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The Demise of Short-Term Memory Revisited: Empirical and Computational Investigations of Recency Effects

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In the single-store model of memory, the enhanced recall for the last items in a free-recall task (i.e., the recency effect) is understood to reflect a general property of memory rather than a separate short-term store. This interpretation is supported by the finding of a long-term recency effect under conditions that eliminate the contribution from the short-term store. In this article, evidence is reviewed showing that recency effects in the short and long terms have different properties, and it is suggested that 2 memory components are needed to account for the recency effects: an episodic contextual system with changing context and an activation-based short-term memory buffer that drives the encoding of item–context associations. A neurocomputational model based on these 2 components is shown to account for previously observed dissociations and to make novel predictions, which are confirmed in a set of experiments.

In recent years, the memory literature has seen an increased interest in theoretical accounts of serial-position effects in list memory (J. R. Anderson, Bothell, Lebiere, & Matessa, 1998; Haarmann & Usher, 2001; Howard & Kahana, 1999, 2002; Nairne, Neath, Serra, & Byun, 1997; Tan & Ward, 2000; Ward, 2002). This body of work, partially motivated by the controversy over the need to assume a short-term buffer in accounting for data in list memory, has centered on two versions of the free-recall paradigm: the immediate and the continuous-distractor free recall task (also known as the through-list distractor procedure).

In immediate free recall, participants are presented with a sequence of items and, after presentation of the final item, are required to report all items in any order. Compared with middle list items, the final few (or *recency*) items are reported with a higher probability. This finding has been called the *recency effect* (which in this article is referred to as *short-term recency*). The original explanation of the short-term recency effect was that at the start of the recall phase, the final few items reside in a capacity-limited short-term buffer, from which the items can be reported immediately. Subsequent items are then subject to a slower, probabilistic retrieval process from a long-term store (Atkinson & Shiffrin, 1968; Glanzer, 1972; Waugh & Norman, 1965).

This dual-store approach to human memory gained much support as several manipulations were identified that differentially affected recall performance for recency and prerecency (middle list) items (for a review, see Glanzer, 1972; for a critical discussion, see Wickelgren, 1973). For example, short-term recency was eliminated when participants were engaged in a distractor task (e.g., counting backward) after list presentation for as little as 15 s (e.g., Glanzer & Cunitz, 1966) or when participants were instructed to start the recall with items from the beginning of the list (Dalezman, 1976). The recall probability of prerecency items was not affected by these manipulations but was negatively affected by increasing the list length or presentation rate (Glanzer & Cunitz, 1966; Murdock, 1962; Raymond, 1969) and was prone to being affected by proactive interference (Craik & Birtwistle, 1971) and brain damage in amnesia (Baddeley & Warrington, 1970). These latter manipulations did not affect recency items.

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Later on, however, the dual-store approach to short-term recency was challenged when recency was obtained in situations in which the last items or events in memory should have been eliminated from the short-term buffer, both in real-life situations (Baddeley & Hitch, 1977; da Costa Pinto & Baddeley, 1991; Hitch & Ferguson, 1991; Sehulster, 1989) and in the experimental laboratory. In particular, long-term recency effects were observed in continuous-distractor free recall (Bjork & Whitten, 1974, Tzeng, 1973), which is identical to immediate free recall with the exception of including a distractor task before and after every item in the list. According to the dual-store approach, the distractor task following list presentation displaces the last list items, which are presumed to reside in the short-term buffer. Hence, a recency effect is not expected to be found. Given that a recency effect is found in continuous-distractor free recall, it follows that this *long-term recency effect* has a different source, most probably related to mechanisms of retrieval from the long-term store (but for a dual-store interpretation of the long-term recency effect, see Koppenaal & Glanzer, 1990; for a rebuttal of such an interpretation, see Neath, 1993a; Thapar & Greene, 1993).

The now-standard account of long-term recency is based on encoding and retrieval processes within a single memory store. This position can be understood to account for recency by assuming that the recall probability of an item is a function of the (global or local) distinctiveness of that item along a temporal (or perhaps positional) dimension (Crowder, 1976; Glenberg & Swanson, 1986; Nairne et al., 1997; Neath, 1993b). Operationally, the discriminability of an item can be defined as a function of the ratio between the temporal distance between two items (the interpresentation interval; IPI) and the temporal distance between the final item and the recall phase (the retention interval; RI). Indeed, Glenberg and colleagues (Glenberg, Bradley, Kraus, & Renzaglia, 1983) have shown that the logarithm of the ratio between IPI and RI predicts the slope of the best-fitting linear function over the last three serial positions (but see Nairne et al., 1997, who found with a constant IPI:RI ratio that the slope decreases with increases in distractor interval).

A more mechanistic account of both short-term and long-term recency effects within the single-store framework is based on the assumption that during the encoding phase, the episodic context changes and gets associated with currently presented items. At retrieval, the recall probability of an item is a function of the similarity between the test context and the context that was associated with that item during study (Dennis & Humphreys, 2001; Glenberg et al., 1980, 1983; Howard & Kahana, 1999, 2002; Mensink & Raaijmakers, 1988; see also Estes, 1955, 1997; Murdock, 1972). Recently, much progress has been obtained within the framework of models that show how contextual retrieval can mediate list memory (Howard & Kahana, 1999, 2002), providing a detailed account of both serial-position functions and contiguity effects (i.e., effects of *lag recency*, a measure based on the conditional probability for successive outputs; see the next section) in both immediate and continuous-distractor free recall. Remarkably, as these single-store theories provide a unifying account for the recency effects in both immediate and continuous-distractor free recall and their absence in delayed free recall (here and elsewhere, *delayed free recall* refers to recall of items following a distractor task; e.g., Glanzer & Cunitz, 1966), some theorists have gone so far as to proclaim the "demise of short-term memory" (Crowder, 1982; but for criticism, see Healy & McNamara, 1996; Raaijmakers, 1993).

In principle, the dual-store account of recency in immediate free recall is not inconsistent with a contextual retrieval account of long-term recency, as the two effects could be the products of different mechanisms. Nevertheless, as advocated by Crowder (1993), the principle of parsimony may require that "the burden of evidence should be with those who say these two, similar recency effects are caused by different mechanisms" (p. 143). In this article, we attempt to meet this challenge.

Because of the commitment to a single mechanism, single-store models tend to predict that experimental manipulations have equivalent effects on short- and long-term recency. Indeed, it has even been suggested that associations exist between the two tasks under the manipulation of variables such as semantic similarity, word frequency, and list length (Greene, 1986a; Greene & Crowder, 1984). Although these associations support the unitary view, there are at least four reasons to interpret them with caution. First, it is not at all clear that all dual-store models must predict a dissociation on all these variables (see Simulation 2).[1] Second, these associations constitute null effects, which are difficult to prove. Third, the variables have never been manipulated within a single study that examined both tasks. Therefore, differences in methodologies (design, material, or procedure) may have introduced confounds that masked possible dissociations. Fourth, contrary to Greene and Crowder's (Crowder, 1993; Greene, 1986a; Greene & Crowder, 1984) claims, over the years a number of dissociations between short- and long-term recency effects have been uncovered, as we describe below.

Although it is true that both immediate and continuous-distractor free recall reveal recency effects, in many studies the level of recall for the last few items is larger in immediate than in continuous-distractor free recall with a constant IPI:RI ratio (e.g., Howard & Kahana, 1999; Nairne et al., 1997; Poltrock & MacLeod, 1977). Furthermore, unlike long-term recency effects, short-term recency effects are sensitive to output order (Dalezman, 1976; Whitten, 1978). Moreover, short-term effects alone are insensitive to damage to the medial–temporal lobe (Carlesimo, Marfia, Loasses, & Caltagirone, 1996; see also the next section). Yet another dissociation is found when a final free recall task is required after a series of study lists. In immediate recall, a negative recency effect (lower recall for recency items compared with prerecency items) is found (Craik, 1970). Such an effect is absent in continuous-distractor free recall (e.g., Bjork & Whitten, 1974). Finally, even though recently developed contextual retrieval theories account for contiguity effects (measured by conditional response probabilities for successive recalls; Kahana, 1996), these

[1] The idea that lexical and semantic variables affect only the long-term memory component is a conclusion of a specific interpretation of the original dual-store model (Atkinson & Shiffrin, 1968, 1971), which viewed the short-term buffer as purely phonological and thus unaffected by lexical–semantic variables. The more general dual-store model ("the modal model"; Murdock, 1967) was not committed to this assumption, the buffer being seen as central to conscious thoughts and thus necessarily having a lexical–semantic content. More recently, the existence of lexical–semantic content within the buffer has been explicitly suggested in neuropsychological studies (R. C. Martin et al., 1994; Romani & Martin, 1999; see also Haarmann & Usher, 2001, and the General Discussion).

theories are silent to the observation that these effects differ between immediate and continuous-distractor free recall for the first few output positions (see the next section; see also Howard & Kahana, 1999; Kahana, 1996).

In this article, we argue that now, after a number of powerful single-store theories have taken into account the objections against dual-store models (see Crowder, 1982; Greene, 1986b; Howard & Kahana, 1999) and have highlighted the important contribution of contextual retrieval in list memory (Glenberg & Swanson, 1986; Howard & Kahana, 1999, 2002), it may be time to explore whether a theory that combines a contextual retrieval component with an additional short-term store component might provide an even more comprehensive account of serial-position effects in list memory. In particular, such a combined *context–activation theory* might be able to explain the dissociations that have been observed between short- and long-term recency effects.

A combined theory including two components (i.e., a short-term buffer and a changing episodic context) has previously been developed by Mensink and Raaijmakers (1988) but has not been used to account for data in the continuous-distractor task. In this article, we present a computational context–activation model based on similar components to account for serial-position effects in list memory, focusing on the dissociations between short- and long-term recency as well as on lag-recency effects (which are described in the next section). More important, the model predicts a novel dissociation between short- and long-term recency, on the basis of a manipulation of proactive interference.

Although similar to the Mensink and Raaijmakers (1988) model, our model implements the short-term buffer in terms of activation levels rather than through the use of a box metaphor with a fixed number of slots. In this model, items are removed from (being deactivated in) the buffer because of mutual inhibition with newly entered items. This implementation allowed us to address the internal dynamics of the buffer, thereby leading to a second prediction involving a shift from recency to primacy with an increase in the presentation rate. The predictions of a dissociation on the basis of proactive interference and of a shift from recency to primacy were tested in two experiments.

The model we present here applies to a number of tasks that measure item information in list memory. Among them are primarily the free-recall task and its related versions (immediate, delayed, and continuous-distractor recall), all of which have played a central role in earlier investigations. In addition, as we show, the model applies to the cued-recall paradigm (Waugh, 1970; Waugh & Norman, 1965). Although we did not attempt here to model in detail control processes and semantic effects, we indicate how the model can address such processes (see the Utility of the Dynamic Buffer section). In the General Discussion, we examine how the model can be extended beyond accuracy data to address response latencies. At the outset we note that our model does not address serial-order recall, which we see as involving additional processes that are not part of the current model, such as rehearsal and phonological encoding.

The remainder of this article is organized as follows. First, we outline some relevant data that we believe require a dual-store explanation. We then present our combined context–activation model and discuss its account of recency and lag-recency effects in immediate and continuous-distractor free recall and of the dissociations discussed above. Subsequently, we examine the model's predictions and report the experimental tests, and finally, we explore the properties of the activation buffer and its function in memory control.

Critical Data

There is a large database of findings that can inform a theory of list memory. Here, we focus on those that are relevant (and perhaps critical) to the debate regarding the need for postulating a second component (e.g., a short-term store or an activation component) above and beyond a contextual retrieval component (e.g., episodic long-term memory). These effects involve dissociations between immediate and continuous-distractor free recall that have been documented over the years, some of which may not have received enough attention in the memory literature. The effects include output-order effects on serial-position functions (Dalezman, 1976; Whitten, 1978), dissociations due to amnesia (Carlesimo et al., 1996), negative recency effects (Craik, 1970), and output-position effects on lag recency (Howard & Kahana, 1999; Kahana, 1996). Additional dissociations have also been reported, raising further challenges for single-store models (for a review, see Cowan, 1995; for supporting neuroimaging data, see Talmi, Grady, Goshen-Gottstein, & Moscovitch, in press). However, we do not focus on these additional dissociations, as they involve serial-order recall and modality effects, which are beyond the scope of the current study.

Dissociation I: Directed Output Order

In both immediate and continuous-distractor free recall, participants are free to recall the items in any order. However, in immediate free recall, participants typically recall items from the end of the list before reporting other items (Dalezman, 1976; Howard & Kahana, 1999; Kahana, 1996; Nilsson, Wright, & Murdock, 1975). This pattern is not always found in continuous-distractor free recall (Bjork & Whitten, 1974; but see Howard & Kahana, 1999). Of importance, when instructions are used to manipulate the order of recall—starting with items from the end (*end first*) or beginning (*beginning first*) of the list—a dissociation is found between immediate and continuous-distractor free recall (see Figure 8 with model simulations). In immediate free recall, short-term recency is present under end-first instructions (and does not differ from standard immediate free recall) but is absent under beginning-first instructions (Dalezman, 1976). In contrast, long-term recency is present both under end-first instructions and under beginning-first instructions (Whitten, 1978; and under both sets of instructions, does not differ from performance in standard continuous-distractor free recall; cf. Bjork & Whitten, 1974). This dissociation led one of the original discoverers of the long-term recency effect to suggest that "it seems most reasonable to search for different explanations for short-term and long-term recency effects" (Whitten, 1978, p. 690). We embrace this suggestion.

Dissociation II: Amnesic Syndrome

A neuropsychological dissociation strengthens the conclusion that short- and long-term recency rely on different cognitive processes (Carlesimo et al., 1996). Carlesimo and colleagues (Carlesimo et al., 1996) showed that the absolute immediate free recall performance of the last three (i.e., most recent) serial positions of a 10-word list did not differ between amnesic patients and healthy control participants (see also Baddeley & Warrington, 1970; Capitani, Della Sala, Logie, & Spinnler, 1992). However, performance for prerecency positions in immediate free recall and for all serial positions, including recency positions, in continuous-distractor free recall was lower for the patients compared with the control participants (see Figure 7 with model simulations).

Dissociation III: Negative Recency

A dissociation in performance between immediate and continuous-distractor free recall that has been ignored in the literature is the negative recency effect (i.e., worse recall performance for recency compared with prerecency items) in final free recall. In immediate free recall, if participants are given an unexpected final free recall task at the end of the experiment and are asked to report words from all the lists they previously studied, worse memory is found for the items that occupied the last positions in the original lists. The worse memory for the last items is labeled the "negative recency effect" (Craik, 1970). The finding of negative recency has been replicated many times and with different immediate memory paradigms (e.g., R. L. Cohen, 1970; Craik, Gardiner, & Watkins, 1970; Engle, 1974; Madigan & McCabe, 1971).

A common dual-store interpretation for the negative recency effect is that recency items are in the buffer for a relatively shorter duration than are prerecency items and, therefore, have less time to be episodically encoded. In the final recall test, only the episodic traces contribute to performance, and thus the recency items are at a relative disadvantage and are more poorly recollected. In contrast, a test of final free recall after a series of continuous-distractor trials does not produce negative recency (e.g., Bjork & Whitten, 1974; Glenberg et al., 1980; Koppenaal & Glanzer, 1990; Tzeng, 1973; Whitten, 1978).

Dissociation IV: Interaction of Task and Output Position on Lag Recency

Kahana (1996) showed that recall transitions follow a robust contiguity (lag-recency) pattern. That is, the probability of recalling item j immediately after recalling item i was larger when the words (i, j) were more contiguous, that is, when the lag, $|i - j|$, between the presentations of both items in the study sequence was smaller. In addition, this *lag-recency effect* was found to be asymmetric, such that forward transitions were more likely than backward transitions (i.e., after recall of item i, item $i + 1$ was more likely to be recalled than item $i - 1$). The presence of a lag-recency effect in immediate, delayed, and continuous-distractor free recall motivated Howard and Kahana (1999, 2002) to develop a single-store model that accounts for all these effects (but see Kahana, 1996, who used a short-term buffer to interpret lag-recency effects in immediate free recall).

However, despite the impressive success of Howard and Kahana's (1999, 2002) theory in accounting for data patterns in immediate and continuous-distractor free recall, one aspect of the data on lag recency has not yet been explained. In delayed and continuous-distractor free recall, the lag-recency effect is independent of the output position. In immediate free recall, however, the asymmetry is stronger for the first few recall transitions (Kahana, 1996; Kahana, Howard, Zaromb, & Wingfield, 2002), suggesting a different underlying mechanism. Specifically, in immediate free recall, participants typically start with an item that was presented two or three positions before the end of the list, and then recall proceeds in the forward direction (Kahana, 1996; Laming, 1999). This interaction between task, output position, and lag recency can be explained if one assumes a short-term buffer from which the initial few items in immediate free recall are retrieved in the order in which they entered the buffer (with the oldest item being retrieved first; Davelaar, 2003; Howard & Kahana, 1999; Kahana, 1996).

In summary, we believe that to account for the different dissociations between recency and prerecency items, the existence of a short-term buffer must be assumed. According to this assumption, items that reside in the buffer at the end of the encoding phase are negatively affected by a beginning-first recall, are unaffected in amnesic patients, are less episodically encoded (leading to patterns of negative recency in final recall), and are reported in a predominantly forward manner.

Expected New Dissociation: Proactive Interference

As mentioned in the introduction, several variables, such as list length, presentation rate, word frequency, semantic similarity, and proactive interference affect immediate free recall performance of prerecency but not of recency positions (Craik & Birtwistle, 1971; Glanzer, 1972). Although some of these variables have been reported to have similar effects in continuous-distractor free recall (Greene, 1986a; Greene & Crowder, 1984), we focus here on the manipulation of proactive interference, whose effect has not yet been investigated in continuous-distractor free recall and is theoretically predicted to dissociate the two tasks.

Proactive interference is the observation of a negative correlation between recall performance and the number of preceding trials. Proactive interference is especially large when the items of previous and current trials belong to the same category (Wickens, 1970). The effect of proactive interference in immediate free recall was demonstrated in a study by Craik and Birtwistle (1971) in which participants performed five trials with 15 words per list. All 75 words came from the same semantic category (e.g., animal names). The results showed that recall probability for the items in the list became lower as the lists progressed. Of importance, the recall of the last 6 items in the list (but not of earlier items) was unaffected by proactive interference. Thus, the manipulation of proactive interference dissociated memory for prerecency and recency items. This dissociation was explained in terms of the last items being in the short-term buffer, thereby rendering them immune to proactive interference.

Craik and Birtwistle (1971) approximated the contributions of retrieval from the short- and the long-term stores and found that proactive interference affected only the retrieval from the long-term store. This is consistent with the views that proactive interference is due to competition from related items in previous trials (which are encoded in episodic memory) on the retrieval of items in the current trial (e.g., Wixted & Rohrer, 1993) and that proactive interference does not affect the capacity-limited short-term buffer, as it is found for supra- but not for subspan lists (Halford, Maybery, & Bain, 1988). Because in continuous-distractor free recall all items are retrieved from the long-term store, we expect that all

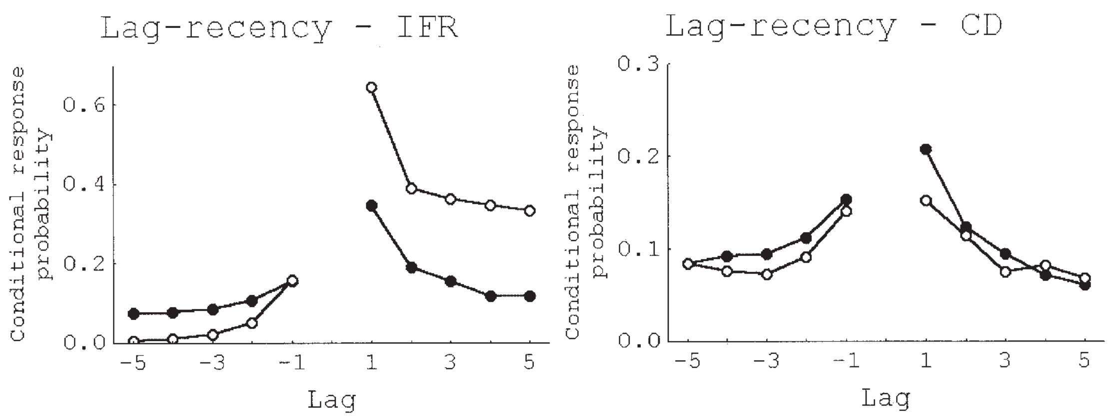

Figure 11. Lag-recency functions for immediate free recall (IFR; left) and continuous-distractor free recall (CD; right). Lines with solid circles represent lag-recency functions computed over all output positions, and lines with open circles represent lag-recency functions of the first-recall transition.

The second dissociation is the decreased recall performance for recency items in continuous-distractor free recall but not in immediate free recall in amnesic patients. The model explains these results in terms of the difficulties that amnesic patients have in episodic memory processes like encoding and retrieval while having an intact short-term buffer (Baddeley & Warrington, 1970). In continuous-distractor free recall, all items are retrieved from episodic memory and are, therefore, affected in amnesic patients. In immediate free recall, however, only the prerecency items are affected, as they are the ones that are retrieved from episodic memory, whereas the recency items reside in the intact short-term buffer.

The third dissociation between immediate and continuous-distractor free recall is that in a final free recall task, a negative recency effect is found for immediate free recall but not for continuous-distractor free recall. To account for this finding, the model suggests that in final free recall, retrieval relies on the strength of the episodic traces that have been laid down during study. Because in continuous-distractor free recall the strengths of all traces are equal, a negative recency effect is not found. In immediate free recall, however, the strengths decrease toward the end of the list, leading to negative recency. Moreover, in immediate free recall, the contextual contribution to recency is not sufficiently strong to override the negative recency profile in the strengths of final list items.

The fourth dissociation is that lag-recency functions differ across the first output positions in immediate but not in continuous-distractor free recall. The model captures this dissociation by assuming that items in the buffer in immediate free recall are reported in a predominantly forward manner according to their episodic strengths. However, in the continuous-distractor task the buffer does not play any role and all traces are of equal strength. Therefore, the model does not predict any such interaction between output position and lag recency.

The reported results form a double dissociation between short- and long-term recency, for which our model provides a parsimonious account by assuming a critical contribution made by a short-term buffer. Indeed, these dissociations, together with the dissociation that is described in Experiment 1, meet the challenge set forth by Broadbent (1971), who pointed out that

> In general, one must be aware of concluding that the appearance in short-term memory of an effect known from longer-term studies is evidence for identity of the two situations. . . . Only success or failure of attempts to show differences between the two situations is of interest in distinguishing the theories. (pp. 342–343)

Given that our context–activation model has accounted for the critical data, we now turn to describe two further predictions that rely on the postulated existence of a short-term buffer.

Predictions of the Model

Proactive Interference

The neuropsychological dissociation between short- and long-term recency was localized at the episodic component that is used to retrieve prerecency items. The buffer component is postulated to be intact, and therefore, the short-term recency effect is spared. As discussed in the introduction, another effect that is present for prerecency but not for recency items in immediate free recall is proactive interference (Craik & Birtwistle, 1971). Dual-store theories can account for this finding by assuming that, as in the amnesic syndrome, proactive interference affects the retrieval from the long-term store. As such, the short-term recency effect, which is due to unloading from the short-term buffer, should be unaffected by proactive interference. With regard to continuous-distractor free recall, all items are retrieved from the long-term store, and so proactive interference was predicted to occur at all serial positions, including recency positions.

We simulated 1,000 pairs of trials in immediate and continuous-distractor free recall. In each pair, the start context for the second trial was the context that was active at the end of the retrieval of the first trial. There are two sources for proactive interference in the model. First, items in the two lists can be associated with the same context unit (because the random walks overlap), and the item–context associations formed during encoding of List 1 items

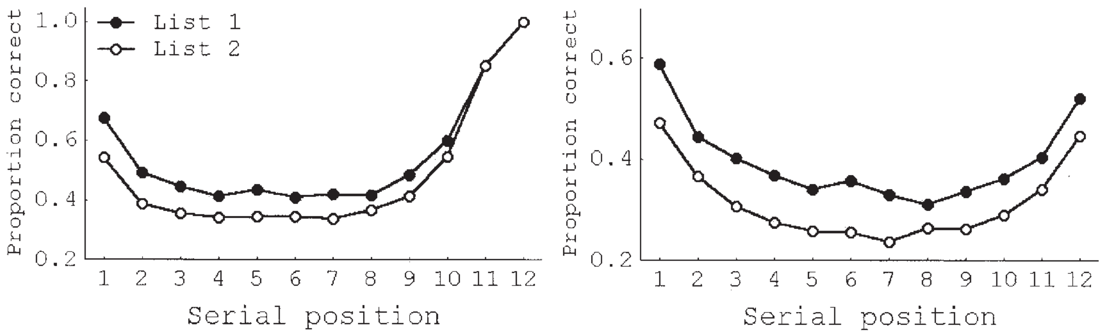

Figure 12. Model predictions for the presence of proactive interference in immediate free recall (left) and continuous-distractor free recall (right). The serial-position function of List 2 is compared with that of List 1 and shows that the proactive interference manipulation affects recency positions only in the continuous-distractor task.

were maintained during the encoding of List 2 items. As a result, during episodic retrieval of List 2 items the context units used to retrieve List 2 items may also retrieve those items from List 1 with which they are associated. Second, in typical proactive interference experiments, all items are drawn from the same semantic category. To simulate this, during the selection and recovery stages of retrieval,[11] we gave all items an additional semantic input (the contribution was chosen to be about one third of the typical episodic trace strength). Both sources lead List 1 items to intrude during retrieval of List 2 items (see Appendix A for the simulation protocol).

As can be seen in Figure 12, in immediate free recall, the model exhibits proactive interference for prerecency positions but not for recency positions. In contrast, in continuous-distractor free recall, the model shows proactive interference at all positions including the recency positions. The model, therefore, predicts another dissociation between short- and long-term recency, which forms a conceptual analogue to the neuropsychological dissociation above, in that both dissociations are based on a variable that affects retrieval from the long-term store.

A related prediction of the model concerns the conditions under which the dissociation as a function of proactive interference should emerge. Our model predicts that the dissociation with proactive interference should not be found if recall begins with items from the beginning of the list (the beginning-first condition) but should be found if recall begins with items at the end of the list. The reason for this is that when recall starts with items from the beginning of the list, recency items are recalled only relatively late in the recall phase and hence, if in fact recalled, are retrieved only from episodic memory. Figure 13 shows simulation results of the effect of proactive interference on the immediate recall of two lists when recall starts with items presented at the beginning of the list (all parameters were the same as those in the previous simulations). Critically, the recency effect is absent in this beginning-first condition (which is in accordance with the analysis under Simulation 3). That proactive interference is not present in immediate free recall in the end-first condition, even for recency items, places an important constraint on the conditions for which a dissociation between short- and long-term recency is observed with proactive interference—that is, this dissociation is observed only when recency items are recalled first.

Presentation Rate

When exploring the parameter space of the activation-based buffer, we noticed that the model predicts an interaction between presentation rate and serial position: a shift from recency to primacy with an increase in presentation rate. Here, we describe the mechanism that we argue to be responsible for this shift. To illustrate this shift, we ran 1,000 simulation trials with lists of 12 items for four different presentation durations, in which presentation duration corresponded with the number of iterations that an item representation receives sensory input. We kept the other parameters the same as in the other simulations and disabled the episodic component in order to detect the pure contribution of the buffer. As the episodic component contributes very little at fast presentation rates, the results (for fast presentation rates) do not change when the full model (buffer plus episodic component) is used. However, at slow presentation rates, the episodic component is expected to add a baseline to recall performance that is independent of the shift from recency to primacy. Here we focus only on the buffer prediction involving this shift.

Figure 14 shows serial-position functions of the probability that an item is in active memory at time of test for the different presentation rates. This may correspond to a test of cued recall (if the cue uniquely specifies the item) or to a hypothetical test of free recall in which all active items could be reported. What is immediately striking is that with an increase in presentation rate, the recency profile turns into a primacy profile. Note that this primacy profile is not due to episodic encoding or retrieval (as in immediate free recall under a slow presentation rate) but has its source solely within the short-term buffer.

The mechanism responsible for the shift from recency to primacy in the model can be understood as follows. Activated representations corresponding to items presented in the memory list compete with each other because of the global inhibition in the buffer. Therefore, because it takes time to build up activation, the maximum activation level that each item can reach depends on the presentation duration. With a slow presentation rate (see Figure 15, top), each item can

[11] Because all list items belong to the same semantic category, we decided to add a general category bias rather than include interitem associations (α_2), as they are effectively equivalent.

overcome the inhibition of preceding active items, reaching a higher level of activation, and eventually displace earlier items from the buffer. With a faster presentation rate (see Figure 15, bottom), however, less time is available for each item to reach the level of activation of the preceding items, leading to a relative disadvantage for later items compared with preceding items. Therefore, early items are not displaced by later items, leading to a primacy profile.

The shift from recency to primacy as function of the presentation rate is in stark contrast to the predictions of a whole family of models that view recency in list memory as a characteristic of the retrieval process based on temporal discriminability (Crowder, 1976; Neath, 1993b; Tan & Ward, 2000; Ward, 2002). Although these models may show some sensitivity to presentation rate, they do not predict such a dramatic shift. In fact, the default assumption of temporal discriminability models is that recall is determined by the temporal scale–invariance ratio rule (Crowder, 1976; Neath, 1993b). Accordingly, recall is a function of the ratio of the durations of the IPI and the RI at the end of the list, which are unaffected by presentation rate. The recency-to-primacy shift also contrasts with buffer models that use a first-in, first-out (knock-out model; Kahana, 1996; Philips, Shiffrin, & Atkinson, 1967) or random (Kahana, 1996; Raaijmakers & Shiffrin, 1980, 1981) displacement process. In these models, the buffer is insensitive to presentation rate and always contains the most recently presented items (for further discussion of these issues, see the Utility of the Dynamic Buffer section).

Experimental Tests

The first experiment addressed the model's prediction of a dissociation between short- and long-term recency with proactive interference. The second experiment focused on the prediction of an interaction between presentation rate and serial position. As discussed below, both predictions were confirmed.

Experiment 1: Proactive Interference

As discussed in the introduction, proactive interference has been found to affect prerecency items only in immediate free recall (Craik & Birtwistle, 1971). One interpretation of this result is that proactive interference affects only items that are retrieved from episodic memory. Specifically, the retrieval of prerecency List 2 items is negatively affected by intrusions of List 1 items, both of

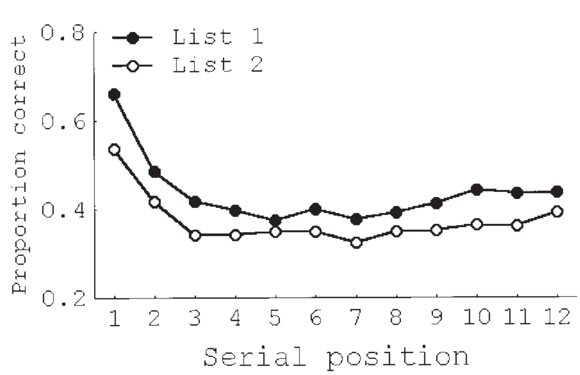

Figure 13. Model predictions of proactive interference in immediate free recall under beginning-first instruction. Note that the recency effect is eliminated and that proactive interference occurs even at recency positions.

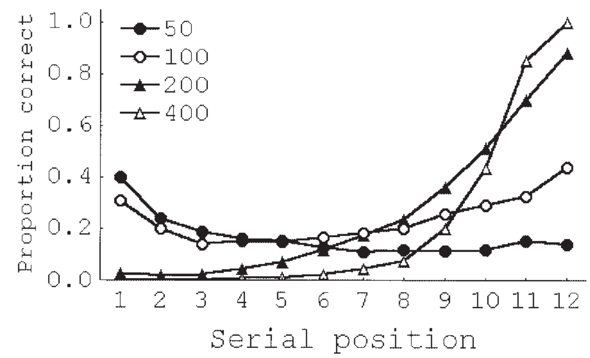

Figure 14. Model predictions for the effect of presentation rate on the serial-position profile for four rates (measured by the number of iterations per item). Profiles represent the probability that an item at that position is active above threshold at test.

which are retrieved from episodic memory. The recency List 2 items, however, are immune to proactive interference, because these items are unloaded from a short-term buffer that is not affected by proactive interference. According to this interpretation, in continuous-distractor free recall, in which all items are retrieved from the episodic system, proactive interference should affect performance at all serial positions, even for recency items. This was indeed the prediction of our model. Hence, a dissociation is predicted between short- and long-term recency.

Although we found no explanation of Craik and Birtwistle's (1971) findings by single-store theorists, proponents of such a view might argue for a different interpretation of the proactive interference dissociation between recency and prerecency items in immediate free recall, leading in turn to a different prediction concerning the effect of proactive interference in the continuous-distractor task. According to this hypothetical interpretation, in immediate free recall, recency items may be immune to proactive interference not because they are unloaded from a short-term buffer but because of their high level of temporal distinctiveness (Bjork & Whitten, 1974; Crowder, 1976; Glenberg et al., 1983). One should then expect no dissociation with proactive interference between immediate free recall and the continuous-distractor task because in both tasks, recency items are temporally distinct.

It is unclear at the moment whether such a temporal distinctiveness interpretation can indeed be supported by computational models of temporal context, because it is not a priori obvious that the higher overlap between the retrieval context and the encoding context of recency items would render these items immune to proactive interference. Indeed, our particular context–activation model, in which the temporal context component is responsible for long-term recency, predicts that recency items should not be immune to proactive interference in the continuous-distractor task.[12] Still, we do not want to exclude the possibility that a different model of contextual retrieval could be formulated that would show immunity from proactive interference at recency in both immedi-

[12] In our model, the random walk of the context and the switch to the start context during retrieval lead to contextual overlap between items in consecutive lists. This in turn leads to intrusions of List 1 items during retrieval of List 2 items.

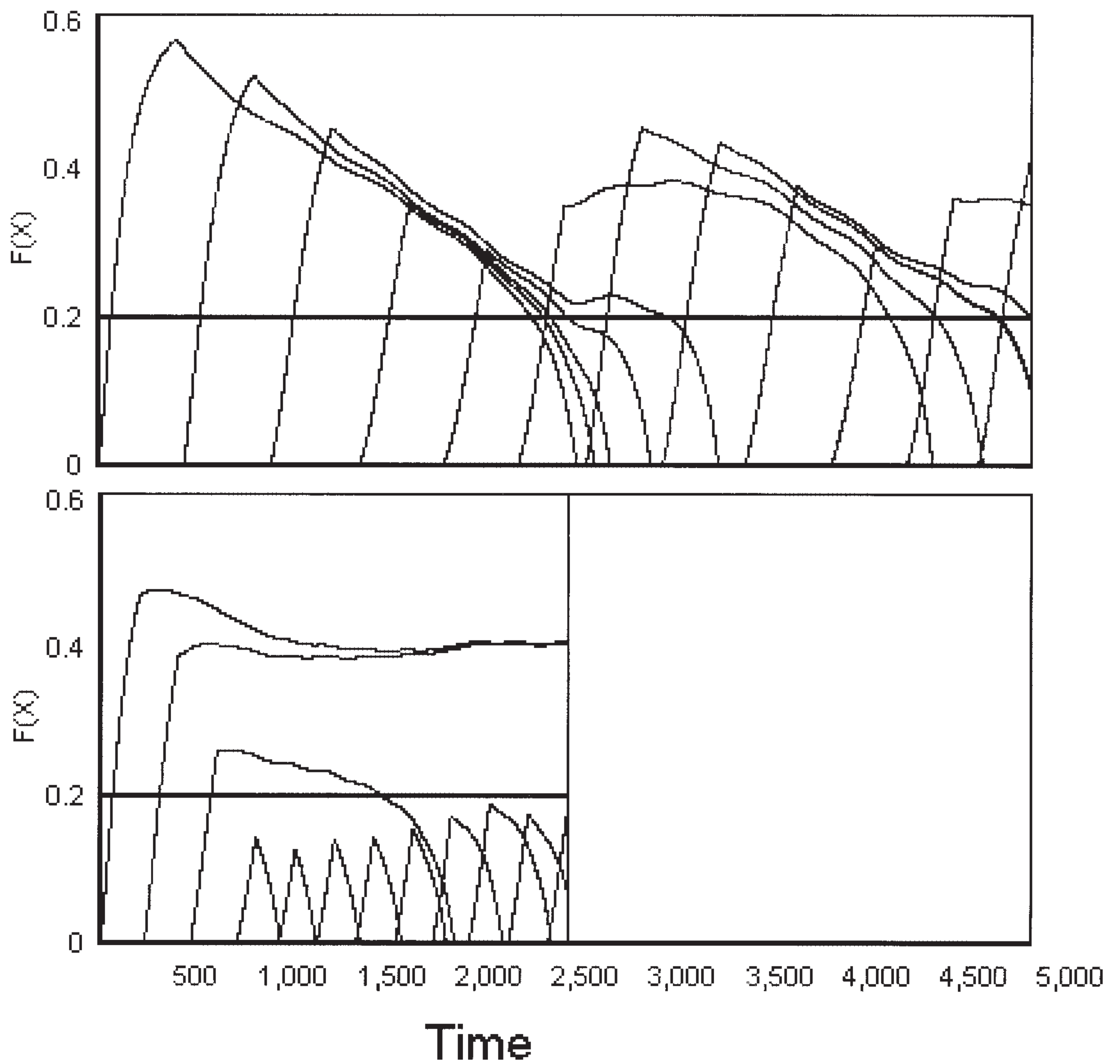

Figure 15. Activation trajectories for two presentation durations. Top: Slow presentation rate (400 iterations per item). Bottom: Fast presentation rate (200 iterations per item). F(x) = output activation value.

ate free recall and the continuous-distractor task without relying on a short-term buffer. Therefore, our manipulation of proactive interference (in two tasks within the same experiment) is important, not only for verifying the validity of our model but also to constrain future models of list memory that address the debate regarding the existence of a short-term buffer in immediate free recall.

In summary, the purpose of Experiment 1 was to determine whether temporal context is a general mechanism underlying both short- and long-term recency effects that can render recency items immune to proactive interference. An association between short- and long-term recency (in terms of the effect of proactive interference) would, therefore, support a single-store model of memory. Alternatively, temporal context may provide an incomplete account for recency effects, and a short-term store needs to be added to account for dissociations in recency effects in immediate and continuous-distractor free recall. A dissociation between the two tasks (in terms of the effect of proactive interference) would, therefore, support a dual-store model of memory and, in particular, a context–activation type model.

In a pilot study, Goshen-Gottstein, Ashkenazi, and Usher (2000) manipulated the task (immediate vs. continuous-distractor free recall) between participants and used an IPI:RI ratio of 10:30 in continuous-distractor free recall. A significant triple interaction (Task × List × Position) was obtained (experimental design and data graphs are available from http://freud.tau.ac.il/~goshen/data.htm), with proactive interference affecting only prerecency items in immediate free recall but affecting both prerecency and recency items in continuous-distractor free recall. In the pilot study, the number of possible confounds in design, materials, and procedure was kept to a minimum through the use of both tasks in a single study. Still, the IPI:RI ratio was close to unity in immediate free recall but was smaller than unity in the continuous-distractor task, and this confound may have mediated the dissociation. Also, it is possible that despite the random allocation procedure, participants who were allocated to the continuous-distractor task were more susceptible to proactive interference than were those who were allocated to the immediate free recall task (for research on individual differences in the susceptibility to proactive interference, see Kane & Engle, 2000). To overcome the earlier criticisms, in the current experiment we used a within-subjects design and set the IPI equal to the RI in the two tasks. Following the typical procedure of proactive interference studies (e.g., Craik & Birtwistle, 1971), we used lists of words chosen from the same semantic categories in consecutive trials, as this manipulation was shown to increase proactive interference.

Method

Participants. A total of 31 Tel-Aviv University undergraduates, ages 22–28 with normal or corrected-to-normal vision, participated in the experiment for course credit.

Design and materials. The design crossed the within-subject factors task (immediate and continuous-distractor free recall), position (1–12), and list (first, second). The two tasks were presented in separate blocks, with the order of the blocks counterbalanced across participants.

There were 10 pairs of critical lists (for a total of 20 lists), 5 pairs for each task. One additional pair of practice lists preceded each of the blocks. All lists contained 12 words. To maximize proactive interference between the first and second lists, we created each pair of lists such that it contained words from the same semantic category. To minimize interference across list pairs, we ensured that the semantic categories of each pair were unique and differed not only from other list pairs but also from the practice-list categories (i.e., release from proactive interference; Wickens, Born, & Allen, 1963). The two practice trials contained words from different semantic categories to acquaint participants with changes in the semantic category.

The 10 pairs of lists were separated into two different sets, with each set containing 5 different pairs of critical lists. The two sets were counterbalanced across participants so that each set appeared an equal number of times in immediate and continuous-distractor free recall. The order of the lists (i.e., List 1, List 2) within the pairs was also counterbalanced, such that across participants each list appeared an equal number of times as the first list and as the second list in both tasks. The words within each list were randomized for each participant. All the words were recorded in a male voice and were judged by two judges for clarity. The volume of the auditory presentation was kept constant during the entire experiment (measured at 45–55 dB).

For the continuous-distractor task, the distractor activity consisted of solving mathematical problems for 15 s following the presentation of each of the words as well as prior to the presentation of the first word (i.e., IPI = RI = 15 s). The problems consisted of the addition or subtraction of two single-digit numbers (e.g., $3 + 4 =$) that were displayed on the computer monitor, for which the result was always a positive value between 1 and 9. The numbers were presented in 48-point font.

Procedure. The instructions of the immediate free recall task and the continuous-distractor task were presented on the monitor and read aloud by the experimenter prior to administration of the corresponding task. For both tasks, participants were told that they would hear a number of lists of words presented by the computer. Prior to hearing any list, they were told which category the items belonged to (e.g., "The following list includes names of vegetables").

For the continuous-distractor task, participants were told that immediately after the presentation of each word (and prior to the presentation of the first word), mathematical problems would be displayed on the monitor, one immediately after the other. The position of the problem alternated between 2.5 and 3.0 cm from the top of the screen (and was centered horizontally). Participants were asked to read aloud the problems and to state the solutions (verbally and by typing on the numerical keypad) to as many of the problems as possible. Each mathematical problem was displayed separately and remained on the screen either until the answer was typed or until the next word was delivered, whichever came first. It was emphasized that the mathematical task and the memory task were both important and that for the mathematical task, speed and accuracy were equally important.

After the final word (immediate free recall) or problem (the RI of the continuous-distractor free recall), the word *recall* appeared on the computer screen, prompting the participant to write down as many of the words that he or she could recall within 1 min on a blank page given by the experimenter (one page per list). Participants were not informed of the practice lists, and as far as they knew, all of the lists were test lists.

During the retrieval interval, a small clock that appeared on the lower side of the monitor showed the remaining time for the retrieval interval. At the end of each retrieval interval, the experimenter took the paper from the participant, and the following category name was announced (e.g., "The following list includes names of vegetables"). Immediately afterward, the participant pressed a key to start presentation of the next list.

Results

The simulations indicated that the dissociation between short- and long-term recency would be largest when recall starts with items from the end of the list. As such, only those trials (i.e., pairs of lists) in which participants started with items from the second half of the list on both lists (henceforth, *useful trials*) were included in the analysis. This procedure led to differences in the number of useful trials that participants contributed in each of the tasks. To overcome disproportionate contributions, we weighted every participant according to the lowest number of useful trials between the two tasks. For example, a participant who contributed four out of five useful immediate free recall trials and three out of five useful continuous-distractor free recall trials was weighted at 3.

The participants in the continuous-distractor group performed almost at ceiling on solving the math problems. Figure 16 presents descriptive serial-position curves, which, for the purpose of presentation, were smoothed by averaging each score with the preceding and following scores (in the actual analysis, the raw data were analyzed). Examination of Figure 16 reveals that the overall level of performance on the second list was lower than that on the first, in both tasks, establishing that we were successful in inducing proactive interference. In addition, only the recency positions in immediate free recall were unaffected by proactive interference.

The weighted contributions were submitted to a 2 (task) × 2 (list) × 12 (position) mixed analysis of variance (ANOVA). This yielded significant main effects of task, $F(1, 63) = 23.35$, $MSE = 0.173$, $p < .001$; list, $F(1, 63) = 76.65$, $MSE = 0.064$, $p < .001$; and position, $F(11, 693) = 68.88$, $MSE = 0.054$, $p < .001$. Of the interactions, only the interaction between task and list was marginally significant, $F(1, 63) = 3.86$, $MSE = 0.050$, $p < .055$, whereas all other interactions were significant: Task × Position, $F(11, 693) = 3.77$, $MSE = 0.054$, $p < .001$; List × Position, $F(11, 693) = 2.15$, $MSE = 0.056$, $p < .05$; and Task × List × Position, $F(11, 693) = 2.71$, $MSE = 0.056$, $p < .001$.

When the averaged recall performance for the middle (Serial Positions 5–8) and end (Serial Positions 9–12) clusters were submitted to the same analysis, all main effects remained significant: task, $F(1, 63) = 25.86$, $MSE = 0.026$, $p < .001$; list, $F(1, 63) = 39.18$, $MSE = 0.016$, $p < .001$; and cluster, $F(1, 63) = 279.96$, $MSE = 0.028$, $p < .001$. Of the two-way interactions, only

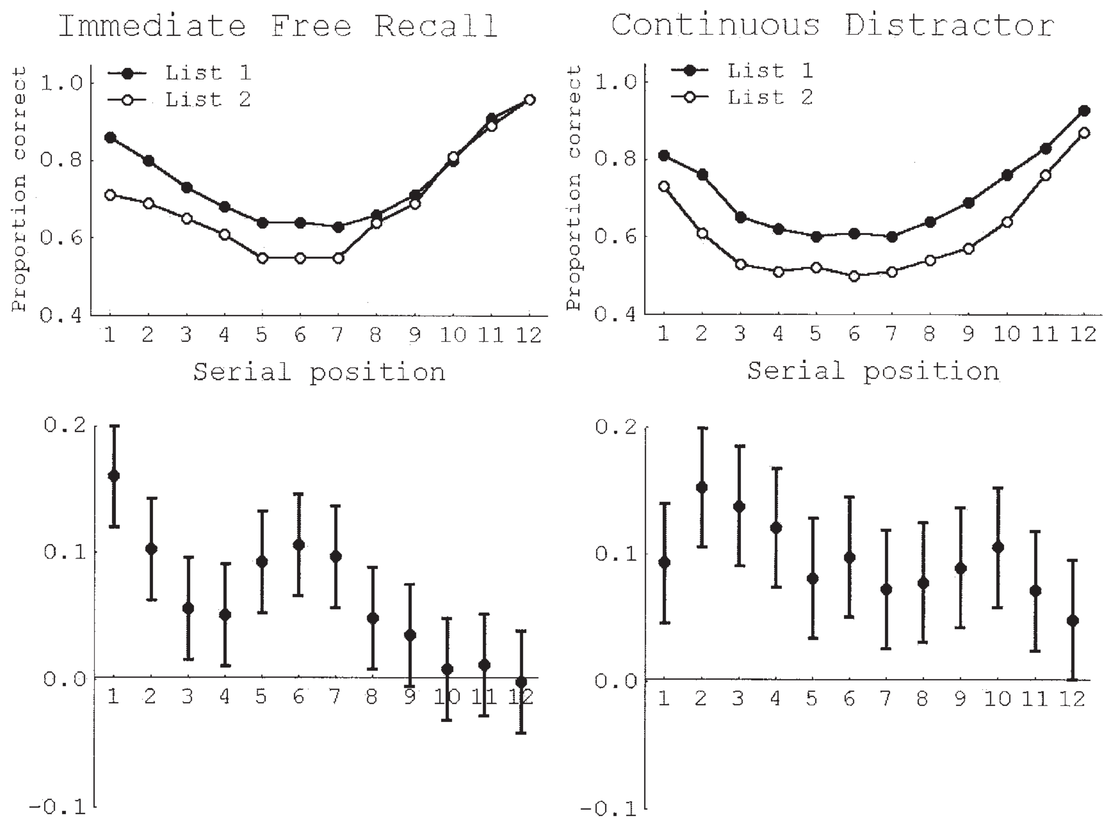

Figure 16. Results of Experiment 1: Serial-position functions of the first and second lists of a pair. Left: Immediate free recall. Right: Continuous-distractor free recall. Differences in performance between the second and first lists are plotted in the bottom graphs. Error bars represent 95% confidence intervals for within-subject designs (see Loftus & Masson, 1994).

the interaction between list and cluster, $F(1, 63) = 4.99$, $MSE = 0.014$, $p < .05$, was significant. Most important, the three-way interaction reached significance, $F(1, 63) = 6.99$, $MSE = 0.014$, $p < .05$.

To understand the nature of this triple interaction, we conducted separate analyses for immediate and continuous-distractor free recall. These analyses revealed that the triple interaction was due to the presence of a significant two-way interaction between list and cluster in immediate free recall, $F(1, 63) = 15.13$, $MSE = 0.011$, $p < .001$, but not in continuous-distractor free recall, $F(1, 63) < 1$, $MSE = 0.017$, *ns.* In immediate free recall, there was an effect of list at middle but not end positions, whereas in continuous-distractor recall, there was an effect of list at both middle and end positions (see the confidence intervals in Figure 16). Together, these results establish that the proactive interference manipulation affected all positions in continuous-distractor free recall but only prerecency positions in immediate free recall.

Discussion

In this experiment, we obtained short- and long-term recency effects in immediate and continuous-distractor free recall, respectively. Most important, the results indicate that short- but not long-term recency is immune to proactive interference. This is consistent with the view that long-term recency depends on retrieval from episodic memory, which is affected by manipulations such as proactive interference. In contrast, short-term recency is thought to be predominantly dependent on retrieval from a short-term buffer and is, therefore, not affected by the proactive interference manipulation.

It is important to point out that the triple interaction was significant when those trials were included in the analysis in which the participant started the recall phase with items from the second half of the list. When we included all trials in which the participants started with items from the beginning of the list, the triple interaction was not significant in both the analyses of the full ($2 \times 2 \times 12$ ANOVA), $F(11, 330) < 1$, $MSE = 0.033$, *ns,* and averaged ($2 \times 2 \times 2$ ANOVA), $F(1, 22) = 1.10$, $MSE = 0.013$, *ns,* data. Indeed, our computational model had predicted that there would be a dissociation only if items from the second list half were reported first. That this constraint was borne out by the data provides additional support for the validity of the model and demonstrates its usefulness in informing experimental design.

The model accounts for the dissociation in terms of the reliance of long-term recency on retrieval from episodic memory, a memory system that is susceptible to proactive interference. On the other hand, in immediate free recall (in which recall starts with items from the end of the list), recency items are unloaded from an activation-based short-term buffer, and therefore, it is only these items that are immune to proactive interference. As such, any dual-store model could account for the dissociation when both contextual retrieval and unloading from a buffer are built into the design. Still, our model is unique in that it details the nature of the contribution of the short-term buffer as well as the contextual system and provides an exact account of how these two components contribute in their unique way to short- and long-term recency effects. Nonetheless, in Experiment 2 we focus on a manipulation that affects the fine balance between excitation and inhibition within the activation-based buffer. This manipulation would provide support for our view that the short-term buffer itself needs consideration beyond that of a single parameter for buffer capacity (e.g., Raaijmakers & Shiffrin, 1980; see also Appendix C). We thereby address the mechanisms of the buffer and its defining property: capacity limitations.

Experiment 2: Presentation Rate

Experiment 2 was designed to test the context–activation model's prediction that a shift from recency to primacy would occur when the presentation duration for items is shortened. This prediction is particularly important because existing single- and dual-store theories do not predict this shift in the profile; they predict a recency function for all presentation durations. As discussed earlier, this shift is mediated by the dynamics of the global inhibition and self-excitation in the activation buffer. Although previous research has reported shifts from recency to primacy induced by increasing the duration of the RI (e.g., Neath & Crowder, 1990), the effect of presentation rate on the amount of recency and primacy has not yet been investigated.

As we tried to estimate the dynamics of the activation buffer with regard to serial position of items in the list, we chose an experimental setup that maximizes the contribution of the buffer while minimizing the contribution of episodic memory and, at the same time, provides a clean version of serial-position information. To this end, and following the results of Experiment 1, we set the proactive interference to a relative high level by using a small word pool with replacement. Furthermore, we also imposed a deadline for recall that penalized slow episodic retrieval processes (Waugh, 1970).

An additional change in procedure was made in this experiment because the serial-position functions in tasks such as free recall are affected by factors such as output interference and recall strategies (which are difficult to model; but see Gronlund & Shiffrin, 1986). Factors such as output interference and recall strategies may obscure the memory availability of items from different serial positions at the moment of recall. To reduce the influence of such factors, we used cued recall as the retrieval task. In this task, a single serial position is probed per list, eliminating output interference and constraining the recall strategy.

Method

Participants. Twenty undergraduates (age range = 19–30 years) from the University of London, London, participated in the experiment in exchange for £5 (U.S.$9). All participants were native speakers of English, were right-handed, and had normal or corrected-to-normal vision.

Design and materials. The experiment conformed to a 4 × 6 within-subject design, with presentation rate (100, 200, 400, and 800 ms) and serial position as independent variables. Recall accuracy was measured as function of serial position.

Twenty-four words taken from six different semantic categories formed a word pool from which the lists were constructed with replacement. Every list had one word from each category. The words, the probed position, and the probed category were not repeated on consecutive trials. The presentation of the trials at the different rates was blocked such that in each block, all serial positions were probed five times, with the probed position and category randomly varied across trials. The order of the presentation rate conditions was counterbalanced across participants. Each participant completed 30 trials at every presentation rate.

Procedure. Participants were given instructions on the screen as well as verbally by the experimenter. Participants were shown the category names and exemplars for 1 min before the practice trials. The experiment had a total of 16 practice trials plus 120 experimental trials. Before each block, 4 practice trials were given at the presentation rate of that block. A trial started with a fixation stimulus (+++, for 1 s) accompanied by an alerting beep, which was followed by the words of the trial, presented one at the time at one of the fixed durations of 100, 200, 400, or 800 ms. After the last word, a category name was presented, prompting the participant to verbally recall the item that had been presented in the list belonging to the cued category within 1.5 s (a second beep was presented after this time). The experimenter recorded the verbal response. The participant initiated the next trial by pressing the space bar.

Results

Experiment 2 tested the prediction of the context–activation model by varying the presentation duration through four levels. The model predicts that to obtain the shift from recency to primacy, the rate of presentation should be very fast. To quantify the primacy–recency gradient, we calculated a *primacy–recency index* (PR_{index}) from the sum of the multiplications of the probability of correct recall $P(i)$ at position i, with the position number normalized for the sum of probabilities and the list length L, as in

$$PR_{index} = \frac{\Sigma P(i) \cdot i}{(L + 1)\Sigma P(j)}. \tag{5}$$

This index, which has a value between 0 and 1, indicates the relative degree of recency and primacy. Values larger than .5 correspond to greater recency compared with primacy, and the reverse is true for values smaller than .5.[13]

Two statistical analyses were conducted. In the first, recall probabilities were entered as function of serial position and presentation rate. The second tested the PR_{index} as a function of the presentation rate, which is a more direct test of the hypothesis regarding whether the amount of primacy and recency is affected by presentation rate.

The results are shown in Figure 17. As the main focus of the experiment was on the two extreme rate conditions, the two middle rates are combined for the purpose of presentation. The analysis, however, was performed on the full factorial design. Figure 17

[13] The exact boundaries of the index are $1/(L + 1)$ and $L/(L + 1)$. The denominator assures that when there is as much primacy as there is recency, the index is .5. To see this, let us assume a constant (flat) serial-position function. One can easily check from Equation 5 that the PR_{index} equals .5, corresponding to a serial-position function with neither recency nor primacy. Similarly, PR_{index} = .5 for every serial-position function that is symmetrical around the middle point $[(L + 1)/2]$.

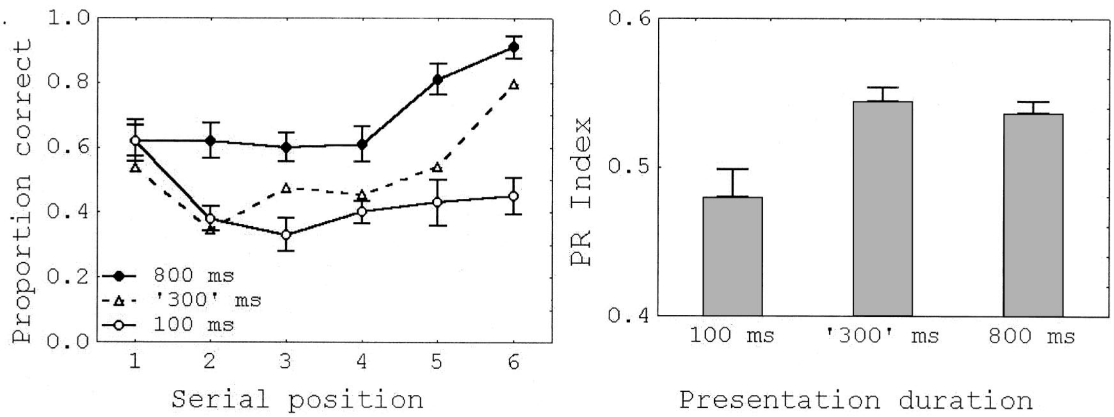

Figure 17. Results of Experiment 2: Presentation rate effects in category-cued recall. Presentation rates were 100, 200, 400, and 800 ms; the middle rates are combined ('300') in the figure. Left: Effect of presentation rate on the serial-position function. Right: Effect of presentation rate on the primacy–recency (PR) index. Bars represent standard errors.

shows the serial-position functions (left) and the PR_{index} (right) as function of presentation rate. It can be seen that the total recall performance decreased with the increase in presentation rate. More important, the slowest condition showed recency, whereas the fastest condition showed a shift to primacy. The middle presentation conditions fell approximately between the two extremes. The PR_{index} shows an abrupt drop, indicating a shift toward primacy at the fastest presentation condition.

A 4 (rate) × 6 (position) repeated measures ANOVA revealed a main effect of rate, $F(3, 57) = 47.82$, $MSE = 0.034$, $p < .001$; a main effect of position, $F(5, 95) = 16.71$, $MSE = 0.061$, $p < .001$; and the predicted interaction between rate and position, $F(15, 285) = 3.38$, $MSE = 0.046$, $p < .001$. Adjusted t tests (significance level at $.05/8 = .006$) revealed that when the first (for primacy) and last (for recency) items were compared with the average of the two middle items, only the 800-, 400-, and 200-ms conditions showed recency, $t(19) = 5.75$, $p < .001$, $t(19) = 5.45$, $p < .001$, and $t(19) = 7.60$, $p < .001$, respectively, whereas only the fastest (100-ms) condition showed primacy, $t(19) = 3.42$, $p < .005$. A second ANOVA conducted on the PR_{index} revealed a significant decrease with increase in presentation rate, $F(3, 57) = 7.20$, $MSE = 0.003$, $p < .001$, which was due to the abrupt drop between the 200- and 100-ms conditions, $t(19) = 3.94$, $p < .001$.

Discussion

The data demonstrated that with an increase in presentation rate, the serial-position function changes from one with a recency profile to one with a primacy profile. This supports our activation-based model, which explains this effect in terms of the dynamics within the short-term buffer. However, a possible alternative explanation might be that the primacy effect in the fastest condition was due to forward masking of all words except the first word (which had no premask). To rule out this interpretation, we ran a control experiment to test this masking hypothesis. We tested 4 participants on 576 trials (96 trials per serial position) with lists that were presented at a rate of 100 ms per word (the critical condition). In addition, the list was both pre- and postmasked (i.e., a row of six ampersands was presented for 100 ms before the first item and 100 ms after the last item in the list). Contrary to the masking hypothesis, a clear primacy effect was obtained, extending over two serial positions. Compared with the average of the two middle positions, recall was better for Positions 1, $t(3) = 4.54$, $p < .05$, and 2, $t(3) = 6.31$, $p < .01$.

The activation-based buffer model predicts that with the increase in presentation rate, the serial-position function shifts from recency to primacy. The results presented here and, in particular, the contrast between the two extreme presentation rate conditions challenge theories that maintain that all memory phenomena can be accounted for in terms of retrieval from a single recency-based memory system that conforms to a ratio-rule-type principle (Crowder, 1976; Neath, 1993b). Without auxiliary assumptions, such theories do not predict a shift from recency to primacy with an increase in presentation rate.[14]

Our alternative account of recency, which is based on the activation buffer, is able to explain these effects and provides important insight into the nature of the displacement process that takes place in the short-term buffer. This process is dynamic and is dependent on presentation rate, which affects the effective level of competition between activated representations. Further properties of the dynamic buffer are investigated in the next section.

Utility of the Dynamic Buffer: The Control of Memory

In the previous sections of this article, we have presented evidence that suggests a role for a dynamic buffer in recall performance. However, it is difficult to imagine that such a buffer

[14] A single-store recency-based theory extended with a refractory encoding limitation (i.e., after an item is encoded, a refractory time needs to be available before a new item can be encoded) may predict a decrease in performance after the first item (although masking is factored out). Such a theory, however, should predict that the refractory effect is maximal at Item 2, which is not consistent with our data. Further investigations could further contrast alternative explanations for the recency to primacy shift.

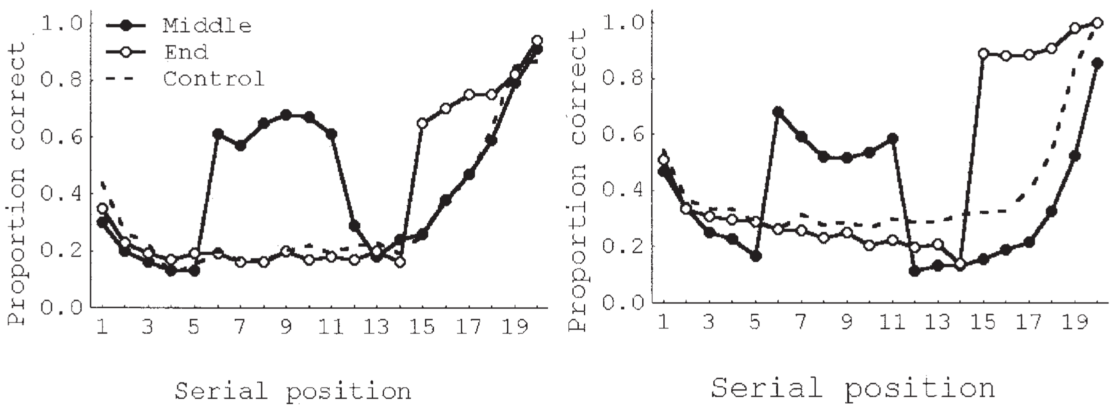

Figure 18. Comparison between data on the effects of semantic clustering in immediate free recall and the simulation. Left: Data from Craik and Levy (1970). Adapted from "Semantic and Acoustic Information in Primary Memory," by F. I. M. Craik and B. A. Levy, 1970, *Journal of Experimental Psychology, 86,* p. 80. Copyright 1970 by the American Psychological Association. Right: Model simulation. In the simulation, the associates have interconnections of strength .14. Standard values were used for all other parameters.

evolved only to enable humans to unload the most recent items in recall tasks. Indeed, there are more rigid ways in which a buffer could have been designed, in particular, with a fixed capacity (of *n* slots) and with a first-in, first-out (knock-out model; Kahana, 1996; Philips et al., 1967) or with a random displacement rule (Kahana, 1996; Raaijmakers & Shiffrin, 1980, 1981). In the following sections, we suggest possible advantages of having self-excitatory and competitive interactions dynamically control the content of the buffer. As these simulations are meant to explore more theoretical issues related to the properties of the buffer and its function, readers whose interest focuses on accounting for recency data may prefer to go directly to the General Discussion.

Content Can Attenuate the Displacement Process: The Role of Semantics

In rigid buffers, the semantic content of items does not influence the probability that the item will be displaced from the buffer. However, if one assumes that semantically related items are interconnected within the dynamic buffer (our buffer is the activated part of a lexical–semantic memory), then, as we show here, these items will remain longer in the buffer, even at the expense of the more recent item (if that recent item is itself unrelated). That is, displacement from our dynamic buffer may display intelligent properties that not only favor the maintenance of the more recent items but also factor in the semantic content of items. This idea is contrary to the traditional view that the buffer represents exclusively phonological information (Baddeley, 1972; but see R. C. Martin, 2003, for a revaluation of this view). Note that whereas an exclusively phonological buffer would be rather limited in its cognitive utility,[15] a buffer that is sensitive to semantic variables is likely to support a wider range of cognitive functions, such as language comprehension (Haarmann, Cameron, & Ruchkin, 2002, 2003; Haarmann, Davelaar, & Usher, 2003; Jackendoff, 2002; R. C. Martin & Romani, 1994), reasoning (Haarmann, Davelaar, & Usher, 2003), and contextual processing (Haarmann, Ashling, Davelaar, & Usher, in press). With regard to memory, we now demonstrate that the dynamic properties of the buffer can lead to semantic effects in immediate free recall that have previously been thought of as stemming from long-term memory.

A well-known finding of semantic effects in immediate free recall was obtained in a study by Craik and Levy (1970). In this study, participants were tested with lists of 20 words presented under three semantic clustering conditions (Craik & Levy, 1970). In the control condition, all the words in the list were unrelated. In the end condition, there was a cluster of 6 semantically related words at the end of the list (Positions 15–20). In the middle condition, there was a cluster of 6 semantically related words in the middle of the list (Positions 6–11). The results revealed that in both the middle and the end conditions, the cluster words were recalled better than the corresponding words in the control condition (see Figure 18, left).

Craik and Levy (1970) interpreted these semantic clustering effects as emerging from long-term memory, by estimating the separate contributions of short- and long-term memory using the procedure derived by Waugh and Norman (1965). However, the application of this procedure required the assumption that semantically related middle list items are not maintained in the buffer, an assumption that is questionable for a dynamic buffer (e.g., Davelaar & Usher, 2003; Watkins, 1974).[16]

In our dynamic buffer, semantically related items can prevent each other from being displaced by strengthening the activation of

[15] Besides its involvement in serial recall, the phonological loop has also been suggested to be instrumental in learning new language (Baddeley, Gathercole, & Papagno, 1998).

[16] The main assumption of the Waugh and Norman (1965) procedure is that items from the middle positions are retrieved from episodic long-term memory alone. Thus, Craik and Levy (1970) used the recall performance of the cluster of middle list items (in the middle condition) to estimate the contribution from long-term memory to the cluster in the end condition. Using this assumption, Craik and Levy concluded that the contribution from short-term memory actually decreased under the semantic clustering manipulation. Although their assumption seemed logical at the time, we are now in a position to make use of an explicit computational model to show that the main assumption is questionable for a dynamic buffer.

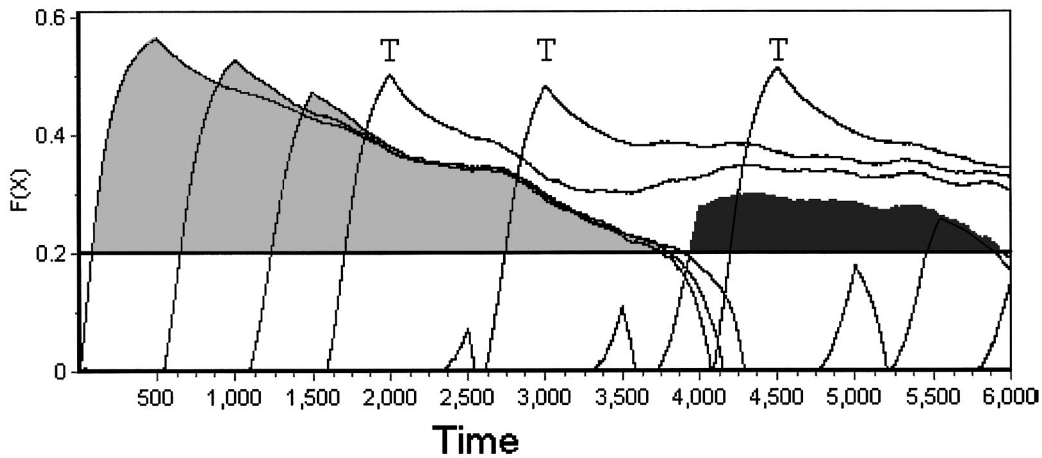

Figure 19. Activation trajectories for a list of 12 items (Items 4, 6, and 9 are the targets). Targets receive an attentionally controlled input of .33, whereas distractors receive an input of .24. Note that only the targets are active at the end of the sequence. F(x) = output activation value; T = target.

one another (Haarmann & Usher, 2001; Usher & Cohen, 1999; for detailed analysis, see Davelaar, 2003). To examine the context–activation model's prediction for the semantic clustering effect, one must set α_2 in Equation 1 to represent associative (excitatory) connections between items; for simplicity, we use only two levels of association strengths (unrelated: $\alpha_2 = 0.00$; related: $\alpha_2 = .14$). The simulation result is presented in Figure 18 (right).

The model reproduces most of the patterns observed in the data. Moreover, it demonstrates that the elevated recall of middle list positions occurs because these items have a lower probability of being displaced from the buffer. Finally, the longer maintenance time of the associates in the buffer leads to stronger episodic connections to the context layer. The enhanced episodic contribution is thus also mediated by the buffer. In summary, our buffer displays intelligent properties that allow it to keep items active on the basis of not only the time they entered the buffer but also their semantic content.

Attentional Control of the Buffer Dynamics: Selective Updating and Selection

In the previous section, we demonstrated how a dynamic activation buffer can make use of the associative structure of the learning material to achieve a type of control over the items it maintains. In this section, we examine two other types of memory control processes that further extend the cognitive utility of the buffer. The first is selective updating, which involves the ability to maintain items that are evaluated as particularly significant (even though they may not be the most recent ones) and update the buffer content depending on the relative significance of incoming items. The second is adapting the buffer parameters to the requirements of the task (e.g., encoding vs. retrieval).

There are many situations that require flexible (selective) updating of information so that only a prespecified subset of items (targets) is designated as important for performance while other items (distractors) are to be ignored (e.g., remembering only the digits within a sequence of digits and letters). Such situations require that, following a fast categorization stage, a selective attention mechanism is recruited to boost the input of the targets (or to attenuate the input of the distractors) into the activation buffer.

In previous work, researchers have explored how such a selective boosting of input can be realized by neuromodulatory brain mechanisms (Usher, Cohen, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999; see also Braver & Cohen, 2000) that control the buffer. Here, we assume that the input to the activation buffer can change in proportion to the importance of the item (akin to gain modulation of input in the cognitive control model of Braver & Cohen, 2000). Figure 19 illustrates the activation trajectories for a memory list of 12 items, out of which only Items 4, 6, and 9 are designated as targets. To simplify, we assume two levels of input modulation, with distractors receiving a weak input of $I_n = .24$ and targets receiving a stronger input of $I_t = .33$.

Examination of the trajectories reveals that the dynamic buffer behaves intelligently in that it can selectively maintain some items (the targets), even at the expense of more recent ones. This is due to the targets receiving larger modulated input, which helps them reach higher levels of activation, whereas distractors either are displaced from the buffer or never succeeded in entering it (as they do not receive enough input to overcome the inhibition from the targets).

A more complex type of selective updating is needed if one is presented with a sequence of objects from which only the largest objects have to be reported (Palladino, Cornoldi, De Beni, & Pazzaglia, 2001). In such a task, what is considered a target at one time in the sequence can later turn out to be a distractor. This situation can also be modeled via the simulation in Figure 19 (assuming that the input to large items is higher than the input to small items as a result of a fast categorization process, which was not modeled explicitly). We can observe that small items (1–3) are maintained in the buffer until larger items (4 and 6) are presented; until that moment, Items 1–3 are rightfully considered *initial targets.* A valuable utility of dynamic buffer is its ability to deactivate initial targets to enable storage of subsequent items that turn out to be the true targets (e.g., Items 4, 6, and 9).

However, having occupied the buffer carries with it a hidden cost. The initial targets are predicted to be encoded more strongly than other distractors (i.e., the small items) that never occupied the buffer because they were presented after the real targets (see the gray and black areas in Figure 19, which are proportional to the episodic trace strengths of early and late distractors, respectively). Therefore, the initial targets are predicted to cause more intrusions, as recently reported by Palladino et al. (2001).

The second utility of the activation buffer, which allows it to control information, is the ability to adapt its processing parameters to the task and process demands. To illustrate the need for this, we consider the difference between encoding and retrieval in free recall or the difference between retrieval in free recall and in cued recall. During encoding, it is advantageous to maintain a larger number of items in the activation buffer (the longer the item is in the buffer the stronger the episodic learning). In contrast, at retrieval, a more restrictive capacity is advantageous to implement selection for output. Similarly, in free recall, a reasonable strategy to optimize performance may be to maintain all the active items in the buffer until they are reported (see Appendix C). In contrast, in cued recall, a selection needs to be made immediately after the probe presentation, and so a more restrictive strategy may be optimal. We propose that a neuromodulatory control of the buffer parameters can help to optimize task performance by modulating the self-excitation and global inhibition (via dopamine and norepinephrine; e.g., O'Reilly, Braver, & Cohen, 1999; Usher et al., 1999).

To illustrate how the control of the parameters adapts the buffer to the requirements of the task, we show in Figure 20 a simulation exploring a way to implement retrieval in a category-cued recall task (see Experiment 2). Without modulation of the buffer parameters and without a probe-related input, the model is able to retain three items at the end of the list presentation (see Figure 12, top) but is unable to select the relevant one. If we assume that the category probe sends a small amount of activation ($I = .10$) to its exemplar, which in this example is the fifth item (see Figure 12, middle),[17] we see that despite an increase in activation for the target item, the model is unable to make a clear selection. Modulation of the global inhibition, however, can facilitate the selection process. When the global inhibition is increased (from .15 during encoding to .45 during retrieval, $t > 3,000$), a correct selection of the target item is made (see Figure 12, bottom).

Together, the simulations shown in this section suggest that the dynamic activation buffer transcends the role of a temporary store. Rather, this buffer (in interaction with attentional and neuromodulatory systems) may play an active role in memory control, which is an essential function of working memory (Atkinson & Shiffrin, 1968, 1971; Baddeley, 1986; Baddeley & Hitch, 1974). In particular, when the memory list includes related words or when the task specifies only some items as targets, the buffer exhibits intelligent behavior that involves a selective type of updating. In addition, the modulation of the parameters can switch the buffer function from maintenance at encoding to selection at retrieval.

General Discussion

In this article, we have presented a neurocomputational model of list memory that includes two components, a changing context/episodic system and a capacity-limited activation buffer. This context–activation model has been shown to account for a host of results, which we now summarize.

First, the model accounts for serial-position functions in immediate free recall and in the continuous-distractor task. In particular, the changing context enables the model to account for long-term recency effects, because the context when retrieval begins is more similar (in terms of proximity within the context layer) to the context when the last list items were encoded. The changing context also allows the model to account for the general pattern of lag-recency effects. These effects arise because items that are studied in close proximity to each other are encoded with context units that are proximal and tend to follow each other. This is our simplified way to account for contextual similarity (Howard & Kahana, 2002) within a localist framework.

Using the notion of two different sources dominating short- and long-term recency, we could also accommodate the larger recency that is typically found in immediate free recall. The larger effect in immediate free recall can be understood as emerging from the errorless unloading of items from the short-term buffer. This contrasts with the recency effect in the continuous-distractor task, which is primarily mediated by the reinstatement of the encoding context in episodic memory and is error prone.

Second, the context–activation model provides a coherent explanation for four dissociations reported in the literature between recall patterns in immediate free recall and in the continuous-distractor task to which, we believe, insufficient attention has been paid. The first dissociation is the absence of recency in immediate, but not in continuous-distractor, free recall when participants are instructed to start with items from the beginning of the list (Dalezman, 1976; Whitten, 1978). The second dissociation is the neuropsychological dissociation in amnesia showing a decrease in performance for recency items in the continuous-distractor task but not in immediate free recall (Carlesimo et al., 1996). The third dissociation is the appearance of negative recency in final free recall in the immediate, but not in the continuous-distractor, paradigm. The fourth dissociation is that lag recency changes with output position in immediate free recall but not in continuous-distractor free recall. All these dissociations are accounted for as the result of the contribution of the short-term buffer to the recency effect in immediate free recall but not in the continuous-distractor task, as described in the *Discussion of Dissociation Simulations* section.

Third and most important, the context–activation model gave rise to two novel predictions that critically depended on the presence of an activation-based buffer. The first prediction was that the performance for recency items is immune to proactive interference in immediate, but not in continuous-distractor, free recall, even when the ratio between IPI and RI in the tasks is preserved. Our model predicts the dissociation with proactive interference. The long-term recency is purely due to contextual retrieval-based mechanisms that are susceptible to proactive

[17] This magnitude of the input was chosen so that it would not be large enough to reactivate items that had been displaced from the buffer yet would be sufficiently large to elevate the activation of the exemplar. The probe-related input is thus thought to select among active items (nonactive items require additional episodic retrieval processes to be selected; cf. Diller, Nobel, & Shiffrin, 2001).

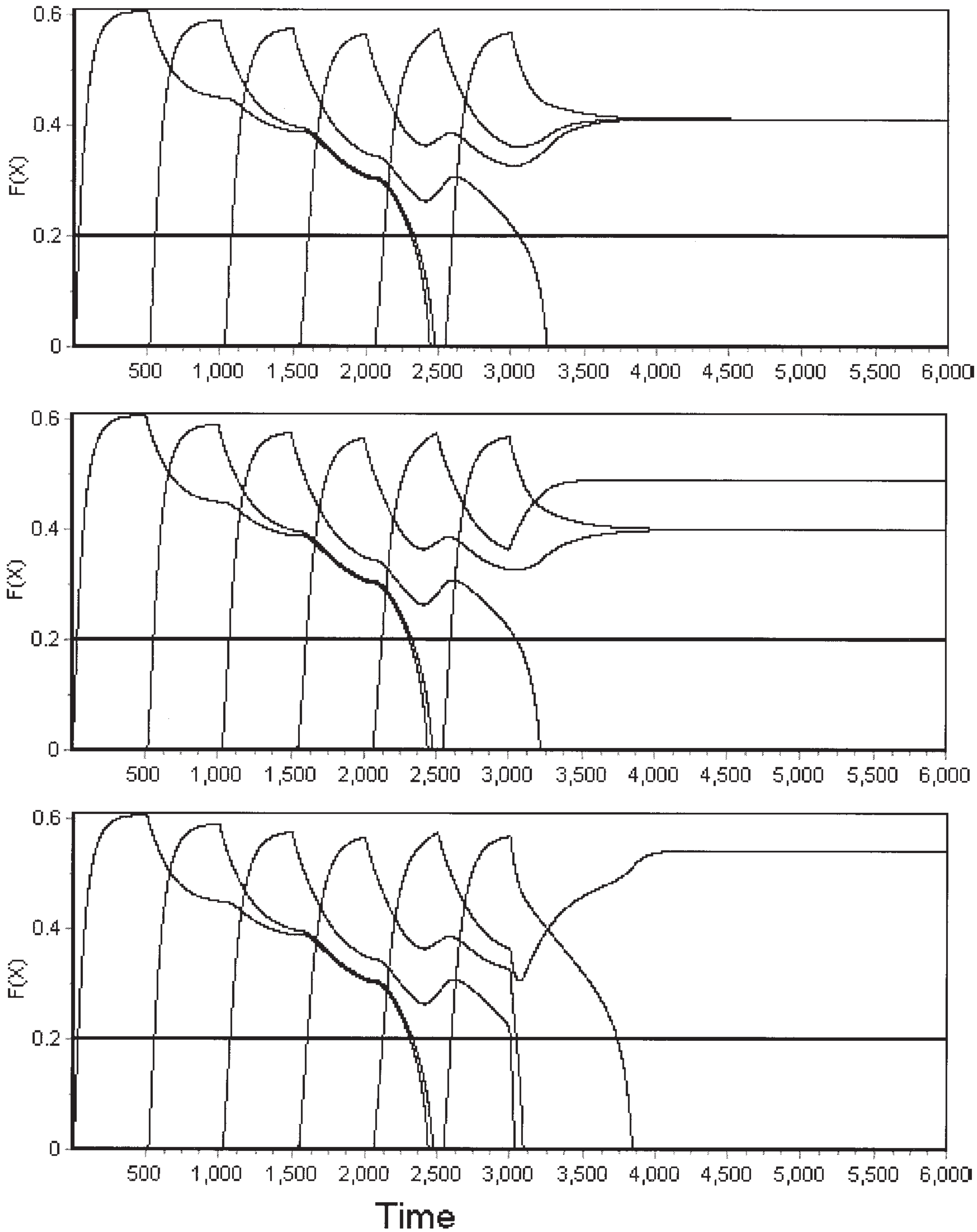

Figure 20. Activation trajectories for a category-cued recall task with a six-word list. Top: Inhibition remains constant ($\beta = .15$) during encoding and retrieval. The probe does not activate its exemplar. Middle: Constant inhibition and the probe activate the target (Item 5) with I = .10. Bottom: An increase in inhibition from .15 to .45 and probe activation lead to correct selection of the target item (Item 5). F(x) = output activation value.

interference. In contrast, the model's short-term recency effect is predominantly the result of unloading of the contents of the activation buffer, which are immune to proactive interference.

Experiment 1 showed that proactive interference dissociated short-term recency from long-term recency, thereby confirming the first prediction of our model. Unlike previous studies that reported associations between immediate free recall and the continuous-distractor task in different experiments across different labs (Greene, 1986a; Greene & Crowder, 1984), our study was the first to examine the two tasks within a single experiment using the same materials, design, and procedure, thereby avoiding potential confounds.

The model's second prediction involved a shift from recency to primacy with an increase in presentation rate. This prediction arose from the internal dynamics of the activation buffer. The nature of the displacement process in the buffer depends on a fine balance between excitation and inhibition. At slow presentation rates, an incoming item accumulates enough activation for self-support and enough activation to overcome the inhibition from previously presented items. Therefore, a displacement process can ensue, during which early items in the buffer are more likely to be displaced than newer ones. At fast presentation rates, however, incoming items do not accumulate enough activation to overcome the competition from previous items in the buffer. In other words, at fast presentation rates, new items are less likely to enter the buffer, thereby leading to a primacy effect. This prediction was confirmed in Experiment 2. In the following sections, we address a number of key implications arising from the model, discuss the nature of the activation buffer and its extension to response latencies, and compare the model with other prevalent theories.

The Need for a Buffer System: Single- Versus Dual-Store Theories

The results have a series of implications in the wider debate between single and dual theories of list memory. First, the four dissociations between immediate and continuous-distractor free recall (directed output order, amnesic syndrome, lag-recency/output-position interaction, and negative recency in final recall) are in stark contradiction with earlier claims of single-store theorists (Crowder, 1982; Greene, 1986a, 1992) that experimental manipulations have equivalent effects on short- and long-term recency. As we have shown, our dual-store model provides a natural account for these dissociations.

Second, the context–activation model demonstrates that a single-store retrieval mechanism based on contextual change does not necessarily account for the proactive interference dissociation between short- and long-term recency with equal IPI:RI ratios, whereas a dual-store account can. In the model, when we disabled the retrieval from the activation buffer, we found parallel serial-position functions for the first and second trials in immediate as well as in continuous-distractor free recall. Thus, the contextual component alone does not account for the immunity to proactive interference at recency in immediate free recall that was found in our Experiment 1 and in Craik and Birtwistle (1971). Although none of the existing models of contextual encoding have yet been used to account for proactive interference on serial-position functions, one cannot dismiss the idea that a more complex single-store model might still be able to account for the immunity to proactive interference at recency in immediate free recall. The challenge for such a model, however, would be to account simultaneously for the absence of proactive interference at recency in immediate free recall and its presence in the continuous-distractor task.

Third, the shift from recency to primacy with presentation rate (Experiment 2), which was predicted by the dynamics of the activation buffer, poses a problem for current single-store models (e.g., Glenberg et al., 1983; Howard & Kahana, 2002; Tan & Ward, 2000; Ward, 2002). These models view recency as a generic property of memory retrieval due to the enhanced similarity between encoding and retrieval contexts of the last list items (and they do not address the probability for episodic encoding). Recently, such a theory was proposed by Ward and colleagues (Tan & Ward, 2000; Ward, 2002), who have shown that a recency-based model that includes a mechanism of overt rehearsal can also account for primacy effects and lexicality effects in immediate free recall. However, this approach is silent with respect to the presence of primacy effects in continuous-distractor free recall, whose raison d'être is the elimination of rehearsal. More important, such models will have difficulty explaining (without auxiliary assumptions) how the mere increase in the presentation rate, which in fact precludes rehearsal, makes the recall at primacy positions better than that at recency positions.

Fourth, a dynamic activation buffer not only is useful in list-memory tasks but also allows the system to flexibly allocate its cognitive resources to wider domains of information processing. The buffer exhibits sensitivity to semantic organization, such that associates that are presented in close temporal proximity are maintained longer than unrelated items, even when the latter are more recent. Moreover, the dynamic nature of the buffer provides the system with a means to control the type of incoming information and to adapt to task requirements (encoding vs. retrieval). Together, the storage function and the relation to cognitive control make the dynamic activation buffer a credible candidate for being central in a general working-memory system, as originally suggested in the Atkinson and Shiffrin (1968, 1971) model.

Although it may be possible to construct single-store models that account for dissociations between immediate and continuous-distractor free recall, it is the consideration of a large data set (as well as theoretical considerations on memory control) that informs the debate on whether it is necessary to postulate a short-term buffer. This data set includes not only dissociations with experimental variables (directed output order, negative recency in final recall, proactive interference) but also neuropsychological dissociations (amnesic) and detailed information on recall transitions (e.g., lag recency) as well as presentation rate effects. It is this rich data set that suggests to us that the concept of a short-term buffer has an explanatory value in the study of basic effects (e.g., recency effects) in list memory (see Cowan, 1995, Section 4.2, for additional arguments against the sufficiency of the single-store accounts). We believe that, taken together, the presentation rate effect and the set of dissociations we reviewed and reported here support a dual-activation/context-type theory of memory and provide a challenge to the opponent single-store account. To rephrase comments by Mark Twain,[18] we suggest "it seems that reports of the demise of short-term memory may have been much exaggerated."

The Nature of the Buffer and Insights From Neuroscience

One of the textbook objections to the dual-store memory models is based on neuropsychological data of the short-term memory syndrome (Shallice & Warrington, 1970). This syndrome involves

[18] Mark Twain reacted to a report about his own death (Twain, 1940).