Contiguity in Episodic Memory

M. Karl Healey
Michigan State University

Nicole M. Long
University of Oregon

Michael J. Kahana
University of Pennsylvania

Author Note

This research was funded by National Institutes of Health Grants AG048233 and MH55687. We thank Patrick Crutchley, Jonathan Miller, and Isaac Pedisich for assistance with designing and programming the experiments and Adam Broitman, Elizabeth Crutchley, Kylie Hower, Joel Kuhn, and Logan O'Sullivan for help with data collection. We thank Jeremy Caplan and Marc Howard for helpful comments on the manuscript.

Correspondence concerning this article should be addressed to M. Karl Healey (khealey@msu.edu) at Michigan State University, Department of Psychology, 316 Physics Rd., East Lansing MI or Michael J. Kahana (kahana@psych.upenn.edu) at University of Pennsylvania, Department of Psychology, 3401 Walnut St., Room 303, Philadelphia PA.

phone: (215) 746–3500

Abstract

Contiguity is one of the major predictors of recall dynamics in human episodic memory. But there are many competing theories of how the memory system gives rise to contiguity, including the suggestion that contiguity is an artifact of task-specific strategies. To help adjudicate between these theories, we present analyses of both new and archival free recall data to identify variables that modulate the magnitude of the contiguity effect. We examine 26 factors such as the subject's age, individual differences, presentation rate, and the semantic associations among list items. Many of these reliably modulate contiguity, but few eliminate it. Moreover, we show that contiguity is observed in a range of tasks including recognition, paired associates, and autobiographical recall and across a range of time scales including minutes, days, weeks, and years. The broad pattern of results point toward a model in which contiguity arises from fundamental memory mechanisms that encode and search an approximately time scale invariant representation of temporal distance.

Keywords: episodic memory; free recall; recognition; paired associates; temporal contiguity

Contiguity in Episodic Memory

Recall of one event tends to be followed by recall of events that occurred close in time to the just-recalled event (Kahana, 1996). How does the memory system generate this *temporal contiguity effect*? Some theories suggest that contiguity is a direct, nearly unavoidable consequence of basic mechanisms that operate whenever we form new memories or search for existing ones. Other theories suggest contiguity is generated by mechanisms that operate only under specific encoding and retrieval conditions. And still other theories suggest that the memory system is generally insensitive to temporal distance and that contiguity is an artifact of task-specific mechanisms or strategies. Although these theories are all consistent with the existence of the contiguity effect, they make different predictions about which variables will, and will not, modulate the contiguity effect.

Here we have three main goals. The first is to provide an overview of what we currently know about contiguity effect on a empirical level by reviewing existing findings and presenting novel analyses of archival datasets and a new experiment. The second is to evaluate whether this empirical picture places any strong constraints on theories of the underlying cognitive mechanisms that generate the contiguity effect. In particular, are there any properties that these contiguity-generating mechanisms are especially likely to posses? The third goal is to use these insights to identify new areas of inquiry that are likely to help further constrain theorizing about the contiguity effect.

The paper is organized in four main sections. We begin with a very brief history of the role of contiguity in memory theory. We then outline some of the basic properties of the mechanisms that have been proposed to account for the effect. Next, we review a range of empirical findings in light of these mechanisms. Finally, we end by evaluating the existing theoretical landscape and pointing to some important gaps in our understanding.

A Very Brief History of the Contiguity Effect

For centuries philosophers have suggested that contiguity plays an important role in memory and cognition (Aristotle, 350 B.C.E.; Herbart, 1834; Husserl, 1966). According to

Hume (1748), memory is useful precisely because it encodes the contiguity of events:

> ...after the constant conjunction of two objects—heat and flame, for instance, weight and solidity—we are determined by custom alone to expect the one from the appearance of the other.... Custom, then, is the great guide of human life. It is that principle alone which renders our experience useful to us, and makes us expect, for the future, a similar train of events with those which have appeared in the past. (Hume, 1748, section V, part I, paragraph 36)

The prominence of contiguity was carried forward by Ebbinghaus (1885/1913) in his analysis of remote associations in serial learning and has since been a continuous thread in the memory literature (Kahana, 2012).

The contiguity effect is readily observed by having subjects search memory for multiple events in the absence of strong external cues. This is usually accomplished by having subjects study and then recall lists of items. During the verbal learning era, many scholars noted that in such tasks subjects recalled the words in an order that was similar to the original presentation order (Greenhouse, 1967; Hasher, 1973; Hogan, 1975; Jahnke, 1965; Johnson, 1972; Kintsch, 1970; Murdock, 1974; Postman, 1971, 1972; Primoff, 1938; Rozov, 1964; Spear, Ekstrand, & Underwood, 1964; Wallace, 1969). That is, items experienced close together in time tend to be recalled close together in time.

Kahana (1996) quantified the contiguity effect by computing the probability of successively recalling items as a function of their distance from each other in the study list. This analysis revealed that after recalling an item studied in position i of a study list, the probability of transitioning to next recall an item studied in position $i + lag$, conditional on the availability of that item for recall, was a sharply decreasing function of $|lag|$. For a given lag, the *conditional-response probability* is computed by dividing the number of times a transition of that lag was *actually* made by the number of times it *could* have been made (Kahana, 1996).[1] This conditional response probability as a function of lag (or lag-CRP;

---

[1] When determining the number of times a transition of a given lag could have been made, transitions

Figure 1A) shows a strong contiguity effect, with a forward asymmetry such that forward transitions are more likely than backward transitions for small absolute values of lag. Contiguity also manifests as faster inter-response times for absolute values of lag (Figure 1B).

When the list is long, allowing for transitions at long-lags, the lag-CRP decreases monotonically with $|lag|$ (Figure 1A plots the lag-CRP to $|lag| = 10$ for 24-item lists). For shorter lists, long-lag transitions tend to involve transitions to primacy or recency items, which can introduce a non-monotonicity in the lag-CRP (Farrell & Lewandowsky, 2008; Howard, Sederberg, & Kahana, 2009). The contiguity effect also tends to be larger for the first few items recalled than for later output positions due to the strong recency effect, especially in immediate free recall (Farrell & Lewandowsky, 2008; Howard et al., 2009).[2] The influence of temporal associations extends over multiple recall transitions. Lohnas and Kahana (2014) showed that the size of the contiguity effect for a particular transition is modulated by the lags associated with previous transitions in the recall sequence. Specifically, they found that the contiguity effect was larger when the previous transition had been a $lag = +1$ transition than when it had been a transition of $|lag| > 3$. This finding suggests that subjects use a compound cue composed of several previous recalls.

Contiguity-Generating Mechanisms

Most contemporary theories of episodic memory include at least one cognitive mechanism that can produce a basic contiguity effect like that described above. The specifics of the contiguity-generating mechanism differ from theory to theory. Some theories can produce contiguity via direct item-to-item associations that form between temporally contiguous items when they share time together in a short-term buffer. Other theories do not form such direct item-to-item associations and instead form associations

---

that would lead outside the list boundaries are excluded (e.g., a +2 lag is impossible after recalling the 15^{th} item in a 16-item list), as are transitions that would lead to already-recalled items.

[2] Therefore, in the remaining analyses we focus on $|lags| \leq 5$, and unless we are specifically investigating the influence of output position, we exclude the first two outputs from the lag-CRP analyses in this paper.

between items and a representation of time (Brown, Neath, & Chater, 2007; Howard, Shankar, Aue, & Criss, 2015) or mental context (Lohnas, Polyn, & Kahana, 2015). And other theories suggest that contiguity arises from specific strategies employed by the subject, such as integrating each new list item into an ongoing story.

All of these mechanisms are consistent with the basic facts about the contiguity effect that we have reviewed so far. In later sections, we will review many additional findings in an effort to differentiate among the theories. But we encounter a problem from the outset: The literature contains so many different theories and contiguity-generating mechanisms that it would be intractable to consider each one separately and ask which provides the best account of the data. Therefore, it is useful to switch the focus from specific theories and specific mechanisms to the general properties that a contiguity-generating mechanism needs to possess to account for the data. By analogy, if we wanted to find the best car for, say, highway travel, we could consider each specific make and model separately, or we could focus on general properties the car should possess. Should it have a gas engine or an electric engine? Should it be self-driving or human-driven? For reasons we outline in the next paragraph, we choose to focus on two key properties of contiguity-generating mechanisms: task-specificity and time scale-specificity.

Time scale-specificity refers to whether a contiguity-generating mechanism produces a contiguity effect only at a specific time scale, such as when events are separated by seconds in laboratory tasks or whether it generates contiguity at a variety of time scales, such as when life events are separated by hours, days, or weeks. Task-specificity refers to whether a contiguity-generating mechanism will produce a contiguity effect only in specific situations, such as when an ad hoc strategy is adopted to meet the demands of a particular laboratory task or whether it generates contiguity in a variety of situations, including laboratory tasks and more naturalistic settings. We focus on these properties because both time scale-specificity (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Howard et al., 2015) and task-specificity (Hintzman, 2016) have been the focus of recent theory development. Moreover, mechanisms that do versus do not possess these properties often suggest starkly different predictions about what will happen to the contiguity effect under different experimental manipulations.

Time Scale-Specificity

Some cognitive mechanisms can generate a contiguity effect between events that are separated by a small amount of time (on the order of seconds) but would fail to generate a contiguity effect between events that are more widely separated in time. Such mechanisms are time scale-specific in that they operate only at short time scales. Although one could imagine a time scale-specific theory that generates contiguity only at long time scales, such a theory would be at odds with all of the existing data on short-time scale contiguity, and therefore we do not consider them.

Short-time scale mechanisms generally operate by forming item-to-item associations between events that occur within a few seconds of each other. These item-to-item associations can then generate a contiguity effect as recall of one item will provide a cue for items studied nearby in time. For example, associative chaining models assume new associations are created between successive items during study, forming a chain of item-to-item associations (e.g., Humphreys, Bain, & Pike, 1989; Lewandowsky & Murdock, 1989; Solway, Murdock, & Kahana, 2012). Similarly, under dual-store models, contiguity can arise when items studied in adjacent serial positions share time together in the short-term buffer and thus form item-to-item associations (e.g., Kimball, Smith, & Kahana, 2007; Raaijmakers & Shiffrin, 1981; Sirotin, Kimball, & Kahana, 2005). Because items studied in adjacent serial positions will tend to share more time in the short-term buffer than items studied far apart in the list (Phillips, Shiffrin, & Atkinson, 1967), a contiguity effect naturally emerges (Kahana, 1996).

The fact that these mechanisms depend on forming direct associations among items makes them unlikely to produce contiguity when the items are widely separated in time.

The reason is that forming a direct association between events that are separated in time requires that some representation of the first event be maintained until the second event occurs, even though the perceptual stimuli that constituted the first event have disappeared. These mechanisms have no way of bridging this gap between perception and long-term association, particularly when the gap is long and filled with other events. A short-term store, for example, is unlikely to form associations between items that are separated by several seconds of a distractor task because the distractor pushes the first item out of the buffer. If the time scale is even larger, say events that are separated by hours, these mechanisms seem quite unlikely to generate contiguity.

Other contiguity-generating mechanisms are less sensitive to the *total* amount of time that separates events and thus can produce contiguity between events separated by longer time intervals. These mechanisms generally form associations between item representations and a "context" representation that slowly changes as time passes, such that items presented close together in time are associated with more similar states of this second representation than are events separated by longer time periods (e.g., Howard et al., 2015; Lohnas et al., 2015). In some cases, this representation is explicitly temporal. For example, the SIMPLE model associates items with temporal markers such that the psychological distance between the present moment and temporal markers is logarithmically compressed (much like how telephone poles in the distance seem closer together than those nearby; Brown et al., 2007).

These mechanisms are approximately time scale invariant because they are sensitive to the relative amount of time separating events, rather than the total amount of time. That is, just as items separated by 1 second are more similar than items separated by 5 seconds, items separated but 1 hour are more similar than items separated by 5 hours.

Task-Specificity

Most theories of memory are intended to be task-general in that their aim is not simply to provide an algorithm for completing some specific laboratory task, like free recall. Instead, they aim to provide some insight on principles of memory that operate across a broad array of situations, both inside and outside the laboratory (Hintzman, 2011). For example, working or short-term memory is thought to be a task-general system that can store recent events in a free recall task, a recognition task, or in a movie theater when trying to follow a convoluted plot line (Baddeley, 2003; Miyake & Shah, 1999).

Most contiguity generating mechanisms that have been incorporated into memory theories share this task-general feature. For instance, we have used the idea that events become associated with a slowly drifting mental context representation to model both free recall (Lohnas et al., 2015) and recognition (Healey & Kahana, 2016) and have suggested the same mechanisms play a role in memory outside the lab (Healey, Crutchley, & Kahana, 2014).

Of course, one must also consider the possibility that contiguity-generating mechanisms are task-specific and that under most circumstances the memory system ignores temporal distance (Hintzman, 2016). Hintzman argues that because laboratory tasks require subjects to do something they do not usually do (e.g., learn lists of largely unrelated words), they are forced to devise novel strategies to effectively complete the task. Such task-specific strategies, rather than task-independent memory mechanisms, could account the contiguity effect.

Hintzman (2016) does not argue for a specific contiguity-generating mechanism but rather urges modelers to consider the general null hypothesis that *some* task-specific strategies may account for contiguity in free recall. For example, in a standard free recall task, subjects may adopt the strategy of linking successive list items together to tell a story. Alternatively, a strategy like the method of loci could be adopted. The key point is that subjects deploy these strategies only because they happen to be well-suited to the specifics of the task, not because the strategies make use of task-general mechanisms that are fundamental to human memory. Thus, the distinguishing feature of a task-specific mechanism is that it will operate only in a limited range of situations. Consequently, any contiguity effect generated by such a mechanism should appear only in a limited range of situations.

By nature of being specific to a given task, the explanatory power of a task-specific mechanism cannot be evaluated by examining a single data point—one can always think of a particular strategy that would account for an isolated finding. Instead, we take the approach of asking whether task-specific mechanisms can provide a unified account of the broad pattern of data we review below, or does one need to make many ad hoc assumptions about which mechanisms are deployed in which situations. As an example, consider a seriation strategy involving deliberately trying to form a chain of associations between successive items. Indeed, it would seem that a such a strategy would tend to produce a steep contiguity effect that is extremely biased toward $lag + 1$ transitions. To account for the more modest asymmetry observed in the actual data, one would have to make additional assumptions about which specific strategies subjects adopt. One could, for example, add the assumption that some subjects are drawn toward a strong forward order seriation strategy whereas others are drawn to a strategy that produces a symmetric contiguity effect, such that one sees moderate asymmetry when averaging across subjects.

Before moving on to review empirical findings, we stress that our emphasis will be on general properties of contiguity-generating mechanisms, not specific theories. There are important differences among the theories that nonetheless share some key properties, and likewise there are similarities among theories that have differing properties. There are also many theories that incorporate more than one contiguity-generating mechanism. For example, contemporary dual-store models (e.g., Davelaar et al., 2005; Lehman & Malmberg, 2013) include context drift mechanisms that can produce contiguity at longer time scales than a short-term store. Therefore, our goal here is not to evaluate specific theories but is to consider which types of mechanisms best account for the known facts about the contiguity effect.

The Generality of the Contiguity Effect

In this section we examine how the contiguity effect responds to a range of variables, including individual differences, age, level of practice, variation in encoding efficiency, and task parameters, such as list length and presentation rate. For each variable, we will discuss whether its effect can be accounted for by a contiguity-generating mechanism that is a) time scale-specific, b) time-scale general, c) task-specific, d) task-general. In some cases, we will argue that a mechanism with a given property can easily account for the effect, in other cases that it can account for the effect but only with some principled modifications, and in some cases we conclude that it cannot account for the effect at all. We track these observations in Table 1. To examine these variables, we will use a combination of archival data and new data from the Penn Electrophysiology of Encoding and Retrieval Study (PEERS, Healey et al., 2014; Healey & Kahana, 2014, 2016; Lohnas & Kahana, 2013, 2014; Miller, Kahana, & Weidemann, 2012), which we describe in detail in the Appendix. The Appendix also includes Table B1 which, for each finding, lists the original reference for the finding, where it is discussed in the current manuscript, and the data used to show or replicate the finding in the current manuscript.

Variation among Individuals

Most work on the contiguity effect has reported data averaged across individuals, leaving open the possibility that only some fraction of people show the effect (Hintzman, 2011). Healey and Kahana (2014) directly tested this in a sample of 126 young adult subjects and found that, depending on how contiguity was measured, 96%–100% of individuals showed a contiguity effect. To illustrate this across-subject consistency, we use here *temporal factor scores* (Polyn, Norman, & Kahana, 2009; Sederberg, Miller, Howard, & Kahana, 2010) to quantify the size of the contiguity effect for each younger and older adult in Experiment 1 of PEERS. Temporal factor scores involve ranking the temporal lag of each actual transition with respect to the lags of all transitions that were possible at that time. Figure 2A shows the average lag-CRP for subjects in the top half of the temporal factor score distribution and compares it with the lag-CRP of the 5 subjects with the lowest temporal factor scores. Even the subjects with the lowest temporal factor scores show a clear contiguity effect. Similarly, although the magnitude of the contiguity effect does vary across the lifespan, increasing in childhood (Lehman & Hasselhorn, 2012; Lehmann & Hasselhorn, 2010; but see Jarrold et al., 2015) and decreasing in old age (Healey & Kahana, 2016; Kahana, Howard, Zaromb, & Wingfield, 2002; Wahlheim & Huff, 2015), even those with the lowest levels of contiguity still show a clear effect. Figure 2B illustrates this point with lag-CRPs for younger (18–30 years) and older adults (61–85 years) in PEERS Experiment 1.

The finding that virtually every individual shows contiguity is consistent with both time scale-specificity and time scale-generality because the task used a single time scale.[3] It is, however, more informative about task-specificity. If contiguity is a fundamental, task-general, property of the memory system, then we would expect everyone to show a contiguity effect. If instead the contiguity effect is produced by task-specific strategies that subjects adopt, the prediction is less clear. Subjects self-report a diverse array of strategies, from rote rehearsal, to "just staring at the words", to creating interactive images from list items (Delaney & Knowles, 2005). We would expect some of these strategies to promote a lot of contiguity and others to promote little (e.g., a strict seriation strategy that one would apply to memorize a phone number would produce more contiguity than a strategy based on using the items to tell a story would). An account of the contiguity effect based on task-specific strategies must make the ad hoc assumption that all effective strategies produce contiguity (Table 1). This raises the question of why only contiguity-producing

---

[3] Indeed, most of the tasks we consider in the first few sections use a single time scale on the order of a few seconds between words. Therefore, data from these tasks are consistent with a time scale-specific mechanism. For the sake of brevity, we note this fact in Table 1 without mentioning it in the text

strategies should be effective if contiguity is not a general principle of the memory system?

The fact that a qualitatively similar contiguity effect is consistently observed across individuals and age groups should not be taken to mean that quantitative variation in magnitude of the effect is unimportant. Indeed, subjects who show the most contiguity also recall the most words (Healey et al., 2014; Sederberg et al., 2010; Spillers & Unsworth, 2011) and do the best on tests of general intellectual ability (Healey et al., 2014). Figure 3 shows the correlation of contiguity (measured by temporal factor scores) with both overall recall and WAIS IQ among the younger adults in PEERS Experiments 1–3. Figure 2C illustrates how the size of the contiguity effect varies with IQ by showing the lag-CRPs for the younger adults in the top and bottom quartile of the younger adult IQ distribution. Healey et al. (2014) found that the correlation between temporal contiguity and IQ remains even after accounting for variance in other aspects of recall dynamics, such as semantic contiguity. By contrast, these other measures of recall dynamics failed to correlate with IQ when variance related to temporal contiguity was accounted for. It is important to note that the robust correlation between temporal contiguity and IQ does not imply causality. For example, it could be that both temporal contiguity and IQ share variance with some third factor, such as the ability to constrain search sets (Unsworth, 2007; Unsworth, Spillers, & Brewer, 2012) or to control the drift of mental context (Healey et al., 2014). Critically, for our purposes, although the direction of the relationship remains unclear, there is something special about temporal contiguity in predicting recall and IQ.

Both individual and age-related variation in the magnitude of the contiguity effect could be explained by a task-general mechanism by allowing the parameters that govern that mechanism to vary among individuals. That is, by assuming that all individuals use the same mechanisms, but that there are quantitative differences among individuals in the efficiency of those mechanisms (for examples of this approach applied to aging see, Farrell, 2012; Healey & Kahana, 2016). A task-specific account could be modified to assume that lower preforming individuals and older adults either have difficulty implementing contiguity generating strategies or are more likely to employ non-contiguity generating strategies.

Variation within Individuals

Next, we consider two potential sources of *within* individual variation in contiguity: practice and variation in encoding efficiency. To examine contiguity at the naïve end of the practice spectrum, we looked at data from the initial screening session of PEERS in which subjects studied 12 lists of 16 items for immediate free recall. Figure 2D shows the lag-CRP for subjects' 1^{st} free recall list versus their 12^{th} list. A clear contiguity effect is seen on the 1^{st} list and becomes steeper by the 12^{th} list. To examine how contiguity evolves as subjects gain expertise in the task, we consider data from PEERS Experiment 4. In this experiment, a group of subjects who were initially naïve to the free recall task completed 24 sessions of free recall after the initial screening session. In each session, subjects studied 24 lists of 24 items for delayed recall. Figure 2E shows that a strong contiguity effect is present in the 1^{st} session and remains in the 24^{th}.

The fact that expertise with the free recall task has only a modest influence on contiguity is consistent with task-general mechanisms—subjects are already experts at using these mechanisms to remember information in their daily lives. It is also consistent with time-scale specific mechanisms because the time scale of the task remains constant. The observed effect of practice is, however, difficult to reconcile with a task-specific mechanism. If the memory system typically ignores temporal distance, how and why do subjects so quickly adopt a contiguity-generating strategy when encountering the free recall task for the first time?

Regardless of level of practice, the efficiency of a subject's encoding mechanisms will vary from moment to moment (Hintzman & Hartry, 1990; Kahana, Rizzuto, & Schneider, 2005; Sadeh, Moran, & Goshen-Gottstein, 2015). Any autocorrelation in this variability means that temporally adjacent items will tend to have similarly high (or low) probabilities of being recalled, creating temporally isolated ”pockets” of successfully encoded items.

Such pockets can influence the size and shape of the contiguity effect (Hintzman, 2016). Consider the primacy effect: early list items tend to have higher recall probabilities than mid-list items. Now, consider all the possible ways one can make a short-lag transition, say +1, between items i and j. For many of these ways, both i and j will be from primacy positions (e.g., transitioning from item 1 to item 2). But for longer transitions, say +5, many of the possible ways must involve positions from the middle of the list (e.g., transitioning from item 1 to 6). Given that making a transition between two items is only possible if those items have both been successfully encoded and because the primacy effect suggests that items from the middle of the list are less likely to be encoded successfully, short-lag transitions are naturally more likely to occur than long-lag transitions. This means that a contiguity effect could emerge simply as an artifact of variation in goodness of encoding.

We can directly test whether autocorrelated encoding really provides a switch that turns contiguity on and off. Specifically, we can eliminate the influence of variability in goodness of encoding by recomputing the lag-CRP, conditional on recall of both item i and item j. That is, we can equate rate of successful encoding across lags by considering a transition of a given lag possible only if both items involved in that candidate transition were actually successfully recalled at some point in the recall sequence.

To illustrate, we created simulated data in which the contiguity effect *is* an artifact of variation in goodness of encoding. We started with an idealized serial position curve with pronounced primacy and recency effects (see the inset in Figure 4A). In other words, a serial position curve with two "pockets" of well-encoded items separated by many poorly encoded items. We then used this curve to define a binomial distribution of recall success for each serial position. Then, for each of 100,000 simulated lists, we predetermined which serial positions would be successfully recalled by a random draw from the distribution of each serial position. The model then output these recalled words in random order (i.e., input order does not directly influence output order).

Figure 4A shows that simulated data from this model do indeed exhibit a contiguity effect when the lag-CRP is computed in the standard way. However, the adjustment for goodness of encoding acts as a switch, completely eliminating the artifactual contiguity effect—when considering only items that are successfully recalled, the lag-CRP from the simulated data is flat. What about real data? Figure 4B shows the availability adjustment applied to immediate free recall data (the list length 30 condition of Murdock, 1962) and Figure 4C shows the adjustment applied to delayed free recall data (Experiment 4 of PEERS).[4] This immunity of contiguity to variation in encoding efficiency is consistent with any contiguity-generating mechanisms provided they do not rely on autocorrelation in encoding.

The supplemental materials include an alternate set of figures which apply this adjustment to all the lag-CRP analyses. That is, the main text presents standard lag-CRPs and the supplemental materials present adjusted versions. In no case did the adjustment eliminate the contiguity effect. This includes the correlation between temporal factor scores and both overall recall and IQ, which were recomputed considering only transitions to recalled items as possible.

Variation in Task Parameters

We have seen that factors related to the subject modulate, but do not eliminate, the contiguity effect. Do factors related to the task itself modulate contiguity as they do for other aspects of memory search (e.g., the influence of retention interval and presentation modality on the recency effect, Glanzer & Cunitz, 1966; Murdock & Walker, 1969; Postman & Phillips, 1965)?

One of the first factors shown to influence the size of the contiguity effect was

---

[4] It is worth noting that the artifactual contiguity effect produced by variation in encoding efficiency differs from the contiguity effect in real data in two important ways. First, it is much smaller (notice the difference in scale between Figure 4A and B-C). Second, whereas the real contiguity effect is highly non-linear, the artifactual effect produced by a U-shaped serial position curve is essentially linear. These differences further suggest that variation in goodness of encoding explain neither the magnitude nor the functional form of the contiguity effect.

position in the output sequence (Kahana, 1996). As shown in Figure 2F, the contiguity effect is large for the first pair of items output and then drops, but remains robust, for intermediate output positions before rebounding for later outputs (for discussions of the sources of the effect see, Farrell & Lewandowsky, 2008; Howard et al., 2009; Kahana, 1996). Robust contiguity for all output positions would be expected if contiguity arises from something fundamental about how events are encoded and how memory is searched (i.e., task-general mechanisms). But if contiguity arises from some task-specific mechanism (e.g., a strategy like the method of loci), one might have expected that at some point in the output sequence the strategy would fail. Subjects would then fall back on more general, but non-contiguity producing mechanisms, and thus show less contiguity. Therefore, a task-specific account must make the assumption that subjects rely on the strategy for all outputs. Again, because the task uses a single short time scale, the data are also consistent with a time scale-specific mechanism.

We can also examine contiguity as a function of serial position at study. Figure 2G shows lag-CRPs for transitions between items i and j separately for cases where item i was from early, mid, and late serial positions. A clear contiguity effect is present across input positions. It is worth noting that for early serial positions, the negative-lag conditional response probabilities are elevated, consistent with Murdock's (1974) observation that after recalling several items from late serial positions, subjects tend to jump back to early serial positions. Neither task-specificity nor time scale-specificity make clear *a priori* predictions about the effect of serial position on contiguity; therefore, we take this pattern of results as consistent with all 4 types of mechanisms.

By contrast, one might expect the number of items in a list to powerfully influence encoding strategies. For example, the method of loci seems unlikely to succeed for a list with dozens of items, unless subjects are already experts at employing the strategy. Cortis, Dent, Kennett, and Ward (2015) examined lag-CRPs for ten different list lengths, between 2 and 15, and found a contiguity effect at all lengths. Figure 2H compares lists of 20 versus

40 items in the Murdock (1962) dataset. Although the longer lists show somewhat more contiguity, both list lengths show a substantial effect. Given that this was a single session experiment, a task-specific account would have to assume subjects can effectively apply the strategy to very long lists with minimal practice.

Modality of presentation may also strongly influence the types of task-specific mechanisms that are effective. If words are presented visually, subjects can easily switch back and forth between reading/studying the current word and thinking back to earlier words (e.g., to form inter-item associations). With auditory presentation, subjects would have to ensure that they do not forget the current word while thinking back to earlier ones. Figure 2I shows only a modest increase in contiguity for visual presentation. Similarly, writing the words down as you recall them (as opposed to saying them aloud) allows you to see the words you have already recalled and more easily use them as cues to their list-neighbors. Yet, as shown in Figure 2J, the effect of spoken versus written recall is small. Of course, a task-specific mechanism could account for both of these findings by making ad hoc assumptions about the nature of the mechanism.

In standard free recall, subjects are given no specific instructions on how to process the words. In a variation of the task, subjects are given an encoding task that requires carrying out a specific type of processing on each word. In PEERS, subjects were asked to carry out a processing task for all items in some lists (a size or an animacy judgment) whereas on other lists, they were given no specific encoding task. Forcing subjects to attend to specific aspects of the meaning of words might discourage them from adopting strategies that emphasize seriation and instead adopt strategies that emphasize semantic associations. As seen in Figure 2K, a clear contiguity effect emerges regardless of encoding task condition (Long & Kahana, 2016). Again, the modest effect on the lag-CRP is consistent with a task-general mechanism; however, to explain these data, a task-specific mechanism would need to assume that subjects engage the same task-specific encoding mechanism regardless of processing task instructions or that different contiguity-promoting strategies are, for some reason, effective and preferred under different encoding tasks.

So far we have focused mainly on studies of immediate free recall in which items are presented one after the other with a short inter-item delay and subjects are asked to recall the words immediately after the presentation of the final list item. Delayed free recall adds a retention interval by asking subjects to engage in a distractor task for a period of time after the final item but before recall. Continual distractor free recall also has a delay after the final item but also introduces a distractor-filled delay between each item during presentation (Bjork & Whitten, 1974). Figure 2L shows that all three versions of the task produce a clear contiguity effect (Howard & Kahana, 1999).

Again, a task-specific account must include some ad hoc explanation of why changing the time scale of the task does not disrupt this mechanism. One possibility is to assume that the strategy includes some mechanism to associate items separated by distractors (e.g., deliberately retrieving earlier items following a distractor). The CDFR data are also highly diagnostic about the time scale of the cognitive mechanisms that generate contiguity. A time scale-general mechanism could clearly account for the data. For example, the SIMPLE (Brown et al., 2007) model with its logarithmic temporal representation may be able to fit the data. The approximate time scale invariance of contiguity is also consistent with some versions of clustering models, notably the Farrell (2012) model which has been fit to the data because they include representations at multiple time scales. Similarly, in retrieved context models, approximate time scale invariance is a natural consequence of combining contextual drift (which allows the *relative* similarity of items' associated contexts as a function of lag to be insensitive to adding distractors) with a competitive choice rule (Howard & Kahana, 2002a).

Time scale-specific mechanisms have more difficulty with CDFR data. For a chaining model to account for the contiguity effect in continual-distractor free recall, the retrieval probe (i.e., the just-recalled item) would have to provide an effective cue for multiple items that were separated by distractor intervals while being invariant to the length of the delays.

Formation of such time scale invariant remote associations seems implausible. Dual-store models have even greater difficulty dealing with these data because a difficult distractor should displace items from the buffer. This should dramatically reduce the amount of time items from distant lags spend together in the buffer and thus, contrary to the data, should sharply attenuate the contiguity effect. Although a basic dual-store model has difficulty with contiguity in continual distractor free recall because the distractors should empty the buffer and prevent formation of temporally graded associations, modern dual-store models can produce contiguity in the presence of distractors by incorporating contextual drift (Davelaar et al., 2005; Lehman & Malmberg, 2013) which allows for contiguity at multiple time scales.

Presentation rate might also strongly influence how items are encoded. For example, longer presentation rates give subjects more time to chain items together or to engage in strategies that might promote contiguity. Figure 2M shows a robust contiguity effect for presentation rates of 0.5 seconds and 1 second. Howard (2017) examined very fast presentation rates and found a robust contiguity effect at rates as fast as 4 words per second . At 8 words per second, they found the lag-CRP began to flatten, perhaps due to an attentional blink-like effect. That is, contiguity was seen when words were presented as rapidly as once every 250 ms. It seems quite implausible that subjects complete the basic visual processing of the current word and still have time left to engage in the sorts of complex strategies that have been suggested to create contiguity (e.g., rehearsal, telling a story). At the other extreme, Nguyen and McDaniel (2015, Experiment 3) examined lag-CRPs when subjects were allowed to self pace their study of line drawings of familiar objects. Subjects studied each picture for an average of over 6 seconds but still showed a robust contiguity effect. The relative immunity of the contiguity effect to variation in presentation rate does not help adjudicate between models in which the effect is due to task-general or time scale-general mechanisms, but this finding is powerful evidence against a task-specific account. Can we reasonably argue that subjects are effectively engaging a task-specific strategy when they are encoding 4 words per second?

Variation in Stimuli Characteristics

The presence of strong semantic associations among list items could mitigate the need to rely on temporal associations to guide recalls. Yet, the contiguity effect is seen even when every item is drawn for the same semantic category (Miller, Lazarus, Polyn, & Kahana, 2013), which should provide very strong semantic cues. McCluey, Burke, and Polyn (2016) directly assessed the influence of such strong cues by having subjects study lists in which each item was drawn from the same category or each item was drawn from a different category. As shown in Figure 2N, although contiguity was modestly reduced in the same-category lists, it was still substantial and robust (see also Kintsch, 1970). That is, even when subjects have strong semantic associations to rely on, temporal associations among words still powerfully influence recall order. These data are difficult to explain under the assumption that contiguity is generated by task-specific mechanisms, and the memory system tends to ignore temporal information unless a task lacks non-temporal information to guide recall.

In a related study, Ward, Woodward, Stevens, and Stinson (2003) examined the effect of word frequency and found a strong contiguity effect for both high and low frequency words in both mixed and pure lists. Similarly, McDaniel, Cahill, Bugg, and Meadow (2011) had subjects study lists that included orthographically distinctive items (i.e., words with unusual letter combinations such as *lynx, methyl, knoll, calypso*) and orthographically common items. The lists were either pure (all either distinctive or common) or mixed. They found substantial contiguity effects in mixed lists and pure common lists but found a reduced effect in pure distinct lists. These results suggest that orthographically distinct words may disrupt the mechanisms that generally produce contiguity, which poses a challenge to any model that relies on a task-general mechanism, as they would predict a residual contiguity effect. This is particularly true given that it seems unlikely that orthographically distinct words have pre-existing associations that could mitigate the need to rely on temporal associations in the same way pre-existing semantic associations could. This study is the only free recall study we are aware of that shows an absence of a contiguity effect—and as such argues against a task-general mechanism. Given the theoretical implications of this null finding and the fact that it is based on only 3 lists from each of 36 subjects, it is an important target for adequately-powered replications.

Another aspect of meaning that influences recall order is the emotional content of stimuli (Long, Danoff, & Kahana, 2015; Siddiqui & Unsworth, 2011). In their first experiment, Siddiqui and Unsworth (2011) gave subjects a single list that was composed of eight positively valanced words, eight negatively valanced words, and eight neutral words, presented in random order. Subjects showed a modest temporal clustering effect, even though the emotional context provided the opportunity to cluster recalls based on valence, and it was subject's first list, which as we have seen (Figure 2D) tends to show smaller contiguity effect. In a second experiment, the researchers made the emotional content of the items more salient by asking subjects to rate the pleasantness of each item during study. This manipulation did increase clustering based on valence and reduce temporal contiguity but did not totally eliminate it. That is, the CRP for $lag+1$ was approximately 0.07, which is somewhat lower than the approximately 0.11 seen in Experiment 1 of that paper (as a rough comparison, PEERS subjects had a $lag+1$ of approximately 0.17 for their first list). This effect seems consistent with either a task-specific or a task-general mechanism.

Sometimes temporal and semantic associations will tend to guide memory search in the same direction, as when a close semantic associate of the just-recalled word was studied in an adjacent serial position. Other times, the two types of associations can compete, as when a strong semantic associate of the just-recalled item was studied in a remote serial position. The PEERS dataset allows us to assess contiguity in these two situations (for a similar analysis focusing on semantic contiguity see Howard & Kahana, 2002b). As described in detail in the Appendix, using the Word Association Space model (Steyvers, Shiffrin, & Nelson, 2004), each list was constructed so that it had two pairs of high-similarity ($\cos\theta > 0.7$) words such that members of one pair were presented in adjacent serial positions and the members of the other pair were separated by at least two other items. We examined recall transitions from items in cases in which a high-similarity associate of the item was available at a near lag (≤ 2). In this case, temporal and semantic information complement each other. We also examined transitions from items in cases in which a high-similarity associate of the item was available only at a remote lag (> 5). Here, temporal and semantic information compete with each other. As a control, we also examined transitions from items in cases in which no strong associate of the item was available at any lag. As seen in Figure 2O, the presence of a strong associate modulated the lag-CRP in a systematic way, making it steeper when the associated was available at a near lag and making it shallower when the associate was available at a distant lag. Yet, subjects still show a strong tendency to make temporally adjacent transitions when a strong semantic associate is "pulling" them toward a temporally remote transition. These data could only be explained by a task-specific mechanism if one assumes the tendency to use the mechanism is so strongly ingrained that subjects do not deviate from it even when semantic cues are available.

Most of the studies we have reviewed have used words as stimuli. In terms of perceptual complexity, words are quite impoverished compared to the things we usually want to remember outside the laboratory (e.g., complex visual scenes). It may be that encoding temporal proximity is a strategy subjects fall back on when encoding impoverished stimuli and that the contiguity effect may disappear when detail-rich stimuli are used. Although contiguity was not their main focus, Nguyen and McDaniel (2015) suggested that memory for pictures might show a reduced contiguity effect due to less reliance on contextual details. Their stimuli were line drawings that were either complex (e.g., a drawing of a car including details like door handles and headlights) or simple (e.g., an outline of a car with no details). Stimuli were assigned to either pure lists of complex pictures, pure lists of simple pictures, or mixed lists. They found a clear contiguity effect with a forward asymmetry in all conditions with no significant differences between list conditions. Perhaps, because the pictures are nameable, subjects translate them into verbal codes. Cortis et al. (2015) examined contiguity under a variety of conditions designed to reduce reliance on verbal codes (e.g., visuospatial locations studied while performing an articulatory suppression task). They too found clear contiguity effects with all stimuli types.

Another critical aspect of the stimuli is the importance of the items to the subject. Nairne and colleagues (for a review see Nairne & Pandeirada, in press), have argued that the purpose of memory is fundamentally to remember information that is important to the subject, such as information that has survival value. Under a task-general mechanism, contiguity should be observed regardless of importance. Yet, there is considerable evidence that the perceived importance of information influences memory performance (e.g., Castel, 2005; May, Rahhal, Berry, & Leighton, 2005). Even assigning arbitrary value to items can influence how information is remembered (Castel, Benjamin, Craik, & Watkins, 2002). Thus, one might expect value assignments to influence strategy-use. Stefanidi and Brewer (2015) examined the influence of such value assignments on contiguity. In 10-item lists, they assigned each item a value between 1 and 10 and told subjects that the items with the highest values were the most important to remember. In one condition, values were randomly assigned to serial positions, in another condition, values were assigned to serial position in ascending order (i.e., the value of serial position 1 = 1, value of serial position 2 = 2. etc.), and in another, they assigned values in decreasing order of serial positions (i.e., the value of serial position 1 = 10, value of serial position 2 = 9, etc.). One could reasonably expect that these conditions would strongly influence both the encoding and search strategies subjects engage in (e.g., trying to recall the highest value items first). Indeed, recall probability increased as a function of value in all conditions. Yet, they found a typical forward asymmetric lag-CRP in all conditions, and the degree of contiguity did not differ substantially from a control condition in which subjects were told to ignore the numbers presented along with each item and not told they represented the value of the items. This finding seems inconsistent with a task-specific strategy account: Why would subjects employ a strategy that relies on temporal associations when they are explicitly told to focus on item's assigned values?

Contiguity Emerges even when it Would be Difficult or Counterproductive to Deliberately Encode Temporal Distance

The goal of recalling as many items as possible from a free recall list is well-served by encoding associations among items, which might make it difficult to find conditions that produce little contiguity. In this section, we consider situations in which encoding information about the temporal distance between events is less well-aligned with task goals.

Contiguity in Recall Errors

In free recall, the subject's main task is to learn and then to recall each individual list as it is presented, which entails avoiding interference from items from previous lists. As such, there is little incentive, and a potentially strong disincentive, to encoding the temporal distance between successive lists. Yet, if we examine the likelihood of errors, we see that intrusions are most likely to come from the most recent list (Murdock, 1974). Zaromb et al. (2006) directly investigated the influence of temporal associations on the commission of prior list intrusion (PLI) errors by creating lists that contained some items that were repeated from earlier lists. Subjects were clearly instructed to recall items from the current list only. Most task-general contiguity-producing mechanisms would predict that such repetitions should encourage intrusions of items that were presented near the original presentation of the repeated item. But because the design amplifies the potential for temporal associations formed on an earlier list to interfere with recall of the current list, savvy subjects should not employ a strategy that is vulnerable to such interference. Indeed, some task-specific contiguity-promoting strategies such as telling a story about the list items, could actually serve to immunize against such interference (e.g., intrusions from a prior list are unlikely to fit with the story being told about the current list). Yet, intrusions were more likely to follow successful recall of one of the repeated items than recall of a non-repeated item. Moreover, these repetition-evoked PLIs tended to be from the same list as the just-recalled repeated item and from serial positions near to the repeated item's position in the original list. Even clearer evidence of the role of temporal associations in driving intrusions can be seen by examining cases in which subjects make several PLIs in succession: such chains of intrusions showed a clear contiguity effect such that subjects were most likely to transition between PLIs that were temporally contiguous in the original list.

Contiguity in Final Free Recall

Across-list temporal associations can also be examined in studies that include a final free recall phase after all lists have been presented in which subjects are asked to freely recall items that appeared on any earlier list. Perhaps not surprisingly, final free recall transitions between words studied in the same list show a clear contiguity effect (Howard, Youker, & Venkatadass, 2008; Loaiza & McCabe, 2012; Unsworth, 2008). But contiguity manifests even when subjects *do not* transition between items from the same list: when they make an across-list transition it tends to be to items presented in temporally adjacent lists (Howard et al., 2008; Unsworth, 2008). Across-list contiguity is also apparent in the list-lag of errors when subjects are probed with an item from one list and asked to recall another item from the same list but erroneously recall an item from a different list (Kılıç, Criss, & Howard, 2013). These across-list contiguity effects suggest that subjects are encoding information about temporal distance at the level of lists, even when it is a potential source of interference.

In Figure 5, we replicate the final free recall across-list contiguity effect with data from PEERS. This across-list CRP considers only transitions during final free recall that consist of correct recalls from one list to correct recalls of a different list. This analysis controls for the fact that it becomes less likely to transition to a particular list as the number of items that have already been correctly recalled from that list increases. For example, if a subject recalls an item from list 4, it is possible that the next item they recall correctly could be anything that has not already been recalled. If the subject had previously recalled 5 words from list #2, and 10 words from list #9, then there are 11 different items from list #2, and 6 different items from list #9 (assuming 16 item lists) that could be transitioned to. We would increment the denominator for the -2 and +4 possible lags accordingly. The numerator is incremented in the same way; if the next correct recall turns out to be from list #6, and 3 words had already been recalled from that list, then the +2 lag will be incremented by 13. Following Howard et al. (2008), we also created a surrogate dataset to control for the effects of recency and autocorrelated goodness of encoding. To construct this surrogate data, we took each pair of across-list transitions that were made and then shuffled them so that the same items could not be matched and the pairs must come from different lists. A CRP was then calculated from that shuffled data using the methods described above. This was done 10,000 times for each final free recall session, and then averaged across sessions within a subject, and then across subjects. Although these surrogate data, shown as the solid gray line in Figure 5, do show a small contiguity effect, it cannot account for the large effect seen in the actual data.[5]

The presence of contiguity both within a single list and across multiple lists is difficult to reconcile with a single contiguity-generating mechanism that operates only on the time scale of single lists. For example, under a chaining theory, it seems quite implausible that subjects form remote associations across items separated by a list

---

[5] It has been suggested that the across-list contiguity effect in final free recall may be due to prior-list intrusions and not to temporal assocations (Hintzman, 2016). That is, if when originally recalling list l, subjects intrude an item from list $l - n$, they may form new associations between list l items and list $l - n$ items. Then, during final free recall, these new intrusion-mediated associations would drive across-list transitions. This is implausible given that intrusions are quite rare and unlike the contiguity effect which extends to lags of 5, intrusions show a very steep recency effect (on average, less than 0.3 of an item per list in the PEERS data, with most coming from no more than 2 lists back; Healey & Kahana, 2016). More to the point, the entire explanation is based on assuming that subjects form associations between temporally contiguous items during recall, despite there being no incentive to form such associations.

boundary and several minutes. Similarly, a short-term store could not account for across-list contiguity because it provides no mechanism for items from distant lists to share time in the buffer. Across list contiguity is also difficult to reconcile with a task-specific strategy-based account as it would make little sense for subjects to encode information about items separated by multiple lists. One could assume that there are multiple mechanisms that each operate under different tasks and time scales, but across-list contiguity is much easier to handle if one assumes contiguity is produced by a mechanism that is both task-general and, at least approximately, time scale invariant.

Contiguity in Serial Recall

Serial recall also provides some insight on whether subjects form temporal associations that do not support task goals. A good approach to a serial recall task would be to form strong unidirectional (i.e., forward) associations between adjacent items, and weak, if any, associations at longer lags, especially negative lags. If, however, as has been repeatedly demonstrated, serial recall relies on many of the same mechanisms as free recall (Bhatarah, Ward, & Tan, 2006; Spurgeon, Ward, & Matthews, 2014; Spurgeon, Ward, Matthews, & Farrell, 2015; Ward, Tan, & Grenfell-Essam, 2010), we might expect to see similar contiguity effects in the two tasks. Indeed, both some early data (Lee & Estes, 1977) and more recent analyses using lag-CRP methodology show that although there is a strong forward bias, serial recall shows a clear contiguity effect (Spurgeon et al., 2015) that extends over multiple lags in both the forward and backward direction (Klein, Addis, & Kahana, 2005).

Errors in serial recall are possibly even more informative than contiguity among correct recalls. To the extent that subjects are attempting to remember which items followed each other, rather than to encode the full set of temporal distances between all items, they should be making every effort to form associations between adjacent items *and avoid* forming associations between non-adjacent items. If forming temporal associations is not something the memory system tends to do, then avoiding these non-adjacent associations should be easy. Yet, applying lag-CRP analyses to recalls following an order error shows a contiguity effect with a clear gradient across lags (Kahana & Caplan, 2002; Solway et al., 2012). Although details of the task such as list length and whether subjects are allowed to skip items appear to impact the exact pattern of errors observed (Farrell, Hurlstone, & Lewandowsky, 2013; Osth & Dennis, 2015), the general pattern is difficult to reconcile with a strategy-based account. To account for these data with a task-specific strategy, one would have to make the implausible assumption that subjects have a tendency to erroneously apply the strategy to items at remote lags.

Contiguity in Item Recognition

In recognition, the task is explicitly to memorize individual items in preparation for a test in which the cue is the item itself. Forming associations between temporally adjacent items does not directly facilitate this goal, and in fact, devoting effort to forming such associations would divert attention from more transfer-appropriate processing of the item. However, if temporal associations are naturally formed when encoding episodic memories, we would expect to observe contiguity effects in recognition. In Schwartz, Howard, Jing, and Kahana (2005) , subjects studied lists of pictures for a recognition test. During test, items that had been studied in adjacent positions in the study list were sometimes probed successively during the test. If temporal associations had formed between items during study, having two successive probes be from adjacent list positions should help recognition because the first item will help cue the second. Such a benefit was observed. Moreover, upon making a high-confidence response for probe i, subjects' probability of making a high-confidence response to probe $i+1$ was a decreasing function of the $|lag|$ between i and $i+1$ in the study list. That is, if you were highly confident about one probe, then you would be highly confident about the next probe if it came from a nearby position in the list. Sadeh et al. (2015) reported a similar result in free recall using the remember/know paradigm. They found that transitions from items for which the subject "remembered" they were on the list showed a stronger contiguity effect than transitions from items which they simply "knew" were on the study list. These results could occur because temporal associations form during study and allow list-neighbors to cue each other if probed consecutively, but it could also be observed if the quality of encoding is autocorrelated such that neighboring items are encoded with similar confidence levels. Critically, under the correlated-encoding account, we should see an effect even if the items are not probed successively. Although Schwartz et al. (2005) did observe some evidence of such a correlated-encoding effect, it was not nearly large enough to account for the full contiguity effect. Contiguity in recognition is consistent with any mechanism that is task-general and operating whenever new memories are formed, but it seems inconsistent with the sort of task-specific mechanisms that have been argued to produce contiguity in free recall.

Hintzman (2016) observed that because Schwartz et al. (2005) drew their stimuli from a relatively small pool of pictures, there might be some association between pairs of pictures (e.g., because both involve water) that is not fully controlled by randomly assigning items to list position. If subjects notice such associations, Hintzman suggests that they may encode the items into a "configural trace." Critically, subjects would be most likely to notice these associations when items are presented in adjacent positions, producing an adjacency effect based on pre-existing associations, not temporal associations. This explanation strikes us as somewhat ad hoc; one could just as easily argue that associations among pictures would create interference, impairing rather than facilitating performance (e.g., the subject would be unsure whether they saw this particular water-related picture). More direct evidence comes from a recent study by Averell, Prince, and Heathcote (2016) who replicated the basic Schwartz et al. (2005) finding that matching test order to study order facilitates recognition, but Averell et al. (2016) did so using word lists generated from a large pool of words. It seems quite unlikely that chance associations among adjacent list items can account for the effect in such a situation.

Contiguity in Paired Associate Learning

In paired associate learning, subjects have a strong incentive to form associations between items in the same pair but have absolutely no reason to form associations between items in temporally adjacent pairs. In fact, forming such across-pair associations should actually be harmful as it creates a powerful source of interference (Primoff, 1938). Despite these strong incentives to avoid inter-pair associations, analyses of errors in cued recall suggest subjects do indeed form inter-pair associations. Davis, Geller, Rizzuto, and Kahana (2008) examined cases in which subjects incorrectly recalled (intruded) an item from an uncued pair. As in a lag-CRP analysis, they conditionalized the probability of intruding an item from a given lag on the availability of the pair at that lag. These intrusions showed a clear, forward-biased, contiguity effect that extends across many lags (for a similar finding see, Caplan, Glaholt, & McIntosh, 2006).

As with contiguity in item recognition, a task-general mechanism could account for contiguity in paired associate intrusions. Regarding a task-specific strategy account, Hintzman (2016) argues that the contiguity observed in this study is an artifact of an unusual method that makes it difficult to keep track of the pair boundaries and forces them to use a seriation strategy. This critique is inconsistent with the very low levels of intrusions observed in the study and the tendency to intrude the first or second member of the neighboring pair with nearly equal probability. Even if the method did make it difficult to segregate pairs, why would a subject's response to this difficulty be to adopt a strategy that is not only ineffective but also detrimental?

Contiguity outside the Laboratory

Perhaps the strongest test of whether contiguity arises from task-general memory mechanisms is to ask whether people encode information about temporal distance as they live their daily lives, laying down weeks and years of autobiographical memories. Does recall of autobiographical memories show a contiguity effect? People can reconstruct the order of real world events (e.g., the sequence of events on September 11), and the pattern of order errors shows a clear temporal gradient around the correct position that is remarkably similar to the pattern seen in laboratory list learning tasks (Altmann, 2003). In these studies, subjects were explicitly asked to reconstruct the order of events. Does temporal information influence the recall order when subjects are free to recall autobiographical memories in any order? Moreton and Ward (2010) asked subjects to free recall events that had occurred in their lives within the last 5 weeks, 5 months, or 5 years. Within each targeted recall-period, subjects showed a contiguity effect, a tendency to make recall transitions between events that were within the same relative retention interval (e.g., upon recalling an event from 3 weeks/months/years ago, they were more likely to transition to recalling another event that occurred 3 weeks/months/years ago than one that had occurred 2 or 4 weeks/months/years ago). A limitation of this study is that it potentially confounds semantic similarity with temporal distance (Hintzman, 2016). For example, events that occur during temporally-proximate periods of your life are more likely to involve similar people and places than events that occur during more temporally-distant periods.

Although, to our knowledge, Moreton and Ward (2010) is the only study to examine the contiguity effect in autobiographical memory using behavioral measures, Nielson, Smith, Sreekumar, Dennis, and Sederberg (2015) examined contiguity in the neural representations of autobiographical events. They had subjects wear "lifelogging" cameras and GPS devices for a month and then had them recall specific events, cued by pictures from the camera, while undergoing MRI scans. For each pair of events, they computed the similarity between their neural representations and found that this similarity was robustly correlated with the temporal distance separating the events. That is, events that occurred in the same day had neural representations that were more similar to each other than did events that occurred in the same week, which in turn had more similar neural representations than events that occurred in the same month. This was true *even after controlling for the spatial distance between the events.* These results would be naturally predicted by any task-general mechanism that translates the temporal distance between events into the distance between cognitive (neural) representations of those events. The findings are, however, quite difficult to explain under a task-specific account; why would people employ such a strategy when not doing a specific memory task? These real-world contiguity effects also strongly suggest that contiguity is generated by a time scale invariant mechanism rather than a mechanism that operates on a single, short time scale.

Evaluation of Theories

We began by asking how the memory system generates the contiguity effect. To help answer this question, we reviewed the existing findings on the contiguity effect and asked what general properties a contiguity-generating mechanism would need to possess in order to account for the data. Specifically, for each finding, we asked if it could be accounted for by a contiguity-generating mechanism that is a) time scale-specific, b) time scale-general, c) task-specific, d) task-general. Table 1 lists all of the effects that we have considered and, for each, indicates which types of mechanisms can account for the effect without modification, with some additional assumptions, or not at all. Several conclusions can be drawn from examining Table 1.

First, the broad pattern of the data do not sit well with the idea that a task-specific mechanism produces the contiguity effect: of the 28 findings listed in the table only 5 can be straightforwardly accounted for by a such a mechanism. Thirteen of the findings could be handled by a task-specific mechanism, but only by making 11 separate, and largely ad hoc, assumptions. Ten of the findings were, by our assessment, simply incompatible with a task-specific mechanism. In light of this pattern, we can safely reject the null hypothesis that the memory system typically ignores temporal distance and endorse the alternative hypothesis: contiguity is generated by a mechanism that naturally encodes information about the temporal distance between events.

The second conclusion is that the specific memory mechanisms that encode temporal distance are approximately time scale invariant. Those mechanisms that assume temporal information is only encoded at short time scales, such as item-to-item chaining and binding in a short-term buffer, fail to capture several key effects that show contiguity when recalling events that were separated by seconds, minutes, days, weeks, and years.

However, the table also points to some important gaps in our knowledge. Here, we highlight what we see as three of the most pressing open questions; questions that may help adjudicate between existing theories.

Is the Contiguity Effect Truly Time Scale Invariant?

Several types of models include mechanisms that could generate a time scale invariant contiguity effect. These include retrieved context models (Lohnas et al., 2015) which achieve approximate time scale invariance by combing drifting context with a competitive decision rule, the SIMPLE model (Brown et al., 2007) which achieves time scale invariance by using a logarithmic temporal representation, and clustering models such as the one described by Farrell (2012) which can produce contiguity at multiple time scales by associating items with a hierarchy of representations with increasingly coarse time scales (e.g., a within-list chunk representation, a list-level representation).

It is important to realize, however, that not all of these mechanisms are truly time scale invariant. We will use the retrieved context models we have used in our own work as an example: In these models, context drifts at a single time scale causing the expected similarity between context at one time point, i, and another time point, $i + lag$, to drop to zero as lag grows larger (for a discussion of scale in these models see Howard, 2004). Despite this feature, retrieved context models can fit contiguity effects at a wide range of time scales because they use a decision rule that is sensitive to the *relative*, rather than absolute, similarity between the current context and candidates for retrieval. However, this success likely depends on picking a context drift rate appropriate for the time scale of the contiguity effect being considered, and it seems unlikely that any single drift rate would allow these models to simultaneously capture contiguity over the course of seconds observed in immediate free recall (Kahana, 1996), minutes as observed in final free recall (Howard et al., 2008; Unsworth, 2008), weeks as observed in experience sampling work (Nielson et al., 2015), and years as observed in autobiographical recall (Moreton & Ward, 2010).

This raises two questions that we see as important targets for episodic memory researchers. First, does the behavioral data suggest true time scale invariance or does the magnitude of the contiguity effect decrease at longer time scales (Howard, 2004)? The data in Figure 2L show a somewhat smaller effect in continual distractor free recall than in immediate free recall. Similarly, as noted by Howard et al. (2015), the contiguity effect observed in final free recall is shallower and less asymmetric than that observed in immediate free recall. These observations suggest that the effect may not be precisely time scale invariant, but comparing lag-CRPs across task conditions is complicated by variations in overall recall level—as discussed in the section on autocorrelation in goodness of encoding, differences in the shape of the CRP could be due to differences in item availability rather than the strength of temporal associations. To our knowledge, there has been no systematic analysis of the contiguity effect across multiple time scales that controls for item availability.

The second question is whether a model needs to be truly scale invariant to capture these effects. It is possible to incorporate a scale invariant representation of time into the retrieved context framework by replacing the single drifting context representation with a family of "time receptors" each tuned to a different time scale. Shankar and Howard (2012) and Howard et al. (2015) showed that such a model can capture the reduced contiguity over long time scales. It is, however, possible that effects could be captured by a model with a smaller number of time scales, such as hierarchical models (Farrell, 2012) or versions of the retrieved context framework in which different regions of the context representation drift at different rates.

Is Temporal Contiguity Important when Material is Richly Semantically Related?

Most of the studies we have considered deliberately minimize semantic associations among items to isolate the influence of temporal associations. But as we have seen in Figure 2N&O, the presence of semantic associations can dampen the temporal contiguity effect. This was true despite the fact that the stimuli were still lists of isolated words that did not form a coherent story, leaving open the possibility that temporal associations are only influential when stimuli are impoverished and lack sufficient meaning-based coherence to support memory search.

When materials with realistic meaning structures are used, is the influence of temporal associations washed out by non-temporal associations? This is a difficult question to answer as it requires precisely controlling these factors in the lab or precisely measuring them in real-world settings. For example, Moreton and Ward (2010) found evidence of temporal contiguity in the recall of life events, but it remains unclear whether this effect would survive if semantic associations among events were measured and their influence statistically controlled. The time has come for the field to tackle this challenge and add some complexity back into our tasks.

Does Temporal Contiguity Require Intent to Learn?

Almost all of the tasks we have considered explicitly ask subjects to memorize a list of stimuli. Does temporal contiguity emerge when encoding is incidental? There is little evidence one way or the other in the existing literature.

Glenberg and Bradley (1979) attempted to address this issue with several incidental learning experiments that required subjects to repeat a pair of words while trying to retain digits for 1, 5, or 10 seconds. After 81 such trials, subjects were given surprise memory tests for the words. All subjects were first given an item recognition test (i.e., asked if an item was seen before, regardless of which other item it was paired with) and performance was above chance. Following this, subjects were given either a cued recall test (given one word from a pair, recall the other) or a pair recognition test (discriminate intact from mismatched pairs). Performance was extremely low on the cued recall test, but was above chance for the pair recognition test. A second experiment that used fewer trials (to reduce interference) also found very low cued recall performance but above chance performance on an associative matching test in which the first members of each pair were presented in one column and the second members of the pairs were presented in another column, but in random order, and subjects had to indicate the correct pairings. They also found no evidence that the number of rehearsals increased associative memory. Bradley and Glenberg (1983) replicated their earlier findings and added many control conditions, including a ”sheer contiguity” condition in which the words were not presented simultaneously as in the previous experiment but merely in close temporal proximity (as is the case in free recall). In this condition, performance on the associative recognition task was not above chance. Bradley and Glenberg (1983, p. 665) concluded “that sheer temporal contiguity, that is, adjacency of processing, is not sufficient to produce the associations observed in these experiments.”

The Bradley and Glenberg work tested for incidentally encoded temporal associations by asking subjects to decide if particular items had been studied together, but the fact that people fail to explicitly recall which words were paired together does not necessarily mean that they cannot use temporal information to guide the order of free recalls. Unfortunately, almost all free recall studies which have reported measures of temporal contiguity have been explicit memory studies in which subjects are fully aware that their memory will be tested. One exception is a series of studies reported by Nairne, Cogdill, and Lehman (2017), which were designed to investigate the causes of the survival processing effect (Nairne, Thompson, & Pandeirada, 2007). In the first experiment, subjects completed a survival processing task: viewing a list of items and for each rating its relevance to a survival (or control) scenario. Critically, the task instructions do not mention the need to memorize the items, but there was a surprise free recall test approximately two minutes after the end of the list. Despite recalling many words (approximately 45% accuracy across conditions), temporal clustering was not significantly above chance as assessed by the temporal factor score. A second experiment used a different processing task as a control to the survival processing task. Again, there was no evidence of temporal contiguity.

Does this finding falsify models that assume that temporal distance is naturally encoded along with episodic memories? Not necessarily, the experiment did not include an explicit encoding control condition and it is possible that aspects of the task other than intent masked contiguity. Indeed, Nairne et al. (2017) included a third experiment that used the same incidental encoding procedure as their first two experiments, but instead of a free recall test, subjects were provided with all of the words from the list and asked to reconstruct the order. This test did reveal a robust temporal contiguity effect in both the survival processing and the control condition. This finding suggests that subjects may be encoding information about temporal order even under incidental conditions. Nonetheless, the extent to which temporal contiguity in memory search requires explicit encoding is a critical question for the field.

Summary and Final Remarks

Memory search unfolds as a series of retrievals, with one retrieved memory triggering retrieval of another. This chain of retrievals is driven by the similarity among memories. The temporal distance between events is one of the most powerful determinants of similarity: upon successfully retrieving one event, subjects have a strong bias to next retrieve an event that occurred close in time to the just-recalled event. Here, we have examined how this contiguity effect is influenced by a range of variables with the purpose of better understanding which cognitive mechanisms give rise to contiguity. We found that although variables act as dials that modestly influence the magnitude of the contiguity effect in the free recall task, there are few, if any, switches that turn it off completely.

We saw that the contiguity effect is present in essentially all individuals with its magnitude is positively correlated with both recall success and general intellectual ability. Within individuals, a robust contiguity effect is observed on the very first free recall trials and remains even after subjects have weeks of experience with the task. Moreover, the effect cannot be explained by within-individual variation in goodness of encoding. Contiguity is robust to many different parameters of the free recall task, including list length, presentation rate, modality of presentation, modality of recall responses, retention interval, inter-item delay, encoding task, and the semantic associations among list items.

The contiguity effect also generalizes beyond the accurate retrievals in the free recall task and is observed even in situations where it would be difficult or counterproductive to deliberately encode temporal distance. These include across-list transitions in final free recall, intrusion errors in free recall, order errors in serial recall, across-pair intrusions in paired associate learning, and compound-cuing in recognition. A clear contiguity effect remains even in situations in which temporal associations are a potential source of interference, and thus, if it could, the memory system should ignore temporal distance. Finally, we discussed several studies that showed contiguity effects in the recall of real-life memories formed outside the lab.

On a theoretical level, the pattern of data is inconsistent with task-specific mechanisms that produce contiguity under circumscribed conditions. Instead, to account for the data, a model must include task-general mechanisms that encode information about temporal distance at multiple time scales, either by including an approximately time scale invariant representation (e.g., retrieved context models and some positional coding models) or by including multiple representations each with a different time scale (e.g., some versions of hierarchical clustering models).

The weight of this evidence is, in our view, sufficient to conclude that temporal contiguity guides memory search in a range of laboratory paradigms and real-world situations. This empirical fact is important in two senses. First, contiguity is a central feature of people's intellectual lives. It situates our memories in time, giving them their autobiographical flavor, defining our personal histories. Moreover, something about the ability to recover the temporal sequence of our past experience is highly correlated with intelligence. The contiguity effect is also important in that the theoretical constructs that have been developed to explain it, such as temporal context, are driving progress in both the psychology (Jarrold et al., 2015; Karpicke, Lehman, & Aue, 2014; Lehman & Hasselhorn, 2012; Sahakyan, Delaney, Foster, & Abushanab, 2013; Sahakyan & Smith, 2014; Wahlheim & Huff, 2015; **?**) and the neuroscience (Ezzyat & Davachi, 2014; Howard, Viskontas, Shankar, & Fried, 2012; Hsieh, Gruber, Jenkins, & Ranganath, 2014; Long & Kahana, 2015; Manning, Polyn, Baltuch, Litt, & Kahana, 2011; Miller, Neufang, et al., 2013; Turk-Browne, Simon, & Sederberg, 2012; Yaffe et al., 2014) of human memory.

References

Altmann, E. M. (2003). Reconstructing the serial order of events: A case study of september 11, 2001. *Applied Cognitive Psychology*, *17*(9), 1067–1080.

Aristotle. (350 B.C.E.). De memoria et reminiscentia. retrieved from http://classics.mit.edu/aristotle/memory.1b.txt.

Averell, L., Prince, M., & Heathcote, A. (2016). Fundamental causes of systematic and random variability in recognition memory. *Journal of Memory and Language*, *88*, 51–69.

Baddeley, A. (2003). Working memory: Looking back and forward. *Nature Reviews Neuroscience*, *4*(10), 829–839.

Bhatarah, P., Ward, G., & Tan, L. (2006). Examining the relationship between free recall and immediate serial recall: The effect of concurrent task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(2), 215–229.

Bjork, R. A., & Whitten, W. B. (1974). Recency-sensitive retrieval processes in long-term free recall. *Cognitive Psychology*, *6*, 173–189.

Bradley, M. M., & Glenberg, A. M. (1983). Strengthening associations: Duration, attention, or relations? *Journal of Verbal Learning and Verbal Behavior*, *22*(6), 650–666.

Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, *114*(3), 539–576.

Caplan, J. B., Glaholt, M., & McIntosh, A. R. (2006). Linking associative and list memory: Pairs versus triples. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *32*(6), 1244–1265.

Castel, A. D. (2005). Memory for grocery prices in younger and older adults: The role of schematic support. *Psychology and Aging*, *20*(4), 718–721.

Castel, A. D., Benjamin, A. S., Craik, F. I. M., & Watkins, M. J. (2002). The effects of aging on selectivity and control in short-term recall. *Memory and Cognition*, *30*(7), 1078–1085.

Cortis, C., Dent, K., Kennett, S., & Ward, G. (2015). First things first: Similar list length and output order effects for verbal and nonverbal stimuli. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(4), 1179.

Davelaar, E. J., Goshen-Gottstein, Y., Ashkenazi, A., Haarmann, H. J., & Usher, M. (2005). The demise of short-term memory revisited: Empirical and computational investigations of recency effects. *Psychological Review*, *112*, 3–42. doi: 10.1037/0033-295X.112.1.3

Davis, O. C., Geller, A. S., Rizzuto, D. S., & Kahana, M. J. (2008). Temporal associative processes revealed by intrusions in paired-associate recall. *Psychonomic Bulletin & Review*, *15*(1), 64-69.

Delaney, P. F., & Knowles, M. E. (2005, Jan). Encoding strategy changes and spacing effects in the free recall of unmixed lists. *Journal of Memory and Language*, *52*(1), 120-130.

Ebbinghaus, H. (1885/1913). *On memory: A contribution to experimental psychology.* New York: Teachers College, Columbia University.

Ezzyat, Y., & Davachi, L. (2014). Similarity breeds proximity: Pattern similarity within and across contexts is related to later mnemonic judgments of temporal proximity. *Neuron*, *81*(5), 1179–1189.

Farrell, S. (2012). Temporal clustering and sequencing in short-term memory and episodic memory. *Psychological Review*, *119*(2), 223-271. doi: 10.1037/a0027371

Farrell, S., Hurlstone, M. J., & Lewandowsky, S. (2013). Sequential dependencies in recall of sequences: Filling in the blanks. *Memory & Cognition*, *41*, 938-952.

Farrell, S., & Lewandowsky, S. (2008). Empirical and theoretical limits on lag recency in free recall. *Psychonomic Bulletin and Review*, *15*, 1236-1250. doi: 10.3758/PBR.15.6.1236

Glanzer, M., & Cunitz, A. R. (1966). Two storage mechanisms in free recall. *Journal of*

Verbal Learning and Verbal Behavior, *5*, 351-360.

Glenberg, A. M., & Bradley, M. M. (1979). Mental contiguity. *Journal of Experimental Psychology: Human Learning and Memory*, *5*(2), 88.

Greenhouse, P. (1967). Free recall of categorized and unrelated words under serial or grouped presentation. *Psychonomic Science*, *8*(10), 447–448.

Hasher, L. (1973, January). Position effects in free recall. *American Journal of Psychology*, *86*(2), 389–397.

Healey, M. K., Crutchley, P., & Kahana, M. J. (2014). Individual differences in memory search and their relation to intelligence. *Journal of Experimental Psychology: General*, *143*(4), 1553–1569. doi: 10.1037/a0036306

Healey, M. K., & Kahana, M. J. (2014). Is memory search governed by universal principles or idiosyncratic strategies? *Journal of Experimental Psychology: General*, *143*, 575–596. doi: 10.1037/a0033715

Healey, M. K., & Kahana, M. J. (2016). A four–component model of age–related memory change. *Psychological Review*, *123*(1), 23-69.

Herbart, J. F. (1834). Lehrbuch zur Psychologie. In K. Kehrbach (Ed.), *Sämtliche Werke* (2nd ed., Vol. 4, p. 376-377). Königsberg: August Wilhelm Unzer.

Hintzman, D. L. (2011). Research strategy in the study of memory: Fads, fallacies, and the search for the "coordinates of truth". *Perspectives on Psychological Perspectives on Psychological Science*, *6*(3), 253-271.

Hintzman, D. L. (2016). Is memory organized by temporal contiguity? *Memory & Cognition*, *44*, 365–375.

Hintzman, D. L., & Hartry, A. L. (1990). Item effects in recognition and fragment completion: Contingency relations vary for different subsets of words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 965-969.

Hogan, R. M. (1975). Interitem encoding and directed search in free recall. *Memory & Cognition*, *3*, 197-209.

Howard, M. W. (2004). Scaling behavior in the temporal context model. *Journal of Mathematical Psychology*, *48*, 230–238. doi: 10.1016/j.jmp.2004.03.004

Howard, M. W. (2017).

Manuscript in preparation.

Howard, M. W., & Kahana, M. J. (1999). Contextual variability and serial position effects in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 923–941. doi: 10.1037/0278-7393.25.4.923

Howard, M. W., & Kahana, M. J. (2002a). A distributed representation of temporal context. *Journal of Mathematical Psychology*, *46*, 269–299. doi: 10.1006/jmps.2001.1388

Howard, M. W., & Kahana, M. J. (2002b). When does semantic similarity help episodic retrieval? *Journal of Memory and Language*, *46*, 85–98.

Howard, M. W., Sederberg, P. B., & Kahana, M. J. (2009). Reply to Farrell & Lewandowsky: Recency-contiguity interactions predicted by the temporal context model. *Psychonomic Bulletin & Review*, *16*, 973–984. doi: doi:10.3758/PBR.16.5.973

Howard, M. W., Shankar, K. H., Aue, W. R., & Criss, A. H. (2015). A distributed representation of internal time. *Psychological Review*, *122*(1), 24-53. doi: 10.1037/a0037840

Howard, M. W., Viskontas, I. V., Shankar, K. H., & Fried, I. (2012). Ensembles of human MTL neurons "jump back in time" in response to a repeated stimulus. *Hippocampus*, *22*, 1833–1847.

Howard, M. W., Youker, T. E., & Venkatadass, V. (2008). The persistence of memory: Contiguity effects across hundreds of seconds. *Psychonomic Bulletin & Review*, *15*, 58–63. doi: 10.3758/PBR.15.1.58

Hsieh, L.-T., Gruber, M., Jenkins, L., & Ranganath, C. (2014). Hippocampal activity patterns carry information about objects in temporal cortex. *Neuron*, *81*, 1165–1178.

Hume, D. (1748). *An enquiry concerning human understanding* (L. A. Selby-Bigge, Ed.). Retrieved from Project Gutenberg: http://www.gutenberg.org/files/9662/9662-h/9662-h.htm.

Humphreys, M. S., Bain, J. D., & Pike, R. (1989). Different ways to cue a coherent memory system: A theory for episodic, semantic, and procedural tasks. *Psychological Review*, *96*, 208-233.

Husserl, E. (1966). *The phenomenology of internal time-consciousness.* Bloomington, IN: Indiana University Press.

Jahnke, J. C. (1965). Primacy and recency effects in serial-position curves of immediate recall. *Journal of Experimental Psychology*, *70*(1), 130.

Jarrold, C., Hall, D., Harvey, C. E., Tam, H., Towse, J. N., & Zarandi, A. L. (2015). What can we learn about immediate memory from the development of children's free recall? *The Quarterly Journal of Experimental Psychology*, *68*(9), 1871–1894.

Johnson, M. K. (1972). Organizational units in free recall as a source of transfer. *Journal of Experimental Psychology*, *94*(3), 300-307.

Kahana, M. J. (1996). Associative retrieval processes in free recall. *Memory & Cognition*, *24*(1), 103–109. doi: 10.3758/BF03197276

Kahana, M. J. (2012). *Foundations of human memory.* New York, NY: Oxford University Press.

Kahana, M. J., & Caplan, J. B. (2002). Associative asymmetry in probed recall of serial lists. *Memory & Cognition*, *30*, 841-849.

Kahana, M. J., Dolan, E. D., Sauder, C. L., & Wingfield, A. (2005). Intrusions in episodic recall: Age differences in editing of overt responses. *Journal of Gerontology: Psychological Sciences*, *60*, 92–97. doi: 10.1093/geronb/60.2.P92

Kahana, M. J., Howard, M. W., Zaromb, F., & Wingfield, A. (2002). Age dissociates recency and lag recency effects in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 530–540. doi: 10.1037/0278-7393.28.3.530

Kahana, M. J., Rizzuto, D. S., & Schneider, A. (2005). Theoretical correlations and measured correlations: Relating recognition and recall in four distributed memory models. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 933-953.

Karpicke, J. D., Lehman, M., & Aue, W. R. (2014). Retrieval-based learning: An episodic context account. *Psychology of Learning and Motivation*, *61*, 237–284.

Kılıç, A., Criss, A. H., & Howard, M. W. (2013). A causal contiguity effect that persists across time scales. *Journal Experimental Psychology: Learning, Memory and Cognition*, *39*(1), 297–303.

Kimball, D. R., Smith, T. A., & Kahana, M. J. (2007). The fSAM model of false recall. *Psychological Review*, *114*(4), 954–993. doi: 10.1037/0033-295X.114.4.954

Kintsch, W. (1970). Models for free recall and recognition. In D. A. Norman (Ed.), *Models of human memory* (pp. 331–373). Academic Press New York.

Klein, K. A., Addis, K. M., & Kahana, M. J. (2005). A comparative analysis of serial and free recall. *Memory & Cognition*, *33*, 833–839.

Lee, C. L., & Estes, W. K. (1977). Order and position in primary memory for letter strings. *Journal of Verbal Learning and Verbal Behavior*, *16*, 395-418.

Lehman, M., & Hasselhorn, M. (2012). Rehearsal dynamics in elementary school children. *Journal of Experimental Child Psychology*, *111*(3), 552–560.

Lehman, M., & Malmberg, K. J. (2013). A buffer model of memory encoding and temporal correlations in retrieval. *Psychological Review*, *120*(1), 155-189. doi: 10.1037/a0030851

Lehmann, M., & Hasselhorn, M. (2010). The dynamics of free recall and their relation to rehearsal between 8 and 10 years of age. *Child Development*, *81*(3), 1006–1020.

Lewandowsky, S., & Murdock, B. B. (1989). Memory for serial order. *Psychological Review*, *96*, 25-57. doi: 10.1037/0033-295X.96.1.25

Loaiza, V. M., & McCabe, D. P. (2012). Temporal-contextual processing in working memory: Evidence from delayed cued recall and delayed free recall tests. *Memory & Cognition*, *40*(2), 191–203.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*, 476-490.

Lohnas, L. J., & Kahana, M. J. (2013). Parametric effects of word frequency effect in memory for mixed frequency lists. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(6), 1943–1946. doi: 10.1037/a0033669

Lohnas, L. J., & Kahana, M. J. (2014). Compound cuing in free recall. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *40*(1), 12-24. doi: 10.1037/a0033698

Lohnas, L. J., Polyn, S. M., & Kahana, M. J. (2015). Expanding the scope of memory search: Intralist and interlist effects in free recall. *Psychological Review*, *122*(2), 337-363.

Long, N. M., Danoff, M. S., & Kahana, M. J. (2015, October). Recall dynamics reveal the retrieval of emotional context. *Psychonomic Bulletin and Review*, *22*(5), 1328-1333.

Long, N. M., & Kahana, M. J. (2015). Successful memory formation is driven by contextual encoding in the core memory network. *NeuroImage*, *119*, 332–337.

Long, N. M., & Kahana, M. J. (2016). Modulation of task demands suggests that semantic processing interferes with the formation of episodic associations. *Journal of Experimental Psychology: Learning, Memory, and Cognition.*

Manning, J. R., Polyn, S. M., Baltuch, G., Litt, B., & Kahana, M. J. (2011). Oscillatory patterns in temporal lobe reveal context reinstatement during memory search. *Proceedings of the National Academy of Sciences, USA*, *108*(31), 12893–12897. doi: 10.1073/pnas.1015174108

May, C. P., Rahhal, T., Berry, E. M., & Leighton, E. A. (2005). Aging, source memory, and emotion. *Psychology and Aging*, *20*(4), 571.

McCluey, J. D., Burke, J. F., & Polyn, S. M. (2016). Temporal and semantic structure of a study list alters temporal organization in free recall. *Manuscript in preparation.*

McDaniel, M. A., Cahill, M., Bugg, J. M., & Meadow, N. G. (2011). Dissociative effects of orthographic distinctiveness in pure and mixed lists: an item-order account. *Memory & Cognition*, *39*(7), 1162–1173.

Miller, J. F., Kahana, M. J., & Weidemann, C. T. (2012). Recall termination in free recall. *Memory & Cognition*, *40*(4), 540–550. doi: 10.3758/s13421-011-0178-9

Miller, J. F., Lazarus, E., Polyn, S. M., & Kahana, M. J. (2013). Spatial clustering during memory search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 773–781.

Miller, J. F., Neufang, M., Solway, A., Brandt, A., Trippel, M., Mader, I., . . . Schulze-Bonhage, A. (2013). Neural activity in human hippocampal formation reveals the spatial context of retrieved memories. *Science*, *342*(6162), 1111-1114.

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* Cambridge, England: Cambridge University Press.

Moreton, B. J., & Ward, G. (2010). Time scale similarity and long-term memory for autobiographical events. *Psychonomic Bulletin & Review*, *17*(4), 510–515.

Murdock, B. B. (1962). The serial position effect of free recall. *Journal of Experimental Psychology*, *64*, 482-488. doi: 10.1037/h0045106

Murdock, B. B. (1974). *Human memory: Theory and data.* Potomac, MD: Lawrence Erlbaum and Associates.

Murdock, B. B., & Walker, K. D. (1969). Modality effects in free recall. *Journal of Verbal Learning and Verbal Behavior*, *8*, 665-676.

Nairne, J. S., Cogdill, M., & Lehman, M. (2017). Adaptive memory: Temporal, semantic, and rating-based clustering following survival processing. *Journal of Memory and Language*, *93*, 304–314.

Nairne, J. S., & Pandeirada, J. N. S. (in press). Adaptive memory: The evolutionary significance of survival processing. *Perspectives on Psychological Science.*

Nairne, J. S., Thompson, S. R., & Pandeirada, J. N. (2007). Adaptive memory: survival processing enhances retention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(2), 263.

Nguyen, K., & McDaniel, M. A. (2015). The picture complexity effect: Another list composition paradox. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(4), 1026.

Nielson, D. M., Smith, T. A., Sreekumar, V., Dennis, S., & Sederberg, P. B. (2015). Human hippocampus represents space and time during retrieval of real-world memories. *Proceedings of the National Academy of Sciences*, *112*(35), 11078–11083.

Osth, A. F., & Dennis, S. (2015). The fill-in effect in serial recall can be obscured by omission errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 1447–1455.

Phillips, J. L., Shiffrin, R. J., & Atkinson, R. C. (1967). The effects of list length on short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *6*, 303-311.

Polyn, S. M., Norman, K. A., & Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychological Review*, *116*, 129-156. doi: 10.1037/a0014420

Postman, L. (1971). Organization and interference. *Psychological Review*, *78*(4), 290.

Postman, L. (1972). The experimental analysis of verbal learning and memory: Evolution and innovation. In C. P. Duncan, L. Sechrest, & A. W. Melton (Eds.), *Human memory: Festschrift in honor of Benton J. Underwood.* New York: Appleton Century Crofts.

Postman, L., & Phillips, L. W. (1965). Short-term temporal changes in free recall. *Quarterly Journal of Experimental Psychology*, *17*, 132-138.

Primoff, E. (1938). Backward and forward associations as an organizing act in serial and in paired-associate learning. *Journal of Psychology*, *5*, 375-395.

Raaijmakers, J. G. W., & Shiffrin, R. M. (1981). Search of associative memory. *Psychological Review*, *88*, 93-134. doi: 10.1037/0033-295X.88.2.93

Rozov, A. (1964). Formation and dynamics of topic clusters in free recall. *Soviet Psychology and Psychiatry*, *2*(3), 19–26.

Sadeh, T., Moran, R., & Goshen-Gottstein, Y. (2015). When items 'pop into mind': variability in temporal-context reinstatement in free-recall. *Psychonomic Bulletin & Review*, *22*(3), 779–790.

Sahakyan, L., Delaney, P. F., Foster, N. L., & Abushanab, B. (2013). List-method directed forgetting in cognitive and clinical research: a theoretical and methodological review. *Psychology of Learning and Motivation*, *59*, 131 - 189.

Sahakyan, L., & Smith, J. R. (2014). A long time ago, in a context far, far away: Retrospective time estimates and internal context change. *Journal Experimental Psychology: Learning, Memory and Cognition*, *40*(1), 86-93. doi: 10.1037/a0034250

Schwartz, G., Howard, M. W., Jing, B., & Kahana, M. J. (2005). Shadows of the past: Temporal retrieval effects in recognition memory. *Psychological Science*, *16*, 898-904. doi: 10.1111/j.1467-9280.2005.01634.x

Sederberg, P. B., Miller, J. F., Howard, W. H., & Kahana, M. J. (2010). The temporal contiguity effect predicts episodic memory performance. *Memory & Cognition*, *38*(6), 689–699. doi: 10.3758/MC.38.6.689

Shankar, K. H., & Howard, M. W. (2012). A scale-invariant internal representation of time. *Neural Computation*, *24*, 134-193. doi: 10.1162/NECO_a_00212

Siddiqui, A. P., & Unsworth, N. (2011). Investigating the role of emotion during the search process in free recall. *Memory & Cognition*, *39*(8), 1387–1400.

Sirotin, Y. B., Kimball, D. R., & Kahana, M. J. (2005). Going beyond a single list: Modeling the effects of prior experience on episodic free recall. *Psychonomic Bulletin & Review*, *12*(5), 787–805. doi: 10.3758/BF03196773

Solway, A., Murdock, B. B., & Kahana, M. J. (2012). Positional and temporal clustering in serial order memory. *Memory & Cognition*, *40*(2), 177–190.

Spear, N. E., Ekstrand, B. R., & Underwood, B. J. (1964). Association by contiguity. *Journal of Experimental Psychology*, *67*(2), 151.

Spillers, G. J., & Unsworth, N. (2011). Variation in working memory capacity and temporal–contextual retrieval from episodic memory. *Journal Experimental Psychology: Learning, Memory and Cognition*, *37*(6), 1532–1539.

Spurgeon, J., Ward, G., & Matthews, W. J. (2014). Examining the relationship between immediate serial recall and immediate free recall: Common effects of phonological loop variables but only limited evidence for the phonological loop. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(4), 1110.

Spurgeon, J., Ward, G., Matthews, W. J., & Farrell, S. (2015). Can the effects of temporal grouping explain the similarities and differences between free recall and serial recall? *Memory & Cognition*, *43*(3), 469–488.

Stefanidi, A., & Brewer, G. A. (2015). *The recall dynamics of importance in delayed free recall* (Unpublished master's thesis). Arizona State University.

Steyvers, M., Shiffrin, R. M., & Nelson, D. L. (2004). Word association spaces for predicting semantic similarity effects in episodic memory. In A. F. Healy (Ed.), *Cognitive psychology and its applications: Festschrift in honor of Lyle Bourne, Walter Kintsch, and Thomas Landauer.* Washington, DC: American Psychological Association.

Turk-Browne, N. B., Simon, M. G., & Sederberg, P. B. (2012). Scene representations in parahippocampal cortex depend on temporal context. *Journal of Neuroscience*, *32*(21), 7202 - 7207. doi: 10.1523/JNEUROSCI.0942-12.2012

Unsworth, N. (2007). Individual differences in working memory capacity and episodic retrieval: Examining the dynamics of delayed and continuous distractor free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(6), 1020.

Unsworth, N. (2008). Exploring the retrieval dynamics of delayed and final free recall:

Further evidence for temporal-contextual search. *Journal of Memory and Language*, *59*, 223-236. doi: 10.1016/j.jml.2008.04.002

Unsworth, N., & Brewer, G. (2010). Variation in working memory capacity and intrusions: Differences in generation or editing? *European Journal of Cognitive Psychology*, *22*(6), 990-1000. doi: 10.1080/09541440903175086

Unsworth, N., Brewer, G., & Spillers, G. (2009). There's more to the working memory capacity–fluid intelligence relationship than just secondary memory. *Psychonomic Bulletin and Review*, *16*(5), 931–937.

Unsworth, N., Spillers, G. J., & Brewer, G. A. (2012). Working memory capacity and retrieval limitations from long-term memory: An examination of differences in accessibility. *The Quarterly Journal of Experimental Psychology*, *65*(12), 2397–2410.

Wahlheim, C. N., & Huff, M. J. (2015). Age differences in the focus of retrieval: Evidence from dual-list free recall. *Psychology and Aging*, *30*(4), 768.

Wallace, W. P. (1969). Clustering in free recall based upon input contiguity. *Psychonomic Science*, *14*(6), 290–291.

Ward, G., Tan, L., & Grenfell-Essam, R. (2010, September). Examining the relationship between free recall and immediate serial recall: the effects of list length and output order. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(5), 1207–1241.

Ward, G., Woodward, G., Stevens, A., & Stinson, C. (2003). Using overt rehearsals to explain word frequency effects in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 186–210.

Wechsler, D. (2008). *Wechsler Adult Intelligence Scale* (4th ed.). San Antonio, TX: Pearson.

Yaffe, R. B., Kerr, M. S., Damera, S., Sarma, S. V., Inati, S. K., & Zaghloul, K. A. (2014). Reinstatement of distributed cortical oscillations occurs with precise spatiotemporal dynamics during successful memory retrieval. *Proceedings of the National Academy of*

Sciences, *111*(52), 18727–8732.

Zaromb, F. M., Howard, M. W., Dolan, E. D., Sirotin, Y. B., Tully, M., Wingfield, A., & Kahana, M. J. (2006). Temporal associations and prior-list intrusions in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(4), 792–804. doi: 10.1037/0278-7393.32.4.792

Table 1

Which theories can account for the full set of benchmark contiguity effects?

Effect	Task-Specific	Task-General	Time Scale-Specific	Time Scale-General
Contiguity in immediate free recall	✓	✓	✓	✓
Forward asymmetry	$\ominus_1$	✓	✓	✓
Ubiquity across individuals	$\ominus_2$	✓	✓	✓
Changes across the lifespan	$\ominus_3$	✓	✓	✓
Positive correlation with recall and IQ	$\ominus_2$	✓	✓	✓
Present from first list to 24^{th} session	×	✓	✓	✓
Immune to variation in goodness of encoding	✓	✓	✓	✓
Higher for early and late output positions	$\ominus_4$	✓	✓	✓
Consistent across serial positions	✓	✓	✓	✓
List Length	$\ominus_5$	✓	✓	✓
Presentation Modality	$\ominus_6$	✓	✓	✓
Recall Modality	$\ominus_7$	✓	✓	✓
Encoding Task	$\ominus_8$	✓	✓	✓
Approximate time-scale invariance	$\ominus_9$	✓	×	✓
Robust to very slow and fast presentation rates	×	✓	✓	✓
Present in same-category lists	×	✓	✓	✓
Absent in orthographically distinct lists	×	×	×	×
Present when semantic associates compete	$\ominus_{10}$	✓	✓	✓
Present when list includes emotional items	$\ominus_{10}$	✓	✓	✓
Robust to variation in stimuli complexity	✓	✓	✓	✓
Present when items vary in assigned value	×	✓	✓	✓
Contiguity in FR intrusions	×	✓	✓	✓
Across-list contiguity in final free recall	×	✓	×	✓
Contiguity in SR errors	×	✓	✓	✓
Compound cuing in recognition	$\ominus_{11}$	✓	✓	✓
Contiguity in PA intrusions	×	✓	✓	✓
Contiguity in autobiographical memory	×	✓	×	✓
Absent when subjects do not intend to encode	✓	×	×	×

✓= The standard version of the model accounts for the effect. $\ominus$ = The model can account for the effect by adding an additional assumption. Some models require different modifications to account for different effects—the subscript indicates which specific modification accounts for the effect. × = The model cannot account for the effect even with reasonable modifications.

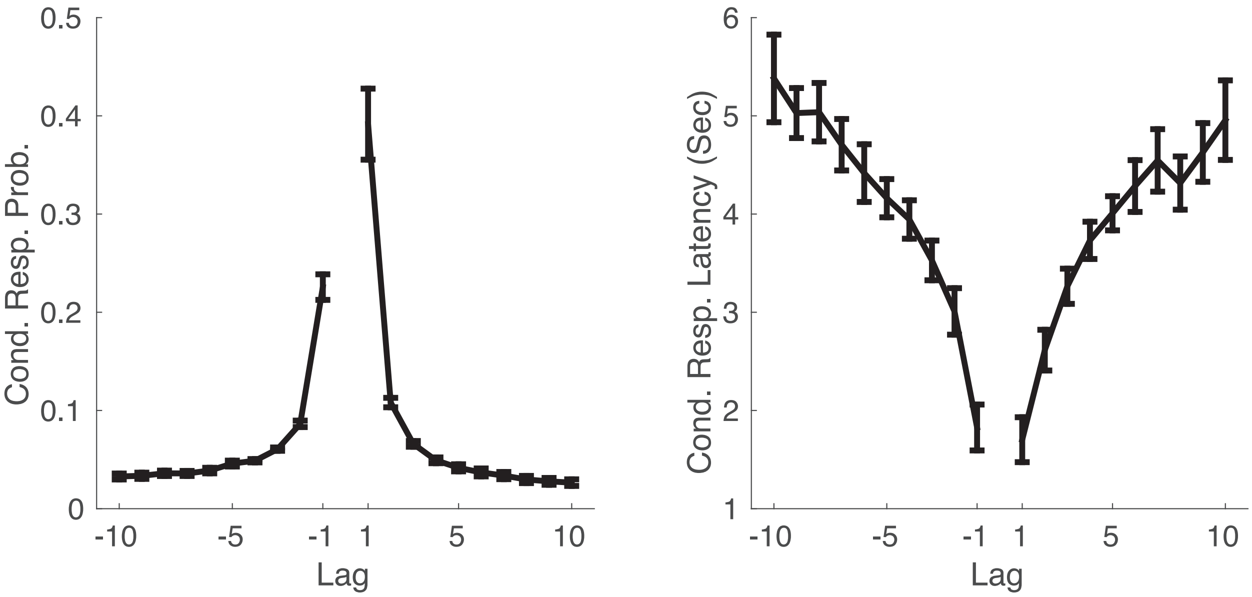

Figure 1. The contiguity effect: Recall of one event triggers recall of other events that occurred near in time. (A) The conditional response probability as a function of lag shows the probability of recalling an item from serial position $i + lag$ immediately following recall of an item from serial position i. (B) The conditional response latency as a function of lag shows the mean inter-response time between successive recalls of items from serial positions i and $i + lag$. Data are from Experiment 4 of the Penn Electrophysiology of Encoding and Retrieval Study (PEERS). Subjects studied lists of 24 words for delayed free recall. Error bars are 95% within-subject confidence intervals (Loftus & Masson, 1994).

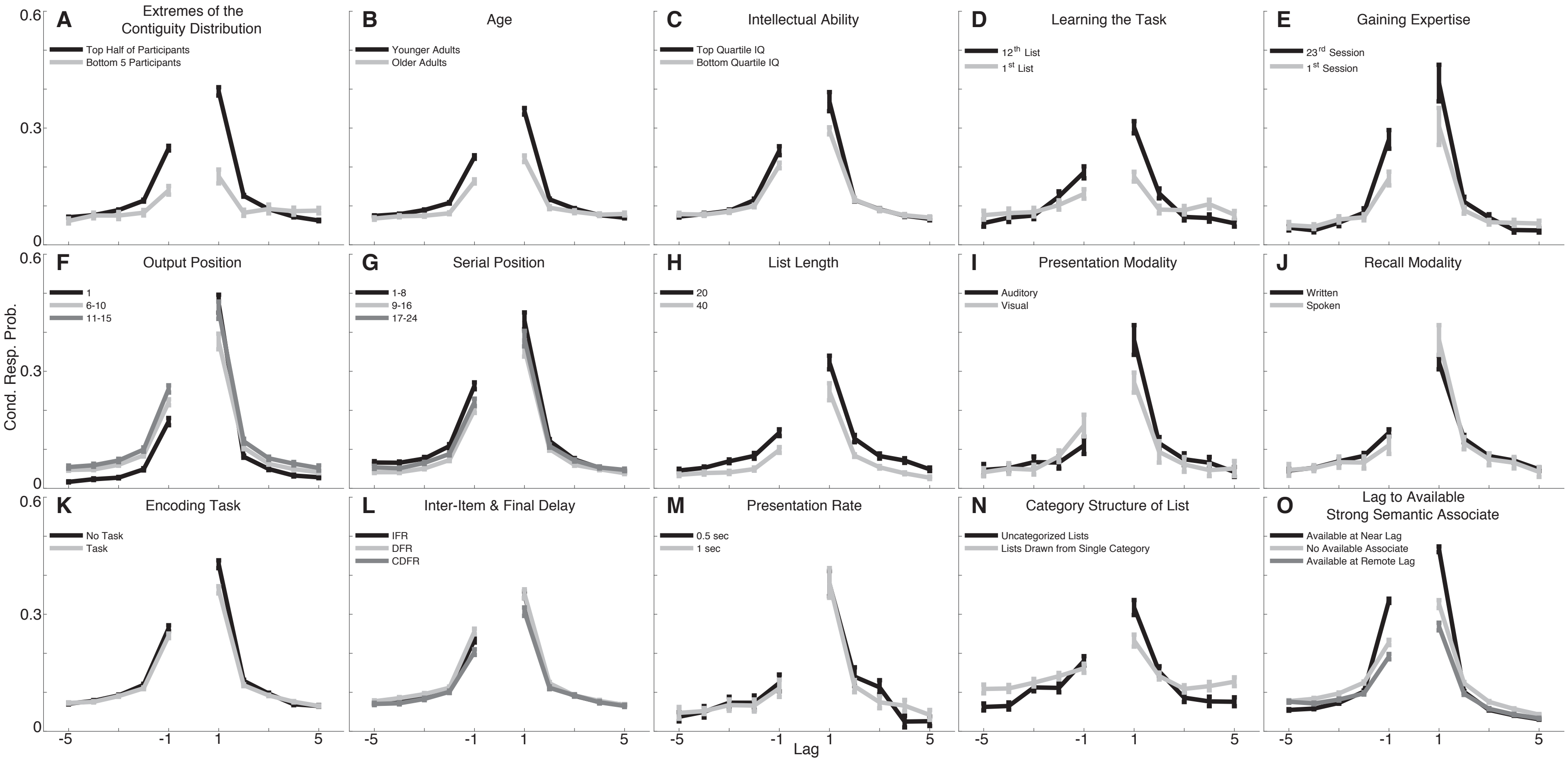

Figure 2. Many variables modulate, but do not eliminate, the contiguity effect. (A) Subjects with the temporal factor scores in the top half of the distribution vs. subjects with the 5 lowest scores across both age groups in PEERS Experiment 1. (B) Younger vs. older adults in PEERS Experiment 1. (C) Top vs. bottom quartile of the younger adult IQ distribution in PEERS Experiment 1. (D) First vs. last (12^{th}) list in the screening session of PEERS. (E) Naïve subjects' first vs. 23^{th} session in PEERS Experiment 4. (F) Output position 1 vs. output positions 6–10 and 11–15 from PEERS Experiment 4. (G) Transitions originating from serial positions 1–8, 9–16, and 17–24 from PEERS Experiment 4. (H) List length 20 vs. 40 in Murdock (1962, 1 sec presentation rate). (I) Auditory vs. visual presentation in the 1 sec presentation rate condition in Experiment 1 of Murdock and Walker (1969). (J) Written vs. spoken recall in Murdock and Walker (1969) and Murdock (1962) respectively (20-item lists presented auditorily for 1 sec/item in both cases). (K) Lists with vs. without an encoding task in Immediate free recall lists of PEERS Experiments 1–3. (L) Immediate, delayed, and continual distractor recall conditions from PEERS Experiments 1–3. (M) Presentation rates of 0.5 sec vs. 1 sec in Experiment 1 of Murdock and Walker (1969). (N) Uncategorized lists vs. lists drawn from a single category in McCluey et al. (2016) (O) Transitions originating from items that had a strong associate (WAS $cos(\theta) > .7$) available only at $lags > 5$ vs. items that had a strong associate available at $lags \leq 2$ vs. items that had no strong associates available.

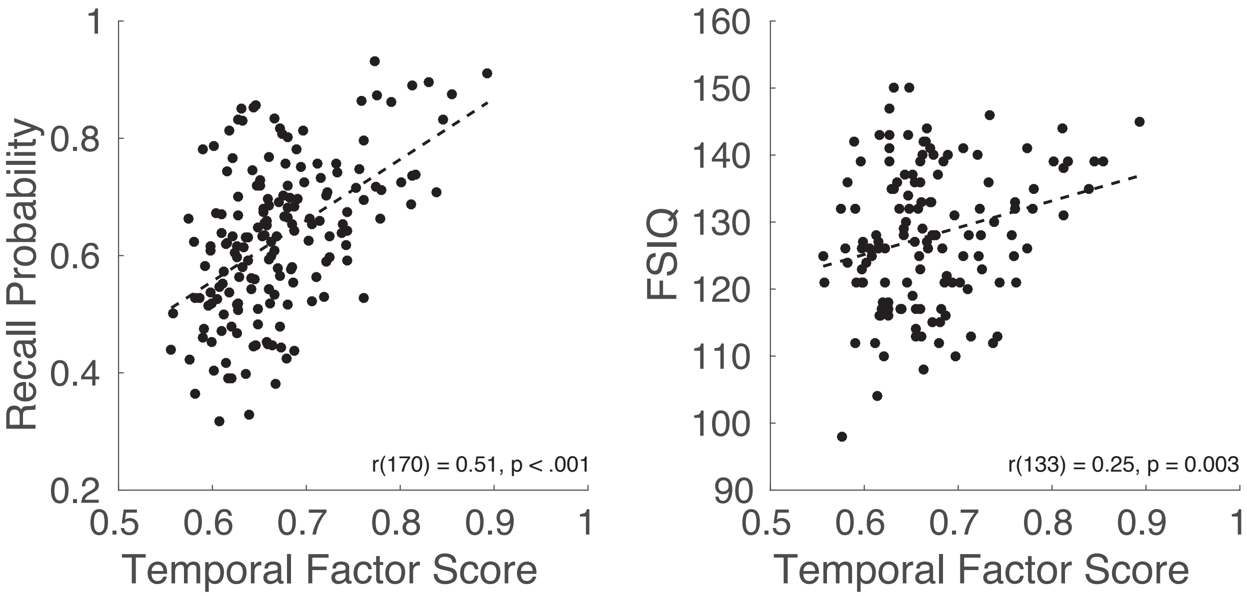

Figure 3. Individual differences in contiguity predict memory performance and IQ (A) The correlation between temporal factor scores and overall recall probability. Temporal factor scores give the average percentile ranking the temporal lag of each actual transition with respect to the lags of all transitions that were possible at that time. (B) The correlation between temporal factor scores and full-scale Wechsler Adult Intelligence Scale IV IQ. Computed using all immediate free recall trials from younger adults in Experiments 1–3 of the Penn Electrophysiology of Encoding and Retrieval Study (PEERS). In each session, subjects studied lists of 16 words for immediate free recall.

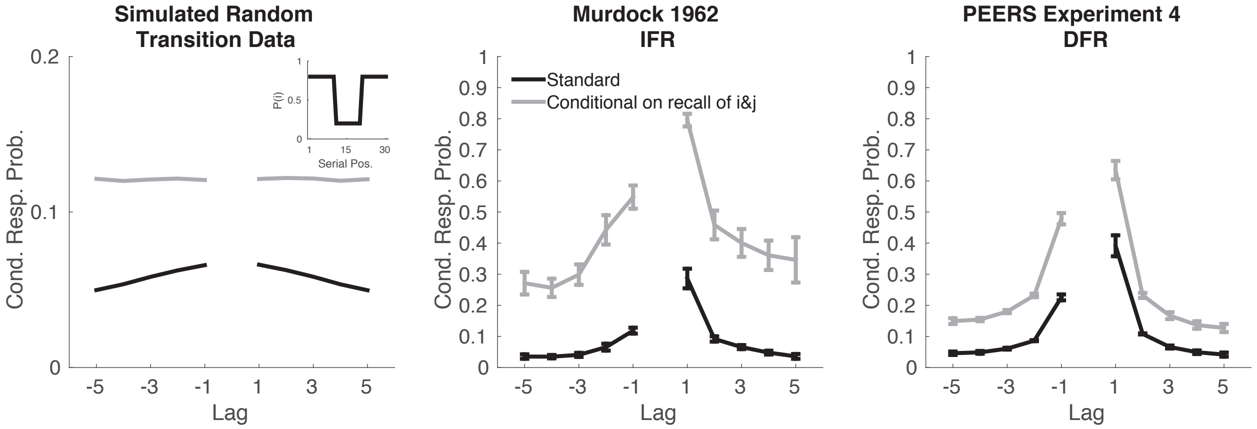

Figure 4. Conditionalizing on availability of both items i and j does not eliminate the contiguity effect. (A) A simulated artifactual contiguity effect from a model in which the probability of successful encoding varies by serial positions (see inset) but transitions between items are random with respect to study lag. (B) Immediate recall of 30-item lists from Murdock (1962). (C) Delayed free recall of lists of 24 items in PEERS Experiment 4. Error bars are 95% within-subject confidence intervals (Loftus & Masson, 1994).

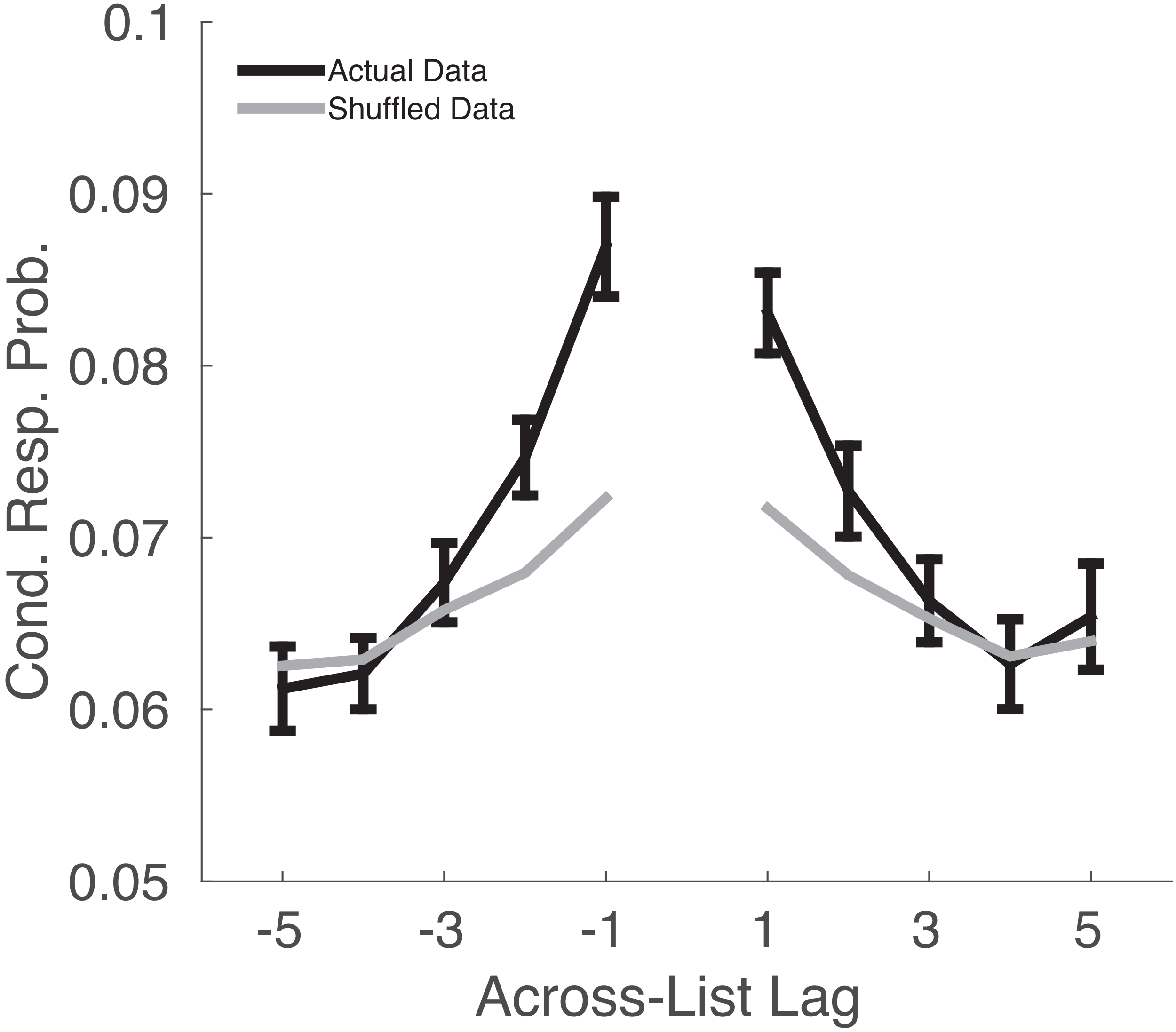

Figure 5. Across-list transitions during final free recall show a contiguity effect. The black curve shows the conditional response probabilities computed from the actual data. The gray curve shows the conditional probability from surrogate data in which the order of recalls are randomly shuffled. The across-list contiguity effect is larger in the actual data than in the surrogate data. Data are from PEERS Experiments 1–3. Error bars are 95% within-subject confidence intervals (Loftus & Masson, 1994).

Appendix A

Penn Electrophysiology of Encoding and Retrieval Study

The Penn Electrophysiology of Encoding and Retrieval Study (PEERS) aims to assemble a large database on the electrophysiological correlates of memory encoding and retrieval (Healey et al., 2014; Healey & Kahana, 2014, 2016; Lohnas & Kahana, 2013, 2014; Miller et al., 2012). Here, we report data from Experiments 1 and 4. We describe the methods of those experiments in detail (for full details on the design of PEERS, see Healey & Kahana, 2014; Lohnas & Kahana, 2013).

Subjects

The present analyses are based on the subjects who had began PEERS as of April 2015. The sample included 466 subjects who completed an introductory session. Of these, a subset consisting of 172 younger adults (age range: 18–30 years) and 38 older adults (age range: 61–85 years) completed all sessions of Experiment 1 (see Healey & Kahana, 2016, for full details on the older adult sample). Of the younger adult sample, 31, the practiced group, also completed at least 12 sessions of Experiment 4. A second subset of 20 younger adults, the naïve group, completed at least 12 sessions of Experiment 4 but had *not* participated in Experiments 1–3. All subjects were right-handed native English speakers. The methods for this study were approved by the University of Pennsylvania Institutional Review Board.

PEERS Introductory Session

Prospective subjects completed a introductory session to introduce them to the free recall task and ensure they did not make any excess of eye movements during item presentation epochs (to avoid muscle artifacts making EEG data unusable) and had a probability of recall less than 0.8 (to avoid subject's being at ceiling even before practice). The introductory session consisted of 12 lists of 16 words presented one at a time on a computer screen for 1600 ms, followed by a jittered (i.e., variable) inter-stimulus interval of 800–1200 ms (uniform distribution).

The final word of each list was followed by a distractor period in which subjects answered math problems of the form $A + B + C = ?$, where A, B, and C were positive, single-digit integers, though the answer could have been one or two digits. When a math problem was presented on the screen, the subject typed the sum as quickly as possible. The task was self-paced and lasted a minimum of 20 s although if the subject was working on a problem when the time expired, they were allowed to complete that problem.

PEERS Experiment 1

Subjects performed a free recall experiment consisting of 1 practice session and 6 subsequent experimental sessions. Each session consisted of 16 lists in which 16 words were presented one at a time on a computer screen. Each study list was followed by an immediate free recall test. At the end of each session, there was a recognition test and, for a subset of sessions, a final free recall test.

Words were either presented concurrently with a task cue, indicating the judgment that the subject should make for that word, or with no encoding task. The two encoding tasks were a size judgment (“Will this item fit into a shoebox?”) and an animacy judgment (“Does this word refer to something living or not living?”), and the current task was indicated by the color and typeface of the presented item. There were three conditions: no-task lists (subjects did not have to perform judgments with the presented items), single-task lists (all items were presented with the same task), and task-shift lists (items were presented with either task). List and task order were counterbalanced across sessions and subjects.

Each word was drawn from a pool of 1638 words. Lists were constructed such that varying degrees of semantic relatedness occurred at both adjacent and distant serial positions. Semantic relatedness was determined using the Word Association Space (WAS) model described by Steyvers et al. (2004). WAS similarity values were used to group words into four similarity bins (high similarity: $\cos\theta$ between words > 0.7; medium–high similarity, $0.4 < \cos\theta < 0.7$; medium-low similarity, $0.14 < \cos\theta < 0.4$; low similarity, $\cos\theta < 0.14$). Two pairs of items from each of the four groups were arranged such that one pair occurred at adjacent serial positions and the other pair was separated by at least two other items.

For each list, there was a 1500 ms delay before the first word appeared on the screen. Each item was on the screen for 3000 ms, followed by a jittered (i.e., variable) inter-stimulus interval of 800–1200 ms (uniform distribution). If the word was associated with a task, subjects indicated their response via a keypress. After the last item in the list, there was a jittered delay of 1200–1400 ms, after which a tone sounded, a row of asterisks appeared, and the subject was given 75 seconds to attempt to recall aloud any of the just-presented items. If a session was randomly selected for final free recall, following the immediate free recall test from the last list, subjects were shown an instruction screen for final free recall, telling them to recall all the items from the preceding lists. After a 5 second delay, a tone sounded and a row of asterisks appeared. subjects had 5 min to recall any item from the preceding lists. After either final free recall or the last list's immediate recall test, there was a recognition test, which is not considered here (for full details, see Healey & Kahana, 2016; Lohnas & Kahana, 2013).

PEERS Experiment 2

Experiment 2 was identical to Experiment 1 except as described below. Each of the 6 non-practice sessions consisted of 12 study lists of 16 words. Distractor tasks consisted of answering math problems of the form $A + B + C =?$, where A, B, and C were positive, single-digit integers, though the answer could have been one or two digits. When a math problem was presented on the screen, the subject typed the sum as quickly as possible. The task was self-paced, such that a subject may have been presented with, but not responded to, a problem at the end of the distraction interval. Subjects were given a monetary bonus based on the speed and accuracy of their responses. In the first two trials, subjects performed free recall with one trial having a distractor period following the last word presentation for 8 s. For the other of the first two trials, subjects performed an 8 s distractor period prior to and following each word presentation. In the remaining 10 trials, subjects performed free recall with 5 possible time durations for the between-item and end-of-list distractor tasks. As listed here, the first number indicated the between-list distractor duration and the second number indicated the end-of-list distractor, both in seconds: 0-0, 0-8, 0-16, 8-8, 16-16. A 0 s distractor refers to the typical, non-filled duration intervals as described for Experiment 1. Within each session, half of the lists were randomly chosen to be task-switch lists, and the other half were single-task lists.

The first session in this experiment was designed to introduce subjects to the math task. This session was identical to the experimental sessions except as described below. This session contained 14 lists, the first 4 of which were 2 lists of 8-8 and 2 lists of 0-8, with the order randomly chosen. These lists were all single-task lists, two each of each judgment type randomly chosen. The remaining 10 lists had distractor tasks as in the experimental sessions. All of these lists were single-task lists, with half randomly chosen to be of one task. This session always contained a final free recall period.

PEERS Experiment 3

Experiment 3 used the externalized recall (ER) procedure (Kahana, Dolan, Sauder, & Wingfield, 2005; Unsworth & Brewer, 2010; Unsworth, Brewer, & Spillers, 2009; Zaromb et al., 2006) to obtain more complete information on subjects' tendency to commit intrusions during recall and on their ability to distinguish between intrusions and correct responses. In Experiment 3, 96 subjects were given externalized recall instructions and the remaining subjects were given standard free recall instructions.

In the ER procedure, after subjects had become familiar with the standard free recall instructions, we asked them to say out loud all words that came to mind at the time of test, even if they thought those words did not occur in the most recent list, which they are explicitly attempting to recall. To separately examine the internal censoring process during recall, we asked subjects to indicate when they have recalled an item they believe was not on the most recent list by pressing the spacebar immediately following recall of that item.

The ER procedure was introduced in a preliminary session which began identically to Experiment 1. After the third list, instructions appeared on the computer screen indicating that subjects should additionally say aloud every time a specific, salient word came to mind while performing free recall. Subjects were also instructed to press the spacebar immediately following recall of an intrusion or repetition. An experimenter sat in with the subject during this session to ensure that the subject understood these instructions. Following this preliminary session, subjects performed five experimental sessions with methods identical to Experiment 1 except that subjects were given ER instructions at the beginning of each free recall session. Three out of the six (one practice and five experimental) sessions were randomly chosen to have final free recall, and each of the final free recall periods also began with the ER instruction.

PEERS Experiment 4

Subjects performed a delayed free recall experiment consisting of 24 experimental sessions. Each session consisted of 24 lists of 24 words that were presented one at a time on a computer screen. Each study list was followed by a 24 s distractor-filled delay before a free recall test.

Each session requires $24 \times 24 = 576$ words. For each subject, a unique word pool of 576 word was drawn from the larger 1638-word pool used in Experiment 1. This same 576-word pool was used to generate the lists for each session 1–23. That is, subjects saw the same set of words across sessions 1–23, but randomly assigned to different lists in each session. The 24^{th} session introduced some new words, which were drawn from the remaining words in the larger 1638-word pool. Specifically, the 24^{th} session included 8 lists composed of 8 old/16 new words, 8 lists composed of 12 old/12 new words, and 8 lists composed of 16 old/8 new words. Within all sessions, words were randomly assigned to lists with the following constraints: Lists were constructed such that varying degrees of semantic relatedness occurred at both adjacent and distant serial positions. WAS similarity values were used to group words into four similarity bins using the same procedure described for Experiment 1. Two pairs of items from each of the four groups were arranged such that one pair occurred at adjacent serial positions and the other pair was separated by at least two other items.

For all lists, there was a 1500 ms delay before the first stimuli appeared on the screen. For a random half of the lists in each session (excluding list 1), subjects completed a pre-list distractor task for 24 s before presentation of the first word, with a 800–1200 ms (uniform distribution) jittered delay between the last distractor problem and the presentation of the first list word. Each word was on the screen for 1600 ms, followed by a jittered (i.e., variable) inter-stimulus interval of 800–1200 ms (uniform distribution). Following the presentation of the last word in each list, subjects performed a distractor task for 24 s. Both the pre-list and post-list distractor task consisted of answering math problems of the form $A + B + C = ?$, where A, B, and C were positive, single-digit integers, though the answer could have been one or two digits. When a math problem was presented on the screen, the subject typed the sum as quickly as possible. The task was self-paced, such that a subject may have been presented with, but not responded to, a problem at the end of the distraction interval. Subjects were given a monetary bonus based on the speed and accuracy of their responses. After the post-list distractor task, there was a jittered delay of 1200–1400 ms, after which a tone sounded, a row of asterisks appeared, and the subject was given 75 s to attempt to recall aloud any of the just-presented items.

Intelligence Testing

The Wechsler Adult Intelligence Scale (WAIS) IV (Wechsler, 2008) was administered to 135 of the younger adults who completed Experiment 1. WAIS testing was conducted by a trained clinical psychologist in one–on–one sessions after completing all free recall sessions. We omitted the working memory index of the WAIS as we were concerned that subjects' extensive practice with free recall would artificially inflate their scores.

Appendix B

Original References for Findings

Table B1 lists each major finding discussed in the paper, the page/figure where it is presented, and the source of the data.

Table B1

References for benchmark contiguity effects.

Effect	Originally reported in	Figure or Page in current paper	Shown/Replicated in current paper with data from
Contiguity in immediate free recall	Kahana (1996)	Figure 1A	PEERS
Forward asymmetry	Kahana (1996)	Figure 1A	PEERS
Ubiquity across individuals	Healey & Kahana (2014)	Page 11	PEERS
Changes across the lifespan	Kahana et al. (2002)	Figure 2B	PEERS
Positive correlation with recall	Sederberg et al. (2010)	Figure 3A	PEERS
Positive correlation with IQ	Healey et al. (2014)	Figure 3B	PEERS
Present from first list to 24^{th} session	Current paper	Figure 2D&E	PEERS
Immune to variation in goodness of encoding	Current paper	Figure 4	Murdock (1962); PEERS
Higher for early and late output positions	Kahana (1996)	Figure 2F	PEERS
Consistent across serial positions	Current paper	Figure 2G	PEERS
List Length	Current paper	Figure 2H	Murdock (1962)
Presentation modality	Current paper	Figure 2I	Murdock & Walker (1969)
Recall modality	Current paper	Figure 2J	Murdock & Walker (1969); Murdock (1962)
Encoding task	Long & Kahana (2016)	Figure 2K	PEERS
Approximate time-scale invariance	Howard & Kahana (1999)	Figure 2L	PEERS
Robust to very fast presentation rates	Howard (2017)	Page 20 & Figure 2M	Murdock & Walker (1969)
Robust to very slow presentation rates	Nguyen & McDaniel (2015)	Page 20 & Figure 2M	Murdock & Walker (1969)
Present in same-category lists	McCluey et al. (2016)	Figure 2N	Reproduced from McCluey et al. (2016)
Absent in orthographically distinct lists	McDaniel et al. (2011)	Page 21	-
Present when semantic associates compete	Current paper	Figure 2O	PEERS
Present when list includes emotional items	Siddiqui & Unsworth (2011)	Page 22	-
Robust to variation in stimuli complexity	Nguyen & McDaniel (2015)	Page 23	-
Present when items vary in assigned value	Stefanidi & Brewer (2015)	Page 24	-
Contiguity in FR intrusions	Zaromb et al. (2006)	Page 25	-
Across-list contiguity in final free recall	Howard et al. (2008); Unsworth (2008)	Figure 5	PEERS
Contiguity in SR errors	Klein et al. (2005)	Page 28	-
Compound cuing in recognition	Schwartz et al. (2005)	Page 29	-
Contiguity in PA intrusions	Davis et al. (2008)	Page 31	-
Contiguity in autobiographical memory	Moreton & Ward (2010)	Page 32	-
Absent when subjects do not intend to encode	Nairne et al. (2017)	Page 37	-

PEERS = Penn Electrophysiology of Encoding and Retrieval Study (Healey et al., 2014; Healey & Kahana, 2014, 2016; Lohnas & Kahana, 2013, 2014; Miller et al., 2012).