Free recall and memory search

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When trying to remember a specific event or autobiographical memory, it can often feel like we are searching through our vast store of memories to find the relevant memory. Arguably no experimental task evokes this process more than the free recall paradigm. In this paradigm, a participant is presented with a list of items, and then must recall as many items as possible in any order. As such, the participant is constrained to recalling information from a specific list, not unlike searching through one's memory of a specific time and place. This chapter introduces the experimental set-up and then overviews some of the major theoretical approaches to understanding memory search. Details of dynamics in free recall responses are then discussed in light of these theories. How participants initiate recall, transition between items, and terminate recall provide insight into memory search, organization, representation and association. Insights from other memory paradigms are then described, and the chapter ends with a discussion of the ecological validity for characterizing memory search in experimental settings.

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1 Introduction

"What did you do last weekend?"

To answer this question, you must retrieve memories associated with a specific range of time. Such memories, formed by integrating information into an episode or event, and associating the episode with the time and place it occurred, are termed *episodic* memories (Tulving, 1972). Yet the above question distinguishes itself from other assessments of episodic memory in two important ways. First, this question requires retrieval of the relevant information without any additional cues or reminders from the questioner. Second, the question does not impose a specific order on the information being retrieved, so long as the information occurred during the specified time window (last weekend). For instance, you could recount an event from Sunday morning before discussing what you did on Friday evening. The free recall paradigm is meant to encapsulate just this set of restrictions on memory, but under conditions in which researchers have more control over what is experienced and what is tested. As described in more detail below, this paradigm is typified by presenting a participant with a list of items one at a time, and then asking the participant to recall as many items as possible from that list, in any order. Note that, in the context of these experimental paradigms and thus this chapter, an instruction to *recall* means to state one's internal retrievals overtly or explicitly. Thus, in this chapter, it is assumed that the process of recall refers to reporting an item retrieved from memory, and a *recalled* item, or recall, refers to the reported item. By contrast, an item which is *retrieved* is generated internally by a participant, but may or may not be reported.

The open-ended nature of free recall provides a rich set of observations from each participant. Beyond a binary distinction between recalled and non-recalled items, researchers may also characterize the order and timing of a participant's recalls. In the weekend example, recalling lunch with friends may evoke recall of another meal-related activity, or may evoke recall of another activity with friends. Such transitions between recalls can inform our understanding of the relationships between what is recalled. At the same time, this open-ended task can provide additional challenges when compared to other episodic memory tasks. That is, in free recall, the participant must search through memory with a minimal cue: to recall items from the most recent (or cued) list. By contrast, other episodic memory tasks may present a participant with a previously presented item or features of that item, which helps to promote retrieval of correct memories. (In the example above, this might be more akin to asking ”Did you go to the lab this weekend?” or showing a picture of your lab and asking if you went there.) As a result, free recall performance tends to be lower when compared to other episodic memory tasks in healthy participants (e.g. Tulving, 1985). In addition, when compared to healthy participants, those participants exhibiting episodic memory impairments, from neurological disorders including schizophrenia, dementia, or even healthy aging, exhibit more striking reductions in free recall than in other episodic memory tasks (Aleman, Hijman, de Haan, & Kahn, 1999; Trenkle, Shankle, & Azen, 2007). That is, if participants have difficulty retrieving episodic memories, this task is even more challenging in free recall, where the cues are more minimal. Having established the defining properties of free recall and how it is meant to approximate everyday life, we next turn to examining these properties in a more controlled laboratory setting.

2 Assessing memory in a laboratory experiment

How might a researcher assess someone’s episodic memories? If a participant describes their experiences but a researcher does not know what actually occurred, it would be difficult to assess memory accuracy for such experiences. Thus, in a research setting, it is less common to query a participant about their memories for episodes prior to the start of the research experiment. Rather, usually a participant is presented with information in the laboratory, and is later tested on that information. In this way, the researcher knows and controls the information that will be tested. Because a participant is presented with, and tested on, information from a specific time and place (i.e. the experiment), this is assumed to draw on episodic memory processes, even if the experimental stimuli are more well-controlled or artificial than everyday experiences. (The ecological validity of this type of task is revisited in Free Recall In the “Real World”.)

Free recall tasks almost always present stimuli as a sequence of words to make it easier for participants to articulate what was presented (though free recall can also be conducted on more complicated stimuli such as a sequence of complex images or even a movie). Each word, and each list of words, can be considered its own episode, associated to a spatiotemporal context within the experiment. Each word or item is considered a fundamental unit of memory representation. Nonetheless, a word's representation is usually assumed to be comprised of meaningful features about that word, such as the font or color of the presented word, as well as semantic or emotional information. However, most of the results can be generalized from words to other types of stimuli, and thus the term *item* is used to refer to a presented stimulus. Regardless of how an item is represented, results in this chapter are interpreted under the assumption that individual items are encoded and retrieved from memory.

To present lists of items, early studies used the technology available at the time, such as using a metronome to ensure that items were presented at a constant rate. In the past few decades presentations take place using a computer, presenting each item one at a time (Figure 5.5.1). A participant usually performs multiple rounds of list presentation (encoding) and recall (retrieval) during a given experimental session. It is often of interest which items the participant will remember, and thus free recall tasks are designed so that recall is not perfect. Some of the classic properties of recall dynamics break down when the lists are very short (e.g. Ward, Tan, & Grenfell-Essam, 2010), and thus will not be considered in this chapter.

Before presentation of the first list, typically a participant is informed in advance that the presented information will be tested on a later memory test (termed *intentional* free recall). However, this need not be the case, as sometimes there is concern that if the participant knows there will be a memory test, this will influence how the words are studied. In *incidental* free recall, participants may be led to believe that they are studying information for a reason other than a pending memory test. Although manipulations during encoding in free recall can influence memory, this chapter is in *Retrieval Processes* because the influence of such manipulations manifest during retrieval.

3 Overview of theories of free recall

In this chapter, results will be discussed according to broad classes of theories and the main principles that divide those theories. One large divide in theories of free recall focuses on whether memory is comprised of two memory "stores"—a short-term store and a long-term store—or whether there is just a single store, operating on both shorter and longer time scales. The debate between dual-store and single-store models extends beyond free recall to episodic memory in general, though this debate is fueled by free recall effects (e.g. Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005). Theories can also be divided based on their assumptions of memory representations. Most models of free recall assume that representations of, and associations between, the presented items themselves can explain memory search phenomena. How these representations are formed and stored can vary widely, but broadly speaking we can consider them in two categories. Most models of free recall assume that individual items are stored in memory. The item-item association strengths between any two items may be stored explicitly in memory as well (e.g. Metcalfe & Murdock, 1981; Raaijmakers & Shiffrin, 1980) or implicitly through the similarity between item representations (e.g. Brown, Preece, & Hulme, 2000). Although subsequent sections will explain how this works in practice, it is important to note here that the order in which items are presented informs their strengths. That is, it is assumed that the last item on the list preserves a representation consistent with being the final list item. By contrast, another theory of item representations assumes that participants are actively but silently rehearsing list items during presentation. Under this assumption, the order and number of rehearsals lay the foundation of memory organization (e.g. Brodie & Murdock, 1977; Laming, 2009; Rundus, 1971; Tan & Ward, 2000). If a participant rehearses items after the final list item is presented, it is as if these items are presented, albeit internally, to the participant.

In contrast to models assuming that item representations serve as the foundation of memory organization, another model category assumes that context is critical for organizational and search processes (e.g. Bower, 1972; Howard & Kahana, 2002a; Murdock, 1997). In this way, each memory consists of the representation of the item representation *and* the context of the item, where context is defined as the set of features surrounding, or not comprised of, an item. For instance, context may include external features such as the experimental environment or timing of the episode, and internal features such as the participant's endogenous thoughts. If a model assumes context is critical to episodic memory, this context information is not necessarily stored at the expense of item information. Indeed, models relying on item-item associations may nonetheless include a context that changes with each list (e.g. Gillund & Shiffrin, 1984). However, some models assume that context changes with each studied item in a list, due to changing internal thoughts and changing time (e.g. Howard & Kahana, 2002a; Lehman & Malmberg, 2013; Murdock, 1997). By contrast, other models assume that a long list of items are subdivided into groups or chunks, and each group creates its own context (Farrell, 2012). For instance, in a list of 16 items, a chunking model would group items together into smaller subsets of items such as 1-3, 4-7, 8-10, 11-14, 15-16. Each of these classes of models are best understood through the lens of the free recall phenomena they are meant to explain, described in the following sections.

4 Memory search during free recall

4.1 Recall initiation

Suppose a participant has been presented with a list of items, and now is prompted to recall as many items from the list as possible, in any order. A researcher may instruct the participant to say aloud, type or write their recalls. With these open-ended instructions, the burden is on the participant to search through memory to initiate recall. A common pattern emerges if we consider the probability of first recall as a function of the position the items were presented in the list, or serial position (Figure 5.5.2). One can also consider probability of first recall as the proportion of lists initiated at each serial position. If participants perform recall immediately after presentation of the list (Figure 5.5.1A), they tend to initiate recall with a recently presented item, i.e. a later serial position (Howard & Kahana, 1999; Ward et al., 2010).

All established models and theories of free recall can account for this well-established finding.

Dual-store models assume that recently presented items are stored in a short-term memory store, and that items in the short-term store are recalled first (Davelaar et al., 2005; Raaijmakers & Shiffrin, 1980). For a single-store model, the explanation of this effect depends on its assumptions of item representations. Some single-store models assume that information from the end of the list (whether context or an item) is used to cue recall. In immediate free recall, this cue will be similar to, and thus promote recall of, recently presented items (e.g. Howard & Kahana, 2002a). By contrast, for single-store models that represent the relative similarity of each item, recently presented items benefit from not having any items presented after them. In this way, recency items share temporal similarity with fewer items, and thus are considered more distinctive. A model assuming such a similarity structure, termed a distinctiveness model, assumes that more distinctive items are more likely to be recalled (Brown, Neath, & Chater, 2007; Nairne, Neath, Serra, & Byun, 1997). As another explanation, rehearsal-based accounts assume that recently presented items have been rehearsed recently, and thus are more accessible to be recalled first (Laming, 2006; Rundus, 1971; Tan & Ward, 2000).

In contrast to immediate free recall, participants are less likely to initiate recall with a recency item when there is a delay between the list presentation and the recall test (Figure 5.5.1B). For this type of task, termed delayed free recall, the delay may last several seconds to several minutes. It may even require participants to perform the free recall test on a later day. To explain the reduced recall of recency items in delayed free recall, dual-store models assume that the final list items are displaced from the short-term store by the information intervening between the final list item and the recall period (Davelaar et al., 2005; Grossberg & Pearson, 2008; Lehman & Malmberg, 2013; Raaijmakers & Shiffrin, 1981; Shiffrin & Steyvers, 1997). As a result, these recency items are no longer available to be recalled first. In single-store models assuming separate representations for each item, the end-of-list distractor is assumed to displace the end-of-list cue, and thus the end-of-list cue is less similar to items from the end of the list (Sederberg, Howard, & Kahana, 2008, see also Bjork & Whitten, 1974). According to single-store distinctiveness models, with the passage of time such as a delay, recency items are no longer as temporally distinct, and thus become less discriminable or more confusable with other list items (Brown et al., 2007; Nairne et al., 1997; Neath, 1993).

Most models of memory capture not just the reduced tendency to initiate recall with a recency item, but also the tendency to initiate recall with an early list or primacy item, in delayed free recall. The rehearsal-based account provides an intuitive explanation for this finding: Primacy items benefit from more rehearsals. For instance, in a list of ten items, a participant can rehearse internally the first presented item as they study each subsequent item. By contrast, the participant has little opportunity to rehearse the final list item before the recall test. Thus, with a filled delay—which prevents recency items from being rehearsed recently—primacy items are more likely to be recalled.

For dual-store models, primacy items benefit from more time in the short-term memory store, which may be due to more rehearsal time (e.g. Raaijmakers & Shiffrin, 1980). At the start of a delayed free recall period, no items remain in the short-term store and thus the primacy items are more likely to be recalled first. (The contribution of more elaborative encoding processes and attention to promote memory arguably emerges at other serial positions as well, as discussed further in List-Level Effects.) Other accounts of the primacy effect provided by dual-store models have also been used by single-store models, because both sets of models assume that primacy items are stored in long-term memory. By one approach, some models assume primacy items are strengthened in memory because items at the start of the list receive more attention (Sederberg et al., 2008) or are treated with a level of novelty which decreases as list presentation continues (Farrell, 2012). These two approaches are not mutually exclusive, as items may receive more attention because the start of a new list serves as a novelty signal. Finally, as another approach unique to single-store models, the primacy items benefit from greater recall for the same reason as recency items: they have fewer neighboring items (as no items are presented beforehand), and thus may not suffer from as much competition. Although this assumption leads to increased recall probability of primacy items, the model predictions of the magnitude of this increase are often much lower than in the typical free recall experiment (e.g. Brown et al., 2007; Howard & Kahana, 2002a).

Thus far, we have reviewed two ubiquitous findings in free recall initiation, and any good theoretical account can explain these findings. However, predictions of recall initiation between single-store and dual-store accounts dissociate in continual-distractor free recall, where there is a distracting task in between each presented item (Figure 5.5.1C). If there is a distractor after the last item, then most dual-store models predict that this distractor replaces any end-of-list items in the short-term store. Thus, recall initiation should be like delayed free recall, with reduced recall of recency items. By contrast, single-store models make a qualitatively different prediction: Recall initiation should be greater for recency items, more akin to immediate free recall. This prediction emerges because every item is followed by a distractor, and thus all items have the same *relative* temporal distinctiveness to one another as in immediate free recall. If there is the same amount of time in between each presented item—whether filled by a distractor or not—single-store modes predict that recall should begin with a recency item. The results are in line with single-store models, as probability of first recall is typically greater for more recently presented items (Bjork & Whitten, 1974; Howard & Kahana, 1999; Laming, 1999; Watkins, Neath, & Sechler, 1989). Further, consistent with the notion that it is more about the relative temporal distinctiveness of items, there is evidence to suggest that the advantage for recency items depends on the ratio of the interitem presentation time and final delay time, rather than the absolute time of the final delay (Nairne et al., 1997; Neath, 1993; Kahana, 2012).

Taken together, consistent patterns emerge in recall initiation across participants, even though a participant is free to recall the list items in any order. Recall initiation is influenced by the item's serial position combined with the presence of distractors. These results are explained more simply by a single-store model of memory. Yet as we continue to review more findings in free recall, we will also continue to discuss the strengths of different classes of models.

4.2 Recall organization

Having established the common findings for the first recalled item, one could next ask: What about the second recall? In immediate free recall, dual-store models generally assume that recall continues with other items in the short-term store (e.g., Davelaar et al., 2005; Raaijmakers & Shiffrin, 1980), and chunking models assume that recall begins with recalling items in the final chunk (e.g., Farrell, 2012). After several recalls, however, all theories assume that items are retrieved from long-term memory. We next characterize transitions from one item to another, assuming that both items are recalled from long-term episodic memory. Such a characterization provides a window into endogenous memory search, whereby a participant incorporates the prior recalled item to navigate through their memories to recall another item.

Most analyses of recall transitions characterize the relationship between the just-recalled item and the next-recalled item based on similarity. These analyses are motivated by two assumptions: (1) a just-recalled item will help to cue recall of the next item; (2) this cue promotes recall of other items sharing similar features to the just-recalled item. As one classic example of such an analysis, Kahana (1996) examined how *temporal* similarity influences transitions, by examining the difference in serial position or *lag* between pairs of successive recalls. For instance, consider the sample list and recalls in Figure 5.5.3A. Recall of the items from serial position 1 then serial position 3 would correspond to a $lag = +2$ as the transition moved forward 2 items in the list. Note that the y-axis for this function is not recall probability, but rather conditional recall probability (CRP), as the availability of recall must be taken into account. For example, from item 1, $lag = -1$ is not possible, because this would refer to an item in (nonexistent) serial position 0. In addition, transitions to previously recalled items are considered repetition errors and thus not possible. For this reason, $lag = 0$ is undefined, as a transition at this lag occurs only if a participant recalls the same item twice in a row. Altogether, this analysis examines the temporal properties of recall transitions while taking into account which transitions are possible.

Despite the freedom to recall the items in any order, participants exhibit two striking regularities in their temporal order of recall transitions in lists of unrelated words. First, participants exhibit a forward *asymmetry effect*, as at a given absolute lag value (e.g. 1), transitions are more likely in the forward direction than the backward direction (e.g. +1 vs. -1), especially at smaller values of absolute lag. Second, participants exhibit a *temporal contiguity effect*, or tendency to recall items with smaller absolute values of lag (Figure 5.5.3B). This temporal contiguity effect also manifests when examining inter-response times (IRTs), the amount of time it takes a participant to transition between two successively recalled items. Figure 5.5.3C shows a typical plot of IRTs (commonly termed latencies for this analysis) between two successive recalls as a function of lag. IRTs are generally faster between items with smaller absolute lags, further underscoring that recall of one item tends to facilitate retrieval of its temporal neighbors. The temporal contiguity effect is a ubiquitous finding in free recall, present across a variety of experimental variables and manipulations, even when there is a distractor between each presented item (for a review see Healey, Long, & Kahana, 2019).[1]

As with the recency effect, most models can account for the temporal contiguity effect. Models assuming direct associations between items provide an intuitive account of the temporal contiguity effect, because recall of an item cues recall of other items with strong associations, including strong temporal associations. However, these models must also assume that these associations are stronger in the forward direction than the backward direction to produce the forward asymmetry in the lag-CRP (e.g. Kahana, 1996). The forward asymmetry effect falls out more naturally from a retrieved context model — a single-store model which assumes that a context representation changes slowly with each studied or recalled item (e.g. Howard & Kahana, 2002a). In such a model, recall of an item coincides with retrieving its temporal context. This leads to a context retrieval cue that promotes recall of items with similar temporal context including the item's just-recalled neighbors. The forward asymmetry arises because temporal context is a recency-weighted sum of presented items, and so the context of an item studied in serial position i is contained in the context of the next item $i+1$, thus promoting its recall.

Temporal contiguity can also be explained by assuming that participants are actively but silently

[1]However, transitions may be more likely at the largest values of absolute lag, when participants transition between the first and final list items (Farrell & Lewandowsky, 2008).

rehearsing items during list presentation. Here the argument is that, because participants tend to rehearse items that were just presented, what seems like recall of successively *presented* items may in fact reflect recall of successively *rehearsed* items. In support of this idea, when participants say aloud the words that they are rehearsing, they tend to recall items in an order that reflects the order in which they were rehearsed (Brodie & Murdock, 1977; Rundus, 1971; Tan & Ward, 2000; Ward, 2002). Nonetheless, the temporal contiguity effect is present even under experimental conditions meant to minimize rehearsal (e.g. Howard & Kahana, 1999; Lohnas & Kahana, 2014), and thus is challenging to explain entirely based on rehearsal patterns.

Models assuming a chunking or grouping structure also predict the temporal contiguity effect. These models assume that recall of an item from one temporal group (e.g. item 16) will promote recall of other items presented within the same group (e.g. item 15). Thus, when a participant successively recalls neighboring items, this may simply reflect recalling the items in the same group (Farrell, 2012; Lehman & Malmberg, 2013; Romani, Katkov, & Tsodyks, 2016). In a typical free recall experiment, it is assumed that group size may vary by list and participant (though some participants may formulate a particular organizational structure with practice; see Romani et al., 2016), so it can be difficult to assess whether participants are indeed grouping items. Nonetheless, models that assume list items are structured into a hierarchical temporal context representation — where item position is subsumed into a group position, which is subsumed into list number — are indeed able to capture the temporal contiguity effect in free recall (e.g., Farrell, 2012; Lehman & Malmberg, 2013).

Because most models can account for the temporal contiguity effect, more nuanced temporal analyses are needed to distinguish between classes of models. Although most models assume that the just-recalled item dominates the recall cue, models differ in their assumptions of the contribution of earlier recalls to the cue. To discern the role of earlier recalls, Lohnas and Kahana (2014) examined how the prior two recalls contributed to the current recall. Lohnas and Kahana (2014) posited that, if only the just-recalled item contributes to the cue, then earlier recalls should not influence the current recall. That is, recall of the item in output position p should only rely on the item in the prior output position $p-1$, but not with earlier items such as $p-2$. As an example, suppose *oar* in Figure 5.5.3A serves as item $p-1$. We might expect the next recall, p, to be a neighbor of *oar*. However, might it matter that, before *oar*, the word *ant* was recalled, as opposed to *sea* or *cup*? To put this another way, might $p-2$ and $p-1$ form a *compound cue* for the item in output position p, or does just $p-1$ form the recall cue?

Lohnas and Kahana (2014) found that participants exhibited an enhanced contiguity effect when $p-1$ and $p-2$ came from consecutive serial positions. Providing further support for the claim that recall $p-2$ can have a direct impact on the current recall p, Lohnas and Kahana (2014) simulated their findings with a model that assumed only the just-recalled item, $p-1$, influences the current recall (Raaijmakers & Shiffrin, 1980; Sirotin, Kimball, & Kahana, 2005). Although this model produces a temporal contiguity effect it does not predict a benefit for compound cuing, as shown in Lohnas and Kahana (2014). Models in which prior items combine to form a compound cue for the next recall naturally account for the observed dependence of recall on multiple past items (Kimball, Smith, & Kahana, 2007; Polyn, Norman, & Kahana, 2009). Taken together, these results suggest that prior items combine to form a compound cue for the next recall, even though the most recently recalled item contributes more strongly to the cue.

Aside from temporal contiguity, other forms of contiguity may be present based on the similarity structure of the presented list. Like the temporal order of the words, other properties may be manipulated experimentally to influence similarity and thus transitions. For instance, in lists of words where modality of presentation for each word could be auditory or visual, participants tend to recall items in "clusters" of the same presentation modality (Hintzman, Block, & Inskeep, 1972; Murdock, 1969). As another example, Polyn et al. (2009) examined how an encoding task influenced recall organization. Participants performed a semantic decision for each presented word (e.g. *Does this word refer to something living or nonliving?*). Although participants performed only one task with each presented word, in some lists they performed two different tasks, switching back and forth with the type of decision for every few words. Polyn et al. (2009) found that participants were more likely to transition between items studied with the same encoding task than different encoding tasks. Further, Polyn et al. (2009) found that IRTs were faster between words presented with the same encoding task. Although items were more likely to be recalled successively from the same task irrespective of their temporal position on the list, transitions were most likely between items in the same "train" of items from the same task, i.e. those items with shared temporal and shared task information. In this way, different forms of similarity can contribute to contiguity effects.

Rather than impose additional manipulations on the word during encoding, another classic approach is to examine the similarity structure inherent in the words themselves. For instance, when participants are presented with lists containing emotionally positive, negative or neutral words, participants are more likely to transition between items of the same emotional valence (Long, Danoff, & Kahana, 2015; Talmi, Lohnas, & Daw, 2019). Contiguity effects have also been characterized by presenting participants with words from semantic categories, such as fruit or tools. With such an experimental set-up, if a list is comprised of words drawn randomly from several different semantic categories, participants tend to recall items in "clusters" of the same category (Bousfield, Cohen, & Whitmarsh, 1958; Kahana & Wingfield, 2000; Polyn, Erlikhman, & Kahana, 2011; Romney, Brewer, & Batchelder, 1993) and exhibit faster IRTs when transitioning between items of the same category (Pollio, Richards, & Lucas, 1969; Patterson, Meltzer, & Mandler, 1971). In parallel to the temporal contiguity effect, these results could be explained by assuming that when an item is retrieved from a specific semantic category, this category information contributes to the cue used to retrieve other items from memory. As a result, this promotes recall of items from the same semantic category (Polyn et al., 2011). According to a rehearsal account of this effect, presentation of an item from a specific semantic category promotes rehearsal of items from the same category, and the shared rehearsal time between items of the same category promotes their successive recall (Rundus, 1971).

Beyond broader semantic categories of words, participants also organize their recalls based on the semantic relationships between words, even in lists of words where semantic relatedness is meant to be minimized. That is, whereas the aforementioned categorical relationships are considered all-or-none, it is also possible to quantify pairwise similarities of words on a continuous scale. For instance, consider the words *lemon*, *apple*, *twig* and *tunnel*. With broad categories, *lemon* and *apple* are both fruits and so are in the same semantic category, but *lemon* is not in the same category as *twig* or *tunnel*. By contrast, one could also quantify the semantic associations, such that *lemon* is most related to *apple*, less related to *twig*, least related to *tunnel*. Although semantic categories are assumed to be more universal across human participants, there is inevitably individual variability in semantic representations. Yet several metrics have been used to quantify these semantic relationships, and provide reasonable interpretation for free recall analyses. These metrics may rely on the co-occurrence of words in texts (e.g. Cilibrasi & Vitanyi, 2005; Landauer & Dumais, 1997; Milne & Witten, 2008), or may be formed by asking participants about word associations (Nelson, McEvoy, & Schreiber, 2004; Steyvers, Shiffrin, & Nelson, 2004).

In one of the earliest examinations of a continuous measure of semantic similarity in free recall, Howard and Kahana (2002b) found that the conditional probability of transitioning to an item increases with its semantic similarity to the just-recalled item. This finding, termed the semantic contiguity effect, has been replicated several times (Healey, Crutchley, & Kahana, 2014; Howard, Venkatadass, Norman, & Kahana, 2007; Long & Kahana, 2017; Talmi et al., 2019; Zaromb et al., 2006). Indeed, even in lists of categorized items, there is evidence for recalling items successively based on their shared semantic similarity (Romney et al., 1993).

Given that temporal and semantic information can both influence recall, there may be competition in memory among strong temporal associates and strong semantic associates. For instance, consider the list and recall sequence shown in Figure 5.5.3A, after the participant has just recalled *oar*. Based on the temporal contiguity effect, we might predict that a neighbor of *oar*, such as *fork* or *sea*, with lags $+1$ and -1, respectively, might be recalled next. However, based on semantic contiguity, we might expect a highly semantically similar item, such as *boat*, to be the next recall, despite have a larger temporal lag of +7. Of course, it is not possible to predict which item will be recalled next for every possible transition and participant. Yet researchers are interested in understanding how the competition among items influences memory search, and ultimately which item is recalled.

As one example of the tradeoffs in semantic and temporal organization, if lists contain pairs of strongly associated semantic items presented far apart, participants tend to recall the semantically related items, leading to reduced temporal contiguity (Healey et al., 2019). This is assumed to reflect the competition between associations during retrieval. For instance, in a list with words of fruits and tools, recall of *apple* may cue recall of *orange* or *lemon* more strongly due to their shared semantic information, even if *hammer* were presented just after *apple*. Although for the purposes of this chapter, the intuition is that different forms of organization may compete to influence recall, processes at encoding undeniably impact recall organization. If, during list presentation, participants are oriented to the semantic features of presented words, this leads to decreased temporal contiguity during recall (Long & Kahana, 2017; Healey & Uitvlugt, 2019). Presumably, this orientation promotes attention to, and thus encoding of, semantic information. As a result, semantic information plays a stronger role in guiding memory search during recall.

Do temporal contiguity and semantic contiguity essentially reflect the same effect, with different dependent variables? Howard and Kahana (2002b) posited that, if temporal contiguity and semantic contiguity have similar properties, then a distractor should decrease temporal contiguity *and* semantic contiguity. However, Howard and Kahana (2002b) found that semantic contiguity decreased with longer distractor periods between items in continual-distractor free recall, yet temporal contiguity remained intact. These results were interpreted as evidence that the semantic information contributing to the recall cue is separable from temporal information contributing to the cue. Building on this work, Morton and Polyn (2016) could best account for recall organization with a computational memory model provided that semantic information and temporal information were represented distinctly, and with different properties. In particular, the model assumed that the temporal cue was context-based, relying on a richer representation of temporal information. By contrast, the semantic cue relied on item representations without the context history of prior recalls. These results, consistent with the compound cuing effect of temporal information reported by Lohnas and Kahana (2014), underscore the distinct representations of temporal information vs.

semantic information in memory. In particular, whereas semantic information most likely influences a memory cue related to the just-recalled item only, the temporal information contributing to the cue most likely contains a temporal history of recalled information. Thus, both temporal contiguity and semantic contiguity would rely on relevant memory associations, yet the temporal information used to cue recall incorporates a richer history of past recalls. The semantic and temporal contributions to the cue may encourage recall of different items.

In summary, both temporal contiguity and semantic contiguity reflect the influence of the recalled item to promote recall of other items with shared features or attributes. Different dimensions of similarity may lead to competition among to-be-recalled items, and may influence the recall cue differently. Yet some properties increase the probability that an item will be recalled, irrespective of its shared features with other items. Like contiguity effects, these properties inform which types of information influence recall, and thus inform theoretical explanations of memory search.

4.3 Item-level effects

Thus far, we have reviewed recall initiation, and how recall of one item serves to cue recall of another item. These recalls tend to be intuited based on the shared features and associations between items, and reveal how such features and associations influence memory search. However, items can have features that influence memory search and lead to improved recall, potentially bypassing the need to be associated strongly to the just-recalled item. For instance, a word repeated in a list is more likely to be recalled than a word presented once, and this probability increases with the number of items intervening between the repeated presentations (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Ebbinghaus, 1885/1913; Donovan & Radosevich, 1999; Madigan, 1969; Melton, 1970). The underlying cause of this latter effect, termed the spacing effect, continues to fuel debate in psychology and neuroscience.

Items are also better remembered if they are presented at a slower presentation rate (e.g., Bhatarah, Ward, & Tan, 2009; Glanzer & Cunitz, 1966; Murdock, 1962). By one explanation, more study time may enable more time to rehearse the presented item, and to rehearse other items in the list. To examine this explanation, researchers instruct participants to say aloud any of their own rehearsals of study items during list presentation. Consistent with this rehearsal-based account of slower presentation rate, if participants rehearse aloud, an item is more likely to be recalled if it was rehearsed more times (Brodie & Murdock, 1977; Rundus, 1971), or if it was rehearsed more recently (Tan & Ward, 2000). This intuition may also be applied to dual-store models, which assume that items benefit by having more time to be rehearsed in the short-term store and increase their associative strengths to other items in the store (Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1980).

Regardless of the explanation for improved recall with increased study time, this increase is magnified for earlier list items (Brodie & Murdock, 1977; Grenfell-Essam, Ward, & Tan, 2013). Further, irrespective of study time, recall is greater for early list items than mid-list items. This effect, termed the primacy effect, is present in almost all free recall experiments (Murdock, 1962; Spurgeon, Ward, & Matthews, 2014). The primacy effect is exhibited in the serial position curve, which displays probability of recall at each serial position (Murdock, 1962), with elevated recall probability at early list positions (Figure 5.5.4).

In brief, the theoretical explanations for the advantage of recall initiation of primacy items in delayed free recall can also be applied to explain the primacy effect of overall recall in all distractor conditions (see Recall Initiation). Due to temporal contiguity, the recall of one primacy item promotes recall of its neighbors, which are also more likely to be primacy items. To distinguish between accounts of primacy, the rehearsal-based account provides the relatively unique prediction that conditions minimizing rehearsal (such as continual-distractor free recall) should reduce overall recall for all items. Further, primacy items should be impacted the most, as these items also benefit the most from rehearsal. These predictions are borne out in experimental data (Glenberg et al., 1980; Marshall & Werder, 1972), and can be seen in Figure 5.5.4 by comparing recall between the immediate and continual-distractor conditions. Dual-store models can explain the reduced recall for primacy items by assuming they spend less time in the short-term store, thus weakening their representations (e.g. Davelaar et al., 2005; Raaijmakers & Shiffrin, 1981).

In parallel to recall initiation, items from the end of the list, or recency items, are more likely to be recalled in immediate and continual-distractor free recall (Bjork & Whitten, 1974; Deese & Kaufman, 1957; Howard & Kahana, 1999; Murdock, 1972). This effect, termed the recency effect, is also apparent in Figure 5.5.4. According to single-store models, once recall begins with a recency item (see Recall Initiation), recall of other recency items are more likely due to temporal contiguity. Dual-store models account for the recency effect in immediate free recall by assuming that all items from the short-term store are recalled first. However, dual-store models that fail to predict properties of recall initiation in continual-distractor free recall also have difficulty capturing the recency effect in this paradigm, yet can account for these findings if the long-term store operates with the same explanation just provided for the single-store model (e.g. Davelaar et al., 2005).

Usually a free recall experiment uses words as stimuli, and word properties can influence recall probability. For example, recall is generally greater for words referring to something living than nonliving (e.g., Popp & Serra, 2015; Nairne, VanArsdall, Pandeirada, Cogdill, & LeBreton, 2013). Free recall is also greater for words presented with auditory presentation than with visual presentation (Murdock, 1969; Murdock & Walker, 1969). Some word properties are highly correlated and thus difficult to disentangle. For instance, words are more likely to be recalled if they are more imageable (Paivio, Yuille, & Rogers, 1969), yet imageable words are also often more concrete (Paivio, Yuille, & Madigan, 1968). To answer the question of whether this phenomenon really reflects imageability or concreteness, however, may be left to those researching perception or linguistics rather than memory. Indeed, to account for the influence of word properties on memory, some theories incorporate processes that occur prior to memory encoding, such as perception or attention. Nonetheless, such properties can be important to control when creating stimuli for a recall experiment.

Other word properties are more readily explained in the context of existing memory theories. For instance, recall of a word is also influenced by the number of different "contexts" in which a word occurs, termed context variability (Reder et al., 2000; Steyvers & Malmberg, 2003). To illustrate, presumably there are a limited number of situations in which *employee* arises, and so this word has low context variability, whereas *youth* has high context variability. Free recall is generally greater for words with low than high context variability (Hicks, Marsh, & Cook, 2005). It is hypothesized that, for high context variability words, it is more difficult to rely on a unique association with the "context" of the current list, as these words are already associated to many contexts. As a result, it would be more difficult for a participant to determine whether a high context variability word was presented on a studied list.

It is important to note that the item properties listed in this section influence recall irrespective of the other types of items in that list. That is, an item may be presented in a *mixed list*, comprised of items of more than one type, such as some words presented with an auditory presentation and others with a visual presentation. By contrast, an item may be presented in a *pure list* consisting of only one item type, such as visual items only. Intriguingly, some item properties influence recall differently when the item is contained in a pure list or mixed list, as discussed in the next section.

4.4 List-level effects

Thus far, I have reviewed how memory search is influenced by associations between items, and by item properties irrespective of associations. However, some item properties lead to improved recall only when presented with, and associated with, other types of items. These properties thus help to explain how items and their associations can influence memory search processes.

An examination of list-level properties typically involves two types of items and three types of lists (Figure 5.5.5A). Items are classified based on their posited strength in memory, typically termed "strong" and "weak". For instance, strong items may be presented with spaced repetitions, whereas weak items may be repeated in mass. Lists are comprised of a combination of strong and weak items (mixed lists) or solely one type of item (pure strong or pure weak). In free recall, there is generally a positive *list-strength* effect: Recall is greater for strong items in mixed lists than pure lists, yet recall is greater for weak items in pure lists than mixed lists (Figure 5.5.5B; Malmberg & Shiffrin, 2005; Shiffrin, Ratcliff, & Clark, 1990; Tulving & Hastie, 1972). This result can be explained by intuiting that the recall cue evokes retrieval of encoded items, and these items compete to be recalled. Whereas in a pure list a weak item competes only with other weak items, in a mixed list the strong items serve as stronger competition against weak items. Thus weak items are less likely to be recalled when in mixed lists than in pure lists. In a similar way, a strong item has fewer strong competitors for recall in a mixed list than in a pure strong list, and thus is more likely to be recalled in a mixed list than a pure list.

Nonetheless, this explanation does not help to explain *why* stronger items benefit from greater recall. Indeed, for some types of item manipulations, even when there is an advantage for posited "strong" items in mixed lists (e.g., longer vs. shorter study time, emotionally negative items vs. neutral items), recall probability of pure strong lists may be equivalent to recall probability of pure weak lists (Malmberg & Shiffrin, 2005; Talmi & McGarry, 2012). This effect, sometimes termed the list-composition effect, has a similar intuition to the list-strength effect, with strong items in mixed lists benefiting from weaker competitors during retrieval, or more elaborate encoding processing during study (McDaniel & Bugg, 2008). Such an explanation can also help to explain why features of an item that a priori may not be considered "strong" can nonetheless influence recall depending on the composition of the list. For instance, consider a list of words where some are presented in blue or green. In this case, neither green nor blue would be strong; recall probability for a list of all blue words should be equivalent to a list of all green words. However, if a list is comprised of words presented all in green except for one item presented in blue, then the blue item is more likely to be recalled. A memory advantage for an item that stands out in a list—irrespective of whether that item would benefit from such an advantage in pure or mixed lists—is termed the isolation effect or distinctiveness effect (Schmidt, 1991; von Restorff, 1933; Wallace, 1965). The results of the list composition effect would look similar to those of the list-strength effect shown in Figure 5.5.5B, except recall in the pure lists is not significantly different between strong and weak items. Also similar to the list-strength effect, the list composition effect is more pronounced in free recall than in other types of memory tests (McLaughlin, 1968; McDaniel & Einstein, 1986). As noted when discussing the primacy effect, one explanation is that the distinct item benefits from greater attentional or novelty processing, but the cognitive and neural mechanisms underlying the mnemonic benefit to the distinct item are still debated. Regardless, the stronger influence of list-level changes in free recall—whether manifest as the distinctiveness effect or list-strength effect—suggest that competitive memory search processes play a role in these effects.

The list-length effect is another prevalent list-level effect in free recall, so termed because as list-length increases, participants tend to recall a smaller proportion of items yet a larger number of items (e.g. Murdock, 1962; Ratcliff, Clark, & Shiffrin, 1990; Roberts, 1972; Ward et al., 2010). The list-length effect is present in nearly every memory paradigm (e.g. Strong, 1912). However, the magnitude of the effect varies, and thus is explained differently, depending on the paradigm. In free recall, one account again relies on the competitive nature of retrieval: As more items compete in memory for recall, the less likely it is that any one item will be recalled. By another account, with increasing list-length more items are presented between an item's presentation and the recall period, and thus an item is less likely to be recalled simply due to the passage of time. This latter account also provides an intuition for findings that recall probability of recency items does not seem to decrease with list-length (Kahana, 2012). The immunity of recency items to list-length has been interpreted to fit with the intuition of a separate, protected short-term store for these items. Yet single-store models can predict this effect as well, because the end-of-list cue used to initiate recall does not vary with list-length; the similarity of the final items to the end of the list is the same irrespective of the number of preceding items (e.g. Brown et al., 2000; Polyn et al., 2009).

Word frequency—how frequent a word occurs in everyday use—has served as an intriguing variable for memory performance in general and for free recall in particular. With pure lists of high-frequency words, participants generally exhibit greater recall than pure lists of low-frequency words (Hall, 1954; Sumby, 1963). High-frequency words are thought to be more easily associated to other list items, thus promoting their recall (Balota & Neely, 1980). However, using mixed lists of high-frequency words and low-frequency words, some experiments yield greater recall of high frequency words (Balota & Neely, 1980; Hicks et al., 2005), some yield greater recall of low frequency words (DeLosh & McDaniel, 1996; Merritt, DeLosh, & McDaniel, 2006; Ozubko & Joordens, 2007), and some do not find significant differences (May, Cuddy, & Norton, 1979; Ozubko & Joordens, 2007; Ward, Woodward, Stevens, & Stinson, 2003; Watkins, LeCompte,

& Kim, 2000). Further adding to this puzzle, the results in item recognition are generally more consistent with greater memory accuracy for low-frequency than high-frequency words, in both pure lists and mixed lists (Criss & Malmberg, 2008; Estes & Maddox, 2002; Glanzer & Adams, 1985; Gorman, 1961; Heathcote, Ditton, & Mitchell, 2006; Malmberg, Steyvers, Stephens, & Shiffrin, 2002; Shepard, 1967). Improved memory for low-frequency words in item recognition (and free recall, if found) is usually assumed to reflect greater attentional processing (Malmberg & Nelson, 2003; Rao & Proctor, 1984). Yet it is not clear why recall properties of word frequency are inconsistent in free recall.

To help reconcile these findings, Lohnas and Kahana (2013) evaluated free recall of words in mixed lists across a range of ten word frequency bins, rather than simply low and high frequency words. They found that free recall was a U-shaped function, with greater free recall for very low or very high word frequency. Lohnas and Kahana (2013) suggested that some of the inconsistencies of prior free recall studies may reflect the choice of word frequency values. That is, the choice of frequency values used for "low" and "high" frequency could influence the results. Although it is not possible to query all past studies, it may be that the values used as "high" frequency in some studies may be numerically and qualitatively much lower than others, thus leading researchers to draw different conclusions. Regardless, the properties of word frequency on free recall are akin to other variables discussed in this section, whereby the influence depends not only on the word itself but also on the overall composition of the list in which the word is contained.

4.5 Errors

4.5.1 Intrusions

If one is "searching" through the contents of memory for a particular set of items, such a search may yield *an* item, but not necessarily a *correct* item. In free recall, a correct item refers to an item presented on the most recent list, and so a participant may mistakenly recall an incorrect item outside of the current list. To account for this possibility, theories and models of memory search often assume that once an item is retrieved from memory, it undergoes additional editing or monitoring to ensure it is a correct item. That is, memory retrieval is a two-stage process: (1) in response to a cue, a participant *generates* an item from memory; (2) a participant applies a *recognition* test to ensure that the generated item is correct for the current task (Bahrick, 1970; Postman, 1976; Lohnas, Polyn, & Kahana, 2015).

As an analogy for this theory, termed generate-recognize theory, suppose the task is not retrieving items from memory, but rather consider my task as a graduate student to retrieve my keys from my jacket pocket once I arrived home. Before finding the keys, I might encounter my phone. Of course, I do not give up searching, nor do I try to get into my home using my phone. Rather, I set my phone aside and continue to search my pockets. I would eventually find a key and try to use that key to get inside. However, I needed two keys: one for the outer door to my apartment building, and one for the door within the building to my apartment. These two keys were similar, and so sometimes I would mistakenly try to use the inner apartment key to unlock the outer apartment building door. Eventually, however, I would find the correct key. These three types of retrieval from my pocket correspond to the three types of retrieval that may occur according to generate-recognize theory, where retrieving something from my pocket parallels generating or retrieving an item from memory, before overtly reporting it on a memory test; recognition refers to the assessment of whether the retrieved or generated item should be used in the current situation (whether to unlock a door, in the analogy, or to report the item in the case of a memory test). Walking through these three examples in relation to memory then: (1) Retrieving my phone instead of my key is analogous to being able to generate an item, yet recognizing the item is not correct. In such a case, a participant thinks of the item silently but does not report it. (2) Mistakenly retrieving the wrong key, and then trying to use that key, parallels generating an item which fails to be recognized as an incorrect item. In this case, a participant commits an intrusion, reporting an item that was not presented on the current list. (3) Using the correct key is meant to reflect a correct item; when it is retrieved a recognition process is performed to confirm that it is from the correct list, after which it is reported.

Considering this second case, intrusions in free recall are broadly classified into two categories.

One type of intrusion, termed extra-list intrusion (ELI), refers to a recalled item that is not presented in any experimental list. The second type of intrusion is a result of the typical free recall, in which participants typically study a list of unique items then perform free recall. Next, they study another list of items, distinct from the first list, and then perform free recall of those items, and so forth. In this way, each is comprised of a distinct set of items from each other list, is treated as its own isolated memory test; performance is averaged across lists under the assumption that each list of items does not interfere with the others. However, if a participant mistakenly recalls an item from a previously presented list, this is termed a prior-list intrusion (PLI). Healthy younger adults rarely make PLIs or ELIs. Indeed, many descriptive and computational models of free recall assume that memory "resets" between lists, such that recalled items are only from the current list. Such models can be remarkably accurate even though this simplifying assumption is not realistic (any participant certainly has more words in their memory than a single list of words from a free recall experiment, typically only 10-40 words!). Nonetheless, a comprehensive model of free recall should take these intrusions into account. Indeed, it is impressive that the average participant can focus their recalls on current-list items while suppressing the interference from past memories, termed proactive interference.

Despite their relatively low occurrence, analyses of intrusions provide useful insights into memory search processes. In particular, participants are more likely to recall PLIs from a more recently presented list than a more distant list (Murdock, 1961, 1974; Unsworth & Engle, 2007; Zaromb et al., 2006). This finding parallels within-list recency effects, in that more recently presented information is more likely to be recalled. Yet why might participants misattribute items from past lists to the current list? One explanation comes from the externalized free recall paradigm (Kahana, Dolan, Sauder, & Wingfield, 2005; Lohnas et al., 2015; Unsworth & Brewer, 2010; Unsworth, Brewer, & Spillers, 2010, 2013b; Zaromb et al., 2006). In this paradigm, participants recall aloud any word that comes to mind while performing free recall, and press a key immediately after the recall of an item they believe was not on the most recent list (indicating a "rejection"). According to generate-recognize theory then, a rejection corresponds to an item that was generated but not recognized. Although participants recall overtly more PLIs in externalized free recall than standard free recall, PLIs from more recent lists are less likely to be rejections (Lohnas et al., 2015; Unsworth et al., 2010). In other words, rejection probability decreases with list recency of PLIs (and rejection probability is near 0 for correct items).

When a participant recalls a PLI from a more recent list, this also arguably reflects the temporal contiguity effect on a longer timescale. To put this another way, if one considers the absolute *list* lag between a current-list item and a PLI, the list lag is generally smaller. In the rare case that a participant recalls two PLIs in a row, these PLIs are more likely to be from nearby lists (Lohnas et al., 2015). Further, if the two PLIs are from the same list, the within-list lag of PLI pairs tend to have a smaller absolute value, consistent with the temporal contiguity effect seen for correct items (Lohnas et al., 2015). Thus, PLIs exhibit temporal contiguity both within lists and across lists, suggestive of stronger temporal associations between these items. These contiguity effects are predicted by a retrieved context model assuming temporal representations on several timescales, including within a list and across lists (Howard, Shankar, Aue, & Criss, 2015). These contiguity effects are also predicted by a retrieved context model with a single temporal context changing slowly with each item (Lohnas et al., 2015). As a result, items presented closer in time have more similar temporal context states, whether considered on the timescale of within a list or across lists. Altogether, PLIs inform memory effects across timescales longer than a single list.

In addition to their shared temporal information with the current list, PLIs may also reflect shared semantic associations to current-list items. For instance, Zaromb et al. (2006) found that, if a participant recalls successively a correct item then a PLI, on average the PLI was more semantically similar to the just-recalled correct item than any other correct item. Further, when several lists of items are all drawn from the same semantic category, such that items from preceding lists are highly semantically similar to items on the current list, this also increases the number of PLIs (Loess, 1967; Wickens, 1970). Altogether, PLIs may be mistaken as correct items due to the same reasons that participants recall correct items: their shared similarity with other correct items.

4.5.2 Repetitions

Aside from intrusions, a participant may err by recalling the same word twice during the recall period, but such repetitions are relatively rare (e.g. Kahana et al., 2005). These types of errors raise the question of how one can keep track of which items one already recalled, to avoid recalling those items again. Although the cognitive processes involved to prevent repetition errors are usually assumed to involve metamemory processes beyond the scope of episodic memory and memory search, this type of recall is important to consider for how recall ends, as described in more detail in the following section.

4.6 Recall termination

If a participant is tasked with recalling as many words as possible, why might they decide to stop searching through memory for another recall? Like recall initiation and recall transitions, this process is informed by analyzing the types and timing of recalls. How these analyses are conducted partially depends on how the recall period ends. Whereas in some free recall experiments, the participant decides when to end the recall period, other experiments have a recall period of a fixed length. In this case, the recall period should ideally be set to be longer than the participant needs. However, a participant may stop recalling items before the recall period actually ends. What makes a participant decide that even with more time, they will be unable to recall more items?

In one of the earliest examinations of recall termination, Murdock and Okada (1970) found that the IRT prior to the final recall was much longer than for earlier recalls. Although this finding is upheld regardless of whether participants are given a fixed amount of time to recall or can control when to end recall, the IRT is generally shorter when participants have control (Hussey, Dougherty, Harbison, & Davelaar, 2014). Further, if a participant chooses when to end recall, then the time between the final response and the choice to end recall becomes faster with more items recalled (Dougherty, Harbison, & Davelaar, 2014; Harbison, Dougherty, Davelaar, & Fayyad, 2009). At the same time, IRTs tend to increase with the number of recalled items (Murdock & Okada, 1970; Wixted & Rohrer, 1994; Unsworth, 2007). These findings provide support for the intuition that, as more items are recalled, it becomes more challenging to use the current memory cue to retrieve items that have not yet been recalled.

Further support for the above intuition arises from classifying the type of the final recalled item. Recall termination is more likely following an error than a correct recall, and in particular termination is more likely following a repetition than an intrusion (Laming, 2009; J. F. Miller, Weidemann, & Kahana, 2012; Unsworth et al., 2010). These recall errors most likely cue retrieval of other errors. As a result, the participant may infer that they cannot retrieve any more correct items. As noted in Unsworth et al. (2010), increased recall termination following a sequence of errors is also consistent with findings from Harbison et al. (2009) that recall termination is faster after more recalls. In this way, recall termination is influenced by the total number of retrievals or retrieval errors a participant makes. Indeed, some models of memory assume that recall stops after a fixed number of failed retrieval attempts (e.g. Raaijmakers & Shiffrin, 1980). Nonetheless, the cognitive processes involved in recall termination remain to be characterized fully.

4.7 Consistency and variability in free recall

Thus far, we have discussed some of the most ubiquitous effects in free recall. Although most participants exhibit recency, primacy, temporal contiguity and semantic contiguity (Healey et al., 2014), there is individual variability in the extent to which each participant exhibits these effects. The interdependence of these effects provides insight into how and why they vary. As noted above, the tradeoff between semantic contiguity and temporal contiguity is suggestive of the competitive nature of retrieval. Further, participants exhibiting greater overall recall tend to exhibit greater temporal contiguity (Sederberg, Miller, Howard, & Kahana, 2010), as well as faster recall latencies and fewer intrusions (Unsworth, 2007, 2009a, 2009b). Participants with greater free recall also tend to have greater working memory capacity and fluid intelligence (Unsworth, 2009a, 2009b).

With these results, does a higher-performing participant have a greater "memory ability", generalizing across working memory and free recall tasks? A line of work by Unsworth and colleagues suggests a more complex story. Unsworth and Spillers (2010) found that individuals with greater working memory capacity exhibited larger improvements in free recall under intentional than incidental recall instructions, suggesting that working memory capacity relates to effective strategies during encoding (Bailey, Dunlosky, & Kane, 2008). In addition, individuals with lower working memory capacity exhibit reduced temporal contiguity (Spillers & Unsworth, 2011), slower recall latencies, recall more intrusions (Unsworth, 2009b), and are more susceptible to proactive interference (A. L. Miller & Unsworth, 2018). Combined, these results suggest that individuals with lower working memory capacity have more difficulty searching through memory to recall correct items. This may reflect difficulty with generating the proper recall cues, retrieving the proper items, and the generate-recognize process (Unsworth & Brewer, 2010).

Beyond cognitive abilities, research has also focused on variability in free recall with age. Older adults generally perform worse on tasks of episodic memory (Light, 1991), but this is more striking in free recall than other episodic memory tasks (e.g. Schonfield & Robertson, 1966). When participants are presented with two lists and then instructed to recall items from either list, older adults are more likely to initiate and recall from more distant positions than younger adults, including items from the previous list (Wahlheim & Huff, 2015). This suggests that older adults may recall fewer current list items in standard free recall because they have more difficulty focusing memory search to current-list items. Further, in standard free recall, older adults tend to exhibit decreased temporal contiguity, produce fewer correct recalls and more intrusions (Kahana, Howard, Zaromb, & Wingfield, 2002). Using an externalized free recall procedure (see Section 4.5.1), Kahana et al. (2005) found that older adults generate more intrusions, and are more likely to misattribute intrusions to the current list. These results further underscore deficits in using retrieval cues effectively. Differences in memory by ability and across the lifespan are discussed at length in Individual Differences and Development.

5 Memory search beyond free recall

This chapter is entitled *Free recall and memory search*, but one doesn't need to perform free recall to search through the contents of memory. Other paradigms have provided useful insights that complement and support findings from free recall. We now turn to some of the most relevant and informative paradigms of episodic memory search aside from free recall.

Before turning to these paradigms, however, it is important to address whether the fundamental difference between free recall and these paradigms occurs at *encoding*, not during search and retrieval. For instance, if a participant is told about the type of memory test in advance, this might lead to different strategies during encoding, which may suffice to explain, or even confound, differences attributed to memory search. This possibility can be explored with studies in which participants are told to study a list of items for an upcoming memory test. They may be informed about the type of memory test in advance (pre-cued) or informed about the test after list presentation (post-cued). If knowing the test in advance changes participants' encoding strategies, then performance should differ with test cue type. However, many critical properties of memory paradigms remain relatively unchanged between pre-cued tests and post-cued tests (e.g. Bhatarah, Ward, & Tan, 2008; Bruder, 1970; Cox & Criss, 2017; Deese, 1957; Wahlheim & Huff, 2015). As a result, differences across memory paradigms cannot be driven solely by anticipating the type of test. I revisit this issue with cued recall, but first discuss paradigms more similar to free recall.

5.1 Probed recall and part-list set cuing

Analyses of free recall often query how recall of one item cues recall of another item. Of course, in these analyses, both items of interest are recalled by the participant. By contrast, in probed recall the researcher presents the participant with an item, and a participant is instructed to recall an item in response. In this way, the researcher controls, and can asked more focused questions about, recall cues and which items are expected to be recalled (termed targets). In probed recall, it is most common for items to be presented one at a time, as in free recall (see Figure 5.5.1A). During test, the researcher will present an item, and ask the participant to recall a specific target, such as the item presented after the cue. With such a set-up, termed forward probed recall, the serial position curve exhibits a primacy effect and recency effect analogous to free recall (Murdock, 1968). Further, providing a compound cue of the prior two items leads to greater recall than just providing the prior item (Posnansky, 1972; Kahana & Caplan, 2002), consistent with findings of greater free recall for item $i+2$ when items i and $i+1$ comprised the prior two recalls (See section 5.5.4.2; Lohnas & Kahana, 2014).

The part-list cuing paradigm further builds on the design of providing a set of cues, rather than one cue. In this paradigm, participants are presented with a list of items one at a time as in free recall (see Figure 5.5.1A). Next, they are re-presented with a subset of the list items as cues (if they studied the list of words in Figure 5.5.1A, then the presented cues might be *sea, boat, fork*). All of the cues are displayed at once, and while viewing such cues they perform free recall of the remaining items, i.e. excluding the cues (Roediger, 1973; Roediger, Stellon, & Tulving, 1977; Rundus, 1973; Slamecka, 1968). Slamecka (1968) introduced this paradigm to adjudicate between two possible outcomes of recall performance, when compared to standard free recall: (1) If associations between items are not independent, then providing some items should lighten the burden on participants to generate their own cues, and thus should increase recall; (2) If associations between items are independent, then providing additional items should leave recall unchanged.

Surprisingly, Slamecka (1968) found that recall was *worse* in part-list set cuing, and this result has been replicated several times (Roediger, 1973; Roediger et al., 1977; Rundus, 1973; Slamecka, 1968, see also Serra & Nairne, 2000). However, this result can be explained using the logic of the list-strength effect, if we view the part-list cue set as repeated items. It is as if the participant is presented with a mixed list of repeated (strong) items and weak (once-presented) items, and the participant needs to recall the weak items (Raaijmakers & Shiffrin, 1981; Roediger et al., 1977). Indeed, the part-list set cuing paradigm is arguably more challenging than free recall because participants must not only keep track of the current-list items, but must also keep track which items were cues, to avoid recalling any of the items from the part-list cue set (Hastie, 1975). By another explanation, reduced recall in part-list set cuing occurs for a similar reason that recall termination is more likely to follow a recall error, in particular a repeat (Rundus, 1973). By this reasoning, repeating some of the items as cues may elicit retrieval of other cue items, and hinder recall of the remaining items. Regardless of the mechanism, this unexpected finding challenged existing theories of associative memory when it was first introduced. This paradigm also highlights how subsequent retrieval is influenced differently if a participant retrieves an item from memory, or is re-presented with the item. Such differences are explored further in Chapter 11.1.

Free recall, probed recall, and part-list cuing provide insight into the competition between items and associations during memory search. Probed recall imposes more control over the items to be recalled, and thus more control over which associations are most useful for recall. For example, forward probed recall would lead to more correct recalls if a participant used forward temporal associations, rather than semantic associations, to guide memory search. Other memory paradigms impose further structure on which associations best serve memory search, allowing researchers to focus on a smaller set of associations. As described in the following section, this localist perspective on associations reveals additional properties of memory retrieval and memory search.

5.2 Cued recall

Whereas some theories of free recall assume associations are formed between items within a list, the cued recall paradigm takes a step back from this interconnected structure, and addresses the more simple task of associating one item to another. Some of the findings from cued recall lay the groundwork for assumptions of associations in free recall, whereas other results stand in opposition to intuitions of free recall effects. In cued recall, it is most common to present items two at a time in pairs during encoding, and thus cued recall centers on the single association formed between two items. During the recall phase, a participant is cued with one item from the pair, and must recall that item's associated pairmate, or target. Whereas in free recall any list item is a correct response, in cued recall of pairs there is typically just one correct response to a cue. Both paradigms restrict recall to information presented during a specific time range, whether that time spans an entire list (free recall) or coincides with a specific pair of items (cued recall).

Cued recall allows for a more flexible design of the timing of presentation and recall test. One possible design for cued recall has the study phase of all possible pairs, and then has the test phase requiring recall of a target given the cue (Figure 5.5.6A). This design most closely parallels free recall. However, sometimes in cued recall participants study and recall the same list of pairs multiple times. In this situation, it is possible to have a mixture of study and test items together. That is, a participant can be presented with two items at once, to be tested later (study) and the very next event could just be a cue item requiring a target response (test), or vice versa. In addition, sometimes researchers use what is termed the anticipation method, which essentially combines study and test for the same pair: A participant just views the cue, and recalls a target, but before moving onto the next pair the target is re-presented. Unless stated otherwise, below we assume that the study/test structure parallels free recall, allowing for easier comparison between the two paradigms.

5.2.1 Comparisons of cued recall and free recall

5.2.1.1 Memory encoding and memory representations Before comparing recall performance between cued recall and free recall, it is worth clarifying similarities between these paradigms with respect to encoding of memory representations. According to some accounts, presentation during cued recall is like free recall, where each item from a pair is studied separately, and items within a pair are studied closer together in time than items from different pairs (Howard, Jing, Rao, Provyn, & Datey, 2009). However, there is also evidence against the view that each item in the pair is represented separately. If items were represented separately, for instance, transitions between adjacent items in cued recall should parallel those of free recall. As described in Recall Organization, in free recall participants generally exhibit a forward asymmetry, such that recall of item i is more likely to be followed by recall item $i+1$ than $i-1$. From this intuition, one may expect cued recall to be greater when cuing in the forward direction, using a pair's first item as a cue, (e.g. cuing with *ant* in Figure 5.5.6A), when compared to cuing in the backward direction (e.g. cuing with *cup* in Figure 5.5.6A). However, cued recall performance is not significantly different when cuing in the forward or backward direction (Asch & Ebenholtz, 1962; Ekstrand, 1966; Kahana, 2002). One possible explanation for these results is that, like free recall, each pair of items shares separate forward and backward associations, yet unlike free recall, the associations are equal in the forward and backward directions. If this explanation were true, then memory for a given pair when tested in the forward direction should not be correlated with memory for the same pair when tested in the backward direction. However, Kahana (2002) found that cued recall for a given pair was highly correlated between the forward and backward directions. Taken together, these results work against the hypothesis that each item within a pair (in cued recall) is equivalent to an individually presented item (in free recall).

Indeed, the symmetry of associations for item pairs within cued recall has been argued to reflect the holistic nature of cued recall pairs (Asch & Ebenholtz, 1962; Kahana, 2002), such that each pair of items forms an inseparable, holistic representation. In this way, being cued with one item from the pair does not evoke retrieval of that specific item and its pairmate, but rather evokes retrieval of item pair representations that include the item cue. Yet if item pairs are represented together in this way, inseparably and without regard to the order in which they were presented, then participants should exhibit poor memory for the order of presentation within each item pair. Kato and Caplan (2017) assessed this possibility, and found that order memory was better than predicted by chance, thus suggesting that order information is retained in memory for each pair. At the same time, models assuming that item order is preserved overpredicted the correlation between this order memory and other measures of association memory. Thus, these results provide some room for each of the cued recall accounts described thus far, as either completely separable items or as a holistic pair.

Whereas in free recall each word is usually considered its own episode and memory representation, in cued recall it remains debated whether each word, or set of words, forms the fundamental unit of representation. This has implications for how the memory cue and memory target are represented, and thus also has implications for what is being ‘searched for’ in response to a cue.

Regardless, cued recall requires a more focused memory search than free recall, as specific target item(s) are associated with each memory cue. Parallels between cued recall and free recall are more straightforward to intuit under the assumption that each item is represented separately. Combined with the aforementioned evidence that it is reasonable to assume each word has a distinct representation, I will make this assumption below unless noted otherwise.

5.2.1.2 Recall and retrieval dynamics Intuitively, cued recall and free recall are relatively similar: In both paradigms, participants are presented with lists of items, then must recall items associated with that list — whether any item from the list (free recall), or a specific item based on a cue (cued recall). Thus it is perhaps unsurprising that an individual's ability to perform well on both tasks is related. In a comprehensive examination of episodic memory tasks including free recall and cued recall, Cox and Criss (2017) found a strong correlational relationship of individual accuracy in cued recall and in free recall. Further, Cox and Criss (2017) found that individual items benefiting from greater free recall were also more likely to be retrieved during cued recall. Beyond individual items, certain types of items benefit from greater cued recall as well. For instance, just as free recall is greater for low contextual variability words (Hicks et al., 2005), cued recall is greater when the cue is a low contextual variability word (Criss, Aue, & Smith, 2011). Like free recall, a low context variability item is assumed to benefit from being associated to fewer pre-experimental contexts. This benefit could manifest during encoding, with associations being more readily made, but could also occur at retrieval, with less competition between a low context variability cue and other potential target items. As another shared item-level effect between cued recall and free recall, cued recall performance is greater when targets are concrete rather than abstract words (Paivio, Walsh, & Bons, 1994).

Several list-level effects present in free recall are also present in cued recall, including the spacing effect (Glenberg, 1976), the recency effect (Murdock, 1967) and the list-length effect; the theoretical accounts of these effects are generally similar in both recall paradigms. In addition, a form of the temporal contiguity effect is present in cued recall. When a participant mistakenly recalls another list item as belonging to the pair, presumably this is due to the cue evoking a target with similar features to the correct target. In cued recall, an incorrectly recalled item is more likely to be from a nearby pair (Caplan, Glaholt, & McIntosh, 2006; Davis, Geller, Rizzuto, & Kahana, 2008). Further, similar to PLIs in free recall, if in cued recall an incorrectly recalled item was not presented on the most recent list, it is more likely to have been presented on a nearby list (Davis et al., 2008). This suggests that beyond the within-pair association, temporal associations may be formed across pairs. However, these temporal effects are weaker than in free recall; some models of cued recall account for the levels of intrusions without assuming that they come from temporal associations (e.g. Mensink & Raaijmakers, 1988). An intrusion may also be semantically similar to the correct item, suggesting that semantic associations influence memory search in cued recall.

Despite the similarities between cued recall and free recall, in cued recall there is generally no list-strength effect (Wilson & Criss, 2017), or if it is present, it is weak (Ratcliff et al., 1990). As described in List-Level Effects, in free recall the intuition was that recall is competitive, and so strong items should be more challenging to recall when competing only with strong items, than when competing with a combination of strong and weak items. By contrast, in cued recall the intuition is that the cue serves to narrow memory search from a set of list items to just one target item. Thus, unlike free recall in which many strong (and weak) items compete for recall, in cued recall the competition from other list items is weaker (Shiffrin et al., 1990).

5.2.2 Beyond free recall

Analyses of memory search often focus on the associative strengths between items, and how such strengths influence competition between items. Whereas in free recall a researcher relies on the participant's recalls to probe such associations, in cued recall a researcher can address more targeted questions about specific associations. In one of the simplest set-ups for querying competition between items, one item is paired with two other items (also see Chapters 6.1 and 6.2).

As an example in Figure 5.5.6A, an item A (*ant*) associated with two different items B and C (*ant-box* in List 1, *ant-cake* in List 2). A participant learns the first pair (A-B) to a criterion. Then, after being presented with A-C, a participant is probed with item A, and may recall either of A's associates. In this task, termed "modified free recall", at first participants continue to recall B rather than C, indicative of proactive interference. The proactive interference driven by the similarity between item pairs (i.e. the overlapping A of A-B, A-C) is not unlike the proactive interference exhibited in free recall when items are drawn from the same semantic category across lists (Loess, 1967; Wickens, 1970). However, if A-C is presented additional times, recall of C becomes more likely than B (Briggs, 1954). This is consistent with the intuition that as C is presented more times and more recently, the proactive interference from B is no longer as strong. Rather, C can be viewed as interfering with the retrieval of B. This type of interference, imposed from newer information (A-C) retroactively on earlier information (A-B), is termed retroactive interference.

Intriguingly, recall increased for B and decreased for C over increasing delays of 1-3 days (Briggs, 1954). Reduced recall of C is surprising because recently presented information is generally better remembered. Improved memory for more distant information at a delay, as is the case with B here, has been termed "spontaneous" recovery. This phenomenon, also present in animal learning, is so termed to convey that such recovery also seems relatively surprising and occurs without external influence. As a comprehensive account of spontaneous recovery, Estes (1955) introduced a computational model which formalized stimulus representations as vectors of features that fluctuate randomly and slowly over time. Thus, items presented nearby in time are more likely to share more of these overlapping features.[2] However, after a sufficient amount of time (and thus fluctuation), as well as with a minimal amount of forgetting, this model predicts the seemingly spontaneous recovery of earlier associations.

These results speak to which association is strongest to A: B or C. However, these results cannot distinguish whether A's association to the unrecalled item is simply weaker or is altogether forgotten. If C is recalled, for example, B might be retrieved covertly but not recalled overtly, or B might be forgotten. To distinguish between these possibilities, Barnes and Underwood (1959) instructed participants to recall both of the items when cued with A (termed "modified modified

[2]This model greatly informed, and shares much of the intuition of, temporal context representations in retrieved context models.

free recall"; bottom panel of Figure 5.5.6A). Barnes and Underwood (1959) found that, after initial A-B presentations, as the number of A-C presentations increased, then the number of recalls for B decreased. Because participants could recall both B and C but tended to recall C only with more A-C trials, they interpreted their results that learning of A-C may lead to "unlearning" of A-B.

Following this logic, for a given item A, the tradeoff between recall of A-B and A-C should occur at the level of individual A-B, A-C items, leading to a negative correlation between not just the average across all B's and C's, but rather recall of B matched to its corresponding C. However, attempts to find such correlations have been unsuccessful (DaPolito, 1967; Kahana, 2000). This has been interpreted as evidence against the notion that learning the A-C association leads to direct inhibition of the A-B association. Rather, it is thought that changes in associations may occur beyond those linking a specific A-B, A-C pair, such as at the level of the entire list of A-B items and A-C items. As one explanation of this finding, a model of cued recall presented by Mensink and Raaijmakers (1988), building on the model of Raaijmakers and Shiffrin (1980), assumes that the memory representation of each item pair includes context elements which fluctuate between lists (c.f. Estes, 1955). This model accounts for several critical findings in modified modified free recall, underscoring the importance of list-level changes and their influence on memory representations. Thus, despite the importance of forming associations between pairs in cued recall, list-level representations may still be influential as in free recall.

This section has explored how cued recall informs memory search beyond free recall. Most of these insights leverage the control over the recall cue and the target recall. In cued recall, there is typically one correct response to each presented item, yet presenting the recall cues makes this task much easier. The next section explores a task where there is also just one correct recall to each cue, yet the participant is responsible for providing the cues as well.

5.3 Memory search in serial recall

The temporal contiguity effect in free recall demonstrates that participants form temporal associations between items, and that these associations guide recall. The serial recall paradigm provides another approach to analyze temporal associations in episodic memory. In this paradigm, participants are instructed to recall as many items from the just-presented list, but must recall the items in the *serial* order in which they were presented. Thus, a schematic for immediate serial recall would look identical to Figure 5.5.1A, except that the screen with asterisks would serve as a cue to recall as many items as possible in their presented order. With only one correct sequence of recalls per list, the serial recall paradigm demands temporal organization beyond free recall. Because in serial recall there is only one “correct” ordering, analyses in this paradigm tend to focus on recall errors rather than correct recalls. This section focuses on findings most relevant to memory search, and the curious reader is encouraged to read Chapter 5.3.

Due to the similarities in task demands, serial recall and free recall share several effects. For instance, in serial recall overall accuracy is greater with shorter list length, longer presentation rate, shorter word length and for concrete or imageable words (Baddeley, Thomson, & Buchanan, 1975; Bhatarah et al., 2009; Paivio et al., 1969; Walker & Hulme, 1999). Further, in serial recall the lag-CRP has the same two pronounced features as in free recall: temporal contiguity and forward asymmetry (Bhatarah et al., 2008, 2009; Klein, Addis, & Kahana, 2005). Because serial recall requires recalling the items in their presented order, it is somewhat of a natural consequence that temporal contiguity is high. Further, an item mistakenly recalled out of order is more likely to be from a neighboring temporal position of the correct item (e.g., Henson, Norris, Page, & Baddeley, 1996; Lee & Estes, 1977; Surprenant, Kelley, Farley, & Neath, 2005), similar to the temporal contiguity effect in free recall. Also like free recall, temporal contiguity is reduced in lists comprised of items related along nontemporal dimensions, such as phonologically similar items (e.g. Watkins, Watkins, & Crowder, 1974) or lists comprised of semantically similar items (e.g. Murdock & vom Saal, 1967). However, whereas in free recall reduced temporal contiguity may not come at the cost of overall recall, in serial recall this hinders participants’ performance to recall the items in order.

Although theories of free recall can be used to explain effects in serial recall, no single account can explain all of the phenomena present in serial recall. Further, a popular theory and type of model of serial recall is typically *only* used for serial recall but not other recall tasks. This theory, termed positional coding theory, assumes that each presented item is associated to a positional code. For instance, consider the third item presented in a list, Item 3. Item 3 would be associated with the positional code Position 3. Recall of Item 3 would lead to retrieval of the next positional code, Position 4, which then leads to recall of the item associated with Position 4. Thus far, we have not needed such a positional assumption to explain recall results, and so such an assumption may seem unnecessary. However, several findings in serial recall work in favor of positional coding theory. As one striking example, if a PLI is recalled in place of a correct item in serial recall, the PLI is more likely to correspond to same serial position as the correct item (Conrad, 1960; Henson, 1998; Melton & Irwin, 1940; Melton & von Lackum, 1941; Osth & Dennis, 2015). This finding is straightforward to explain if one assumes that the positional code is shared among items in the same serial position across lists, yet it is difficult to explain assuming item-item and/or item-context associations drive recall. This finding also raises the question of under which circumstances positional or item information serves as the focus of memory search.

Serial recall and free recall also differ in the initiation of memory search. In free recall a participant may begin with any current-list item that comes to mind, and in an immediate test participants tend to initiate recall with a recently presented item (see Recall Initiation). By contrast, in serial recall a participant must begin with the first list item. In this case, an end-of-list cue might not be as helpful to begin recall. So, how might participants search through memory to retrieve the first list item? Although theoretical accounts of serial recall are discussed elsewhere (Chapter 5.3), the next section discusses a variant of the free recall paradigm in which participants must recall items from the list before the most recent list. Thus, this paradigm also requires searching through memories for temporally distant items, and provides intriguing insights to memory search processes.

5.4 List-before-last paradigm

Recall paradigms help to illuminate the competition and interference between items in memory. In free recall, where participants are tasked with recalling items from the *current list*, it is more challenging to study forgetting and the retroactive interference from current information on past information. The list-before-last paradigm reveals influences of retroactive interference, because participants are not asked to perform free recall of items from the most recent list. Instead, participants are asked to recall as many items as possible in any order, from the list presented *before* the last list (termed the target list; Figure 5.5.6B). Like free recall, this task requires recall of items associated with a restricted range of time. Like delayed free recall, information was presented after the list of to-be-remembered items. However, in this paradigm the distracting information includes other list items, which may be tested later. In this way, retroactive interference is imposed by the list of items presented intervening between a target list presentation and target list recall (termed the intervening list). List-before-last recall shares some similarities with free recall, such as a list-length effect (Shiffrin, 1970), yet recall is generally lower than in standard free recall (e.g. Unsworth, Spillers, & Brewer, 2012). In this task it may be more challenging to create effective retrieval cues, which may be driven by the retroactive interference from intervening-list items.

Most models and theories of free recall assume that the current state of memory is used to cue other memories, and the items with the strongest associations to the current memory are from the list of interest. However, this is not an ideal strategy for the list-before-last paradigm; such an approach would lead to recall of items from the intervening list, not the target list. Some models assume that participants associate a list of items to a list context, and that this list context is reinstated according to task instructions (Jang & Huber, 2008; Lehman & Malmberg, 2009). Based on qualitative patterns of recalls and response times, Unsworth and colleagues asserted that participants can reinstate the target-list context, but this reinstatement is noisy and thus allows for intervening-list intrusions (Unsworth et al., 2012; Unsworth, Brewer, & Spillers, 2013a). This view is consistent with a retrieved context model approach, which assumes that retrieved target items reinstate their associated target-list context, but context reinstatement is imperfect (Lohnas et al., 2015). Alternatively, according to a rehearsal-based account, a subset of target-list items are rehearsed during presentation of the intervening list, and the rehearsed items are readily accessed at the beginning of recall (Ward & Tan, 2004).

In addition, the list-before-last paradigm can help to adjudicate between theories of forgetting in free recall. As noted in List-Level Effects, the list-length effect can be explained by assuming that memory decays over time, and so with more list items a larger proportion of items will be forgotten, especially for items presented earlier in the list. Alternatively, the list-length effect can be explained by assuming that memory search is competitive, and so as more items "compete" to be recalled, a smaller proportion of items are recalled. Shiffrin (1970) introduced an elegant set of manipulations to distinguish between these theories. These manipulations are conveyed in Figure 5.5.6B. Consider Lists 1 and 2, where a target list then an intervening list is presented, then a target-list recall period. Although this is also true of Lists 2 and 3 (where now List 2 is the target list), between Lists 2 and 3, list-before-recall of List 1 is performed. Without recall in between lists (Lists 1 and 2), Shiffrin (1970) found that target-list recalls decreased with longer intervening list-length. This is not so surprising given that recall generally decreases with increasing delay. Strikingly, however, when participants performed recall between presentation of the target list and intervening list (Lists 2 and 3), target-list recall did *not* change with intervening list-length. This suggests that the amount of forgetting cannot be explained by the number of intervening items between presentation and recall. Shiffrin (1970) thus posited that forgetting reflects a failure in memory search and retrieval processes (but for a rehearsal-based account, see Ward & Tan, 2004).

Follow-up studies have examined why recall mitigates retroactive interference from the intervening list. Sahakyan and Hendricks (2012) presented participants with triplets of lists as in Figure 5.5.6B, but manipulated the retrieval difficulty of List 1 by presenting this list 1 hour, 24 hours, or 72 hours prior to the other lists. With increasing delay, recall from List 1 decreased, which Sahakyan and Hendricks (2012) interpreted as increasing difficulty to retrieve List 1 items. However, the delay manipulation of List 1 did not affect target-list recalls (List 2) or intervening-list recalls (List 3), suggesting that recall of List 1 hinders target-list retrieval irrespective of the difficulty of List 1 recall. Jang and Huber (2008) also manipulated the type of memory task in between the target list and intervening list. Intriguingly, they found that when participants performed a recognition memory test (in Figure 5.5.6B, performed on List 1), the influence of intervening-list length was the same as no test between lists, where target list recall decreased with increasing intervening-list length. Further, Jang and Huber (2008) could account for these results using a multinomial model that assumed the recognition test did not elicit retrieval of test items and their surrounding context to the same extent as free recall. These findings, combined with those of Sahakyan and Hendricks (2012), provide strong evidence that episodic context retrieval is critical to reducing the retroactive interference of the intervening list-length on target-list recall.

More broadly, the list-before-last paradigm demonstrates how episodic retrieval can lead to encoding or updating of memory representations, which in turn influence the associations and representations of intervening-list items. Thus far, we have treated encoding and retrieval as two distinct phases, but of course in everyday life this distinction is not always so clear. In the next section, I describe this issue further, as well as other issues related to the ecological validity of free recall.

6 Free recall in the "real world"

A free recall experiment in a laboratory setting is meant to be a well-controlled version of episodic memory, but concerns have been raised that the experimental set-up is not ecologically valid (e.g. Hintzman, 2011, 2016). As noted in the previous section, a simplifying assumption in most free recall studies regards the assumptions of encoding and retrieval: It is commonly assumed that memory "encoding" occurs during the presentation phase, and that "retrieval" from memory occurs during the recall phase. Of course, if the recall period had no memory encoding, then the participant shouldn't remember anything about the recall periods after the experiment was over! Further, during the encoding phase, experimenters rely on participants to retrieve information from memory regarding any experimental instructions. Nonetheless, the simplistic view of distinct encoding and retrieval phases arguably does not interfere with interpretation of free recall results (for an alternate view see Hintzman, 2011). Yet without assuming that the process of memory search influences encoding processes, some experimental manipulations are challenging to explain (for instance, see Chapters 6.2 and 11.1).

As another point raised in concern of ecological validity, participants usually know in advance that they will later be tested on their memory for specific items, and thus may adopt unusual or atypical strategies that they do not use in everyday life. These concerns can be minimized by using a faster presentation rate, as this latter is thought to help prevent elaborative encoding processes such as rehearsal. Faster presentation tends to reduce recall for nonrecency items (e.g. Brodie & Murdock, 1977; Glanzer & Cunitz, 1966; Tan & Ward, 2000; Wixted & McDowell, 1989). However, it may not be possible to fully dissociate how much of this reduced recall reflects reduced rehearsal and artificial experiment strategies, as opposed to less time to encode the items. As another approach, a participant might only be told after being presented with the list of words that their memory will be tested, termed an incidental memory test. In incidental free recall, the temporal contiguity effect is drastically reduced (Healey, 2018; Nairne, Cogdill, & Lehman, 2017). These results suggest that participants' encoding strategies during list presentation contribute to recall organization, as well as which items are recalled.

Further criticism focuses on the timing and stimuli in an experiment versus everyday life. With respect to timing, whereas list presentation and the recall test typically take place on the same day, episodic memories may be retrieved on longer time scales, even years later. In addition, recalling which items were presented during a particular experimental list is argued to a be qualitatively incomparable to recalling life events that were experienced during a particular place and time. This set of differences, spanning memory encoding, representations and retrieval, lead some to argue that effects from recall tasks cannot be generalized to everyday episodic memories.

Of course, only some researchers make these arguments; most if not all recall experiments are conducted under the assumption that the results would advance our understanding of episodic memory. As described in the Introduction, one can also make the case that recall tasks are ecologically valid. Beyond theoretical or philosophical arguments, however, several studies have attempted to link experimental list-learning experiments with more realistic memory tests.

Recent work has helped to mitigate some of concerns regarding the ecological validity of free recall. Moreton and Ward (2010) asked participants to perform free recall of autobiographical events, and then date the events. Consistent with the recency effect, participants were more likely to recall more recent events. Consistent with the temporal contiguity effect, participants were more likely to successively recall events that occurred nearby in time, whether considered on a timescale of weeks, months, or years. Rather than relying on participants' memories of the time associated with each event, Uitvlugt and Healey (2019) had participants recall news headlines, which could be associated with objective dates. Consistent with findings in free recall, Uitvlugt and Healey (2019) found a temporal contiguity effect between successively recalled headlines.

Several studies measuring neural activity of memory retrieval further support the ecological validity of free recall tasks. In these studies, each participant wears a camera while going about everyday life, and either the participant or the camera automatically takes pictures (Cabeza et al., 2004; Hodges, Berry, & Wood, 2011; Milton et al., 2011; Nielson, Smith, Sreekumar, Dennis, & Sederberg, 2015). The participant later performs a memory task on pictures from their camera while their brain activity is recorded. Many of the active brain regions during retrieval in these studies are also more active when performing memory retrieval in a free recall experiment (e.g. Burke et al., 2014; Long et al., 2019; Sederberg et al., 2007).

As a clever bridge between classic recall experiments and everyday episodic memories, Cortis Mack, Cinel, Davies, Harding, and Ward (2017) presented participants with one word every hour on their phones, and then tested participants an hour after the final word presentation. Critically, when performing free recall participants exhibited a temporal contiguity effect and a list-length effect. In addition, in a serial recall condition there was a noticeable primacy effect and error patterns consistent with prior studies. However, although this set-up is most similar to continual-distractor free recall, and thus a primacy effect and recency effect would be expected, both effects were small. Future work remains to explore the boundary conditions of applying experimental findings to everyday life.

7 Summary and conclusions

Given how much remains unknown about memory encoding and memory storage, it may seem premature to devote so much research to processes that rely on encoding and storage, including memory search and retrieval. Yet characterizing properties of retrieval also provides theoretical benchmarks and constraints for memory encoding and storage. For instance, several findings in this chapter highlight the role of temporal information in memory organization of free recall. If the memory test is immediate, participants are more likely to recall recently presented items, and even to initiate recall with a recent item (e.g. Deese & Kaufman, 1957; Murdock, 1962; Ward et al., 2010). The increased recall for recently presented information extends even to recall errors, as when a participant mistakenly recalls an item from an earlier list, such an item is more likely to be from a recent list (Lohnas et al., 2015; Murdock, 1961, 1974; Unsworth & Engle, 2007; Zaromb et al., 2006). Further, when participants are tasked with performing free recall of the list before the most recent list, they recall fewer items than in standard free recall (e.g. Unsworth et al., 2012), suggesting that it is easier to retrieve more recently presented information. Thus, the advantage attributed to recently presented information—exhibited during memory retrieval—provide strong support that temporal representations are encoded and utilized to guide memory search.

Analyses of recall transitions provide further insight into memory retrieval, as well as the stored representations used to guide memory search. A participant is more likely to transition between, or recall successively, items with shared features. For instance, recalls are more likely between two items with shared semantic information (Howard & Kahana, 2002b; Kahana & Wingfield, 2000; Polyn et al., 2009), or items with shared temporal information arising from being presented nearby in time (Kahana, 1996; Healey et al., 2019; Polyn et al., 2009). All leading theories and models of memory assume that the association between any two items is informed by their similarity. With respect to transitions, recall of one item may promote recall of other items with shared features or stronger associations.

Memory search in recall tasks is also influenced by properties of an item irrespective of its associations to other items. Free recall commonly uses words as items, and word properties can influence memorability. Further, recall is improved by more general properties such as the rate at which items are presented (Bhatarah et al., 2009; Glanzer & Cunitz, 1966; Murdock, 1962), or by repeating an item within a list. In addition, some properties reflect an item's position in the presentation list. As one example, recall is greater for items presented in the first few serial positions (Murdock, 1962; Spurgeon et al., 2014). This effect, termed the primacy effect, has several possible explanations. Early list items may benefit from rehearsing items more often or more recently (Brodie & Murdock, 1977; Rundus, 1971; Tan & Ward, 2000), or from greater attentional processing (Sederberg et al., 2008). Attention is also hypothesized to contribute to the isolation or distinctiveness effect, defined by improved memory for a single item with features distinct from all other items in the list (such as a different color; for reviews see Schmidt, 1991; Wallace, 1965). Yet this explanation fails to explain how or why attention influences memory. In addition to attention, this chapter has touched on other cognitive processes that arguably border on memory, such as deciding when to stop attempting to search through memory. A full characterization of episodic memory would be incomplete without a better understanding of these additional processes.

Free recall is an ideal paradigm to characterize memory search because of the range of possible answers: So long as the item was presented in the current list, it is considered a correct response. This means that memory search could yield one of several correct recalls. By contrast, other paradigms such as cued recall, serial recall, and probed recall, there is only one correct recall in response to each memory cue. In free recall, there is strong evidence for greater competition between all current-list items, presumably because any one of them could be correct. The results from other recall paradigms both reinforce and complement those of free recall, as having more experimental control over the memory cue and the expected response can be advantageous. For instance, whereas in free recall a participant may form associations from one item to several other items, in cued recall participants typically are meant to remember items in pairs. This more limited scope of one association between two items has revealed additional properties of competition and interference between associations. Yet probing memory for a specific association does not inform which associations are strongest, or if items are remembered yet lack proper associations. Free recall provides more insight into the competitive nature of associations, and allows for all possible items to be recalled irrespective of their associations to other items. Free recall also conveys how an individual participant's internal representations and associations drive memory search. At the same time, the reliance on endogenous representations and cues, rather than exogenous experimental cues, makes this task more demanding.

The results described in this chapter serve to characterize general properties of memory tasks as they relate to memory search. Further, these results can motivate and refine theoretical accounts of the cognitive underpinnings of memory search. Although several models have been developed to explain episodic memory tasks, no one model can account for all findings. Regardless, the classic and well-replicated findings of free recall serve as a benchmark for any new model. This will be particularly important as many current models and theories are limited to one type of memory task (e.g. free recall but not cued recall). A theory that can only account for a subset of results is, at best, limited in scope; at worst, it may make assumptions that would not withstand all properties and paradigms of episodic memory.

Episodic memory is critical to everyday life. The free recall task is arguably the most open-ended assessment of episodic memory, providing minimal external cues or direction. For participants, the open-ended nature of free recall can make this task more challenging, as well as more sensitive to deficiencies in episodic memory. For researchers, this flexibility provides a more detailed set of responses from participants. Analyses of what participants recall, as well as the timing and orders of their recalls, can be used to discern how information is encoded, organized, and retrieved. Of course, the free recall paradigm is one of many tasks assessing episodic memory, and in an experimental setting operationalizes a simplistic form of episodic memory. Results from free recall experiments, when combined with approaches that query other aspects of memory and employ more realistic stimuli, serve to characterize how one can search through the vast contents of memory to retrieve the proper episode.

Figure Captions

Figure 1: Free recall set-up and conditions. In free recall, participants are presented with a list of items, then must *recall* overtly as many items as possible, but are *free* to do so in any order they wish. In the figure, the cue to begin recall is indicated by asterisks, as participants are often prompted to recall items with a series of asterisks flashing on the screen. Free recall is generally classified by the type of distractor task a participant performs between item presentation and the recall period. **A. Immediate free recall.** Participants are presented with the to-be-remembered items one at a time, and must recall the items shortly after a brief interval following the last presented item. **B. Delayed free recall.** Between presentation of the last list item and the recall period, a participant performs a distractor or filler task. **C. Continual-distractor free recall.** In between each item presentation, a participant performs a distractor task.

Figure 2: Initiation in free recall. Probability of initiating recall of each item as a function of its studied position in the presented list (serial position), for the 3 free recall conditions illustrated in Figure 1. Data are from Experiment 2 of the Penn Electrophysiology of Encoding and Retrieval Study (PEERS). The delayed and continual-distractor conditions refer to the lists with distractor periods of 16 s.

Figure 3: Temporal contiguity effect in free recall. A. Schematic for calculating temporal contiguity. A sample list of presented items and their associated serial positions is shown along with a calculation of lag, or difference in serial positions between two successively recalled items. **B. Conditional response probability of recall as a function of lag.** See text for details. **C. Conditional response latency as a function of lag.** See text for details. Data are from the 16 s delayed free recall condition reported in Experiment 2 of the Penn Electrophysiology of Encoding and Retrieval Study (PEERS).

Figure 4: Serial position effects in free recall. Probability of recall as a function of each item's position in the presented list, or serial position, for the 3 free recall conditions illustrated in Figure

1. Data are from Experiment 2 of the Penn Electrophysiology of Encoding and Retrieval Study (PEERS). The delayed and continual-distractor conditions refer to lists with distractor periods of 16 s.

Figure 5: List-strength effect and list composition effect. A. List presentation. Sample list presentation of the three types of lists included in analyses of the list-strength effect: pure strong lists comprised of strong items only (items begin with 'S' and have thick outlines); pure weak lists comprised of weak items only (items begin with 'W' and have thin outlines); mixed lists comprised of strong and weak items. **B. Idealized results.** The list-strength effect is characterized by greater memory for strong items than weak items in mixed lists. The list-composition effect is characterized by greater memory for strong items than weak items in mixed lists *and* equivalent memory in pure weak lists and pure strong lists.

Figure 6: Other recall paradigms. A. Cued recall and variants. In the most common form of cued recall, participants are presented with pairs of items. *Cued recall:* After presentation of a list of item pairs, memory is tested by presenting one item from the pair (cue item) and requesting the participant recall of the cue item's pairmate (target item). *Modified free recall:* After the first list, participants are presented with another list of item pairs, in which the first item from each pair is from List 1, and the second item in each pair is new. Next, participants may be asked to recall one item: the new associate, the old associate, or whichever one comes to mind first. *Modified modified free recall:* Following presentation of List 2, participants are instructed recall both of an item's prior associates. **B. List-before-last recall.** Participants are required to recall items from the list before the last (termed the target list), in contrast to standard free recall which requires recall of the most recently presented list (here, termed the intervening list). In this example, during List 1 recall, List 1 is the target list and List 2 is the intervening list; during List 2 recall, List 2 becomes the target list and List 3 is the intervening list.

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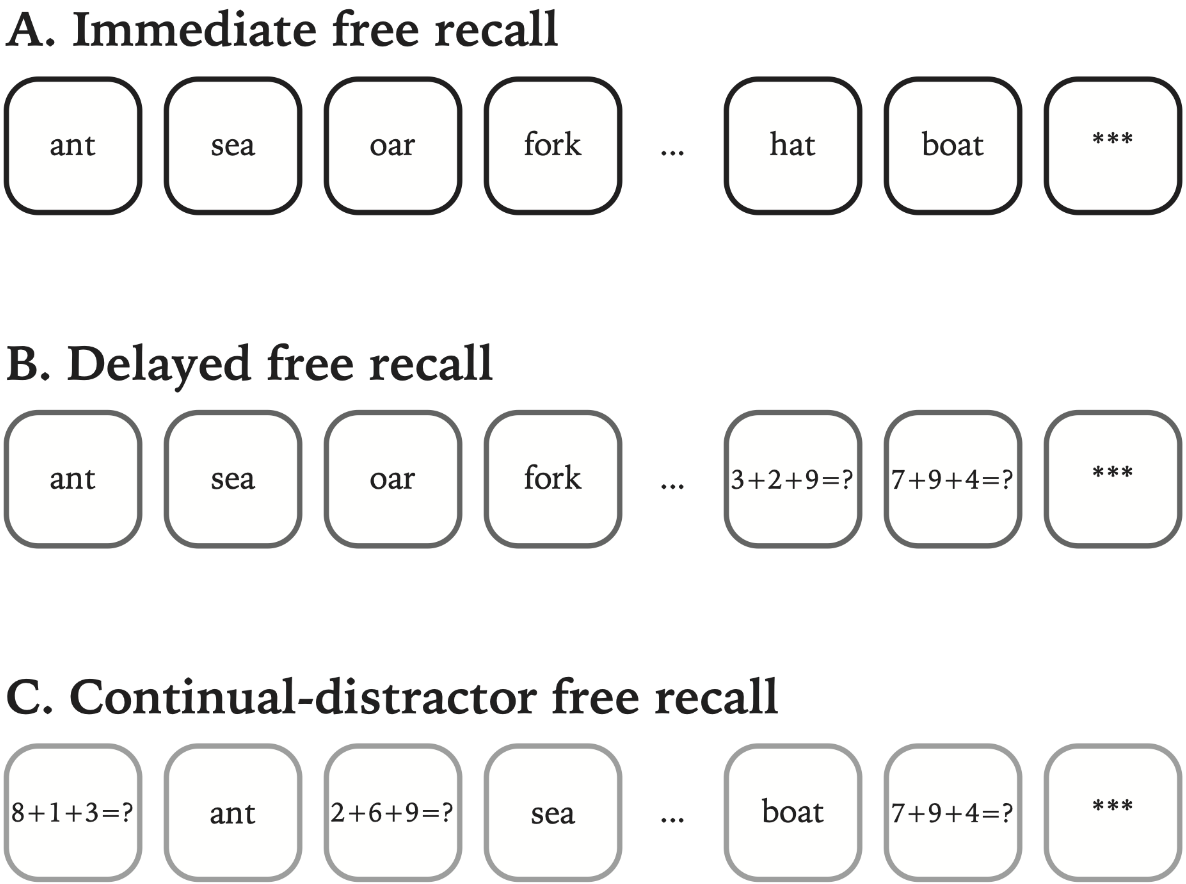
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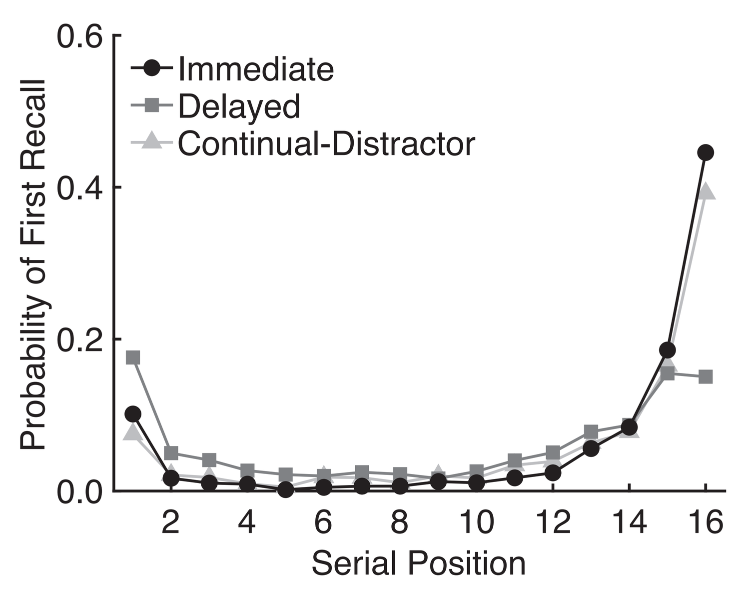

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Probability of First Recall
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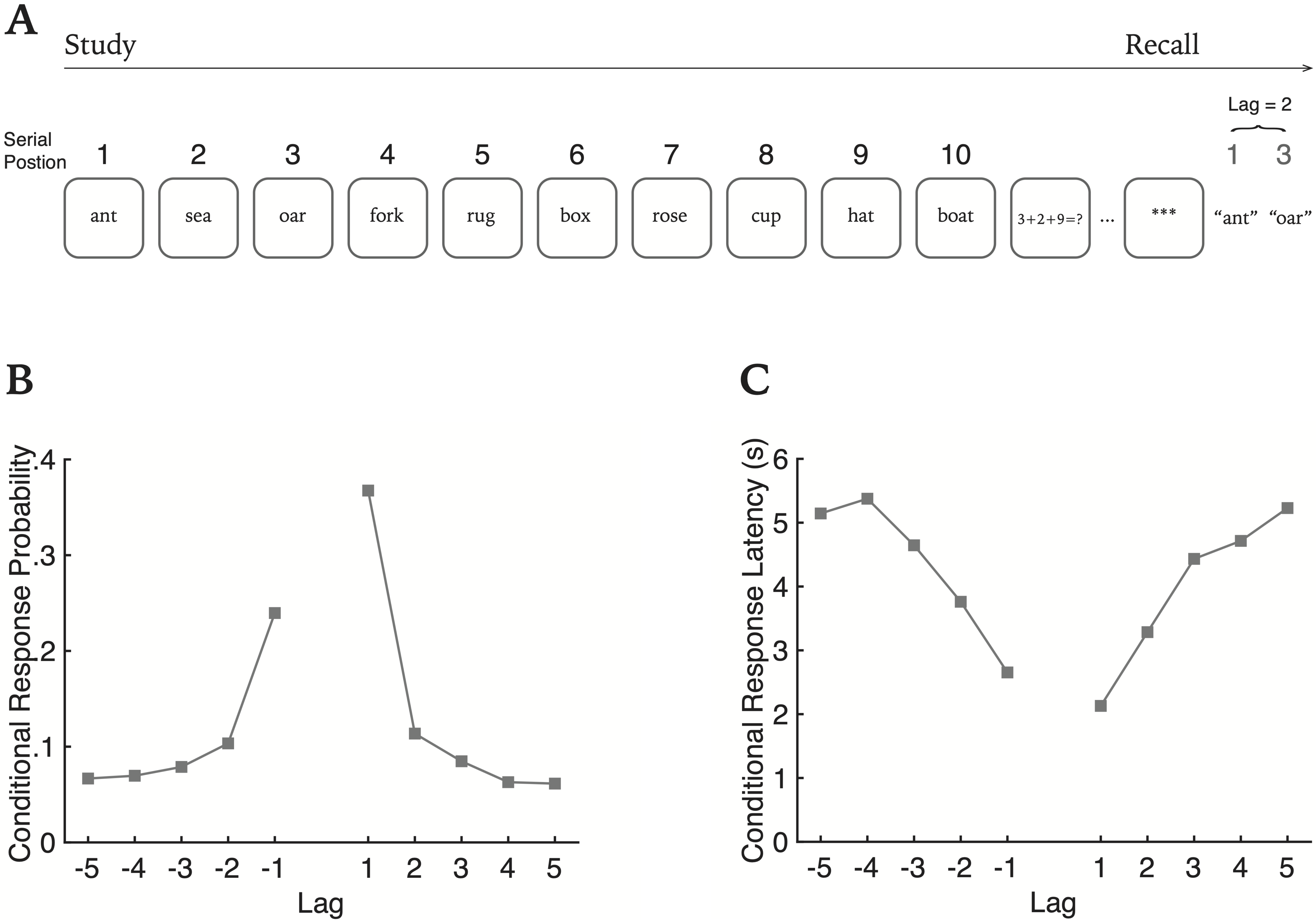
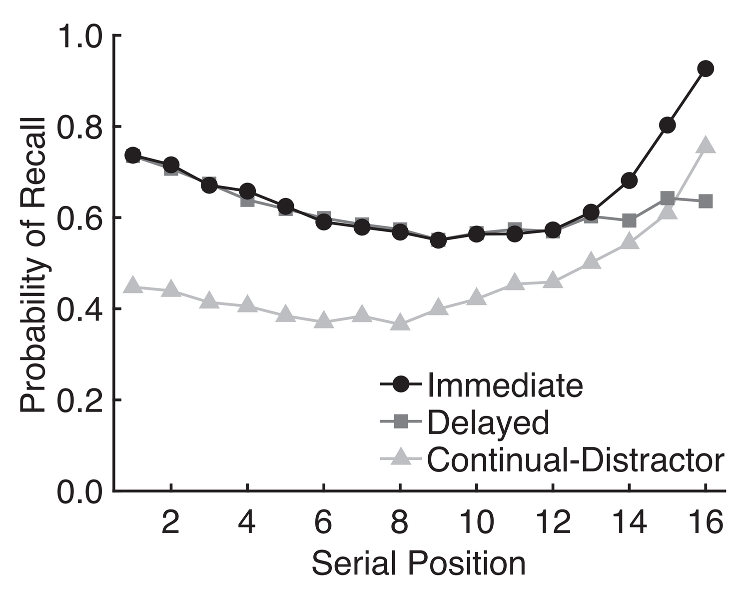
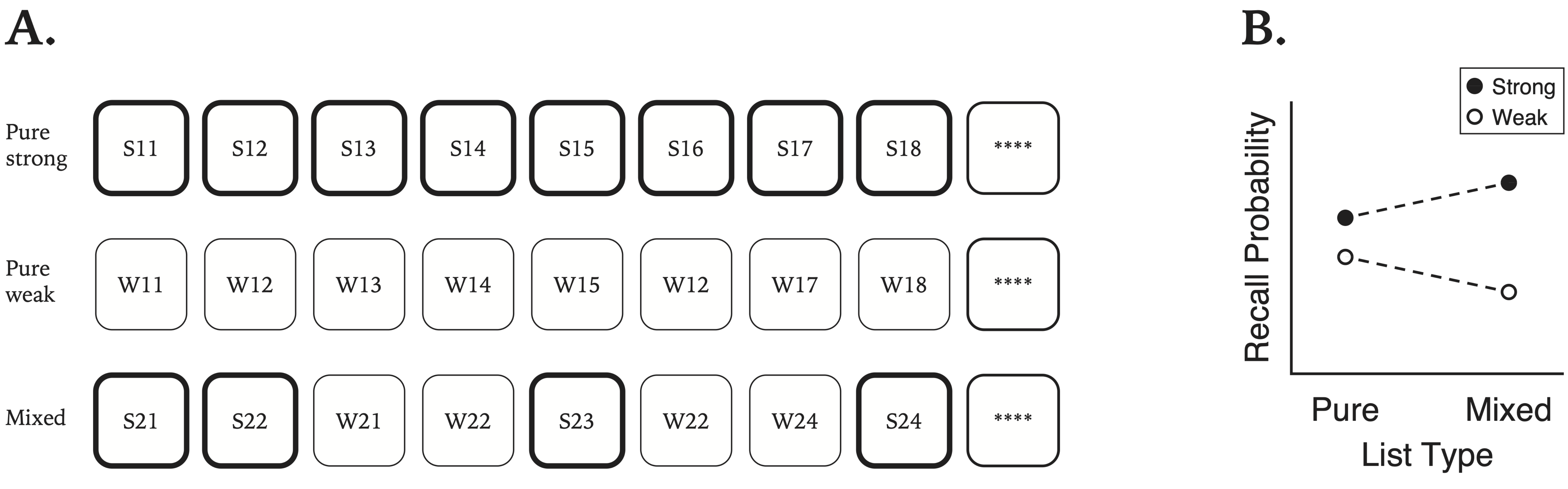
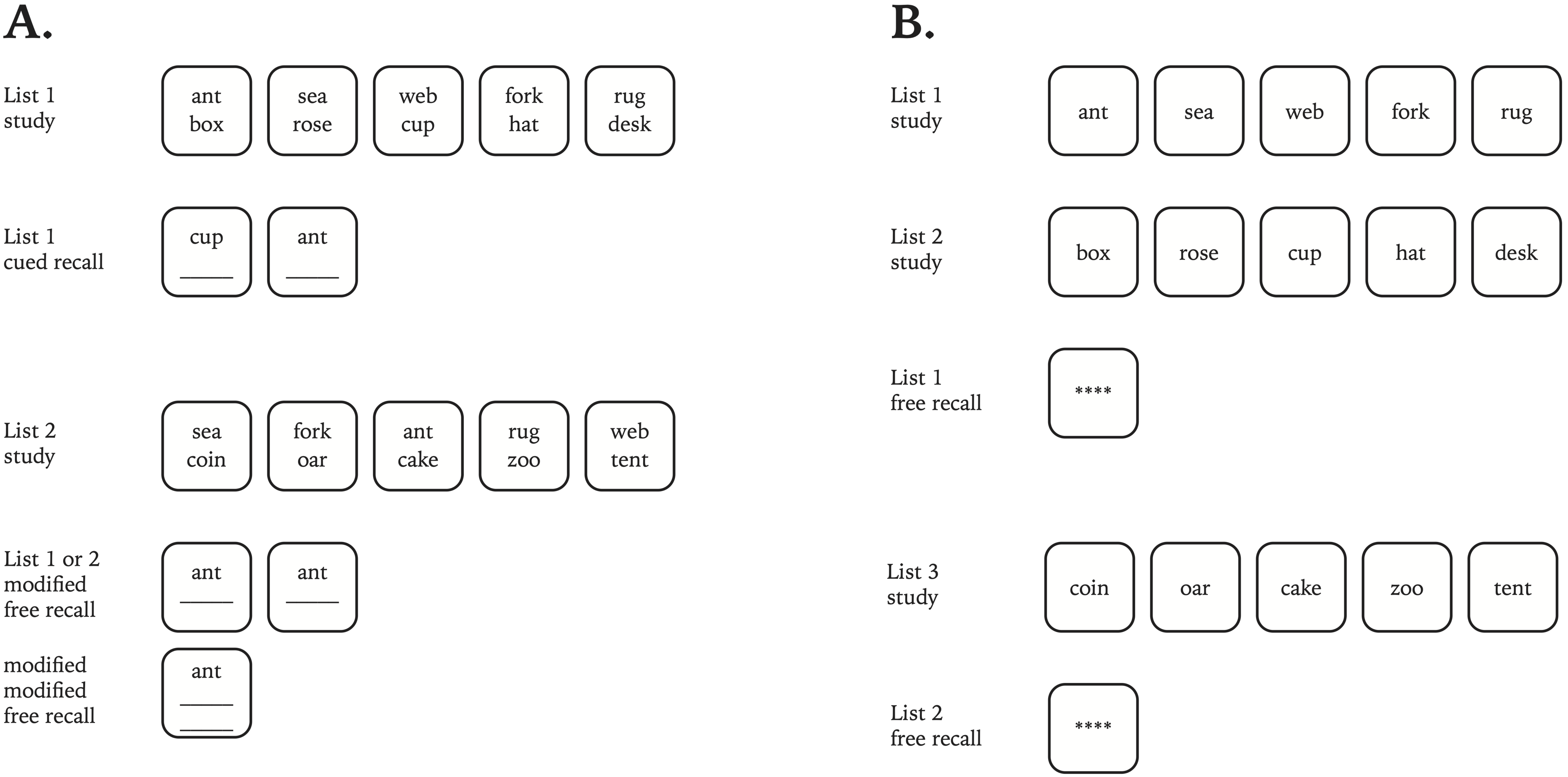
16
Serial Position


A
Study
Recall
Lag = 2
Serial Position
1
2
3
4
5
6
7
8
9
10
1
3
ant
sea
oar
fork
rug
box
rose
cup
hat
boat
3+2+9=?
...
***
"ant"
"oar"
B
Conditional Response Probability
0
.1
.2
.3
.4
-5
-4
-3
-2
-1
1
2
3
4
5
Lag
C
Conditional Response Latency (s)
0
1
2
3
4
5
6
-5
-4
-3
-2
-1
1
2
3
4
5
Lag



1.0
0.8
0.6
0.4
0.2
0.0
Probability of Recall
2
4
6
8
10
12
14
16
Serial Position
Immediate
Delayed
Continual-Distractor


A.
Pure strong
S11
S12
S13
S14
S15
S16
S17
S18
****
Pure weak
W11
W12
W13
W14
W15
W12
W17
W18
****
Mixed
S21
S22
W21
W22
S23
W22
W24
S24
****
B.
Strong
Weak
Recall Probability
Pure
Mixed
List Type


A.
List 1 study
ant box
sea rose
web cup
fork hat
rug desk
List 1 cued recall
cup
ant
List 2 study
sea coin
fork oar
ant cake
rug zoo
web tent
List 1 or 2 modified free recall
ant
ant
modified modified free recall
ant
B.
List 1 study
ant
sea
web
fork
rug
List 2 study
box
rose
cup
hat
desk
List 1 free recall
****
List 3 study
coin
oar
cake
zoo
tent
List 2 free recall
****