. Perhaps the most important these 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 & Dumais, 1997) and the topics model (Griffiths & Steyvers, 2002, 2003) provide some clues as to how such a reconciliation might be possible. LSA and the topics model 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 & Burgess, 1996) and BEAGLE (Jones & Mewhort, in press) 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 & Humphreys, 2001; Howard & Kahana, 2002), in that each process may rely on the presence of a slowly-drifting source of contextual information.

Finally, an unsolved puzzle concerns the asymmetric nature of episodic associations. Although the forward asymmetry is a striking feature of associations in free recall, serial recall, an 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).

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