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A Neurocomputational Account of Short- and Long-Term Recency Effects

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Abstract

We present a neurocomputational model of free recall that combines an activation-based short-term buffer and a weight-based contextual episodic system. The short-term buffer corresponds to neural principles responsible for delay activation in the prefrontal cortex and accounts for recency effects in immediate free recall. The episodic system corresponds to the medial temporal areas and implements a changing context, which underlies recency effects in the continuous distractor task. The model accounts for effects of listlength and proactive interference in list memory. In addition, the model accounts for the dissociation between short- and long-term recency with instructed output order and for a dissociation found with amnesic patients. This work provides an initial step towards a fuller understanding of how the underlying neural principles explain patterns of memory performance and can be instrumental in resolving debates in the cognitive/behavioral literature.

Introduction

The free recall paradigm occupies a unique place in the history of scientific inquiry in immediate memory. It has led many theorists to speculate about the structure of human memory by accounting for a wide range of findings. The task requires participants to report a sequence of words in any order immediately after its presentation. When the proportion of words that were correctly reported is shown as a function of the input position, it can be found that performance is better for the first few, *primacy*, and the last few, *recency*, positions. The traditional view is that primacy effects result from the increased opportunity to rehearse those words (Rundus & Atkinson, 1970), whereas recency effects are due to retrieval from a short-term buffer (Atkinson & Shiffrin, 1968). This view found support in dissociations between primacy and recency effects (Glanzer & Cunitz, 1966), but was challenged by the finding of recency effects in a long-term memory task (Bjork & Whitten, 1974) named the *continuous distractor task*. The procedure in the continuous distractor task is identical to the immediate free recall task, except for the addition of a distractor task (e.g. counting backwards) before and after every word. Although this method is designed to eliminate the presence of items in the buffer, a *long-term recency* effect is found in this task.

The long-term recency effect has been used as evidence against the existence of a short-term buffer (Crowder, 1982). Further empirical support for a single-mechanism of recency comes from studies showing that several variables affect short- and long-term recency in similar ways (Greene, 1986).

In the cognitive literature, the dominant view on memory is that a capacity-limited short-term buffer does *not* play a role in immediate free recall. However, in the neuropsychological literature a dissociation between short- and long-term recency has been reported that supports a dual-store approach to the free recall paradigm (Carlesimo, et. al., 1996). This is further supported by another dissociation, which has largely been neglected, involving the effect of instructed output order on the recency effects.

In this paper, a Hebbian view to short-term maintenance is used, which assumes that the contents of the short-term buffer is the activated portion of (semantic) long-term memory representations, in a specific brain system distinct from the episodic system. The model presented here is based on the neural principles that are proposed to underlie active memory and supplements this with an episodic contextual encoding/retrieval mechanism. Although various (process) models of free recall exist (e.g. Anderson, et. al., 1998; Metcalfe & Murdock, 1981; Raaijmakers & Shiffrin, 1980), no detailed consideration of the debate on the existence of a short-term buffer has been carried out. Here, we show that a neurocomputational model accounts for basic findings in the free recall task and gives a coherent explanation for dissociations between short- and long-term recency.

Neurocomputational Model

The current model is an elaboration of a previous model (Davelaar & Usher, 2002), where the retrieval process was approximated by simplified algebraic equations. Here, a full retrieval process is introduced, in addition to the use of a changing contextual system. The architecture is depicted in Figure 1 and contains an active memory system supported by the prefrontal cortex and a contextual system mediated by medial temporal areas.

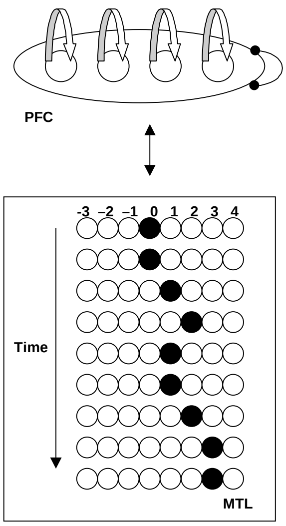

Figure 1: Architecture of the model for free recall. PFC = prefrontal cortex, MTL = medial-temporal lobe. The circular arrows represent the self-recurrency present in the prefrontal cortex. The arrow ending in filled circles represents the global inhibition. In the MTL-context system, the random walk with drift is depicted. Only one context unit is active at a time.

Activation-Based Short-Term Memory

As in previous publications, the process of active maintenance is a consequence of self-recurrency in prefrontal cell-assemblies (Amit, 1995; Carpenter & Grossberg, 1993). Each unit (corresponding to lexical-semantic representation, implemented as temporal-frontal loops) has a self-excitatory connection of strength α and there is a global inhibition of strength β, which underlies the capacity limitation of the buffer. The activation of all units (1 to N, N > listlength) are updated in parallel according to a standard equation where the activation $x_i(t)$ at time t depends on the neural current in the previous time-step, $x_i(t-1)$, the recurrent input (self-excitation and global inhibition) and the external input $I_i(t)$, which is supplemented with zero-mean Gaussian noise ξ with standard deviation σ.

$$x_i(t+1) = \lambda x_i(t) + (1-\lambda)[\alpha F(x_i(t)) - \beta \Sigma F(x_j(t)) + I_i(t) + \xi] \quad \text{(eq. 1)}$$

The activation function $F(x) = x/(1+x)$ (for $x > 0$, 0 otherwise) is a thresholded function that produces fits close to the neurophysiological recordings at low firing rate, while the nonlinearity ensures saturation at high input (see Usher & McClelland, 2001).

Contextual Episodic Memory

There is a general consensus that structures in the medial-temporal lobe play a critical role in the encoding and retrieval of episodic memories (Marr, 1971; Nadel & Moscovitch, 1997; Scoville & Milner, 1957; Squire, 1992). In the model, the medial-temporal lobe is simplified as a linear layer of context units. Each unit is indexed by an integer …, -2, -1, 0, 1, 2, … (see Figure 1). At each time-step, one context unit is active. At the start of a trial (when the GET READY signal is presented), context unit 0 is activated. With every item presentation, the context is updated. With probability P_{inc} and P_{dec}, the context moves to the right or left (it remains at the same position with probability $1 - P_{inc} - P_{dec}$). This contextual change resembles a random walk (see Figure 1) and continues throughout the distractor interval in the continuous distractor task and during the retrieval phase. Because the context drifts away from the starting unit, the contextual system implements a positional coding mechanism that is sensitive to the passage of time, as used in recent models of serial recall that feature a contextual system (e.g. Burgess & Hitch, 1999). The context unit that is active at the end of the retrieval phase will be the begin context for the successive trial.

Encoding and Retrieval

At encoding, supra-threshold active prefrontal representations get associated with active context units. The episodic trace strength, S_i of the connections is computed as:

$$S_i = \int \{\text{Max}[0, F(x_i(t)) - \varphi_1]\} dt, \quad \text{(eq. 2)}$$

where φ_1 ($\varphi_1 = 0.20$) is the activation threshold above which an item is said to be in active memory. The resulting matrix of connection weights constitutes the episodic memory of the list.

At retrieval, items that reside in active memory are immediately reported (see also Anderson, et. al., 1998; Raaijmakers & Shiffrin, 1980), which is followed by a more elaborate episodic retrieval process. During the retrieval phase, the context units are still following a random walk with drift. During this process all representations that have been associated with the active context unit compete for output. This competitive process is approximated by a Luce-choice-rule:

$$P_{s,i} = \frac{\exp(c_1 * S_i)}{\Sigma \exp(c_1 * S_j)} \quad \text{(eq. 3)}$$

where $P_{s,i}$ represents the probability that item i wins the competitive selection process. The probability, $P_{r,i}$ that the selected item will be output is a sigmoidal function of the episodic strength, where S_i is compared to a recovery threshold φ_2.

$$P_{r,i} = \frac{1}{1 + \exp(\varphi_2 - c_2 * S_i)} \quad \text{(eq. 4)}$$

The parameters, c_1 and c_2 are scaling parameters. By default, the retrieval phase starts with the context unit that is active when the prompt for recall is given. After *k* (k = 30) cycles of selection and recovery, the context is reset to the start context and retrieval continues for an additional *k* cycles, in line with analyses showing that participants report recency items first and then continue with the very first item (Metcalfe & Murdock, 1981). Several models make use of the begin-cue as a driving force for recall (e.g. Henson, 1998; Metcalfe & Murdock, 1981), to start serial recall (Burgess & Hitch, 1999; Henson, 1998) or to account for the large increase in inter-response time before the first item is reported (Metcalfe & Murdock, 1981).

Basic Effects

The model described above is used to simulate data on a trial by trial basis, making it a detailed process model of free recall memory based on neural principles. In immediate free recall, recency items are active above threshold, which gives rise to short-term recency. As none of the items are active at retrieval in the continuous distractor task, long-term recency has a different origin (i.e. retrieval from episodic memory). For immediate free recall, the model predicts that the episodic trace strength varies across serial positions, which reflects the longer duration that primacy items are active compared to middle list and recency items. This profile is in line with negative recency effects found in final free recall (Craik, 1970) and primacy effects under rehearsal-preventing conditions (Richardson & Baddeley, 1975). However, the trace strengths for the list items are uniform in the continuous distractor task, as every list item remains in the buffer for equal duration. This implies that not only short- and long-term recency effects have different sources, but that this is also true for primacy effects. Moreover, it suggests that within the current framework, long-term recency is purely due to changing context.

Listlength

One of the robust findings in memory literature is the listlength effect in the serial position function (Murdock, 1962). With increase in the number of items to be retained, performance for pre-recency items decreases, whereas the recency effect is relatively unaffected. Figure 2 shows model predictions for the results of Murdock (1962). In Murdock's experiment, six groups of participants heard a list of words at a rate of one or two seconds per word for free recall. The lists varied in length, such that the combinations used in the experiments were 10-2, 15-2, 20-2, 20-1, 30-1 and 40-1. The first number denotes the listlength and the second number refers to the duration for which a word was presented. As can be seen in Figure 2, the model accounts for the typical serial position function with primacy and S-shaped recency. It also predicts the decrease in recall performance with increase in listlength, which is fully due to the decrease in the probability of selection.

Proactive Interference

The model also accounts for proactive interference in immediate free recall (Craik & Birtwistle, 1971; see Figure 3). Craik and Birtwistle (1971) conducted an experiment in which participants performed five immediate free recall trials with 15 words per list. One group of participants received trials where all 75 words came from the same semantic category (e.g. animal names), whereas for a second group, the first four trials contained words from the same category, but the fifth trial (release-trial) contained words from a different category (e.g. fruit and vegetable). They argued that proactive interference in the fifth trial affected only the contribution from episodic memory. In the model, proactive interference was simulated by assuming that

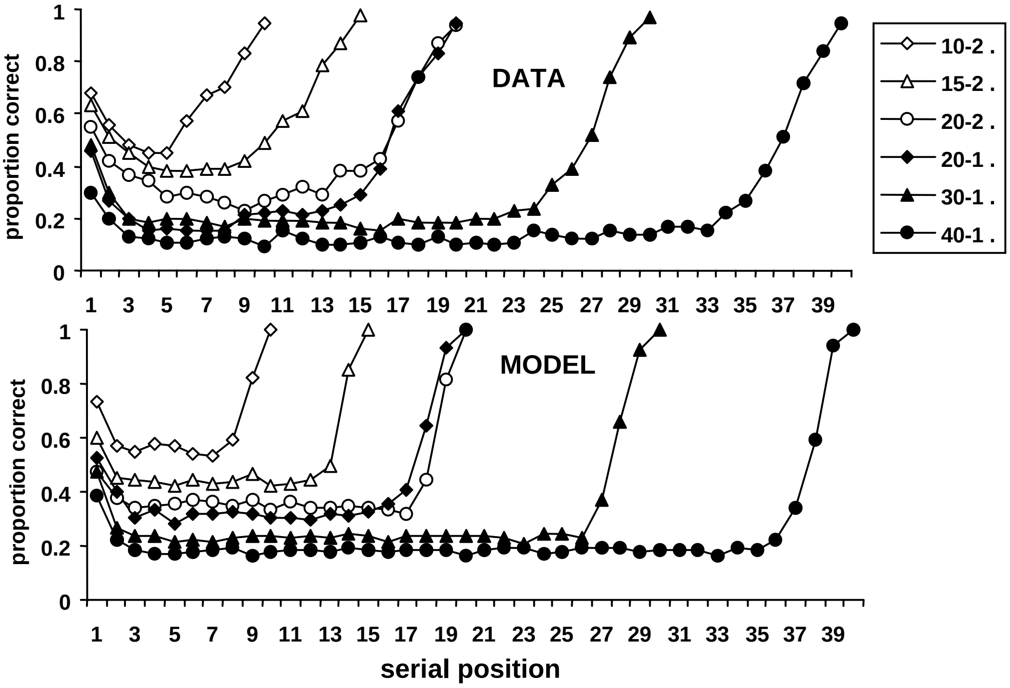

Figure 2: Data (from Murdock, 1962) and model predictions for the effect of listlength in immediate free recall.

the episodic traces of the previous trial compete in the selection process of the current trial (see for a similar view, Wixted & Rohrer, 1993). In the simulation, two trials were run. The first trial was equivalent to those in the previous simulation. The context unit that was active at the end of the retrieval phase of the first trial was automatically the context unit that becomes associated with the start-cue of the second trial. During the episodic retrieval of the items of the second list, the traces of the first trial compete in the selection probability, as list-1 and list-2 items share similar episodic context and belong to the same semantic category. As can be seen in Figure 3, the model predicts the decrease of performance of pre-recency items, while at the same time the recency items are unaffected. This is due to recency items being reported from active memory, which is not affected by proactive interference.

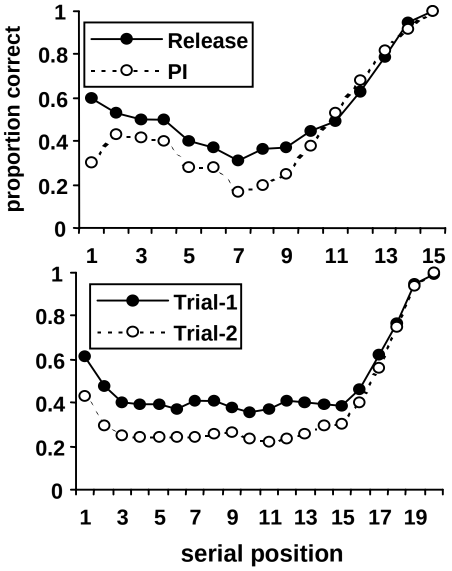

Figure 3: Proactive interference in immediate free recall. Top: Data (adapted from Craik & Birtwistle, 1971). Bottom: Model predictions.

Dissociations in Recency

As mentioned earlier, there are several dissociations between short- and long-term recency effects that disqualify the claim that all recency effects can be explained with a single retrieval mechanism. Two dissociations are simulated, adding additional support for a Hebbian dual-trace model of human memory.

Instructed Output Order

Dalezman (1976) conducted an immediate free recall experiment and asked participants to start their recall with items from the beginning or end of the list. He found that the recency effect was abolished when participants started recall with the first items (primacy-first condition), whereas a recency effect was present when retrieval started with the end-of-list items (recency-first condition). Whitten (1978) conducted a similar study with the continuous distractor task and did not find any effect of starting position on the serial position function. The effect of instructed output order was simulated by starting the retrieval phase with the begin- or end-context cue for 30 attempts followed by another 30 attempts with the other cue. Note that in both conditions both cues are used, but that the order in which the cues are used depends on the instruction. In the case of immediate free recall, the recency-first instruction leads to the emptying of the buffer. For the primacy-first instruction, it is assumed that the retrieval of items interferes with the contents of the short-term buffer. Therefore, the items that were active at the beginning of the retrieval phase have been displaced by the time the end-cue is used. At that time, only the episodic traces can drive recall, which are then similar in strength to that of middle list items (like in delayed free recall). For the continuous distractor task on the other hand, changing the order in which the cues are used does not affect the serial position function, as no changes in episodic trace strength or active memory contribution (which is absent) occur. Figure 4 shows the model results, which are in agreement with the

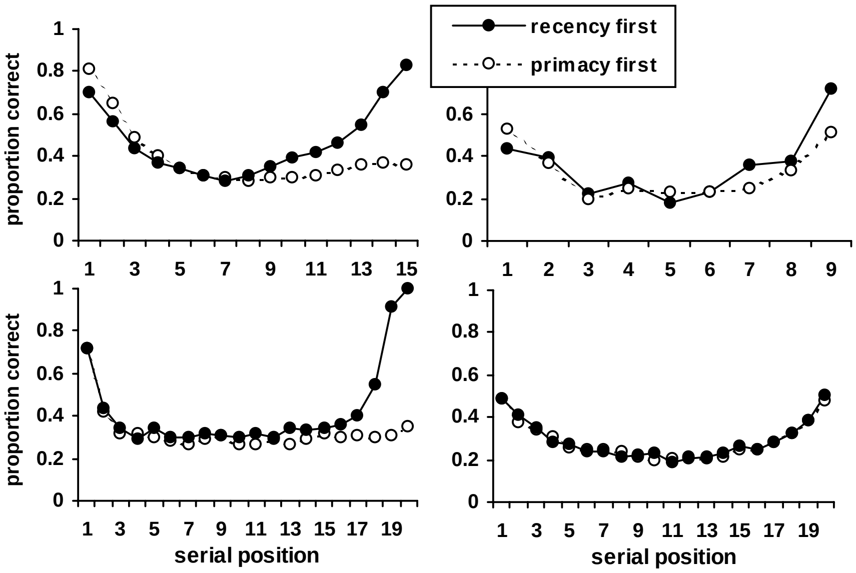

Figure 4: Data (top, adapted from Dalezman, 1976 and Whitten, 1978) and model predictions (bottom) for the effect of instructed output order on immediate (left column) and continuous distractor (right column) free recall.

empirical data. The long-term recency effect is due to the higher probability that the end-context was active during encoding of the final items, whereas the long-term primacy effect is purely due to the use of the begin-context to drive further recall.

Amnesic Patients

Carlesimo and colleagues (Carlesimo, et. al., 1996) showed that compared to matched control participants, amnesic patients have lower performance levels for the pre-recency positions in immediate free recall and for all positions in the continuous distractor task. It is important to stress that the absolute level of short-term recency is unaffected, that the absolute level of long-term recency is affected and that the *slope* of long-term recency is still unaffected. Marks and Cermak (1998) showed that amnesic patients are still sensitive to the ratio between inter-presentation and retention interval, indicating that the mechanism underlying long-term recency is not deficient in these patients. The model accounts for the dissociation in absolute levels of recency by assuming that as these amnesic patients have damage to the medial-temporal lobe, the episodic strengths are lower or more difficult to use. In the current simulation, episodic strengths were decreased by a factor of 100 to implement this deficiency in efficiency of episodic traces. The probabilities underlying the contextual random walk remained unchanged. As the strengths are only used in episodic retrieval, all positions in the continuous distractor task, but only prerecency positions in immediate free recall should be affected by this procedure, as can be seen in Figure 5. All serial positions for which the items are reported via episodic retrieval are reduced. Moreover, the model predicts that the slope of the long-term recency effect is unaffected (see Marks & Cermak, 1998).

General Discussion

The model accounts for dissociations between short- and long-term recency, which have figured prominently in the debate on single- versus dual-store theories. The model implements the short-term buffer according in a Hebbian way; the buffer is not a distinct system, but the activated part of (semantic) long-term memory representations in the prefrontal cortex, while the episodic memory corresponds to synaptic weights to context representations.

Compared to other process models (e.g. Anderson, et. al., 1998; Raaijmakers & Shiffrin, 1980), the current model implements a dynamic activation-based buffer system whose capacity is determined by a competitive activation process. This approach links with the neurophysiological findings of sustained prefrontal activation after stimulus offset (e.g. Miller, Erickson & Desimone, 1996) and behavioral studies on presentation rate effects (Davelaar, 2003). The current model makes a distinction between episodic and semantic memory, where lexical-semantic representations correspond to units of the temporal-frontal system, while episodic memory is encoded in the links between context and those units. Elsewhere, we explored semantic clustering effects in free recall by allowing weak excitatory links between the buffer units. Like the single-store model by Howard and Kahana (2002), but unlike the above models, the current model accounts for long-term recency (and long-term primacy) through a changing context representation. The asymmetry in the drift of contextual change accounts for asymmetric lag-recency effects (Davelaar, 2003) without postulating additional processes, like retrieval of pre-experimental context (Howard & Kahana, 2002). Future research could explore the specifics on the contextual system including its neural underpinnings. As a first approximation a drifting random walk process forms a good alternative.

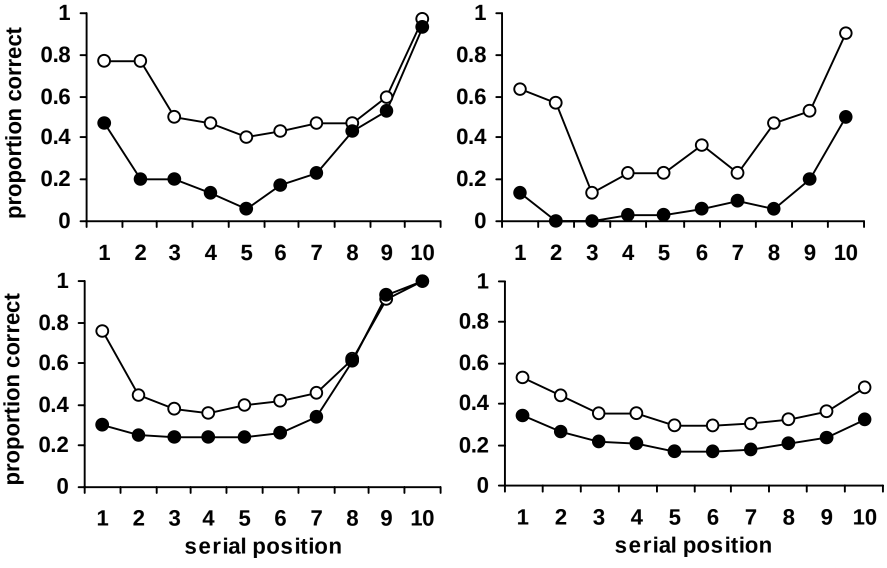

Figure 5: Data (top, adapted from Carlesimo, et. al, 1996) and model predictions (bottom) for the performance of amnesics (filled circles) and controls (open circles) in immediate (left) and continuous distractor (right) free recall.

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