

# Response suppression contributes to recency in serial recall

Simon Farrell · Stephan Lewandowsky

Published online: 4 May 2012  
© Psychonomic Society, Inc. 2012

**Abstract** Serial recall is often assumed to involve response suppression: the removal or inhibition of items already recalled so that they are not recalled again. Evidence for response suppression includes repetition inhibition and the separation of erroneous repetitions. Some theorists have suggested that response suppression, by eliminating competing responses, also contributes to recency in forward serial recall. We present experiments in which performance on the final item was examined as a function of whether or not the preceding retrievals entailed suppression of potential response competitors. In line with the predictions of response suppression, recency was found to be reduced when the earlier recall errors consisted of intrusion errors (which leave list items unsuppressed) rather than transposition errors (which involve suppression).

**Keywords** Working memory · Short-term memory · Recall · Inhibition

Contemporary models of serial recall have assumed various mechanisms to represent order among list items, such as a primacy gradient (Brown, Preece, & Hulme, 2000; Farrell & Lewandowsky, 2002; Lewandowsky & Farrell, 2008b; Page & Norris, 1998) or positional coding (Brown, Neath, & Chater, 2007; Brown et al., 2000; Burgess & Hitch, 1999;

Henson, 1998b). The models also differ with respect to their representational assumptions, relying on either localist (Burgess & Hitch, 1999; Henson, 1998b; Page & Norris, 1998) or distributed (Brown et al., 2000; Farrell & Lewandowsky, 2002; Murdock, 1995) representations. Notwithstanding this diversity, there is some notable convergence between different theories (see Lewandowsky & Farrell, 2008b). One nearly universal assumption is the notion of *response suppression* (Brown et al., 2000; Burgess & Hitch, 1999; Farrell & Lewandowsky, 2002; Henson, 1998b; Lewandowsky, 1999; Lewandowsky & Murdock, 1989; Nairne, 1990; Page & Norris, 1998). This is the assumption that once an item is recalled, it is somehow prevented from competing for report again during subsequent retrievals on a trial.

Although direct evidence for response suppression is difficult to obtain, much indirect empirical support for the notion has been found. For example, the observed patterns of erroneous repetitions (i.e., repeated reports of an item that occurred only once on a list) strongly suggest that an item is suppressed after its first report (Duncan & Lewandowsky, 2005; Henson, 1998a; Vousden & Brown, 1998). Likewise, people's reluctance to report an item twice when it was repeated on the list (i.e., the repetition inhibition, or Ranschburg effect) is also commonly taken to reflect response suppression (Duncan & Lewandowsky, 2005; Henson, 1998a).

Some theorists have attributed an additional role to response suppression in the recency effect, the enhanced recall commonly observed for the final one or two list items (Brown et al., 2000; Farrell & Lewandowsky, 2002; Lewandowsky, 1999; Lewandowsky & Farrell, 2008b; Lewandowsky & Murdock, 1989). According to this view, as recall proceeds, more and more items will be suppressed, thus reducing competition in the pool of recall candidates during the remainder of recall. When the last few output positions are reached, only

---

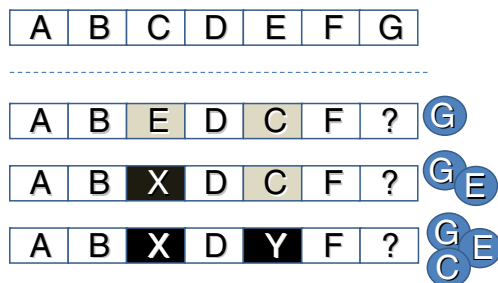
S. Farrell (✉)  
School of Experimental Psychology, University of Bristol,  
12a Priory Road, Clifton,  
Bristol BS8 1TU, U.K.  
e-mail: simon.farrell@bristol.ac.uk  
URL: <http://seis.bris.ac.uk/~pssaf>

S. Farrell · S. Lewandowsky  
School of Psychology, University of Western Australia,  
Crawley, Western Australia, Australia

one or two unsuppressed items will be left to compete for report, thus increasing the probability that the final items will be correctly recalled. This occurs despite the fact that, according to most models, the final list items have the weakest representations (Brown et al., 2000; Farrell & Lewandowsky, 2002; Lewandowsky & Farrell, 2008b; Page & Norris, 1998).

The theoretical linkage between response suppression and recency does not deny that other factors, such as temporal distinctiveness (Brown et al., 2007; Brown et al., 2000; Burgess & Hitch, 1999; Henson, 1998b; Lewandowsky & Farrell, 2008b), might contribute to recency. We show here that a role for response suppression in recency can be demonstrated by considering the impact of events early in recall on later recall attempts. A causal link between response suppression and recency necessarily entails the prediction that the fewer list items are recalled (thus leaving more list items unsuppressed and competing for recall at later output positions), the less recency will occur. Specifically, a list item will remain unsuppressed if it is replaced by an intralist or extralist intrusion. In either case, the failure to recall an item will leave more response alternatives available late in recall, thus lowering accuracy for the final item(s). Importantly, this prediction can be tested while controlling absolute accuracy: If two items are transposed during recall (i.e., two items are recalled in the wrong position), accuracy is identical to the case in which two intrusions (or protrusions) are reported; however, in the former case, two more list items are suppressed than in the latter case (see Fig. 1 for an example).

We present three experiments that examined whether the extent of recency is linked to the number of list items suppressed during recall. Across the three experiments, we



**Fig. 1** Schematic depiction of the effects of response suppression on recall of the last list item for a seven-item list. For the presented sequence “ABCDEFG” (above the dotted line), examples of three possible output sequences are shown, each leaving a different number of list items available for recall at the last serial position. In the first sequence, containing two gray squares denoting two transposition errors, only the last list item, “G,” is left available for recall. In the second sequence, containing one intrusion (“X,” marked in black) and one transposition (the item “C” erroneously recalled at Position 5), items “E” and “G” are left available for recall at the last position. For the last sequence, in which two items “X” and “Y” are intruded, three list items are potentially available for recall at the last position (“C,” “E,” and “G”).

varied the absolute performance level by manipulating variables such as presentation duration, the nature of the materials, and whether or not an interfering task was present. The focus during the analysis of all three studies was on performance on the terminal list item as a function of the number of imputed preceding response suppressions. To preview our main conclusion, we found that recency is a direct function of the number of list items that were reported, and hence were suppressed, during recall.

### Experiment 1

In **Experiment 1**, we sought to provide the opportunity for more intrusions from previous lists, thereby facilitating a conditional analysis in which performance on the final item was examined for various combinations of intrusions (which do not involve suppression of a list item) and transpositions (which do involve suppression of a list item) at preceding output positions. Two presentation durations were used; the presentation duration of each list was pseudorandomly determined, and the condition for that list then was determined by a factorial crossing of the current list duration and the previous list duration. Thus, there were four possible conditions: fast–fast (FF), fast–slow (FS), slow–fast (SF), and slow–slow (SS), where the first letter of each pair refers to the presentation duration of list  $N - 1$ , and the second refers to the duration of list  $N$ . On the basis of demonstrations that a slower presentation rate improves recall (Bhatarah, Ward, Smith, & Hayes, 2009; Tan & Ward, 2008), our reasoning was that items presented at slower rates would be more accessible for recall on their own list, and would also serve as stronger competitors on following lists, leading to more frequent intrusions. Our analysis focused on performance on the terminal item, conditional upon previous reports on that trial. To foreshadow our main result, which applied across conditions, the fewer the list items that were reported at preterminal positions (while keeping the total number of errors and reports constant), the less recency was observed on the terminal output position.

### Method

**Participants and design** A group of 20 members of the campus community at the University of Western Australia participated in exchange for course credit or reimbursement. Two variables were manipulated within participants to form the  $2$  (presentation duration of list  $N - 1$ )  $\times$   $2$  (duration of list  $N$ ) design. The presentation duration was randomly determined on any trial, and thus the numbers of observations for the different conditions and participants were comparable, but not necessarily equal.

**Materials** For each participant, 144 lists of seven unique items were randomly constructed from the set of consonants excluding the letter Y and were subject to two constraints. To allow for discrimination between transpositions and prior-list intrusions, letters used on list  $N - 1$  could not appear on list  $N$ . In addition, meaningful sequences such as “BHP” (a well-known Australian mining company) and “TV” were not allowed. Four additional practice lists were constructed subject to the same constraints.

**Procedure** The experiment was controlled by an IBM-compatible computer with a 15-in. monitor. The participants were informed that they would have to memorize short lists of letters and recall them in the order presented immediately after presentation. The participants were given no other information about list structure or timing, other than that lists did not contain repetitions.

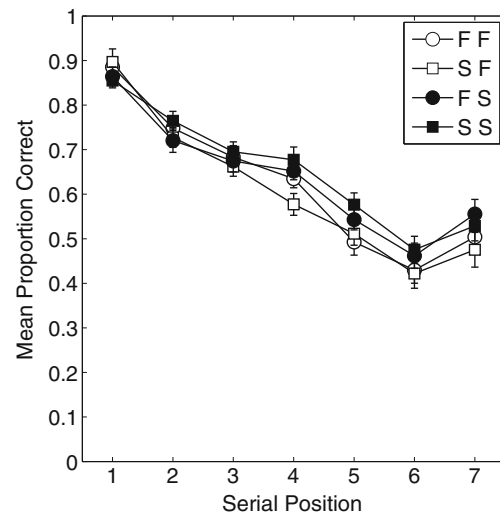
During recall, the participants typed letters on the keyboard using the index finger of their dominant hand. To maximize the occurrence of intrusions, omissions were not permitted and participants were required to guess if necessary.

Each trial was preceded by the message READY, which appeared for 1,000 ms. The screen was then cleared for 1,500 ms, after which the list was presented. Letters were presented one by one in the center of the screen, each letter replacing the preceding one. The presentation durations were 400 and 800 ms, respectively, in the fast- and slow-duration conditions, with a common interstimulus interval (ISI) of 100 ms. Recall commenced immediately after the ISI for the last item, and a 200-ms pause was interposed between the end of recall and the READY signal for the next trial.

The 144 lists were presented in blocks of 18; these blocks were separated by enforced breaks of 30 s. At the end of each break, a message appeared prompting participants to press a key to continue. Four practice trials occurred before the experimental lists. The presentation duration for items on the practice lists was 600 ms (i.e., the mean of the presentation durations for the experimental conditions).

## Results

**Accuracy** Responses were considered correct only if the item was recalled in its correct position; the corresponding serial-position curves for all four conditions are shown in Fig. 2. The accompanying means of correct recall across serial positions for the FF, FS, SF, and SS conditions were .625, .639, .61, and .653, respectively. The three-way repeated measures ANOVA revealed a main effect of serial position,  $F(6, 114) = 39.56$ ,  $p < .001$ ,  $\eta_p^2 = .68$ , and an effect of presentation rate of the target list that approached significance,  $F(1, 19) = 3.58$ ,  $p = .074$ ,  $\eta_p^2 = .16$  (black vs. white symbols in Fig. 2); the effect of the presentation rate of the preceding list was not



**Fig. 2** Effects of the presentation rates of list  $N - 1$  (first character next to each line in the legend) and list  $N$  (second character in the legend) on recall performance in Experiment 1. S, slow presentation rate; F, fast presentation rate. The error bars in all figures demark repeated measures standard errors.

significant,  $F(1, 19) < 1$ . A significant interaction between presentation rate for the target list and serial position was observed,  $F(6, 114) = 4.54$ ,  $p < .001$ ,  $\eta_p^2 = .19$ , whereby the effect of presentation duration increased across serial position. The interaction between the durations of lists  $N$  and  $N - 1$  approached significance,  $F(1, 19) = 3.04$ ,  $p = .097$ ,  $\eta_p^2 = .14$ , with a suggestion that recall of fast lists was better if these were preceded by fast rather than slow lists, while better performance was observed for slow lists if these were also preceded by slow lists. Nonsignificant effects were observed for the interaction between serial position and preceding list duration,  $F(6, 114) = 1.24$ ,  $p = .289$ ,  $\eta_p^2 = .106$ ,  $\eta_p^2 = .06$ , and for the three-way interaction,  $F(6, 114) = 1.79$ ,  $p = .106$ ,  $\eta_p^2 = .09$ .

Because we were primarily interested in recency, we further examined performance on the final item. Figure 2 suggests that the terminal items on slow lists were recalled more accurately than were those on fast lists, but it also appears that at each presentation duration, recall was more accurate if the preceding list was fast rather than slow. A  $2 \times 2$  ANOVA with List  $N - 1$  Duration and List  $N$  Duration as factors and performance on the final item as a dependent measure found only partial support for these effects. The analysis revealed a main effect of list  $N$  duration [ $F(1, 19) = 4.71$ ,  $p = .043$ ,  $\eta_p^2 = .20$ ], but the effect of list  $N - 1$  duration [ $F(1, 19) = 3.00$ ,  $p = .100$ ,  $\eta_p^2 = .14$ ] and the interaction [ $F(1, 19) < 1$ ] were nonsignificant.

The second, and more critical, analysis combined all conditions and examined the extent of recency conditional upon prior output events. Controlling for overall accuracy, performance on the final item was examined as a function of the type of errors that preceded it.

Three response patterns leading up to the last output position were of interest. All patterns included exactly four correct responses and two errors (i.e., 67 % correct) during the first six positions, but they differed with respect to the nature of the errors. The error combinations could be two transpositions, one transposition and one intrusion, or two intrusions on any output position preceding the last one. The position of the errors in the conditional analysis was not controlled, as restricting the analysis to certain positions resulted in too few cases to be analyzed. The lists were excluded from analysis if the last item had been anticipated at an earlier output position, as recall of the last item at an earlier position would make the recall of another item at the last position highly probable. Lists were also omitted if they contained erroneous repetitions prior to the terminal position. One participant for whom no observations occurred in one conditionalization was also eliminated.

The squares in Fig. 3 plot out the proportions of correct recall at the last serial position conditional on the previous trial events (i.e., according to the numbers of preceding intrusions, with the number of errors controlled at two). A one-way repeated measures ANOVA revealed a significant effect of number of preceding intrusions,  $F(2, 36) = 5.60$ ,  $p = .008$ ,  $\eta_p^2 = .24$ , the linear decreasing trend being clearly significant,  $F(1, 18) = 20.64$ ,  $p < .001$ ,  $\eta_p^2 = .53$ .

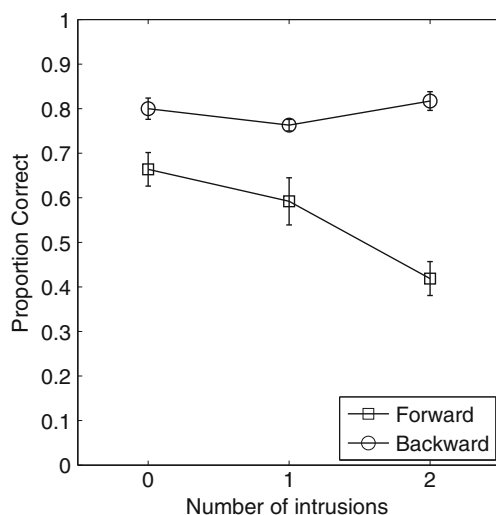
One possible explanation for the relationship between previous events during a trial and last-recall accuracy is that some other variable influences both measures, and therefore introduces a correlation between them. For example, it may be that, between trials, the attention paid by participants to the input list varies. Accordingly, a correlation may be introduced by virtue of the fact that trials on which less attention is paid to the list produce more erroneous recall at

earlier positions and less accurate recall at the final position. To guard against the possibility that some other variability across trials produced the correlation between precency and recency recall, rather than a specific effect of response suppression on recency, a reverse conditional compared performance on the first three serial positions conditional on subsequent errors. Specifically, we examined early-list recall (specifically, the first three positions) according to the number of intrusions occurring in the remaining four output positions. For this analysis, the constraint on transpositions involving items presented at the target positions was relaxed, as the larger number of output positions examined allowed for numerous degrees of freedom in responding. Accordingly, performance at Positions 1–3 was examined as a function of the number of intrusions at Positions 4–7, with the total number of errors in those later positions fixed to two. If the observed effects on recency reflected only forgetting, there should be more errors early in recall if more intrusions were committed in the remainder, reflecting the effect seen when the conditional was applied in the other direction. Mean performance is plotted as circles in Fig. 3 for the 17 participants who produced at least one legitimate response in each of the conditions. A one-way repeated measures ANOVA did not reveal a significant effect of number of intrusions,  $F(2, 32) = 1.30$ ,  $p = .286$ ,  $\eta_p^2 = .08$ , the linear trend also clearly falling short of significance,  $F(1, 16) < 1$ .

The fact that the conditional analysis was powerful enough to reveal a difference in the forward direction, when considering performance on the terminal item, whereas no such difference was revealed in the opposite direction, suggests that the recency results were not caused by differential forgetting or some unobserved variable. To confirm that the difference in the linear trends between the forward and backward conditionals was itself significant, we ran the ANOVA again, but only included participants who had contributed to both analyses. As well as replicating the effects reported above, the ANOVA also revealed a significant difference in the linear trends between the forward and backward conditionals,  $F(1, 16) = 15.42$ ,  $p = .001$ ,  $\eta_p^2 = .49$ .

## Discussion

Together, these results show that intruding items earlier in recall leads to worse recall of the last item, as predicted by the response suppression account. The possibility that this correlation is driven by some unexamined variable, most likely variability in encoding across trials, is unlikely, given that the same relationship does not hold in the reverse direction: The number of later intrusions does not predict performance on earlier list items. The results of Experiment 1 also confirmed that presentation rate had an effect on list



**Fig. 3** Recall accuracy at the final serial position as a function of the number of intrusion errors at previous positions (with the total number of preceding errors fixed at two) for Experiment 1.

recall. Although the findings on presentation rate are a little mixed for the case of serial recall, the finding of an effect adds to the general consensus that slower presentation rates improve recall (Bhatarah et al., 2009; Tan & Ward, 2008).

## Experiment 2

In the second experiment, we sought to maximize performance, and accordingly reduced the list length (from seven to six items) and used an ensemble of nonrhyming consonants. In consequence, because the critical recency analysis involved trials on which participants committed exactly two errors in the first five (out of six) serial positions, results from this experiment were likely to focus on people who performed poorly overall; below, we report another experiment in which we focused analysis on the better-performing participants.

## Method

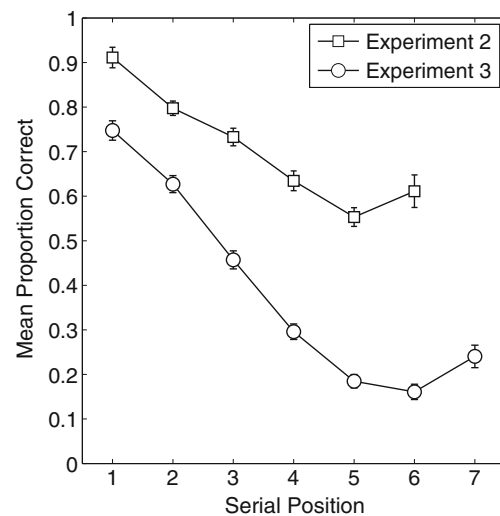
**Participants and apparatus** A group of 20 members of the campus community at the University of Western Australia participated voluntarily in exchange for course credit or reimbursement of travel expenses (A\$10 for the single 1-h session). A Windows-based PC presented all of the stimuli and scored all responses.

**Stimuli and procedure** Each participant performed 120 immediate serial recall trials involving six-item lists drawn from the set of consonants “H,” “K,” “M,” “Q,” “R,” “X,” “L,” “Z,” “W,” and “Y.” The list items were sampled without replacement for each trial.

The experiment proper was preceded by five practice trials during which the experimenter remained present. Each trial commenced with the prompt “Get ready for next list,” which was displayed for 1 s and was followed by a 1-s blank screen. Items were then presented singly and centrally for 400 ms, with a 100-ms ISI. The last item was immediately followed by the recall prompt (a flashing “\_” character). Participants recalled the list via the keyboard in the order in which items had been presented, and they could use the space bar to record omissions. Once entered, a response could not be corrected. The final response was followed by feedback about the total recall time, which had to be acknowledged by pressing the space bar before the prompt for the next trial appeared. Three self-paced break periods were inserted after every 30 trials.

## Results and discussion

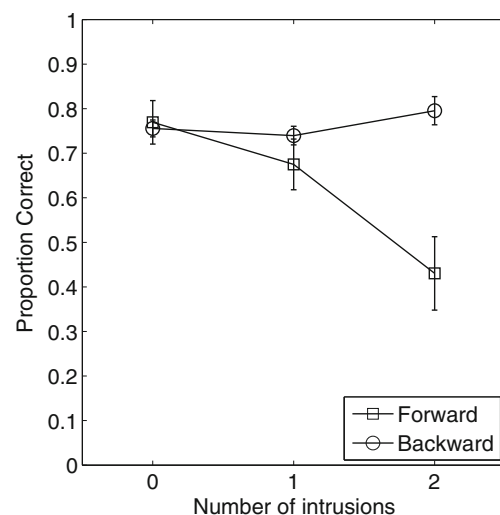
Figure 4 shows the standard summary of the data as a serial-position function (squares), and reveals that the experiment



**Fig. 4** Accuracy serial-position functions for Experiments 2 (squares) and 3 (circles).

produced prototypical primacy and recency effects. A one-way repeated measures ANOVA revealed a significant effect of serial position,  $F(5, 95) = 25.69$ ,  $p < .001$ ,  $\eta_p^2 = .57$ .

Figure 5 shows the results of the conditional analysis in both the forward and backward directions, following the procedure outlined for Experiment 1. Omissions were excluded from the conditional analysis; this also will apply to other analyses reported below on experiments that allowed omissions. Eleven of the participants produced at least one response in each condition for the forward conditional, and 16 participants similarly produced sufficient data under the backward conditional. A one-way repeated measures ANOVA revealed a significant relationship between the number of preceding intrusions and recall accuracy at the



**Fig. 5** Recall accuracy at the final serial position as a function of the number of intrusion errors at previous positions (with the total number of preceding errors fixed at two) for Experiment 2.



last position,  $F(2, 20) = 4.92$ ,  $p = .018$ ,  $\eta_p^2 = .33$ , with a significant linear trend,  $F(1, 10) = 7.60$ ,  $p = .020$ ,  $\eta_p^2 = .43$ . For the backward condition, both the main effect of number of intrusions,  $F(2, 30) < 1$ , and the linear trend,  $F(1, 15) < 1$ , were found to be nonsignificant. An ANOVA examining the interaction between number of intrusions and condition (forward vs. backward) revealed a marginal difference in the linear trend between the forward and backward conditionals,  $F(1, 9) = 3.70$ ,  $p = .087$ ,  $\eta_p^2 = .29$ . This nonsignificance can be attributed to the small number of participants surviving the conditional; the effect itself, as measured by partial eta-squared, was not negligible.

Overall, the results of [Experiment 2](#) replicated those of [Experiment 1](#) in revealing a specific correlation between earlier intrusions and later recall performance.

### Experiment 3

In the third experiment, people engaged in articulatory suppression (AS) throughout study and recall by repeating an irrelevant word aloud. There is common agreement that AS abolishes overt or subvocal rehearsal, thus lowering performance considerably. Because the recency analysis was conditionalized on having exactly two errors in the first six positions (out of seven, in this case), we expected to focus the analysis on the better-performing participants in this study.

#### Method

*Apparatus and participants* A group of 24 first-year undergraduate psychology students from the University of Western Australia participated voluntarily and received course credit in exchange. Each participant completed a single 1-h session.

A Windows-based computer running a MATLAB program, designed using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), displayed all stimuli and recorded all responses.

*Design and procedure* The lists were constructed from 19 letters (all of the consonants except Q and Y), and items were randomly sampled without replacement for each list. The lists contained seven items, and the total presentation duration was constant across all trials.

Because one purpose of this study (not relevant here) was to examine the effects of temporal isolation on serial recall, each list contained one of a possible 720 permutations of the six possible interitem intervals 50, 100, 200, 400, 800, and 1,200 ms. Each participant was assigned at random to one of six possible subsets of 120 permutations. Within each set, each interitem interval was presented the same number of

times (i.e., 20) in each position. The order of the 120 trials was randomized anew for each participant in a subset.

Each trial commenced with a fixation symbol (a “+” sign) centrally presented for 400 ms. The list items were then presented for 400 ms each, with the interitem interval determined by the permutation of intervals for that particular trial. A 1-s pause separated the final list item from the response cue “All:” presented in the center of the screen. The participants’ task was to recall the list items in the order in which they had been presented using the keyboard. The space bar was used to indicate an omission, and participants could not correct a response once entered. The last response remained visible for 300 ms before the screen was cleared and the next trial commenced 3.5 s later.

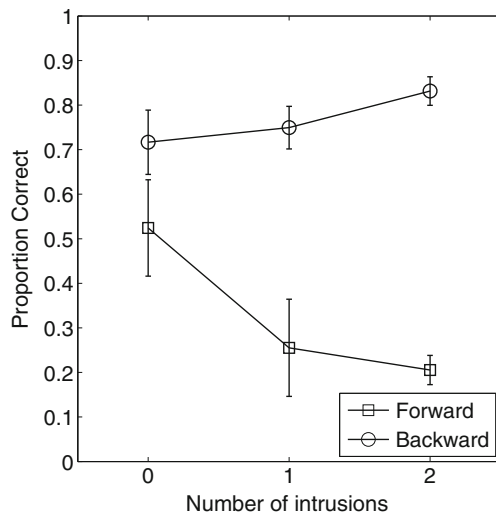
Participants repeated the word “Kalbarri” aloud during list presentation and serial recall. The participants’ verbalizations were recorded to ensure that AS continued for the whole experiment. The experiment commenced with four practice trials, during which the experimenter remained present. Every 30 experimental trials were followed by a self-paced break.

#### Results and discussion

The mean proportion correct across participants was .35 ( $SD = .13$ ). The data of four participants, whose mean performance was below .20, were removed. All of the remaining analyses were therefore based on 20 participants.

Figure 4 shows the standard serial-position function, which again reveals standard primacy and recency effects. A one-way repeated measures ANOVA revealed a significant effect of serial position,  $F(6, 114) = 116.07$ ,  $p < .001$ ,  $\eta_p^2 = .86$ .

Figure 6 plots the results of the conditional analysis, in both the forward and backward directions. Only eight participants produced at least one response in each condition for the forward conditional, and 10 participants similarly produced sufficient data under the backward conditional. The analyses showed that the results replicated those of the first two experiments. A one-way repeated measures ANOVA indicated that the omnibus test of the relationship between the number of preceding intrusions and recall accuracy at the last position failed to reach significance,  $F(2, 14) = 2.39$ ,  $p = .128$ ,  $\eta_p^2 = .25$ , but that the linear trend was nonetheless significant,  $F(1, 7) = 7.43$ ,  $p = .030$ ,  $\eta_p^2 = .51$ . For the backward condition, both the omnibus effect of number of intrusions,  $F(2, 18) < 1$ , and the linear trend,  $F(1, 9) = 1.29$ ,  $p = .285$ ,  $\eta_p^2 = .13$ , were found to be nonsignificant. An ANOVA examining the interaction between number of intrusions and condition (forward vs. backward) revealed a significant difference in the linear trends between the forward and backward conditionals,  $F(1, 6) = 32.82$ ,  $p = .001$ ,  $\eta_p^2 = .85$ .



**Fig. 6** Recall accuracy at the final serial position as a function of the number of intrusion errors at previous positions (with the total number of preceding errors fixed at two) for Experiment 3.

### Analysis of published experiments

To verify the generality of the observed relationship between response suppression and recency, we additionally examined 16 published experiments. Nine of these experiments were found not to produce sufficient numbers of observations in both the forward and backward directions to permit analysis, leaving seven experiments with sufficient data (see Table 1).<sup>1</sup>

The average results of the forward and backward analyses for the seven experiments are shown in Fig. 7. The figure shows a trend comparable to that in the new experiments reported here: Recency performance varies as a function of the number of preceding intrusions (with number of preceding errors controlled), while primacy performance does not vary as a function of later intrusions. The data also show that the difference in results between the forward and backward analyses is not due to a scaling effect (e.g., a ceiling or floor effect on the backward conditional), as the lines diverge from approximately equal performance for the zero-intrusions condition (see also Fig. 5). The analyses provide yet further evidence for the role of response suppression in recency.

### Effects of recall events on error types at terminal position

The relationship between the relative numbers of transpositions and intrusions at preterminal positions and accuracy at

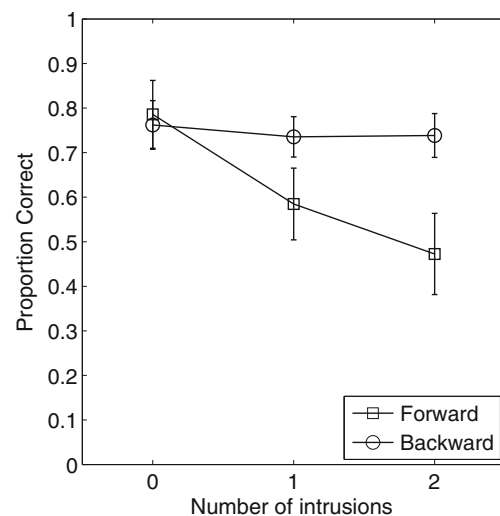
<sup>1</sup> The excluded experiments were Experiment 1 of Farrell, Wise, and Lelièvre (2011); Experiments 1–3 of Lewandowsky, Geiger, and Oberauer (2008); Experiment 1 of Farrell and Lewandowsky (2004); Experiment 1 of Farrell and Lewandowsky (2003); Experiments 1 and 3 of Lewandowsky, Geiger, Morrell, and Oberauer (2010); and Experiment 2 of Lewandowsky and Farrell (2008a).

**Table 1** The analyzed experiments, as well as the numbers of participants contributing usable data to the forward and backward analyses

Experiment	<i>N</i> forward	<i>N</i> backward
E1 of Lewandowsky, Brown, Wright, and Nimmo (2006)	17	17
E1 of Nimmo and Lewandowsky (2006)	17	15
E2 of Nimmo and Lewandowsky (2006) (Auditory presentation)	6	10
E2 of Nimmo and Lewandowsky (2006) (Visual presentation)	8	8
E3 of Farrell and Lewandowsky (2003)	10	10
E2 of Lewandowsky, Geiger, Morrell, and Oberauer (2010)	3	3
E4 of Lewandowsky, Geiger, and Oberauer (2008)	5	13

E1–E4 = Experiment 1, Experiment 2, etc

the last serial position provides some correlational evidence indicating a direct relationship between response suppression and recency. However, for this relationship to hold, it is important that the change in accuracy on the last position be at least partly attributable to a change in the rate of transposition errors. If list items that have not been suppressed (i.e., displaced in recall by intrusions) act as competitors at the final list position, this extra competition should be observable as additional reports of those list items transposed to the terminal position. To confirm this, we separately analyzed the number of transposition and intrusion errors at the last output position, again as a function of the number of preceding intrusion errors (with the total number of preterminal errors controlled at two). For Experiment 1, a significant



**Fig. 7** Recall accuracy at the final serial position as a function of the number of intrusion errors at previous positions (with the total number of preceding errors fixed at two), averaged across the experiments detailed in Table 1.

increasing linear trend was found for transpositions,  $F(1, 18) = 16.64, p = .001$ , but not for intrusions,  $F(1, 18) = 1.95, p = .18$ . For **Experiment 2**, a significant increasing linear trend was likewise found for transpositions,  $F(1, 10) = 10.51, p = .009$ , but not for intrusions,  $F(1, 10) < 1$ . For **Experiment 3**, by contrast, the linear trend was not significant for transpositions,  $F(1, 7) < 1$ , and was significant for intrusions,  $F(1, 7) = 7.02, p = .008$ . An inspection of the data included in the broader analysis (reported in the previous section) revealed an overall increase in both transposition and intrusion errors with an increasing number of intrusions at preterminal positions. Together, these analyses indicate that an increase in the number of transpositions at the final position contributed to the decrease in accuracy seen above, with some additional contribution from an increase in the frequency of intrusion errors at the terminal position.

It should be noted, however, that this relationship did not hold for all experiments; **Experiment 3** showed that only intrusions increased with increasing numbers of preterminal intrusions. One obvious difference between that experiment and **Experiments 1** and **2** was that accuracy was low, and in particular that omission errors were allowed. Further examination of the data revealed that the number of item errors (intrusions + omissions) outweighed the number of transpositions. Accordingly, it may be that we can only see the suppression-associated effects to the extent that the list items are clearly discriminated from extralist competitors and are highly accessible: If earlier (nonrecalled) items are not accessible, an increase in transpositions may not be observable, because the nonrecalled list items are no more accessible than extralist competitors. In other words, when list items are overall more accessible than extralist items, as in **Experiments 1** and **2**, we observe an increase of transpositions with more intrusions, as expected according to the suppression account. By contrast, when list items are weak overall and extralist items are equally accessible (or nearly so), as indexed by the overall level of item errors, the effect cannot manifest itself because people choose from a far larger ensemble of response candidates on the last position. This, in turn, means that the predicted relationship is likely to be observed only where transpositions dominate recall, which is not that surprising, given that the recency effect is specifically linked to a decrease in transposition errors (rather than in item errors) at the final list position (Henson, 1996; Page & Norris, 1998).

What of the increase in intrusions with increasing numbers of preterminal intrusions that was seen in some studies? One explanation might be that when overall performance is worse, more intrusions are committed in both the precency and recency portions of the list. However, our earlier analyses took this possibility into account by examining the conditional in both the forward and backward directions, and they indicated that this is unlikely to explain the decrease

in accuracy on the final item with the increasing number of preterminal intrusions. Instead, this pattern seems to suggest that intrusions beget intrusions, a pattern also seen in free recall of longer lists (Zaromb et al., 2006). Although this pattern might at first glance be taken to imply an additional output mechanism, we argue that it is entirely compatible, and indeed expected, from the same response suppression mechanism responsible for the pattern of transpositions. In particular, the SOB model and its variants (Farrell, 2006; Farrell & Lewandowsky, 2002; Lewandowsky & Farrell, 2008a) assumes that response suppression is accomplished by subtracting items from the connectionist weight matrix storing list representations. If an intrusion is committed, response suppression will have the effect of subtracting an item that was never stored in the first place. Mathematically, the suppression of a nonstudied item is equivalent to the encoding of another pattern (not necessarily identical to the intrusion) that from then on competes with the remaining list items for report. This mechanism may suffice to explain why intrusions beget intrusions within the suppression framework.

## General discussion

The reported experiments explored the role of response suppression in recency by examining the effects of preterminal errors on performance on the terminal item. Given a constant number of preterminal errors, the analysis revealed that an increase in the number of intrusions prior to the final output position was accompanied by worse performance on the terminal position. This supports a response suppression account according to which recency would diminish with a greater number of list items remaining unsuppressed. The influence of overall variability between trials was examined as a potential explanation and ruled out: Reversing the conditional to examine performance on primacy items according to the number of intrusions later in recall revealed no relationship. To underscore the generality of this effect, we reported identical conditional analyses of seven published experiments from our laboratory. In all cases, recency decreased as more list items remained unsuppressed, exactly as was found in the new experiments.

Some caution should be exercised in interpreting the results of conditional analyses, given their correlational nature. For example, one possibility highlighted by a reviewer is that different types of errors prior to the terminal position tend to occur at different serial positions. Table 2 gives the mean serial positions of the first and second errors in each conditional analysis, and it reveals no substantial difference in the mean serial positions of errors between the conditions. To rule this out as a confounding factor that somehow explained our results, we reran all of the analyses reported above, but applying the conditional to only the two



**Table 2** Mean serial positions of the first error and the second error for increasing numbers of intrusions (columns) for all experiments analyzed here (rows)

	First Error			Second Error		
	0	1	2	0	1	2
Number of Intrusions	0	1	2	0	1	2
Experiment 1 (E1)	3.54	3.66	3.70	4.83	5.35	5.63
Experiment 2 (E2)	3.02	3.28	3.10	4.15	4.52	4.49
Experiment 3 (E3)	3.62	4.19	4.29	4.93	5.56	5.66
E1 of Lewandowsky, Brown, Wright, and Nimmo (2006)	3.61	4.29	4.19	4.96	5.62	5.79
E1 of Nimmo and Lewandowsky (2006)	3.50	3.99	3.07	4.64	5.31	5.17
E2 of Nimmo and Lewandowsky (2006) (Auditory presentation)	3.62	4.08	3.40	4.78	5.33	5.42
E2 of Nimmo and Lewandowsky (2006) (Visual presentation)	3.40	3.95	3.30	4.81	5.39	5.10
E3 of Farrell and Lewandowsky (2003)	3.12	3.08	3.56	4.21	4.50	4.79
E2 of Lewandowsky, Geiger, Morrell, and Oberauer (2010)	2.33	2.67	2.67	3.33	3.67	4.00
E4 of Lewandowsky, Geiger, and Oberauer (2008)	2.27	2.18	2.25	3.47	3.83	3.60
Mean	3.20	3.54	3.41	4.41	4.91	4.96

serial positions preceding the terminal position (all other items preceding the last were necessarily correctly recalled). The overall pattern of results was the same, although some analyses were difficult to interpret because we had few participants contributing data, given the strict criterion for usable data. Accordingly, we here report the data as above where we generally had sufficient power to detect patterns of interest.

Notwithstanding the partial assurance provided by Table 2 and the reverse conditional (i.e., that early-list recall was unaffected by the nature of later errors), the caveat remains that some unforeseen factor may have contributed to both the selection of lists for the conditional analysis and the observed extent of recency. Although this possibility cannot be conclusively refuted, conditional or correlational arguments, such as the relationship between speech rate and memory span (Baddeley, Thomson, & Buchanan, 1975; Cowan et al., 1998), have driven theorizing elsewhere in short-term memory research, and individual-differences analyses have made a major contribution to our understanding of working memory (Conway, Jarrold, Kane, Miyake, & Towse, 2007). The present results extend this line of attack to a microanalysis of the processes underlying recency.

It is worth noting that some researchers have questioned the necessity of response suppression to account for the recency effect. Cowan, Saults, Elliott, and Moreno (2002) conducted an experiment in which nine-item lists were presented to participants, but in which both the starting position of recall and the number of items to be recalled were manipulated by postcuing their participants. Of

critical interest was a condition in which, for a given starting position in the list, either three or nine items were to be recalled, but only performance on the first three items was examined. For example, for the list items 1 2 3 4 5 6 7 8 9, participants could be postcued to recall the first three items (1 2 3) or the entire list (1 2 3 4 5 6 7 8 9), with accuracy being compared only for items 1, 2, and 3. Cowan et al. (2002) found a small accuracy advantage when only three items had to be recalled, and they suggested that this reflected a memory load imposed by the need to keep track of to-be-recalled items and their serial positions. On the basis of these findings, Cowan et al. (2002) argued that the diminishing size of this response set across output positions, rather than response suppression, might contribute to the recency effect. However, because response set size and response suppression are necessarily confounded in standard forward serial recall, their account offers little additional explanatory power, despite being considerably more complex than the response suppression notion.

A similar attempt to deconfound input and output ordering was conducted by Oberauer (2003), who randomized the input and output orderings (with respect to spatial ordering) of items in a spatial probed-recall task. Oberauer found that performance monotonically decreased with output position, and on that basis argued against the presence of response suppression, because response suppression should have produced some recency across output positions. However, the randomization of input and output orders in Oberauer's study resulted in a confounding between output position and input–output lag. For example, for the first output position, the shortest retention interval was for the last list item (lag 1 item), whereas the largest retention interval was six (i.e., from the first list item). In contrast, for the last output position, the smallest input–output lag was six (for the last list item) and the largest was 11 (for the first list item). In consequence, items recalled first (i.e., at the first output positions) tended to have a shorter retention interval, thus likely giving rise to better performance (the crucial role of retention interval is attested by the large recency typically found in probed recall of single items; e.g., Murdock, 1968). In Oberauer's study, the effect of retention interval may have been sufficiently strong to counteract the small recency effects typically observed in visual recall. In our experiments, retention interval was controlled and the analysis was conditional upon the inferred extent of response suppression, and accordingly, we found the expected link between suppression and recency.

Our findings complement other results that have underscored the importance of response suppression for ordered recall (Duncan & Lewandowsky, 2005; Henson, 1998a; Vousden & Brown, 1998). These results are problematic for models that rely exclusively on factors other than response suppression to account for recency (Anderson &

Matessa, 1997; Brown et al., 2007; Estes, 1972). While a number of models assume that the increased distinctiveness of items at either end of the list enhances recall, due either to the temporal distinctiveness of those items (Brown et al., 2007) or to the fewer neighbors with similar positional codes (Brown et al., 2000; Burgess & Hitch, 1999; Henson, 1998b), some models rely exclusively on these “edge effects” to explain recency (Brown et al., 2007; Estes, 1972). In addition, the SIMPLE model assumes that recent items are given a boost due to the logarithmic compression of time, which leaves the most recent events particularly distinct. Our analyses make clear that edge effects do not offer a complete explanation for recency in serial recall, given that there is at least some contribution of response suppression to the recall of the terminal list item. Notably, models that rely solely on edge effects to explain recency account only for aggregate effects in recall (Brown et al., 2007; Estes, 1972) and do not offer an account for fine-grained effects occurring within individual trials (e.g., fill-in and infill errors: Henson, Norris, Page, and Baddeley, 1996; Page & Norris, 1998; Surprenant, Kelley, Farley, & Neath, 2005). Along with other findings from both free and serial recall (Couture, Lafond, & Tremblay, 2008; Kahana, 1996; Roediger, 1974), the link between response suppression and recency points to the effect of recall on future memory performance, and to the importance of capturing the dynamics of recall in models of memory.

In finishing, we stress response suppression’s role as a control mechanism for memory (or, at the least, its reflection of the operation of such a mechanism). An important role for similar mechanisms that remove or control unwanted information has been repeatedly identified in research on working memory and episodic memory. For example, paradigms such as working memory updating (Ecker, Lewandowsky, Oberauer, & Chee, 2010; Morris & Jones, 1990; Oberauer & Vockenberg, 2009) arguably require the ability to inhibit information that was previously relevant, and the directed-forgetting paradigm points to a process of active forgetting of information that is identified as irrelevant (Fawcett & Taylor, 2008). Response suppression can be seen as serving a similar process of suppressing irrelevant information, but where the act of recall itself renders information no longer relevant (at least, within a single recall attempt). Indeed, response suppression may relate to more general processes of control of irrelevant information. In the C-SOB model, response suppression is assumed to occur through the unlearning of associations between items and a representation of their position in the sequence, using the same mechanism that is used for the original encoding of information (Farrell, 2006; Lewandowsky & Farrell, 2008b). In a recent extension of this model to complex span—a common measure of working memory in which serial-recall stimuli are interleaved with processing of distracting information (Conway et al., 2003;

Daneman & Carpenter, 1980)—Oberauer et al. (unpublished) assumed that the unlearning mechanism was also used to remove associations between distractors and positional contexts that were formed when processing those distractors. Given Oberauer et al.’s demonstration that individual differences in the effectiveness of this removal could partly explain individual differences in working memory performance more broadly, response suppression may well be a more general mechanism supporting and constraining cognition.

**Author note** This research was supported in part by a Discovery Grant from the Australian Research Council and an Australian Professorial Fellowship to the second author, and a Linkage International grant to both authors, Gordon Brown, and Klaus Oberauer.

## References

- Anderson, J. R., & Matessa, M. (1997). A production system theory of serial memory. *Psychological Review*, *104*, 728–748. doi:10.1037/0033-295X.104.4.728
- Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *14*, 575–589. doi:10.1016/S0022-5371(75)80045-4
- Bhatarah, P., Ward, G., Smith, J., & Hayes, L. (2009). Examining the relationship between free recall and immediate serial recall: Similar patterns of rehearsal and similar effects of word length, presentation rate, and articulatory suppression. *Memory & Cognition*, *37*, 689–713.
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436. doi:10.1163/156856897X00357
- Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, *114*, 539–576.
- Brown, G. D. A., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. *Psychological Review*, *107*, 127–181.
- Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, *106*, 551–581.
- Conway, A. R. A., Jarrold, C., Kane, M. J., Miyake, A., & Towse, J. N. (Eds.). (2007). *Variation in working memory*. Oxford, U.K.: Oxford University Press.
- Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*, 547–552.
- Couture, M., Lafond, D., & Tremblay, S. (2008). Learning correct responses and errors in the hebb repetition effect: Two faces of the same coin. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 524–532.
- Cowan, N., Saults, J. S., Elliott, E. M., & Moreno, M. V. (2002). Deconfounding serial recall. *Journal of Memory and Language*, *46*, 153–177.
- Cowan, N., Wood, N., Wood, P., Keller, T., Nugent, L., & Keller, C. (1998). Two separate verbal processing rates contributing to short-term memory span. *Journal of Experimental Psychology: General*, *127*, 141–160.
- Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466.

- Duncan, M., & Lewandowsky, S. (2005). The time course of response suppression: No evidence for a gradual release from inhibition. *Memory, 13*, 236–246.
- Ecker, U. K. H., Lewandowsky, S., Oberauer, K., & Chee, A. E. H. (2010). The components of working memory updating: An experimental decomposition and individual differences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 170–189.
- Estes, W. K. (1972). An associative basis for coding and organization in memory. In A. W. Melton & E. Martin (Eds.), *Coding processes in human memory* (pp. 161–190). Washington, DC: Winston.
- Farrell, S. (2006). Mixed-list phonological similarity effects in delayed serial recall. *Journal of Memory and Language, 55*, 587–600.
- Farrell, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin & Review, 9*, 59–79. doi:10.3758/BF03196257
- Farrell, S., & Lewandowsky, S. (2003). Dissimilar items benefit from phonological similarity in serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 838–849. doi:10.1037/0278-7393.29.5.838
- Farrell, S., & Lewandowsky, S. (2004). Modelling transposition latencies: Constraints for theories of serial order memory. *Journal of Memory and Language, 51*, 115–135.
- Farrell, S., Wise, V., & Lelièvre, A. (2011). Relations between timing, position and grouping in short-term memory. *Memory & Cognition, 39*, 573–587.
- Fawcett, J. M., & Taylor, T. L. (2008). Forgetting is effortful: Evidence from reaction time probes in an item-method directed forgetting task. *Memory & Cognition, 36*, 1168–1181.
- Henson, R. N. A. (1996). *Short-term memory for serial order*. University of Cambridge: Unpublished doctoral dissertation.
- Henson, R. N. A. (1998a). Item repetition in short-term memory: Ranschburg repeated. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 1162–1181.
- Henson, R. N. A. (1998b). Short-term memory for serial order: The start–end model. *Cognitive Psychology, 36*, 73–137.
- Henson, R. N. A., Norris, D. G., Page, M. P. A., & Baddeley, A. D. (1996). Unchained memory: Error patterns rule out chaining models of immediate serial recall. *Quarterly Journal of Experimental Psychology, 49A*, 80–115.
- Kahana, M. J. (1996). Associative retrieval processes in free recall. *Memory & Cognition, 24*, 103–109.
- Lewandowsky, S. (1999). Redintegration and response suppression in serial recall: A dynamic network model. *International Journal of Psychology, 34*, 434–446.
- Lewandowsky, S., Brown, G. D. A., Wright, T., & Nimmo, L. M. (2006). Timeless memory: Evidence against temporal distinctiveness models of short-term memory for serial order. *Journal of Memory and Language, 54*, 20–38.
- Lewandowsky, S., & Farrell, S. (2008a). Phonological similarity in serial recall: Constraints on theories of memory. *Journal of Memory and Language, 58*, 429–448.
- Lewandowsky, S., & Farrell, S. (2008b). Short-term memory: New data and a model. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 49, pp. 1–48). San Diego, CA: Academic Press.
- Lewandowsky, S., Geiger, S. M., Morrell, D. B., & Oberauer, K. (2010). Turning simple span into complex span: Time for decay or interference from distractors? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 958–978. doi:10.1037/a0019764
- Lewandowsky, S., Geiger, S. M., & Oberauer, K. (2008). Interference-based forgetting in verbal short-term memory. *Journal of Memory and Language, 59*, 200–222.
- Lewandowsky, S., & Murdock, B. B. (1989). Memory for serial order. *Psychological Review, 96*, 25–57.
- Morris, N., & Jones, D. M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81*, 111–121.
- Murdock, B. B. (1968). Serial order effects in short-term memory. *Journal of Experimental Psychology, 76*, 1–15.
- Murdock, B. B. (1995). Developing TODAM: Three models for serial-order information. *Memory & Cognition, 23*, 631–645.
- Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition, 18*, 251–269.
- Nimmo, L. M., & Lewandowsky, S. (2006). Distinctiveness revisited: Unpredictable temporal isolation does not benefit short-term serial recall of heard or seen events. *Memory & Cognition, 34*, 1368–1375. doi:10.3758/BF03193278
- Oberauer, K. (2003). Understanding serial position curves in short-term recognition and recall. *Journal of Memory and Language, 49*, 469–483.
- Oberauer, K., & Vockenberg, K. (2009). Updating of working memory: Lingering bindings. *Quarterly Journal of Experimental Psychology, 62*, 967–987.
- Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105*, 761–781. doi:10.1037/0033-295X.105.4.761-781
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442. doi:10.1163/156856897X00366
- Roediger, H. L., III. (1974). Inhibiting effects of recall. *Memory & Cognition, 2*, 261–269.
- Surprenant, A. M., Kelley, M. R., Farley, L. A., & Neath, I. (2005). Fill-in and infill errors in order memory. *Memory, 13*, 267–273.
- Tan, L., & Ward, G. (2008). Rehearsal in immediate serial recall. *Psychonomic Bulletin & Review, 15*, 535–542.
- Vousden, J. I., & Brown, G. D. A. (1998). To repeat or not to repeat: The time course of response suppression in sequential behaviour. In J. A. Bullinaria, D. W. Glasspool, & G. Houghton (Eds.), *Proceedings of the Fourth Neural Computation and Psychology Workshop: Connectionist representations* (pp. 301–315). Berlin, Germany: Springer.
- Zaromb, F. M., Howard, M. W., Dolan, E. D., Sirotnin, Y. B., Tully, M., Wingfield, A., & Kahana, M. J. (2006). Temporal associations and prior-list intrusions in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 792–804.