RESEARCH REPORT

Prior-List Intrusions in Serial Recall Are Positional

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Henson (1996) provided a number of demonstrations of error patterns in serial recall that contradict chaining models. One such error pattern concerned when participants make intrusions from prior lists: Rather than originating from random positions in the prior list, intrusions tend to be recalled in the same position as their position in the prior list, a finding which led to the endorsement of positional models of serial recall. However, all of the demonstrations of positional intrusions occurred in designs in which relatively small sets of items were repeatedly employed as stimuli. In recent years, a number of investigations have found evidence for chaining in designs in which large sets of items are employed and items are never reused across trials (open sets). We conducted 2 experiments using open sets of items to test whether a pure chaining model is a viable model for open-set conditions. Both experiments revealed that intrusions from the immediately preceding list exhibited a strong tendency to be output in the same position as their position in the prior list, suggesting the usage of positional representations in open-set designs. A chaining model that lacks positional representations provides an inadequate account of serial recall in open-set conditions.

Keywords: serial recall, prior-list intrusions, memory models

One of the oldest debates in the literature on serial-order memory concerns the qualitative nature of learned representations that enable the ability to retrieve ordered sequences. There are two broad classes of theories that address this problem: *positional theories*, which state that items in a to-be remembered sequence are associated with the position of their occurrences, and *chaining theories*, which state that order is implicitly stored via associations among the items in the sequence; retrieval consists of using recalled items to cue their successors and proceeds like running along links in a chain.

A significant advance in the debate between the positional and chaining accounts of serial-order memory came with the seminal dissertation of Henson (1996), who argued that error patterns in serial recall are contradictory to the chaining account and support the positional coding account. Henson argued that a critical prediction of the chaining account is that errors in recall should cause further errors, as the erroneously recalled items would be used to cue items that are adjacent to them. However, two critical tests of this prediction failed to support the chaining account. When mixed lists of phonologically similar and dissimilar items are presented, errors on the similar items do not cause errors on the dissimilar items (Baddeley, 1968; Farrell & Lewandowsky, 2003; Henson, Norris, Page, & Baddeley, 1996). In addition, when an item is erroneously recalled too early in the recall sequence, the next recalled item is more likely to be its predecessor than its successor, an effect dubbed *fill-in* (Farrell, Hurlstone, & Lewandowsky, 2013; Henson et al., 1996; Page & Norris, 1998).

Although such error patterns have been contradictory to chaining models, they have not uniquely supported positional models. Evidence supporting positional models came from regularities in erroneous recall from earlier lists. Although intrusions are rare, when they occur participants exhibit a strong tendency to recall intruded items in the same position that they had occurred in the previous list (Conrad, 1960; Henson, 1996, 1999). That is, if a participant studies and recalls a list with items ABCDE and subsequently studies a list with items GHIJK, if the participant were to make an intrusion when attempting to recall item I in the second list, the intrusion from the first list would be most likely to be item C, which shares the same position (three) with item I, a result which is consistent with the usage of positional representations to carry out memory for serial order. In addition to challenging pure chaining models of serial recall, positional intrusions challenge models that assume that order is stored solely in a primacy gradient across the list items (e.g., Page & Norris, 1998). In the years since Henson's dissertation, the majority of computational models have used positional representations to carry out memory for serial order. These models include the ACT-R model (Anderson & Matessa, 1997), the oscillator-based associative recall model (OSCAR; Brown, Preece, & Hulme, 2000), the model of Burgess and Hitch (1999), the positional variant of the serial order in a box model (SOB; Farrell & Lewandowsky, 2002). Henson's own start–end model (Henson, 1998), and the grouping model (Farrell, 2012).

Despite the recent popularity of positional models, there have been a handful of investigations that have provided data that

support a chaining account of serial-order memory. Kahana, Mollison, and Addis (2010) tested positional and chaining theories in a multitrial serial-recall procedure. The positional account was tested in a variant of the multitrial serial-recall procedure called the *spin-list* condition, in which participants were tested on the same list five times, but on each trial, the list was rotated such that it began at a different position. That is, a list such as ABCDEFG could be "spun" such that on trial two, participants would be presented with DEFGABC. A positional model predicts that performance should degrade from list to list, as each item is associated with a new position representation on each repetition. Chaining models, in contrast, predict improvement from list to list because the linkages among the list items is mostly preserved. The data demonstrated that participants showed consistent improvement from trial to trial in the spin lists for all list-length conditions tested, supporting the chaining account.

In another investigation, Solway, Murdock, and Kahana (2012) conducted a reanalysis of a number of previously published datasets. Contrary to earlier observations of the fill-in effect, they found that when participants erroneously skipped an item during recall, recall tended to continue forward from the erroneously recalled item. The authors were able to account for these results with a compound chaining model[1] but found that a positional model did not properly account for the data.

An open question remains as to why the investigations of Kahana et al. (2010) and Solway et al. (2012) produced evidence in favor of chaining, whereas other prior investigations had not (Baddeley, 1968; Henson et al., 1996). One major departure among these studies was that, in many studies of serial recall, *closed sets* of items are often employed, i.e., a small number of stimuli (such as digits or letters) are sampled with replacement from trial to trial, whereas in the studies of Kahana et al. and Solway et al., *open sets* (large sets of words that were sampled without replacement, such that every trial in the experiment used a completely novel set of stimuli) were employed.

Kahana et al. (2010) and Solway et al. (2012) suggested that positional cues might be employed in situations that benefit the participant, such as when the stimuli are very similar to each other. One possibility is that the usage of a closed set induces the participant to rely on position codes. Independent evidence for this suggestion comes from McNicol (1978), who compared positional and chaining accounts of serial-order memory using different types of across-list repetitions. In the positional-repetition condition, an item was repeated in the same position on each trial. In the condition that promotes chaining, two items were repeated on each trial in adjacent positions, although the position of the pair varied from trial to trial. When digits were employed as stimuli, there was a large advantage for the positional-repetition condition over a baseline condition with no consistent repetition scheme, whereas there was either no evidence (Experiment 2) or modest evidence (Experiment 4) for a benefit in the pair-repetition condition. However, in a subsequent experiment that employed a large open set of words (Experiment 5), a large advantage for the pair-repetition condition emerged.

Although many studies have employed open sets of items (Klein, Addis, & Kahana, 2005; Drewnowski & Murdock, 1980; Bhatarah, Ward, & Tan, 2006, 2008; Bhatarah, Ward, Smith, & Hayes, 2009; Golomb, Peelle, Addis, Kahana, & Wingfield, 2008; Grenfell-Essam & Ward, 2012; Ward, Tan, & Grenfell-Essam, 2010) or compared open and closed sets of items (Coltheart, 1993; Roodenrys & Quinlan, 2000), none of these studies has demonstrated whether intrusions from prior lists exhibit a positional tendency. Instead, the studies that have demonstrated positional intrusions either relied on a small set of digits (Conrad, 1960) or two small sets of items that alternated on each trial (Henson, 1996, 1999).

The aim of the present investigation was to conduct a straightforward set of serial-recall experiments that aimed to address whether positional information is used at retrieval in experiments that employ open sets of items. Because prior-list intrusions are considerably rarer when open sets are used (Coltheart, 1993), we recruited a very large sample of participants in each experiment. In addition, many serial-recall experiments collect their responses using lined-response grids, but we collected responses using a computerized procedure in which participants typed the words one at a time and each word disappeared from the screen upon completion. Such a procedure not only guarantees that participants are entering their responses in order, but also provides no position cues to the participant that might be influencing the positional nature of prior-list intrusions. To ensure generality of our results, we collected two data sets with list lengths of five and six items, respectively. If the intrusions fail to show any positional nature, then this investigation would provide evidence that a simple chaining model such as the one proposed by Solway et al. (2012) might provide an adequate account of serial recall with open sets of items.

Experiments

Participants completed an immediate serial-recall task that employed a large set of words such that the stimuli encountered on each trial were completely novel. Lists were of five or six items in length and list length was manipulated between participants.

Method

Participants

A total of 204 undergraduate psychology students (105 participants for the List-Length 5 condition, 99 for the List-Length 6 condition) from The Ohio State University participated in this experiment in exchange for course credit in an introductory psychology course.

Materials

Participants studied words that were randomly selected from a word pool of 625 words from the Google word-frequency counts, which is a database which indexes how frequently words are used on web sites.[2] Words ranged from four to seven letters in length, 30 to 250 counts per million in word frequency, and comprised all parts of speech.

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[1] In compound chaining models, multiple previously recalled items are used to cue successors in the list instead of just the most recently recalled item.

[2] The Google word frequency counts used in this study can be found at http://mall.psy.ohio-state.edu/wiki/index.php/Google_Word_Frequency_Counts

Procedure

Each session began with four unscored practice lists of three, four, five, and six items to familiarize participants with the nature of the task. They were given feedback upon completion of each of the practice lists. If any errors were made, participants were reminded that they have to recall the items in the order in which they were presented. No feedback was given at any point in the experiment after the practice session was completed.

Upon completion of the practice session, participants were given 62 trials with lists of either five or six items. During the study phase, participants were presented with each word for 1 s followed by a blank screen for 250 ms. Following completion of the study list, participants were presented with a recall prompt that was a series of three question marks (i.e., "???") on the center of the screen. Participants were instructed to begin recalling the items upon seeing the prompt by typing their responses on a keyboard and were given 20 s to recall the sequence. After the first key was pressed, the question marks disappeared and were replaced with the letters typed by the participant. Participants signaled completion of a word by hitting the "enter" key on the keyboard. Upon completing a response, the response disappeared from view on the computer screen and was replaced by the question marks. Participants signaled completion of the recalled sequence by typing the word "done" and hitting "enter." Upon completion of each trial, participants signified readiness to begin the next trial by hitting the "enter" key. Participants were instructed to recall the list naturally and to not be too concerned with spelling. To ensure that participants did not get too fatigued with the task, halfway through the experiment, participants were given a break in which they played a digital card game for 3 min.

Stimulus presentation and response collection were handled using the Python Experimental Library (PyEPL: Geller, Schleifer, Sederberg, Jacobs, & Kahana, 2007).

Results

All responses were spell-checked before the analyses using the ratio function in the Levenshtein package in Python, which computes the similarity between two strings and returns a value between 0 and 1 that indexes the degree of overlap between the two strings. If a participant entered a string that was not among the set of words employed, it was substituted with a word from the word set the similarity of the two strings exceeded .8 and the response was not perceived to be semantically dissimilar from the set word. For instance, if the studied word was "house" but the participant typed "mouse," the similarity among the two strings would be .8, but "mouse" would not be accepted because it is semantically dissimilar from the studied word. All spell-checking was supervised by the first author of the study.

Serial-Position Effects

Serial-position curves for list lengths of five and six items can be seen in Figure 1, scored under two different scoring procedures. On the left is the strict scoring procedure that is commonly used, in which an item is scored correct only if it is recalled in the same position as its original serial position. However, given the large number of omissions and the fact that we did not allow participants the option of
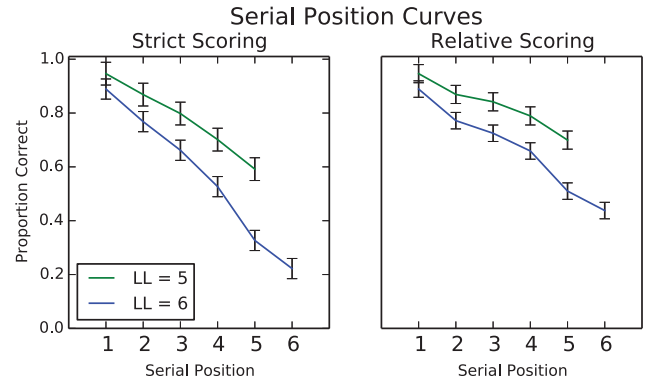

Figure 1. Serial position curves for both the List-Length 5 (top) and 6 (bottom) experiments. Depicted are serial position scores under both strict (left) and relative (right) scoring. Error bars indicate 95% within-subjects confidence intervals. See the online article for the color version of this figure.

using "blank" as a response, strict scoring is punitive for the later list items, as an omission of an item from the early- or middle-list positions would cause all later recalls to be scored as incorrect. We followed the procedure of several other investigations that have employed open sets by including the relative-order scoring method (right side of Figure 1), in which an item is scored correct if its serial position immediately follows the item that was recalled before it (Drewnowski & Murdock, 1980; Kahana et al., 2010; Klein et al., 2005). As an example of how the two scoring methods differ, consider if a participant studies the list ABCDEF and recalls ACDFE. Under strict scoring, only A and E would be scored correctly as they are the only items recalled in their correct positions. Under relative order scoring, D would be scored correctly in addition to A because D followed recall of its predecessor, but E would be scored incorrectly, as it was recalled after a successor.

Performance decreased with serial position under strict scoring for both of the list-length experiments: 5, $F(4, 416) = 208$, and 6, $F(5, 495) = 724.4$, both $ps < .001$. Under relative scoring, performance also decreased with serial position for List-Lengths 5, $F(4, 416) = 141.4$, and 6, $F(5, 495) = 316.5$, both $ps < .001$. Performance was also worse in the List-Length 6 experiment than the List-Length 5 experiment under both strict, $t(201.57)[3] = 9.87$, and relative scoring, $t(201.90) = 9.11$, both $ps < .001$.

We were surprised to find a negative recency effect, in that performance was worse for the last position than the second to last position. This was found for strict scoring in the List-Length 5, $t(104) = -10.82$, and List-Length 6 experiments, $t(99) = -13.76$, both $ps < .001$, as well as under relative scoring for the List-Length 5, $t(104) = -8.86$, and 6 experiments, $t(99) = -6.43$, both $ps < .001$. This is somewhat surprising, given that a number of experiments using open sets have found a recency effect for the last item. However, many of these experiments used either vocalized recall (Klein et al., 2005; Drewnowski & Murdock, 1980; Golomb et al., 2008) or the experimenter provided position cues in the form of lined-response grids (Grenfell-Essam & Ward, 2012;

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[3] Degrees of freedom in all two-sample t tests are corrected degrees of freedom from the Welch-Satterwaithe equation.

Ward et al., 2010). Strict serial-ordered recall was required in our experiments, which has been found to produce decremented recency effects (Tan & Ward, 2007). In addition, the usage of visual presentation in our study may have a contribution as well, which tends to produce considerably attenuated recency effects relative to auditory presentation (Watkins, Watkins, & Crowder, 1974). However, given that this was an unexpected finding that is outside of the interest of the current investigation, we hesitate to make strong conclusions about the source of the effect.

Error Rates

Henson (1996) classified errors in serial recall according to the following: omissions (when an item is not recalled), transpositions (when an item is recalled in the incorrect position), prior-list intrusions, and repetitions. Given that these experiments employ an open set, participants also often recalled words from outside of the experimental set; we have dubbed these *extra-set intrusions*. Proportions of each of these errors relative to the total number of errors for each experiment can be seen in Figure 2. One can see that omissions are the most frequent type of error, occupying more than 50% of the errors in each experiment, although Henson (1996) found that transpositions were more frequent than omissions. However, he had not considered open-set designs, where the availability of item information is relatively poor. Coltheart (1993) found that, with phonologically dissimilar items, transpositions were frequent in closed sets (28% of all errors) but were less frequent in open sets (15% of all errors), in which omissions dominated (33% of all errors).

Gradients of transposition errors, which depict the proportions of recalled items from each serial position, can be seen in Figure 3 for each output position. These transposition gradients replicated those that are commonly seen in the literature, with peaks occurring on the correct position of recall and errors being clustered around the position of the correctly recalled item (e.g., Henson et al., 1996).

Prior-list intrusions were relatively rare in our experiments, occupying only 4.9% and 3.7% of all errors in the List-Length 5 and 6 experiments, respectively. Coltheart (1993) found a similarly low proportion of intrusion errors with phonologically dissimilar items in an open set (6%), which was substantially higher when a closed set was employed (23%).

Prior-List Intrusions

Henson (1996) found that prior-list intrusions became more frequent as retrieval proceeded. We found the same result in our experiments. Intrusion probabilities (defined as the proportion of responses that were intrusions) for each output position in both experiments can be seen in Figure 4. Intrusion probability increased with output position for both the List-Length 5, $F(4, 416) = 24.75$ and 6 experiments, $F(5, 493) = 16.15$, both $ps < .001$.

To establish whether intrusions from prior lists are positional, we adopted the same transformations of the proportion scores that Henson (1996, 1999) advocated. In particular, Henson compared the proportion of intrusions in position to a chance-alone probability (i.e., 50/50). Given that the number of intrusions differed wildly across participants, with some participants exhibiting no intrusions, Henson advocated a weighted-log odds transformation that gives extra weight to participants who exhibit greater numbers of intrusions. We followed his recommendation and adopted weighted-log odds transformations for all the following analyses, as it seemed logically appropriate for this case. Nonetheless, we also conducted analyses on untransformed proportion scores and found the same results in all cases.

Henson found a strong tendency for prior-list intrusions to share the same output position during recall as both of their positions in the previous list. However, what was also found was a tendency for prior-list intrusions to share the same output position across the current recall period as well as the recall period from the previous list. We refer to the former case as an analysis of *input intrusions* and the former as *output intrusions*. Although analysis of input and output intrusions would be expected to be the same when recall on the previous list was correct, they would not be expected to converge if the recall on the previous list were in the incorrect position. For instance, if the third item on the previous list was recalled in the fifth position on the prior list and that item intrudes into the fifth output position of the current list, this would be classified as a positional output intrusion, but not a positional input intrusion. In addition, Henson (1996, 1999) found the strongest evidence for positional intrusions when the analysis was conducted on intrusions from the immediately preceding list. We conducted analyses of intrusions from both the immediately preceding list (which we dub *immediate intrusions*) and from all lists prior to the immediately preceding list (which we dub *distant intrusions*). Immediate intrusions were the bulk of
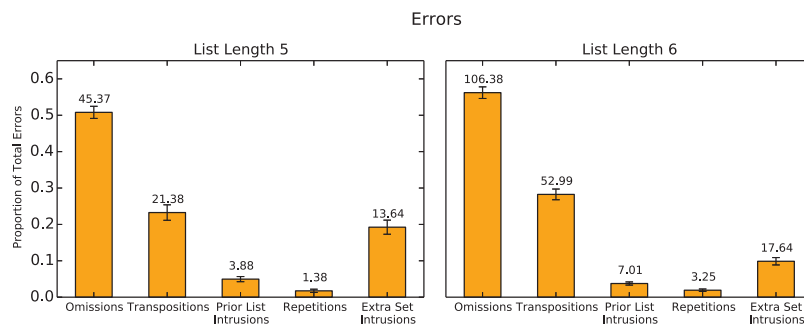

Figure 2.   Proportions of total errors for each error type in the List-Length 5 (left) and 6 (right) experiments. Mean absolute frequency of each error can be seen above the bars. Error bars indicate 95% confidence intervals. See the online article for the color version of this figure.
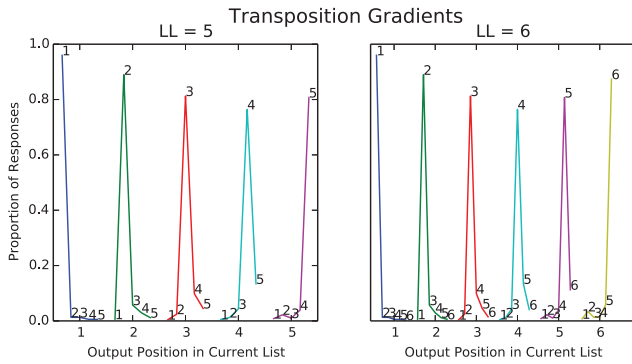
Figure 3. Transposition gradients for each output position. Above each output position is the proportion of items recalled from each serial position on the study list. Recalls were collapsed across participants before proportions were calculated. See the online article for the color version of this figure.

intrusions, occupying 38.3% and 35.1% of all intrusions in the List-Length 5 and 6 experiments, respectively.

Positional gradients of immediate intrusions can be seen in Figure 5. Depicted on the *x* axis are the output positions in the attempts to recall the current list, along with the proportions of intrusions from each position in the prior list. Separately considered are the studied serial positions in the prior list (left panels) and the output positions in the prior list (right panels). Given that these are proportions of all intrusions in each output position, the scores in each output position sum to 1. There is a peaked nature to each of these gradients, with the peaks occurring when the position in the prior list matches the current output position. These gradients bear a resemblance to the transposition gradients seen in Figure 3, except that they are flatter in comparison, implying that there is greater positional certainty for within-list recalls than for intrusions from the preceding list.

There is a similarity in the appearances of the input and output intrusion gradients due to the fact that 70% of the immediate intrusions were correct responses in the previous trial. Nonetheless, there are some subtle differences, including the fact that there is less positional certainty in the final output position for the output intrusion analysis relative to the input intrusion analysis. Tests of weighted log odds were constructed by comparing the proportion of intrusions that were positional to what would be expected by chance, which is one divided by the list length. The proportion of input intrusions that shared the same position as the prior list significantly exceeded chance in both the List-Lengths 5 and 6 experiments, $Z(104) = 3.57$, $Z(99) = 3.53$, both $ps < .001$. respectively. An analysis on output intrusions produced the same results in both the List-Length 5, $z(104) = 2.48$, $p < .01$ and 6, $z(99) = 3.41$, $p < .001$ experiments.

Positional gradients of distant intrusions can be seen in Figure 6. These gradients are considerably wider than the positional gradients for the immediate intrusions seen in Figure 5. For input intrusions, the proportion of intrusions that were positional did not exceed chance for the List-Length Experiments 5, $z(104) < 1$, and 6, $z(99) < 1$. The same results were found when output intrusions were analyzed for the List-Length 5 and 6 experiments, $z(104) < 1$; $z(99) = 1.03$, $p > .05$, respectively. These analyses suggest that when intrusions travel more than one list, they are not likely to be

recalled in the same position as their previously studied or recalled positions. Although some readers might find it peculiar that positional certainty is only found with immediate intrusions and not distant intrusions, the widening of the positional gradients for distant intrusions relative to immediate intrusions is qualitatively consistent with the widening of transposition gradients with increases in retention interval found by Nairne (1992). Indeed, when one compares the transposition gradients in Figure 3 to the intrusion gradients seen in Figures 5 and 6, one can see a progressive flattening of the gradients, with the greatest positional certainty for the current list, less positional certainty for the immediately preceding list, and virtually no positional certainty for lists before that. Nonetheless, visual inspection of the distant intrusions in Figure 6 reveals that the first and second output positions have peaks that are above the chance line; it is possible that it would take much larger quantities than were collected in the present investigation to detect statistical significance in these cases.

One possible source for the positional aspect of immediate intrusions in these experiments is that there may be some participants who failed to encode the current list and merely recalled the entire list of items from the previous study list, an error pattern that could potentially be produced by a pure chaining model. To determine whether this applied to our data, we evaluated the proportion of intrusions that were preceded or followed by another intrusion. For immediate intrusions that were in nonterminal positions of the output sequence, only 6% and 6.8% were followed by other intrusions for the List-Length 5 and 6 experiments, respectively. For immediate intrusions that were not the first position in the output sequence, only 2.6% and 8% were preceded by intrusions. Given that immediate intrusions are not frequently accompanied by other intrusions in the output sequence, it is very unlikely that the positional nature of immediate intrusions is due to participants repeating the output sequence from the previous study list.
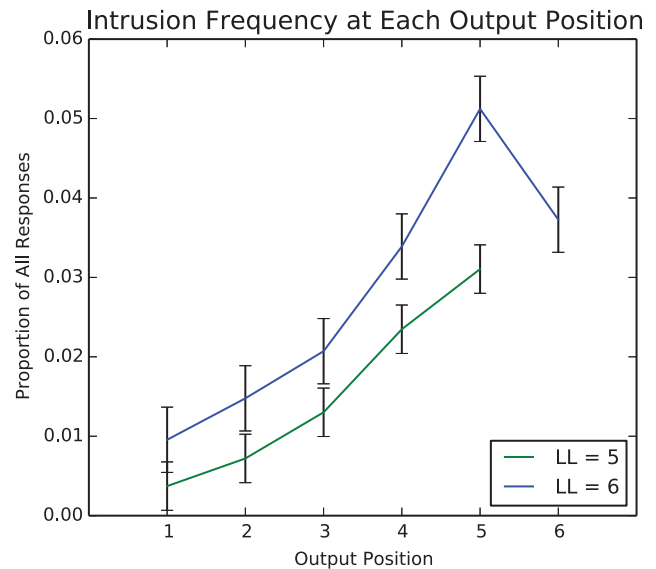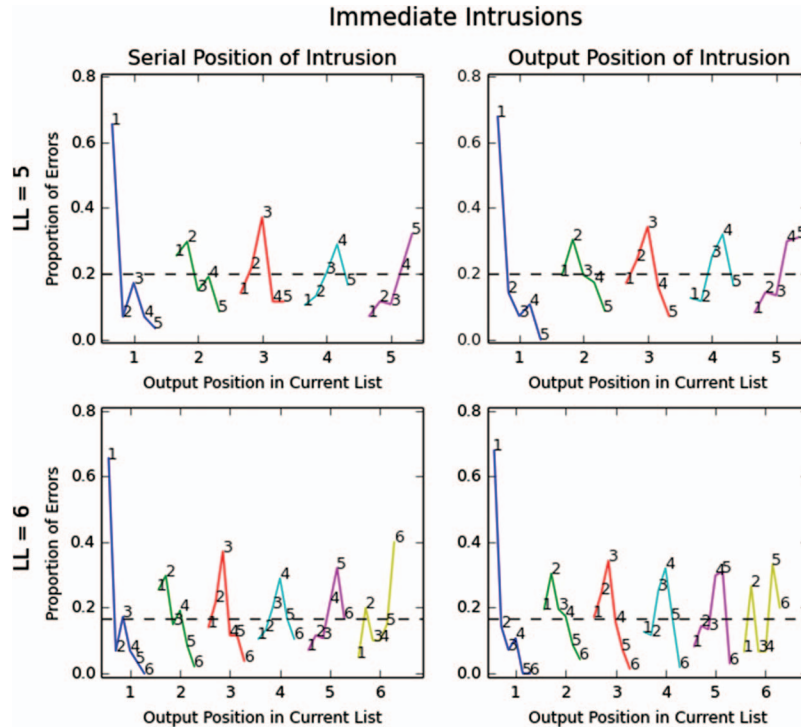

Figure 4. Intrusion probability at each output position for both experiments. Error bars indicate 95% confidence intervals. See the online article for the color version of this figure.

Figure 5. Proportions of immediate intrusions for each of their original studied positions (left) or their output positions in the previous list (right) for the List-Length 5 (top) and 6 (bottom) experiments. Markers on the *x* axis indicate the output position in the current list; the numbers on the lines indicate either the studied position (left) or output position (right) of the intrusion from the prior list. Dashed lines indicate the proportions that would be expected by chance. Intrusions were collapsed across all participants before proportions were calculated. See the online article for the color version of this figure.

General Discussion

Prior-list intrusions from the immediately preceding list in serial recall show a striking positional nature, in that they tend to be output in the same position as their studied position or in the same position as they were output in the prior list. Prior-list intrusions are rare (3–5% of all errors), but when they occur, the positional nature of these intrusions can only be explained using positional representations and cannot be explained using other forms of representations, such as a primacy gradient or the use of interitem associations. The present work replicates the work done by Henson (1996, 1999) and Conrad (1960), but it is in the first demonstration of positional intrusions in open-set conditions that intrusion probabilities are not only significantly lower (Coltheart, 1993), but the experimental parameters are similar to experiments that have revealed evidence for chaining (Kahana et al., 2010; McNicol, 1978; Solway et al., 2012), which raises the possibility that chaining may provide an adequate account of serial recall in open-set designs. In addition, no position cues were provided to the participant in the form of lined-response grids, indicating that the position cues used to generate the positional intrusions had to have been generated by the participant. The fact that immediate intrusions were rarely preceded or followed by other intrusions rules out the possibility that participants were erroneously recalling the list from the prior trial. The evidence presented here demonstrates that a simple chaining model cannot provide a complete account of serial-recall performance in open-set conditions.

Henson (1998) argued that positional intrusions are evidence for a positional model of serial recall. He was able to capture positional intrusions with his start–end model, which assumes that items are bound to both a representation of the list context and representations of the start and end of the list, where the strengths of the start and end markers are proportional to the item's distance from those respective positions, forming a position code for each serial position in the list. In addition, the list context changes from list to list (e.g., Mensink & Raaijmakers, 1988) such that the context cue employed at retrieval is most similar to the most recent list and less similar to prior lists. At retrieval, both the list context and the position code for each intended position are jointly used to cue memory for the list items. The rarity of prior-list intrusions stems from the dissimilarity between the current and prior list context representations, and the positional nature of intrusions stems from the similarity between the position codes of the current and prior list items.

The start–end model employs start and end markers, but models that employ position codes that only represent distance from the start of the list would be equally able to handle the present data, such as the model of Burgess and Hitch (1999). Nonetheless, positional models require that position codes be reused from trial to trial to capture current results, such that for two sequences, ABCDE and FGHIJ, items A and F exhibit similar position codes because they both occupy the first position. The revised Burgess and Hitch (2006) model, however, only reuses position codes under special circumstances,
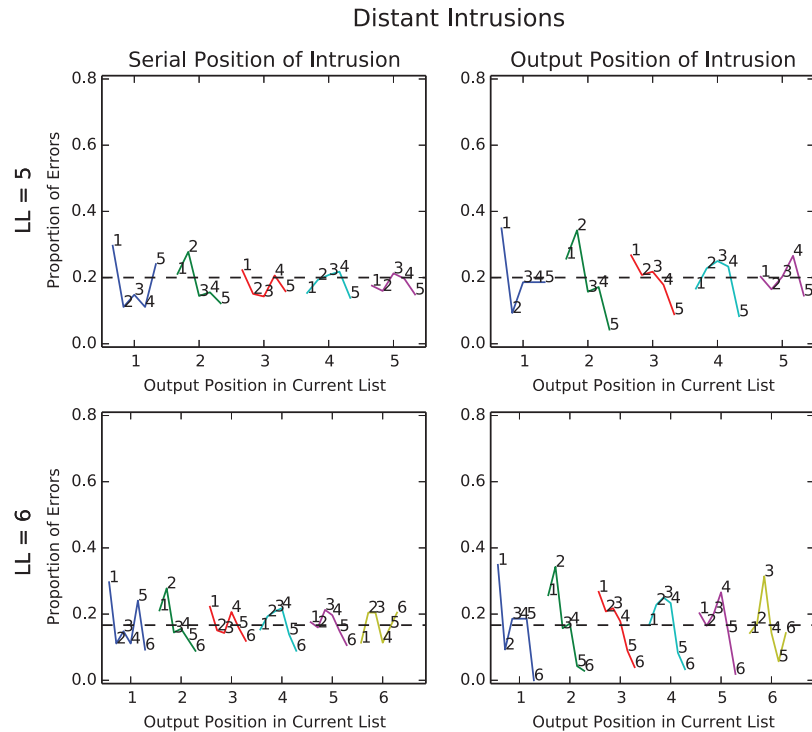
Figure 6. Proportions of distant intrusions for each of their original studied positions (left) or their output positions in the list of origin (right) for the List-Length 5 (top) and 6 (bottom) experiments. Markers on the *x* axis indicate the output position in the current list; the numbers on the lines indicate either the studied position (left) or output position (right) of the intrusion from the prior list. Dashed lines indicate the proportions that would be expected by chance. Intrusions were collapsed across all participants before proportions were calculated. See the online article for the color version of this figure.

namely, when the beginning of the lists are the same. This revision was motivated to capture the data of Hitch, Fastame, and Flude (2005), who performed an experiment in which lists were partially repeated, repeating either the beginning eight items or the last eight items from a training sequence from list to list. A partial repetition advantage was only found in the condition in which the beginning eight items were repeated. Although the revised Burgess and Hitch (2006) model did capture these results by assuming that the reuse of start-list items caused the repetition of the prior list's position codes, this revision implied that prior-list intrusions should only be positional when the two lists share the beginning items. Given that we did not reuse items across trials in our experiments, the model would not reuse position codes across trials and would not accommodate the present data.

The positional nature of serial recall has greater relevance when recent work is considered, demonstrating that both free and serial recall are more similar than they are different. When participants study a list of items and are not informed as to whether they will be performing free or serial recall, performance resembles their initial advanced warning of the retrieval task (Bhatarah et al., 2008). This result suggests that free and serial recall are encoded in the same way, but differ in how they are retrieved, with free recall being initiated with recency items and serial recall with the first list item (Ward et al., 2010). Moreover, when free recall is initiated with retrieval of the first item, free-recall performance

resembles performance in a serial-recall task (Ward et al., 2010; Grenfell-Essam & Ward, 2012).

Considering the similarities between the two tasks, if serial recall relies on positional representations, free recall might, as well. Such an argument was strengthened by Farrell (2012), who was successful in modeling several critical aspects of both free and serial recall using a hierarchical positional model, in which items were associated to positions in their groups and groups were associated to positions in their list context. The model was unique in its approach to free recall in that it possessed no interitem associations. Up to this point, chaining had been the dominant class of free-recall models. Free-recall models that use chaining include the search of associative memory (SAM; Raaijmakers & Shiffrin, 1981), retrieving effectively from memory model (REM; Lehman & Malmberg, 2013), and temporal context models (TCM; Howard & Kahana, 2002; Polyn, Norman, & Kahana, 2009; Sederberg, Howard, & Kahana, 2008)[4].

Despite the popularity of positional models of serial recall, they don't explain other evidence for chaining, including learning in the spin-list paradigm (Kahana et al., 2010). Other evidence for the

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[4] Although the temporal context model has been described as a model that associates items to prior states of context, each prior state of context consists of the items that preceded the current item.

usage of interitem associations includes the advantage for high-frequency bigrams (Baddeley, 1964), the finding that when list items are presented at retrieval in the order in which they are presented, participants show improved recall as if they are using the list items to cue neighboring items (Serra & Nairne, 2000), along with the finding that participants show improvement for adjacent pairs of items repeated across trials (McNicol, 1978). Although we have argued that the present results suggest the usage of positional representations, it is also possible to combine positional and chaining representations in a single model such as in the original version of the Burgess and Hitch (1992) model. Such a hybrid model may be ideal for capturing the full range of serial-recall phenomena.

Conclusion

Prior-list intrusions from the immediately preceding list are positional even in open-set designs in which items are not reused from trial to trial and position cues are not provided by the experimenter. Evidence for a chaining representation has emerged in some investigations that have employed open sets, raising the possibility that participants employ a chaining representation in these designs. The present results suggest that positional representations underlie serial-recall performance in both open and closed set designs, suggesting that a pure chaining model is insufficient in addressing serial-recall performance. These results are challenging not only to chaining models that lack positional representations, but also to positional models that only reuse position codes from trial to trial under limited circumstances.

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