A Post-Encoding Pre-Production Reinstatement (PEPPR) Model of Dual-List Free Recall

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Abstract

Recent events are easy to recall, but they also interfere with recall of more distant, non-recent events. Many computational models recall non-recent memories by using the context associated with those events as a cue. But some models do little to explain how people initially activate non-recent contexts in the service of accurate recall. We addressed this limitation by evaluating two candidate mechanisms within the Context-Maintenance and Retrieval model. The first is a Backward-Walk mechanism that iteratively applies a generate/recognize process to covertly retrieve progressively less recent items. The second is a Post-Encoding Pre-Production Reinstatement (PEPPR) mechanism that formally implements a metacognitive control process that reinstates non-recent contexts prior to retrieval. Models including these mechanisms make divergent predictions about the dynamics of response production and monitoring when recalling non-recent items. Before producing non-recent items, Backward-Walk cues covert retrievals of several recent items, whereas PEPPR cues few, if any, covert retrievals of that sort. We tested these predictions using archival data from a dual-list externalized free recall paradigm that required subjects to report all items that came to mind while recalling from the non-recent list. Simulations showed that only the model including PEPPR accurately predicted covert recall patterns. That same model fit the behavioral data well. These findings suggest that self-initiated context reinstatement plays an important role in recall of non-recent memories and provides a formal model that uses a parsimonious non-hierarchical context representation of how such reinstatement might occur.

Keywords: episodic memory; free recall; metacognition; source monitoring; temporal contiguity

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When we try to recall the past, the most recent experiences are often the first to come to mind. This recency effect appears in many situations, including autobiographical memory (Bahrick, Bahrick, & Wittlinger, 1975; Moreton & Ward, 2010; Rubin, 1982), recall of news stories (Uitvlugt & Healey, 2019), and laboratory tasks such as free recall and item recognition (Murdock, 1962; Murdock & Anderson, 1975). Although, having easy access to memories of recent events is often beneficial, it can also create retroactive interference that makes it harder to access more distant memories (Jang & Huber, 2008; McGeoch & McDonald, 1931; Underwood, 1945; Unsworth, Spillers, & Brewer, 2012). Here, we develop a model of a context-based mechanism that may allow people to overcome the pull of recent memories to access distant memories. Our model is the first variant of the Context Maintenance and Retrieval model (Lohnas, Polyn, & Kahana, 2015; Polyn, Norman, & Kahana, 2009) to include a pre-retrieval cue specification mechanism of the sort proposed in the metacognition literature (Goldsmith, 2016; Jacoby, Shimizu, Daniels, & Rhodes, 2005). We evaluate the ability of this and another candidate context-based model to predict the dynamics of response production in a dual-list free recall paradigm that requires recalling from a list studied *before* a more recent list (Wahlheim, Ball, & Richmond, 2017).

Our approach is inspired by studies showing that subjects can access non-recent memories under conditions of retroactive interference in variants of the list-before-last paradigm Shiffrin (1970). In these paradigms, subjects study multiple lists, but instead of recalling from the most recent list, they recall from the list before the last. Subjects in these tasks recall many items from the non-recent list and, despite the potential retroactive interference from an intervening list, produce few inter-list intrusions (Jang & Huber, 2008; Sahakyan & Hendricks, 2012; Unsworth et al., 2012; Wahlheim & Garlitch, 2020; Wahlheim & Huff, 2015; Wahlheim, Richmond, Huff, & Dobbins, 2016; Ward & Tan, 2004). Here, we model data from the similar dual-list free recall task (e.g., Unsworth,

Brewer, & Spillers, 2013; Wahlheim, Alexander, & Kane, 2019; Wahlheim et al., 2017). In dual-list free recall, illustrated in Figure 1, subjects study two lists separated by a short break (e.g., a space bar press) and then recall from either the recent list (i.e., List 2) or the earlier list (i.e., List 1).¹ This is similar to the list-before-last paradigm as subjects are sometimes required to retrieve distant memories (from List 1) while avoiding retroactive interference from recent memories (List 2). Our goal here is to evaluate the ability of two models with different context reinstatement mechanisms to explain how people retrieve non-recent memories and prevent intrusions from recent memories.

Accessing Non-recent Events: Theoretical Mechanisms

Because a primary challenge when facing retroactive interference is to overcome the pull of recent memories, we start with a theory of the recency effect. Many theories assume that retrieved context can be a cue for accessing *recent* memories (e.g., Estes, 1955; Farrell, 2012; Howard & Kahana, 2002; McGeoch, 1932; Mensink & Raaijmakers, 1988; Underwood, 1945). These models generally conceive of context as a set of feature elements distinct from items, that can each be active to varying degrees at a given moment in time. The ensemble of activation across context elements is assumed to change gradually across time (e.g., by moving gradually through the feature space, or by updating between lists), producing different states of context at different points in time. Items are assumed to form associations with the state of context that prevailed during their presentation. Because context change is gradual, the context state at any moment will be more similar to the context state from the prior moment than states from more distant moments. Therefore, using the current context at the end of a list as a retrieval cue naturally produces the recency effect. Framed in this way, the challenge of recalling from earlier lists is to avoid using current context to *recall* recent items and instead use it to *distinguish* recent from non-recent items (e.g., Jang & Huber, 2008; Lohnas et al., 2015).

¹To avoid using different terminology when discussing list-before-last recall and dual-list recall paradigms, we will refer to the targeted non-recent list as “List 1” and the recent list as “List 2”.

Two qualitatively different cognitive control processes from the metacognition literature suggest different ways that context might be used to make this distinction: front-versus back-end control (Burgess & Shallice, 1996; Goldsmith, 2016; Halamish, Goldsmith, & Jacoby, 2012; Jacoby, Kelley, & McElree, 1999; Jacoby et al., 2005; Johnson & Raye, 2000; Morcom, 2016). Back-end processes are used to guide report decisions after subjects monitor the source of retrieved representations. This serves to prevent candidate responses from non-target sources (i.e., intrusions) from being output (e.g., source-monitoring; Johnson, Hashtroudi, & Lindsay, 1993). By contrast, front-end processes operate before retrieval attempts to specify the context (i.e., source) from which candidate responses should be produced. Such specification enables cue-dependent retrieval from long-term memory representations from target contexts (Tulving, 1983; Tulving & Thompson, 1973) and prevents memories from non-target contexts from coming to mind (e.g., source-constrained retrieval; Halamish et al., 2012; Jacoby et al., 2005). Below we discuss the potential roles of these processes in the dynamics of retrieving non-recent memories.

Back-end control following monitoring. An example of a post-retrieval monitoring process preceding back-end control was proposed in the classic generate-recognize model. In this model, subjects monitor the source context associated with each generated response. Then subjects use control processes to output retrievals they recognize as being from the target source and withhold retrievals they do not recognize (Anderson & Bower, 1972; Atkinson & Juola, 1974; Bahrick, 1970; Kintsch, 1970). When attempting to retrieve events from non-recent contexts, monitoring processes could be used to compare the retrieved context of generated candidates with context from the target source *after* retrieval (e.g., Winograd, 1968). Lohnas et al. (2015) developed a model using such a mechanism. Their Context Maintenance and Retrieval Version 2 (CMR2) model, extended earlier retrieved context models (Howard & Kahana, 2002; Polyn et al., 2009; Sederberg, Howard, & Kahana, 2008) of single-list free recall to various across-list phenomena, including retrieval dynamics from the list-before-last paradigm. In CMR2,

each study item activates an associated context representation. This newly activated context representation drives context updating by partially replacing the state of context that prevailed before the item appeared, such that the context representations of the most recent items are most strongly activated. Thus, once the whole list has been presented, end-of-list recency items are most strongly represented in context.

When simulating standard free recall from the *recent* list, CMR2 uses a generate-recognize mechanism. First, it produces candidate retrievals by using the context state from the beginning of recall as a retrieval cue. When recall is immediate, the model assumes that this beginning-of-recall context is identical to the context that prevailed at the end of the study period. (To foreshadow, this assumption is a critical difference between the models we consider here.) Second, the model limits recall to the recent list using a “recognition” process that determines the source of the item by comparing the item’s context with the context used to cue retrieval. If the item is from the recent list, the context similarity will be high. If the item is from an earlier list, the similarity will be lower.

Lohnas et al. (2015) suggested that the same context-derived recency signal that provides direct accesses to recent items in standard free recall could be leveraged to indirectly access non-recent items. When simulating recall from a non-recent list, CMR2’s production phase is the same as in standard free recall: the beginning-of-recall context cues retrieval from the recent list. But the recognition phase is different: rather than rejecting candidate retrievals when context similarity is *low*, it rejects them when context similarity is *high*, on the assumption that an item with context similar to the beginning-of-recall context is from the recent list. Critically, the context associated with the rejected item is reinstated. Although this reinstated context is recent, it will be less recent than the recall context and can therefore cue even less recent items. Following this logic, the model could access List 1 in a dual-list task by engaging in a series of covert retrievals (and rejections) of progressively less recent List 2 items. Once it retrieves an item with a context that is below the similarity threshold, the model assumes it has reached List 1, outputs the item,

and begins retrieving and outputting additional items associated with similar contexts using the model’s standard recall mechanisms.

If we think of the context associated with the end of List 2 as a physical location, A, and the context associated with the end of List 1 as another location, B, CMR2’s iterative application of the generate-recognize mechanism is like walking backwards such that one’s feet touch many locations between A and B. We therefore label this the *Backward-Walk* mechanism. Lohnas et al. (2015) fit CMR2 to list-before-last data from Jang and Huber (2008) and showed that this mechanism could account for both the overall level of recall from the target list and the number of intrusions from the most recent list. However, Lohnas et al. (2015) did not test whether including this back-end mechanism allowed the model to better account for the data than if a front-end reinstatement mechanism was included instead. In the next section, we discuss the potential advantages of a front-end mechanism over a Backward-Walk mechanism.

Front-end control (cue specification). Computational, neuropsychological, and verbal theories (Atkinson & Shiffrin, 1968; Burgess & Shallice, 1996; Jacoby et al., 2005; Moscovitch & Melo, 1997) have proposed active pre-retrieval processes that allow subjects to effectively specify retrieval cues. According to some perspectives, a self-initiated cue specification process can reinstate contextual information associated with the target source by recapitulating processes deployed during encoding (e.g., Burgess & Shallice, 1996; Goldsmith, 2016; Jacoby et al., 2005; Johnson & Raye, 2000; Morcom, 2016). Doing so serves to increase access to memories from the target context and prevent intrusions from other contexts from coming to mind (Herron & Rugg, 2003; Morcom & Rugg, 2012). When the goal is to recall non-recent events, a perfectly effective cue specification process would reinstate List 1 context *before* response generation, thereby excluding List 2 items from the search set and preventing their production.

Note that such a context reinstatement mechanism operates after items have been encoded during the study list but before they are produced as candidate retrievals at the

start of the recall period. We therefore refer to this class of proactive control mechanisms as Post-Encoding Pre-Production Reinstatement (PEPPR). Apart from CMR2, most formal simulations of list-before-last and related paradigms have implemented a mechanism similar to PEPPR (e.g., Farrell, 2012; Jang & Huber, 2008; Lehman & Malmberg, 2009). These models propose a list-context representation that changes only when a new list begins (a feature they share with many models of standard recall; e.g., Anderson & Bower, 1972; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Kimball, Smith, & Kahana, 2007; Lehman & Malmberg, 2013; Raaijmakers & Shiffrin, 1981).² Prior to attempting to retrieve any items, the PEPPR mechanism attempts to reinstate List 1 context. If successfully reinstated, the list context provides a cue to directly access List 1 item representations. If we again think of moving from the end of the List 2 context to the List 1 context as moving between physical locations A and B, PEPPR allows one to jump from point A to point B such that one’s feet never touch any intervening locations. Jang and Huber (2008) showed that a version of PEPPR was able to account for both accurate recalls and intrusions in list-before-last recall. But a major limitation of most models including a PEPPR mechanism is that they assume that list context *can* be reinstated (e.g., Jang & Huber, 2008; Lehman & Malmberg, 2009), without specifying *how* it is reinstated (Lohnas et al., 2015). As we will show, our implementation of PEPPR extends earlier work by providing a formal model of the reinstatement process.

Adjudicating between Mechanisms

A key challenge in adjudicating between a model that employs a Backward-Walk mechanism versus one that uses a PEPPR mechanism is that both models make similar predictions about summary scores for correct recalls and intrusions. If an idealized subject tried to recall List 1 items using only a Backward-Walk approach, they would successfully recall many List 1 target items and output far fewer List 2 intrusions. An idealized subject

²Though sometimes the choice of including an unchanging list context is described as a convenient but unnecessary simplifying assumption (Lehman & Malmberg, 2009).

using only a PEPPR approach would also enjoy comparable retrieval success. Although the two models make near-identical predictions for summary scores, they make competing predictions about the dynamics of covert retrievals that are withheld from recall.

The subject engaging in Backward-Walk should initiate memory search by producing and withholding List 2 items based on the high similarity between current and retrieved context. That is, a Backward-Walk does not really overcome the pull of recency, rather it *uses* recency to produce and withhold many List 2 items on the way to List 1 items. Indeed, Lohnas et al. (2015, p. 357) assume that “With a pause between lists, CMR2 covertly retrieves more intervening-list intrusions before discovering the target list.” In contrast, the subject who proactively reinstates context cues via a PEPPR mechanism should produce few, if any, List 2 items. Here, the pull of recency is avoided altogether by jumping directly back to the List 1 context.

These predictions cannot be tested in standard recall paradigms because those tasks require subjects to report only the items from the target list and covertly withhold candidates from non-target lists. This report criterion may therefore obscure estimates of intrusions produced with associated List 2 context. Fortunately, the *externalized* free recall procedure (EFR; e.g., Bousfield & Rosner, 1970; Kahana, Dolan, Sauder, & Wingfield, 2005; Roediger & Payne, 1985) allows one to assess both the production and monitoring processes that lead to the response output patterns observed in standard free recall. In EFR, production processes are assessed by instructing subjects to report all items that come to mind as they attempt to recall from only a target list. Monitoring processes are then assessed by instructing subjects to withhold productions that are not from the target list. Although EFR has mainly been used in studies where subjects attempt to recall the most recent list (Kahana et al., 2005; Unsworth & Brewer, 2010; Unsworth, Brewer, & Spillers, 2010), some studies have used EFR to investigate the effects of age and interpolated retrieval on production and monitoring processes involved in recall from non-recent lists (Wahlheim et al., 2019, 2017; Wahlheim & Garlitch, 2020). To directly

compare the Backward-Walk and PEPPR mechanisms, we used EFR data in dual-list free recall from Wahlheim et al. (2017). In the next section, we summarize those data and our modeling approach.

Overview of Data and Model

The Wahlheim et al. (2017) Data

To test competing predictions from the two CMR2 models, we modeled data from a dual-list free recall experiment that included EFR instructions (Wahlheim et al., 2017). We briefly review the method here. The experiment included 30 younger adults (and an older adult group that we do not consider here). On each trial, subjects studied two 10-word lists. Each word appeared for 1 s followed by a 1 s interstimulus interval. Before the first item of each list appeared, the list name (i.e., List 1 or List 2) appeared for 3 s. After studying List 2, subjects were prompted to recall from either one or both lists using one of the following recall prompts: “List 1”, “List 2”, or “Lists 1 and 2”, that appeared for 3 s. Subjects were instructed to type the words from the list(s) indicated by the recall prompts and to report any other words that came to mind while doing so. For each response, subjects pressed a button to indicate whether they thought it was from a target list (i.e., correct) or not from a target list (i.e., incorrect). After each judgment, they rated their confidence in that judgment using a 1 (low) - 3 (high) scale (we do not consider the confidence data here). Each subject completed five study-test trials from each of the three target list conditions (i.e., List 1, List 2, and Both [Lists 1 and 2]) in pseudo-random order.

We first examined recall of responses classified by subjects as being from the correct list(s). Note that these summary scores are comparable to expected scores on a standard free recall task when subjects are instructed to only output target list responses. Figure 2A shows the proportion of items reported *and* endorsed as from a target lists for each study list in each target-list condition. Correct recall was higher from the target list than the non-target list when subjects recalled from only one list. For those trials, subjects correctly

recalled about half the items and reported very few inter-list intrusions. These patterns indicate that subjects could effectively discriminate target from non-target items when the target list was not recent (i.e., List 1 condition).

The Context Maintenance and Retrieval Model Version 2

To examine the mechanisms that enable such targeting of non-recent lists, we fit two versions of the CMR2 model to these data: one that uses a Backward-Walk mechanism (as in Lohnas et al., 2015), and one that uses a PEPPR mechanism that we introduce here. We are primarily interested in the List 1 condition because it requires retrieval of non-recent item representations. Nonetheless, because subjects must encode the lists without knowing which will be the target, we also modeled summary scores in the other conditions. Doing so forced the model to use a common set of study-phase parameters to fit to all conditions and use only test-phase parameters to fit the differences between conditions. Before describing the mechanisms in detail, we provide a non-technical overview of the aspects of the model that the two versions share. A full formal description is available in the Supplemental Materials.

In CMR2, a feature and a context layer are connected by associative weight matrices; an item-to-context matrix and a separate context-to-item matrix. Nodes on the feature layer represent individual items, whereas the corresponding nodes on the context layer represent contextual associates activated by each item. To illustrate how these layers interact during study and recall to elicit episodic memories, we will work through an example using Figure 3 as a schematic representation of the model. For this first example, we will illustrate the steps involved in studying and recalling the items *river*, *money*, and *onion* from most recent list (i.e., standard free recall); later, we will extend the example to recall from a non-recent list.

Simulating encoding during the study phase. Suppose that the word *river* appeared first during study (see first row of Figure 3). The river node would then become

active on the feature layer. This activation would project through the feature-to-context associative matrix to activate the context layer. Conceptually this context layer activity represents various pre-experimental episodic and semantic associates of the word *river*. For example, seeing that word may cause a subject to imagine a river, think of the word’s meaning, or remember when they last swam in a river. Presentation of the next word (second row of Figure 3), *money*, then activates its feature layer representation, which completely replaces the feature layer representation of *river*. That is, feature representations are active on the feature layer only while corresponding items appear. Once *money*’s feature representation is activated, it in turn activates its associated context on the context layer. But unlike the feature layer, context layer activation persists across item presentations such that *money* does not replace *river*.

This process repeats when the next item, *onion*, appears (third row of Figure 3). Notice that although all items are active on the context layer, they are not all equally active. Instead, as each new item appears, the activity of all contexts associated with previous items diminishes. This is illustrated by the size of the images on the context layer in Figure 3. A model parameter, $\beta_{encoding}$, governs the rate at which context activation fades across item presentations. When $\beta_{encoding}$ is close to 1, context changes very quickly such that the context of each newly presented item almost completely replaces the contexts of previous items. By contrast, when $\beta_{encoding}$ is close to 0, context remains largely unchanged when new items are presented. That is, the higher the value of $\beta_{encoding}$, the stronger the potential recency effect. When modeling dual-list recall, the feature and context layers include a node for each List 1 item and each List 2 item, plus an extra element to represent the change in context believed to take place between lists (Lohnas et al., 2015; Sahakyan & Kelley, 2002). The degree of this between-list context updating is governed by a separate parameter, $\beta_{between}$. Critically, when each new item appears, its feature representation forms new associations with the current state of the context representation. For example, when *onion* appears, a new association can form between the

onion item representation and the blended *river/money* context representation, thereby encoding the context in which *onion* was studied.

Simulating the recall period. During the recall test, the current state of context is used as a retrieval cue by projecting the start-of-test context through the matrix of context-to-item associations. As described earlier, cuing with the current state of context generates a particular level of support for accessing each item representation. These support values are then used as input to a competitive decision process. Generally, the start-of-test context best supports retrieval of item representations near the end of the list, so those representations typically win the competition and are the first to be considered for output.

We say *considered* for output because in CMR2 sampling an item representation (i.e., an item winning the competition) is the production phase that occurs before a decision is made about outputting a response. Thus, before the sampled item is output, an editing process allows the winning item to reinstate its associated context representation by projecting the item’s representation through the matrix of item-to-context associations. For example, thinking of *onion* would result in the reinstatement of the *onion* context and the blended *river/money* context that was active when *onion* was encoded. This reinstated context is then compared to the current mental context to determine if the sampled item representation was from the target list (i.e., the most recent list). If the similarity of the two contexts exceeds a threshold, the sampled item is output; if the similarity is below the threshold, it is withheld. Regardless of the winning item’s fate, the reinstated context is integrated with the current mental context, and the resulting updated context cues the next recall. Incorporating the context of the just-sampled item with the context cue biases the next recall attempt to produce an item representation from a nearby serial position.

Related to the present study, Lohnas et al. (2015) used this generate-recognize process to simulate retrieval dynamics in EFR when recalling from non-recent lists. Their version of the model treats an item representation winning the retrieval competition as

equivalent to a subject reporting an item during EFR and treats the post-production output decision based on context monitoring as equivalent to a subject pressing a button to output or withhold the retrieved representation. But when Lohnas et al. (2015) modeled list-before-list recall, there were no available data from an experiment with EFR instructions; therefore, they could not test the specific predictions that we did here. The aspects of the model we have described so far provide the foundation that allows CMR2 to simulate standard recall of the most recent list. Next, we will describe how both the Backward-Walk and the PEPPR variants of CMR2 build on this foundation to initiate retrieval from a non-recent list.

Implementing Backward-Walk

Lohnas et al. (2015) implemented the Backward-Walk mechanism to account for recall initiation in the list-before-last paradigm by modifying CMR2’s retrieval monitoring mechanism. Specifically, they modified the model to target a non-recent list by reversing the context-comparison editing process. In their model, retrieved items with *high* similarity to the context cue are recognized as intrusions from the most recent list and are thus withheld. But the context of each withheld item becomes part of a cue that elicits a subsequent candidate production (i.e., the context updates with each retrieval attempt). When this process is applied iteratively, each successive production is likely to come from an earlier serial position than the last. This backward walk eventually produces a candidate associated with a context that is dissimilar enough from the cue context to surpass the output threshold. At this point, the model assumes the target list context has been reached and reverts to the normal editing process in which retrieval products are output only when their contexts are sufficiently *similar* to the cue context.

Note that the outcome of the editing process can create a distinction between the order in which items are sampled (i.e., win a decision competition and be considered for output) and the order in which sampled items are output (i.e., exceeding the report

threshold and being endorsed as a correct recall). The model makes specific predictions about both sampling and output orders when targeting List 1. Regarding output order, Lohnas et al. (2015) showed that the model predicts that the probability of outputting an item from the most recent list (i.e., intruding a non-target item) should increase across output positions and found that the data from Jang and Huber (2008) supported this prediction. But the model makes very different predictions about sampling order. Specifically, because of the Backward-Walk mechanism, the model predicts that item representations from the most recent list will be sampled early and that items from the target list will be sampled much later, once the Backward-Walk reaches the target list context. Next, we will discuss a mechanism that makes a contrary prediction: that representations from the recent list will be sampled rarely at the outset of the recall period.

Implementing Post-Encoding Pre-Production Reinstatement (PEPPR)

At the heart of the PEPPR mechanism is the assumption that *before* any candidate item representations are sampled, subjects can proactively reinstate contextual features that, during study, had become associated with items from the target list. Other models have implemented a mechanism similar to PEPPR by adopting a hierarchical representational structure in which item representations are associated with a superordinate list-context representation and adding a mechanism that probabilistically reactivates the appropriate list context during recall to provide direct access to items (e.g., Jang & Huber, 2008; Lehman & Malmberg, 2009). But assuming that non-recent *items* are accessed by first reinstating a non-recent *context*, pushes the question of how subjects overcome the potential interference from recent item representations up a level—how do they reinstate non-recent contexts?

We address this issue here by proposing a general mechanism for directly reinstating non-recent contexts that follows naturally from the principals that govern context retrieval dynamics in CMR2. Our mechanism requires a single simple assumption: context change is

driven not only by processing items but also by processing task instructions, such as a prompt to prepare to study List 1 or List 2. That is, processing a task instruction activates a distinct context representation that becomes associated with subsequent item representations. This is similar to how Polyn et al. (2009) modeled the effect of varying encoding operations (e.g., animacy versus size judgments) by assuming that tasks and items activate unique context representations.

When combined with CMR2’s context change and reinstatement mechanisms, the notion that tasks have context representations provides a straightforward account of dual-list free recall. Because task context is persistent, items appearing after a task goal can form associations with the task-context representation. Thus, if each list follows a different task instruction (e.g., “prepare for List 1” versus “prepare for List 2”), the resulting distinct task-context representations provide natural list-context tags. During recall, these tags will be reinstated if the recall instructions (e.g., “recall List 1”) activate task-context representations similar to those that were established after subjects read the study instructions (e.g., “study List 1”).

We implemented these ideas in the model by adding a “List 1” node and a “List 2” node to the feature and context layers. These nodes have no special status and behave like item nodes. That is, reading the instruction to study List 1 activates its node on the feature layer which in turn activates its node on the context layer. This is illustrated in the first row of Figure 4. Once active, the list context element behaves as an item context element—its activity gradually fades as context evolves across the list (rows 2–3 of Figure 4). Note that this fading has two important consequences. First, List 1 items will become associated with the List 1 context when new item-to-context associations are formed. Second, the fading of List 1 context across the list will cause later items to be less strongly associated with the list context.

When List 1 ends and the List 2 study instruction appears, context change continues in the same way. As shown in row 5 of Figure 4, the List 2 context element will be

activated and incorporated with context but will not completely displace the List 1 items (as described above, the extent to which context changes between lists is governed by a parameter). As List 2 items appear, the List 2 context element will gradually fade (rows 6–7 of Figure 4).

The final row of Figure 4 shows what happens when the recall period begins. The task of recalling a particular list (here “recall List 1”) reinstates the context element of the corresponding list, and it is integrated into the current state of context following exactly the same context evolution process that operated during study but with a new parameter, β_{PEPPR} , determining the extent to which a list-context representations replaces the time-of-test context representation. If β_{PEPPR} is close to 1, then the List 1 representation will dominate, effectively cuing List 1 representations. If β_{PEPPR} is close to 0, then little of the List 1 context will be incorporated, weakly cuing List 1 items. Thus, β_{PEPPR} directly controls the efficacy of proactive context reinstatement, which may vary depending on task and participant characteristics (we return to this point in the Discussion).

Like the Backward-Walk model, the PEPPR model makes specific predictions about both sampling and output orders when targeting List 1. For output order, the PEPPR model predicts that subjects should begin recall with an item from List 1 and that this first output item should come from an early serial position. This prediction is consistent with the probability of first recall analyses of past research (Wahlheim et al., 2019, 2017; Wahlheim & Garlitch, 2020). Moreover, the PEPPER model diverges sharply from the Backward-Walk model in predicting that sampling order should closely follow output order, at least for the first several productions. This is because reinstating the List 1 context representation prior to producing any items allows the model to directly access List 1 item representations without needing to first produce and withhold a long sequence of List 2 items.

Simulation Results

Deriving Predictions of Backward-Walk and PEPPR Models

As discussed above, the Backward-Walk model predicts that when attempting to recall from a non-recent list, subjects should begin the recall period by producing items from the most recent list. By contrast, the PEPPR model predicts that subjects should begin recall by reinstating the target-list context and then producing items from that list. To formalize these predictions, we fit both models to the summary scores from Figure 2A (see the Supplementary Materials for details about model fitting). Simulated data from the best fitting parameterizations are shown in Figure 2B and Figure 2C for the Backward-Walk and PEPPR models, respectively. Both models fit the data very well, capturing the key finding of near perfect discrimination of target from non-target items.

We determined the models' predictions about covert response production by recording every item produced when running the best-fitting parameterization for each model (i.e., those that won the retrieval competition). We also recorded whether sampled items were rejected after the context-comparison editing process. For a given sampling position we calculated the probabilities that the item was from List 1 (a correct recall from the target list) or List 2 (an intrusion from the non-target list). Because, like subjects, the model does not always recall all the items; later sampling positions tend to have fewer observations. Therefore, we calculated sampling probabilities for a given position conditional on an item actually having been recalled in that position. Our goal was to identify the list from which the model produced items across the entire recall period. We focused only on trials where the models targeted List 1 because of our interest is in understanding the mechanisms underlying recall from non-recent memories.

Figure 5A shows that when trying to recall from List 1 the Backward-Walk model invariably begins by first sampling an intrusion from List 2. In fact, the best-fitting parameterization sampled *every* List 2 item before it sampled any List 1 item.

By contrast Figure 5B shows that the PEPPR model invariably begins recall by first

sampling a correct recall directly from List 1. Also, unlike the Backward-Walk model, the sampling probability for the PEPPR model varies across sampling positions, with the probability of sampling a correct item (from List 1) gradually decreasing, and the probability of sampling an intrusion from List 2 gradually increasing. At around sampling position 8 (i.e., once the model has recalled almost all of the 10 possible correct recalls), the probabilities crossover such that the model is more likely to sample List 2 intrusions.

In addition to testing the models' predictions about which items are sampled, we also examined their predictions about which sampled items are rejected as intrusions from the more recent, non-target list (i.e., List 2). The Backward-Walk model (Figure 5C) predicts that the first several items it samples (which tend to come from List 2) will almost always be rejected. Once the Backward-Walk model successfully contacts List 1 (i.e., at sampling position 10, which corresponds to having sampled almost all of the items from List 2), the rejection probability drops precipitously. Once again, the PEPPR model (Figure 5D) predicts the opposite: the first sampled items, which are from List 1, will almost never be rejected. But when the model later begins to sample from List 2, those item representations are always rejected.

Testing the Model Predictions

The simulations above clearly showed that the Backward-Walk and PEPPR models make categorically distinct predictions. The EFR data from Wahlheim et al. (2017) allowed us to evaluate which model's predictions are closer to observed patterns of sampling and rejection. We analyzed the subjects' EFR responses in the same way that we analyzed the models' data. We treated all items that subjects reported as sampled and items that they marked as incorrect as rejected. The resulting sampling and rejection probabilities appear in Figure 6. Panel A shows that subjects almost always began recall by sampling from List 1, which was more consistent with PEPPR than Backward-Walk model predictions. Also supporting PEPPR's predictions, the sampling probability from

List 1 gradually decreased across positions while the sampling probability from List 2 gradually increased, with the probabilities intersecting around position 9. Turning to the rejection probability data (Panel B), subjects rarely rejected the first-sampled items, but the sampling probability increased steadily across positions. These data are also more consistent with predictions of the model including the PEPPR mechanism than the model including the Backward-Walk mechanism.

These results provide stronger support for the PEPPR model than the Backward-Walk model. Caution is warranted, however, for two reasons. First, although the PEPPR model predictions qualitatively match the behavior of subjects, there are some quantitative discrepancies. For example, whereas subjects initiated recall by sampling a List 1 item with about 80% probability and a List 2 item with about 10% probability, the PEPPR model initiates by sampling from List 1 with 100% probability. Further, whereas subjects show a gradual increase in the probability of rejecting a sampled item, the PEPPR model predicts a near-step function between an almost 0% rejection probability for early outputs and 100% rejection probability for late outputs. Second, the Backward-Walk model was at a disadvantage because the models were never fit to sampling probabilities, rejection probabilities, or correct recalls as a function of serial position. Instead, the predictions were derived from the model's best-fitting parameterization to summary scores. That is, we have shown that the parameterization of the Backward-Walk model that provides the best-fit to summary scores does not naturally predict subjects' sampling and rejection behavior. Although it seems intuitively unlikely, we must rule out the possibility that the Backward-Walk model could successfully simulate the sampling and rejection behavior if fit directly to the data. Therefore, we attempted to simultaneously fit subjects' sampling probabilities, rejection probabilities, and summary scores. To ensure we explored the parameter space of each model sufficiently to find a good-fitting parameter set, if it exists, we used a differential evolution genetic algorithm that evaluated 30 million parameter sets per model (see the Supplemental Materials for details).

The results of these simulations are shown in Figure 7, the first column reproduces the subjects' data for direct comparison. The second column shows that the Backward-Walk model could not fit the data. Simulated Backward-Walk subjects outputted too few items from List 1 and too many items from List 2 (Panel B); they also showed no bias toward sampling from List 1 at any output position (Panel E). The third column shows that the PEPPR model fared much better. Simulated PEPPR subjects precisely paralleled actual subjects' high level of recall from List 1 and output effectively zero intrusions from List 2 (Panel C). Critically, when fit to the data, the PEPPR model simulated the observation that subjects often, but not always, initiated recall by sampling from List 1, as well as the observation that the rejection probability started at slightly above 0% for sampling position 1 and then steadily increased (Panel F). The only substantial discrepancy between the model and data is that whereas in the data the probability of sampling from List 1 approaches zero by sampling position 15, the PEPPR model predicts that the probability of sampling from List 1 remains at just below 0.5 even for later positions. This likely reflects the fact that subjects make extra-trial intrusions (i.e., from earlier trials and outside the experiment), especially in later sampling positions (Wahlheim et al., 2017). These intrusions allow the probabilities of sampling from List 1 and List 2 to sum to less than 1. The model cannot make such intrusions, and thus 100% of sampled items must be either a List 1 or a List 2 item.

In summary, although predictions of the Backward-Walk model are fully consistent with observed summary scores, the model fails to predict covert sampling patterns even when fit directly to the data. By contrast, the PEPPR model predicted summary scores comparably to the Backward-Walk model while also correctly predicting qualitative patterns of covert sampling and performing quite well when fit directly to those retrievals.

Discussion

Understanding how people overcome the pull of recent memories to recall non-recent events has been a theoretical challenge. We addressed this challenge here by developing a formal model of dual-list free recall including context-based mechanisms inspired by the memory modeling and metacognition literatures. We compared two retrieved-context models that used different mechanisms to produce and output items from a non-recent list. The first model, that we called Backward-Walk, used a back-end mechanism to control the output of items generated from progressively less recent positions (Lohnas et al., 2015). The second model, that we called PEPPR, used a front-end control mechanism to specify retrieval cues in the service of producing non-recent list items and preventing recent-list intrusions from coming to mind. We tested divergent model predictions against data from an experiment in which subjects externalized covert response sampling. The Backward-Walk model’s predictions diverged sharply from subject’s actual behavior especially for covert recalls. By contrast, the PEPPR model’s predictions were in close agreement with the data even for the critical covert recalls. This model comparison highlighted the necessity of considering response sampling dynamics to precisely characterize the context-based mechanisms underlying recall of non-recent events.

Relation to Other Models of Recalling Non-recent Events

Most models of recall of non-recent events assume that item representations are subordinate to list-context representations that can be reinstated via pre-retrieval cue specification (e.g., Jang & Huber, 2008; Lehman & Malmberg, 2009). By contrast, most retrieved-context models have eschewed those notions for parsimony (Lohnas et al., 2015) and instead assume that end-of-study context serves as an initial cue to bootstrap access to non-recent item representations (i.e., the Backward-Walk; but see Polyn et al., 2009). The current simulations show that neither approach is completely correct. Consistent with the view that accessing non-recent items does not require list-context representations, Lohnas

et al. (2015) demonstrated that a Backward-Walk model can account for summary scores in standard free recall. However, without a list-context representation, the Backward-Walk model incorrectly predicts that subjects should generate and reject many recent-list items before accessing non-recent-list items. This failed prediction suggests that the ability to reinstate a list-context representation may be necessary to directly access earlier lists and avoid sampling recent-list intrusions (cf. Jang & Huber, 2008).

The present simulations made the key contribution of showing that including a list-context representation does not have to add complexity to the model's representational structures. Previous models implemented list- and item-context representations using hierarchical structures. Those models also included processes for reinstating each kind of context during recall. By contrast, the model including the PEPPR mechanism affords no special status to list-context representations. Both list and item contexts are elements on the same vector representation that are activated by external stimuli following the same rules. Consequently, list and item contexts change across the study period in the same way. In this sense, our model is a hybrid of Lohnas et al. (2015) and Jang and Huber (2008) that embeds list- and item-context reinstatement processes and preserves the parsimony of the Lohnas et al. (2015) model. That is, our simulations show that the basic mechanisms of context dynamics implemented in retrieved context models (Howard & Kahana, 2002; Polyn et al., 2009; Sederberg et al., 2008) are sufficient to account for the recall of both recent and non-recent memories without postulating new types of representations or retrieval mechanisms.

Broader Implications

Although we focused here on dual-list free recall, the computational principles embodied in the PEPPR model may be relevant to other interference-based paradigms and to research on group and individual differences in episodic memory associated with context processing.

List-before-last recall. Dual-list free recall is similar to the list-before-last paradigm (Shiffrin, 1970). However, one key difference is relevant to how a PEPPR mechanism would operate. In dual-list free recall, each trial includes two labeled study lists and test cues with the same labels. Providing labels supports cue specification, as the model assumes that study labels activate unique list-context representations and test prompts using those labels support the reinstatement of those representations. By contrast, the list-before-last paradigm does not include list labels and requires participants to track list order during study. Nonetheless, a PEPPR mechanism could still operate if different context representations are active during each list. Such representations could emerge from self-initiated strategies, like subvocalizing list numbers. Representations could also emerge incidentally. For example, off-task thoughts, such as thinking about future plans while waiting for a study list could become part of a distinguishable start-of-list context. This would allow subjects to reinstate that context at the start of recall. The mnemonic consequences of such study behaviors could be assessed via thought reports and overt rehearsals (Rundus, 1971; Ward & Tan, 2004) and externalized covert recalls with thought reports before the first retrievals at test.

A second key difference is that whereas the dual-list task presents both lists before recall, the list-before-last task requires recall after each list. Some have argued that interpolated recall induces context change that isolates lists, thereby counteracting retroactive interference (e.g., Jang & Huber, 2008; Pastötter, Schicker, Niedernhuber, & Bäuml, 2011; Sahakyan & Kelley, 2002). Lohnas et al. (2015)’s CMR2 model incorporated this notion by allowing larger context changes between lists separated by interpolated retrieval and was able to simulate the interpolated retrieval effects. One advantage of our approach in taking CMR2 as our starting point is that our model inherits CMR2’s ability to account for such effects. Indeed, a version of CMR2 with the PEPPR mechanism may be able to handle interpolated recall even more easily because PEPPER can directly reinstate list context thereby obviating the need to scan backward through List 2 across

subsequent retrieval attempts.

Serial recall. Serial recall of items in their original order requires initiating retrieval with a non-recent item—the least recent item in the most recent list. The list-context representation in the PEPPR model could be extended with minimal modifications to account for some aspects of serial recall. If a “start-of-list” context element was activated at the outset of study and allowed to fade as context evolves across subsequent items, earlier list items would be more strongly associated with this initial context. Therefore, reinstating the starting context would cue direct access to the first items of the list, leading to a primacy gradient in the serial position curve. This proposal is reminiscent of extant serial recall models with hierarchical representations (e.g. Farrell, 2012; Farrell & Lewandowsky, 2002). It is also consistent with evidence that free and serial recall rely on similar mechanisms (e.g., Bhatarah, Ward, & Tan, 2006; Brown, Chater, & Neath, 2008; Ward, Tan, & Grenfell-Essam, 2010). Clearly, much work is needed to make CMR2 a comprehensive model of serial recall, but the PEPPR mechanism may overcome one of the biggest challenges of developing such a model: how to avoid retroactive interference from recent items.

Standard free recall. A similar application of the PEPPR mechanism may also help retrieved context models account for the primacy effect in standard free recall. There is evidence that the primacy effect arises from recall being initiated from primacy positions and is modulated by subject-controlled factors. For example, subjects more often initiate recall from the first item when they attempt to recall all the items (Tan, Ward, Paulauskaite, & Markou, 2016; Ward & Tan, 2019). This suggests that subjects could use PEPPR to strategically initiate recall to satisfy task demands. Such findings may be accounted for by assuming that list-context representations are more strongly associated with earlier than later list items due to context updating across study events.

Other tasks that require access to specific memories. Thus far, we considered situations where recent items interfere with recall of non-recent items. But recency is not

the only impediment to accessing more distant memories. We propose that a PEPPR mechanism could potentially support access to task-relevant memories in various situations.

For example, classic context dependent memory effects in which memory is better if study and test occur in the same physical context (Godden & Baddeley, 1975) may partly depend on the extent to which a PEPPR mechanism can reinstate the study context. Consistent with this possibility, Smith (1979) showed that context-dependent retrieval requires mentally reinstating study context at test. They eliminated the benefits of physically reinstating the study context at test by asking subjects to mentally reinstate the original study context before being tested in a different physical context. Similarly, encouraging subjects to think back to extra-experimental experiences between two study lists can lead to greater forgetting of the first list, presumably because by inducing mental context change that isolates lists (Delaney, Sahakyan, Kelley, & Zimmerman, 2010; Pastötter & Bäuml, 2007; Sahakyan & Kelley, 2002). Models including a PEPPR mechanism could formally characterize the roles of context-based processes in these and similar effects of subject-controlled context reinstatement.

PEPPR may also be relevant when items must be encoded and accessed according to semantic context. For example, when exemplars from various categories are studied then retrieved, the same neural activity that differentiated categories during study can be reinstated to guide memory search. The degree of such reinstatement predicts the extent of category clustering during recall (Morton et al., 2013; Polyn, Natu, Cohen, & Norman, 2005), implicating a potential neural signature of PEPPR applied to semantic context. Another kind of semantic context is the value associated with items. Studies of value-based encoding show that items assigned higher values during study are better recalled (Castel, 2008) and recognized with more contextual detail (Hennessee, Castel, & Knowlton, 2017). This could reflect self-directed context statement to a “valuable” item category governed by a PEPPR mechanism. Indeed, a similar suggestion was made to account for variations in context-based retrieval across study items assigned different values (Stefanidi, Ellis, &

Brewer, 2018). Note also that when reinstating semantic context, subjects may repeatedly engage PEPPR after the initial recall attempt when the retrieved context does not automatically cue target memories. This could occur, for example, when transitioning recall to a new category after exhausting recall from another category or when subsequently recalling high-value items from more distant temporal contexts (i.e., non-adjacent input positions).

Individual and group differences. Individual differences in context processing have long been linked to differences in memory ability (Healey, Crutchley, & Kahana, 2014; Kane, Conway, Hambrick, & Engle, 2007; Sahakyan, Abushanab, Smith, & Gray, 2014; Unsworth & Spillers, 2010b), particularly in situations that require overcoming interference (Burgoyne & Engle, 2020; Hasher & Zacks, 1988; Healey, 2016; Kane & Engle, 2000; Unsworth & Engle, 2007). There have been few attempts to formally model these differences (Healey & Kahana, 2014; Lehman & Malmberg, 2013). Variation in the efficiency of the PEPPR mechanism may contribute to such associations. For example, people with better cognitive control abilities organize their retrieval from target contexts more efficiently. This has been shown in associations between working memory capacity and both context-based recall (Healey et al., 2014; Spillers & Unsworth, 2011; Wahlheim et al., 2019) and the selection of encoding and retrieval strategies (Unsworth, Miller, & Robison, 2019; Unsworth & Spillers, 2010a).

The principles of PEPPR may also provide insight into group differences. Differences in context processing have often been inferred from studies examining populations with impaired memory abilities, such as schizophrenia patients (Polyn et al., 2015), adults with high subclinical schizotypy symptoms (Sahakyan & Kwapil, 2016, 2018), children and adolescents at risk for schizophrenia (Imamoglu et al., under review), adolescents with ADHD (Gibson, Healey, & Gondoli, in press), and older adults (Wahlheim & Huff, 2015; Wingfield & Kahana, 2002). The memory impairments experienced by these group could partly reflect a dysfunctional PEPPR mechanism. For example, consider age-related

episodic memory deficits. Such deficits may reflect impaired self-initiated processing (Craik, 1983; Craik, Luo, & Sakuta, 2010), including strategic encoding (Dunlosky & Hertzog, 1998) and retrieval (Unsworth, 2017). Furthermore, these deficits may reflect a common underlying dysfunction in the processing of certain kinds of context processing (Farrell, 2012; Healey & Kahana, 2020; Wahlheim & Huff, 2015). PEPPR may provide a common thread to connect these perspectives by suggesting that pre-retrieval processing plays a central role in maintaining memory acuity under conditions of interference (also see, Morcom, 2016). A fruitful approach could be to correlate subject-level estimates reflecting the efficacy of PEPPR, such as β_{PEPPR} , with latent variable estimates of component memory and control processes associated with context processing and control over its reinstatement.

Conclusion

In summary, our current modeling efforts suggested that a front-end cue specification mechanism that uses task goals to drive context updating can promote direct retrieval of non-recent item representations under conditions of retroactive interference. We extended a retrieved-context model by adding a PEPPR mechanism that directly reinstates list-context representations. Importantly, including this mechanism allowed the model to predict precise measures of sampling and output dynamics that could not be accounted for when retrieval initiation was assumed to follow an iterative generate-recognize process starting from the end of the most recent list. Our model holds promise as it may account for cue dependent retrieval phenomena involving front- and back-end control processes that vary across populations with cognitive control differences. The present discovery represents the first step towards a larger enterprise aimed at integrating theoretical concepts, methods, and analytical approaches from the often disconnected but clearly complementary literatures on computational memory modeling and metacognition.

Acknowledgments

We thank Lynn J. Lohnas for many helpful discussions and Mitchell G. Uitvlugt for help producing the figures.

Declarations

Funding

This material is based upon work supported by the National Science Foundation under Grant No. 1848972.

Conflicts of Interest/Competing Interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics Approval

Approval was obtained from the ethics committee of Michigan State University.

Open Practices

Data and code used in this manuscript are available at
https://osf.io/kd9c5/?view_only=711e57606acc46b0a78bcfd5866776e6

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Figure 1. Schematic of the dual-list free recall paradigm from Wahlheim et al. (2017). Subjects studied two 10-item lists that were separated by a short break (i.e., a prompt indicating the start of List 2). At the end of the second list, they were instructed to recall from only List 1, only List 2, or both List 1 and List 2. Here, we focus on the condition where they were instructed to recall non-recent events from List 1, and therefore were tasked to overcome retroactive interference from List 2.

Figure 2. Mean number of items recalled (i.e., were reported *and* endorsed as coming from the target list) as a function of recall test instructions (i.e., recall List 1, List 2, or Lists 1 and 2) and actual list in which endorsed recalls were originally studied (List 1 or List 2). (A) Subject data from Wahlheim et al. (2017). Error bars are bootstrap 95% confidence intervals. (B) Best fitting simulated data from the Backward-Walk model. (C) Best fitting simulated data from the Post-Encoding Pre-Production Reinstatement (PEPPR) model.

Figure 3. Schematic of the evolution of feature and context representations as items appear, according to CMR2. The feature layer includes a node for each item that will be studied (three in this example), but for simplicity we show only the currently studied (second column). Corresponding nodes on the context layer (third column) represent the ensemble of contextual associates activated by that item. The two layers are connected by two associative weight matrices (not shown). One matrix stores feature-to-context associations and the other stores context-to-feature associations. When the first item, *river*, appears, its feature layer node is activated. This in turn activates its context representation by projecting through the feature-to-context matrix. This is illustrated by the river icon in the first row of the third column. The context representation of inactive items that have not yet appeared are shown as empty circles in that same row. When the next item, *money*, appears its feature layer node is activated, which then activates and becomes incorporated with its context representation so that both *river* and *money* are active on the context layer. This process then continues with each subsequent study item. Critically, as each new item is activated on the context layer, earlier item context activations decrease (i.e., context changes), illustrated here by the diminishing sizes of pictures moving down rows in the context layer.

Figure 4. Schematic illustrating how adding task-context representations to CMR2 alters the dynamics of encoding during study and memory search during free recall. All details match the CMR2 illustration in Figure 3, except that layers include representations of study items and task goals (e.g., to study List 1). When the prompt to study List 1 appears, it activates a *list 1* representation on the feature layer, which then activates a corresponding representation on the context layer. These *List 1* context representations and their corresponding item representations become less active with each new study item. When the recall period begins and the prompt to recall List 1 appears, it reactivates the *List 1* feature and context representations, allowing *List 1* context to serve as part of the retrieval cue for the first sampled item. Although all item contexts are active to some degree, the List 1 context is most active.

Figure 5. The top row shows predictions from the (A) Backward-Walk and (B) PEPPR models for the probabilities of sampling correct recalls from List 1 and intrusions from List 2 as a function of sampling position, conditional on an item actually having been recalled in that position.. The bottom row shows model predictions from (C) the Backward-Walk and (D) PEPPR models for the probabilities of rejecting sampled items (i.e., indicating that they are not from the study list) regardless of recall accuracy as a function of sampling position.

Figure 6. (A) Actual conditional probabilities of sampling correct recalls from List 1 and intrusions from List 2 as a function of sampling position. (B) Actual probabilities of rejecting sampled items (i.e., indicating that they are not from the study list) regardless of recall accuracy as a function of sampling position. Error bars are bootstrap 95% confidence intervals.

Figure 7. Simulated data from models fit directly to sampling and output data. The first column shows actual recall data. Error bars are 95% confidence intervals. The second column shows the best-fitting simulated data from the Backward-Walk model. The third column shows the best-fitting simulated data from the PEPPR model. The first row includes summary scores showing the mean number of items recalled (i.e., were reported and endorsed as coming from List 1) for each list. The second row shows the conditional sampling probabilities for correct recalls from List 1 and intrusions from List 2 regardless of whether responses were rejected as a function of sampling position. The third row shows the probabilities of rejecting sampled responses (i.e., indicating that they are not from the study list) regardless of whether responses were rejected as a function of sampling position.