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Timeless memory: Evidence against temporal distinctiveness models of short-term memory for serial order ☆

Stephan Lewandowsky [a,*], Gordon D.A. Brown [b], Tarryn Wright [a], Lisa M. Nimmo [a]

[a] *University of Western Australia, Australia*
[b] *University of Warwick and University of Western Australia, Australia*

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Abstract

According to temporal distinctiveness models, items that are temporally isolated from their neighbors during list presentation are more distinct and thus should be recalled better. Event-based theories, by contrast, deny that time plays a role at encoding and predict no beneficial effect of temporal isolation, although they acknowledge that a pause after item presentation may afford extra opportunity for a consolidation process such as rehearsal or grouping. We report two experiments aimed at differentiating between the two classes of theories. The results show that neither serial recall nor probed recall benefit from temporal isolation, unless participants use pauses to group a list. Simulations of the SIMPLE model provide convergent evidence that short-term memory for serial order need not involve temporal representations.

Keywords: Short-term memory; Serial recall; Time and memory; Computational modeling

Introduction

From simple demands like recalling a phone number to tasks as complex as language comprehension and production, the requirement to store and retrieve information in its correct order is fundamental to cognition. Accordingly, several computational theories have been proposed that explain many, but not all (see, e.g., Murdock, 1995), phenomena of memory for serial order. A basic distinction between theories rests on what role, if any, they ascribe to the passage of time. According to time-based theories (e.g., Brown, Neath, & Chater, 2002; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Page & Norris, 1998), time and memory are closely and crucially linked (e.g., Brown & Chater, 2001). Event-based theories (e.g., Capaldi & Neath, 1995; Farrell & Lewandowsky, 2002; Murdock, 1993), by contrast, consider the role of time to be more indirect, as a facilitator of the cognitive processes governing memory.

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* Corresponding author.
E-mail address: lewan@psy.uwa.edu.au (S. Lewandowsky).
URL: http://www.psy.uwa.edu.au/user/lewan/ (S. Lewandowsky).

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This article critically examines the role of time during encoding in short-term memory for serial order. We report two experiments that compared the predictions of event-based and time-based theories by manipulating the temporal isolation of items during list presentation. The structure of this article is as follows: after briefly describing time-based and event-based theories, we review the existing evidence and find that it is insufficient to adjudicate between the two classes of theories. We then present two experiments in which temporal gaps between list items were unpredictable and find that temporal isolation does not affect serial memory performance in these circumstances. We confirm this conclusion by simulation of a time-based theory of memory.

Temporal distinctiveness theories and encoding effects

According to temporal distinctiveness theories (e.g., Bjork & Whitten, 1974; Brown et al., 2000; Burgess & Hitch, 1999; Crowder, 1976; Glenberg & Swanson, 1986; Neath, 1993), the temporal separation of events at encoding is a crucial determinant of memory performance. All other things being equal, distinctiveness models predict that the memorability of an event increases with its temporal separation from neighboring events. In consequence, people are more likely to remember details about widely separated events (e.g., biennial holidays overseas) than events that are more closely spaced (e.g., frequent trips to overseas conferences).

One recent computational instantiation of the temporal distinctiveness hypothesis is the SIMPLE model (Scale Invariant Memory, Perception, and LEarning) of Brown et al. (2002). In SIMPLE, items are confusable with other items in memory to the extent that they are temporally crowded. More specifically, the confusability between any two memory traces is related to the ratio of the time that has elapsed between their encoding and the time of recall. The lower that ratio, the lower the confusability among items and hence the more likely it is that an item is recalled correctly. This mechanism favors recent items over more distant events. For example, items that were encoded 1 and 2 s ago are less confusable (ratio of .5) than are items from 5 and 6 s ago (.83). The mechanism also favors items that were separated in time over others that occurred in close succession. For example, items that occurred 5 and 10 s ago (ratio .5) will have less confusable memory traces than items that occurred 7 and 8 s ago (.88), notwithstanding the fact that the average retention interval is equal for both pairs of items. It follows that items from further in the past, and items that occurred near each other in time, will be more difficult to recall (see Brown et al., 2002, for further details).

To give a specific example, after study of the list A B...C...D E (where "..." represents a brief temporal gap, perhaps on the order of a second), SIMPLE expects item C to be most distinctive because it was temporally isolated from its neighbors. Items B and D would be of intermediate distinctiveness (compared to A and E) because they were followed and preceded, respectively, by a temporal gap. Accordingly, performance on C (and to a lesser extent B and D) should benefit compared to a condition in which all temporal gaps are equal.

These predictions are not unique to SIMPLE: most models that acknowledge a role of time at encoding would expect recall to be better for items surrounded by pauses. For example, the model by Burgess and Hitch (1999) postulates that encoding and retrieval are governed by a context window that slides, over time, across a set of context units to which events are associated. The OSCAR model (Brown et al., 2000) likewise predicts a beneficial effect of temporal isolation. OSCAR relies on a combination of oscillators to provide a context signal that is associated with each item at presentation. At retrieval, the oscillators are reset to their original state and recall proceeds by retrieving that item, at each time step, that is associated with the most similar state of the oscillators (Brown et al., 2000). Accordingly, temporally isolated items are associated with quite different oscillator activations, thus reducing the potential confusion between response candidates.

In general, temporal distinctiveness theories are bound to predict that recall of an item will improve as its temporal isolation from its neighbors increases. As we show by simulation later, these theories would have considerable difficulty accommodating the contrasting null result; namely, the absence of a temporal isolation effect.

Event-based theories and temporal isolation

Temporal distinctiveness theories stand in contrast to another class of models, which we call "event-based," that assign little or no importance to the passage of time per se either in general (e.g., Farrell & Lewandowsky, 2002; Henson, 1998; Lewandowsky & Murdock, 1989; Murdock, 1995; Nairne, 1990; Neath, 1999) or during specific stages of memory processing (e.g., during encoding, Page & Norris, 1998). On an event-based account, it is not the passage of time that causally affects memory, but the cognitive processes that are given a chance to operate during that elapsed time.

One recent instantiation of an event-based approach is the SOB (Serial Order in a Box) model of Farrell and Lewandowsky (2002). According to SOB, events are added to a composite distributed memory in the order of their occurrence, without regard to their temporal separation. The resulting composite trace is ahistorical and contains no temporal information. It follows that SOB would expect temporal isolation to have no effect on performance, unless it is assumed that people use the temporal structure of the list to engage in some additional processing to consolidate their memory. For example, temporal isolation of an item might enhance the quality of encoding through the opportunity for additional rehearsal; gaps between components of the list might trigger subjective grouping strategies; or temporal crowding may cause people strategically to pay less attention to those items. In this article, we are not concerned with the exact nature of those mechanisms and hence refer to them generically as "consolidation" processes.

We next examine existing results concerning the effects of temporal isolation in serial recall and conclude that they are theoretically more ambiguous than originally thought.

The effects of temporal isolation

Neath and Crowder (1996) systematically varied inter-item intervals during presentation of 5-item lists. Inter-item intervals either remained constant, or they all increased across serial positions, or they all decreased across the list. In the increasing condition, the inter-item interval increased from 50 (between the first two items), to 100 (between items 2 and 3), to 200, and then to 400 ms. The decreasing condition involved the reverse order of these intervals, and the constant condition had a uniform inter-item interval of 50 ms.

In support of the distinctiveness notion, serial recall performance for the last few items was significantly better for the increasing condition compared to the decreasing condition, whereas the reverse was true for the first few items. Performance on the constant-interval control list was in between these two conditions. Neath and Crowder argued that these results were unlikely to be due to overt rehearsal as the inter-item intervals were very short and the overall presentation sequence was very rapid (1100 ms).

Similar results were reported by Welte and Laughery (1971) with slower presentation rates, suggesting that the results of Neath and Crowder (1996) were not tied to the use of very brief intervals. Welte and Laughery (1971) used lists of 9 digits that were presented with either an increasing or a decreasing schedule of intervals. Intervals had a minimum duration of 500 ms with a uniform step-size of 200 ms. Emphasis in Welte and Laughery's experiment was on examining the differences between serial recall and free recall. The results revealed the same beneficial pattern of temporal isolation for free recall as for serial recall, thus extending the generality of the finding by Neath and Crowder (1996). (See also Neath & Crowder, 1990.)

However, two methodological features of the studies by Neath and Crowder (1996) and Welte and Laughery (1971) prevent an unambiguous interpretation. First, the presentation schedules precluded a differentiation of the effects of a temporal gap preceding an item from the effects of intervals following an item. Irrespective of whether intervals increased or decreased across serial positions, pauses before and after each item were necessarily perfectly correlated. Because event-based theories can explain temporal isolation effects on the basis of consolidation processes that necessarily only occur *after* an item's presentation, the data of Neath and Crowder (1996) and Welte and Laughery (1971) thus do not rule out an event-based explanation. Second, in both studies, the gap between the first two items predicted the duration of all following intervals: when the first interval was short, participants knew that the list would end with well-separated items, whereas when the first interval was long, participants knew that the list would end with items crowded together in time. This predictability may have encouraged participants to develop compensatory encoding strategies which in turn may have contributed to the observed isolation effects. Alternatively, participants may have paid attention to a temporal dimension, and hence benefitted from temporal isolation, but only when temporal schedules were predictable.

Both of these methodological features were circumvented in a recent set of studies by Lewandowsky and Brown (2005), in which items were separated by randomly chosen temporal intervals. Their analysis considered the effects of the interval preceding and following an item separately by focusing on a set of critical items in positions 2, 4, 6, and 8 on a 9-item list. The pre-item interval was defined as the interval between a critical item (e.g., in position 2) and the item preceding it (e.g., in position 1), and the post-item interval was the interval between the critical item and the one following it (in this example the 3rd item). Because critical items were separated from each other by an additional intervening list item, the effects of both types of interval could be assessed independently.

Lewandowsky and Brown found that temporal separation led to improved recall performance, but only for time *after* an item's presentation and not for the interval preceding it, which is consistent with event-based theories. In further support of event-based theories, Lewandowsky and Brown also found that the beneficial effect of the post-interval was abolished by articulatory suppression (AS). AS is the repetitive vocalisation of an irrelevant word by the participant during study and is known to disrupt encoding by eliminating rehearsal (e.g., Saito, 2000). The elimination of any temporal distinctiveness effects by AS supports the suggestion that rehearsal, or some other consolidation process affected by AS, was responsible for their occurrence in the first place.

However, the study by Lewandowsky and Brown was limited in a number of ways: first, owing to the random sampling of intervals, the frequencies of the various combinations of pre- and post-item durations were uneven. Second, the number of observations was insufficient to permit an analysis of temporal isolation effects at the level of individual serial positions. Third, the serial position curve for quiet presentation (their Fig. 1) exhibited the scalloping that is characteristic of participants having grouped the 9-item list in a 3-3-3 pattern (this was further confirmed by the unpublished latency serial position curves and transposition gradients). Because the analysis could not partial out the effect of serial position, the observed effect of the post interval may therefore have reflected the benefits that grouping is known to bestow on the first and last item of each group (e.g., Henson, 1999a, 1999b; Hitch, Burgess, Towse, & Culpin, 1996; Ng & Maybery, 2002; Ryan, 1969), rather than general consolidation processes. Fourth, the serial position curve for AS showed no evidence that people grouped the list under those circumstances (that conclusion was again supported by the unpublished latency data and transposition gradients). It follows that the absence of temporal isolation effects under AS may have been the indirect consequence of articulation abolishing grouping, and with it, the apparent effects of temporal isolation.

These limitations were resolved in the experiments reported in this article: although participants could not predict the inter-item intervals, it was ensured that all possible combinations of pre- and post-intervals were represented equally often at all serial positions. Moreover, the number of observations was increased considerably to facilitate analysis at the level of each serial position, thus permitting any effects of grouping to be identified and differentiated from purely temporal effects.

SIMPLE: Time-based vs. event-based predictions

To guide interpretation of the results from our experiments, we used SIMPLE to derive predictions for the standard temporal distinctiveness account as well as for an event-based account that relied on positional coding. Although SIMPLE, by default, relies on time-based representations, its architecture is sufficiently flexible to permit a comparison of those two accounts within a common computational framework. Because neither account included any consolidation processes, the modeling instantiates a procedure in which rehearsal is eliminated by AS.

Presenting contrasting quantitative predictions for the forthcoming studies is important for several reasons: first, it provides the necessary confirmation that an event-based account can be instantiated within the SIMPLE architecture and, relatedly, it ascertains that the predictions of the two accounts diverge sufficiently to permit experimental differentiation. Second, the predictions for each account provide a baseline against which the empirical outcome can be compared and specific deviations can be identified. Third, each account offers a theoretically "pure" platform from which any modifications that might be needed to fit specific outcomes can be derived.

SIMPLE rests on three principal assumptions: (1) Items in memory are represented by their position within a potentially multi-dimensional psychological space, with one of those dimensions necessarily devoted to representing time. Here, the temporal dimension was accompanied by a second, positional, dimension. (2) The similarity between any two memory traces is a declining function of the distance separating them in psychological space. (3) The probability of recalling an

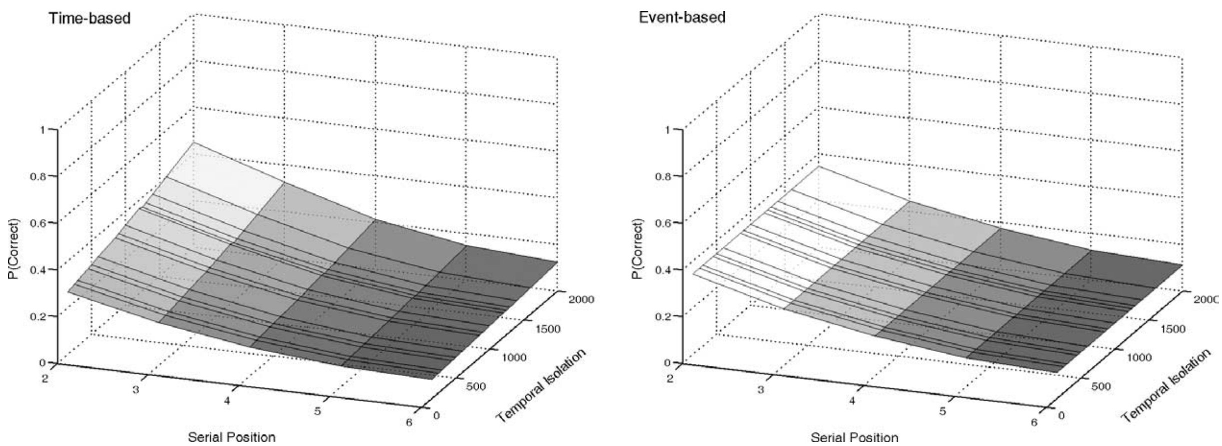

Fig. 1. SIMPLE predictions for Experiment 1 using the time-based account (left-hand panel) and the event-based account (right-hand panel). The 3-D surfaces show the predicted effects of combined isolation and serial position simultaneously (end items are omitted).

item is inversely related to that item's summed similarity to all other response alternatives, as we illustrated at the outset by computing the ratios between elapsed times of item pairs. We now detail each of these assumptions in turn.

Encoding in multi-dimensional space

Memory representations are organized along a primary temporal dimension that reflects the (logarithmically transformed) time since encoding. Retrieval can be cued by the remembered location of an item along this dimension. In the present case, a second dimension represents within-list position, coded by ordinal numbers (i.e., position 1, 2,...). There is ample evidence that positional information—which can be decoupled from elapsed time—is relevant in serial recall (Henson, 1999b; Ng & Maybery, 2002). To illustrate, consider the representation of a two-item list after a 6 s retention interval (with items being separated by 1 s on the list): The two items' memory traces would be in locations {log(7), 1} and {log(6), 2}, respectively, in the {time, position} space.

The relative importance of the two dimensions at retrieval is determined by the parameter *wt*, which is the attentional weight paid to the temporal dimension. The weight given to the positional dimension is given by $1 - wt$, and therefore

$$d_{i,j} = wt|\mathrm{Log}(T_i) - \mathrm{Log}(T)_j| + (1 - wt)|P_i - P_j|, \qquad (1)$$

where $d_{i,j}$ is the psychological distance between stimulus trace *i*, and stimulus trace *j*, T_i is the temporal distance of stimulus trace *i* from the time of retrieval (which is logarithmically transformed to represent the fact that temporally distant events are more compressed than temporally recent ones), and P_i is the ordinal position of item *i*. The attentional parameter *wt* (see, e.g., Nosofsky, 1992) can be thought of as stretching (shrinking) the psychological space along the most (least) important dimension. In the present case, if *wt* is unity, the simulations implement an exclusively time-based representation (for the earlier two-item list, the representation reduces to {log(7)} and {log(6)}). The confusability of items in memory would then be determined solely by their closeness in time. Conversely, as *wt* approaches zero, the representation is no longer time-based but positional and the representation of the list becomes {1} and {2}. Items that occupy nearby positions, such as the second and third item, will then have more confusable memory traces than items that occupy more distant positions (e.g., the second and fifth items); temporal separation per se would have no effect on confusability.

Similarity-distance metric

Following much precedent in the categorization literature, SIMPLE assumes that the similarity of any two memory traces, $\eta_{i,j}$, is a reducing exponential function of the distance between them in psychological space

$$\eta_{i,j} = \mathrm{e}^{-c \cdot d_{i,j}}, \qquad (2)$$

where $\eta_{i,j}$ is the similarity between traces *i* and *j* and $d_{i,j}$ the distance between them as calculated in Eq. (1) above. It follows that memory traces that are very close have a similarity approaching unity, whereas items that are more psychologically distant have a similarity that, in the extreme, approaches zero. The parameter *c* governs the rate of decline of similarity with distance. In conjunction with the logarithmic transformation of time, this similarity metric gives rise to the distinctiveness ratios mentioned at the outset. That is, when temporal distance is the only relevant dimension, the similarity of any two memory traces is the ratio between the times (the smaller divided by the larger) that have elapsed since study, raised to the power *c*. This is because, as per Eq. (1), $d_{i,j} = \mathrm{Log}(T_j) - \mathrm{Log}(T_i) = \mathrm{Log}(T_j/T_i)$, where T_i is the temporal distance of the more recent item and T_j is the temporal distance to the less recent item. As per Eq. (2), the similarity of the memory locations for items *i* and *j* is therefore: $\mathrm{e}^{-c \cdot \mathrm{Log}(T_j/T_i)} = (T_i/T_j)^C$.

Similarity determines recall

The discriminability of an item's memory trace is inversely proportional to its summed similarity to other memory traces. Specifically, the discriminability of the memory trace for item *i*, D_i will be

$$D_i = \frac{1}{\sum_{k=1}^{n}(\eta_{i,k})}, \qquad (3)$$

where *n* is the number of items in the set, which in the present case is assumed to be equal to the number of list items (see Brown et al., 2002, for further discussion). In paradigms where no omission errors are possible, the probability of recalling an item in its correct position is assumed to equal the discriminability of that item in memory. In cases (such as the present standard serial recall paradigm) where omission errors are possible, it is assumed that if discriminability falls below a critical level, an omission error will occur. More specifically, item recall probability, P_i, is assumed to be a thresholding function of trace discriminability

$$P_i = \frac{1}{1 + \mathrm{e}^{-s(D_i - t)}}, \qquad (4)$$

where *s* and *t* are slope (equivalent to noisiness of threshold) and threshold parameters, respectively, and D_i is discriminability as determined by Eq. (3). Any subthreshold trace discriminability will lead to an omission error.

Model parameters

This basic version of SIMPLE thus has four free parameters: (1) *c* governs the rate at which the psychological similarity of two items decreases as a function of the distance between them in psychological space.

Table 1
SIMPLE parameter values used in simulations of Experiment 1

Condition	c	wt	o	t	s	R^2
Quiet	5.73	.003	.75	.63	4.57	.951
AS	5.57	.003	.63	.74	3.86	.966

As c becomes larger, the confusability between items decreases more quickly as a function of their separation, which in turn increases memory performance. (2) wt specifies the amount of attention paid to the temporal dimension (at the expense of attention paid to the positional dimension). (3) s (for "slope") and (4) t (for "threshold") relate to omissions as described above. For serial recall, an additional parameter o is required to accommodate output interference. Lewandowsky, Duncan, and Brown (2004) provide experimental evidence that the extended primacy typically observed in serial recall reflects such a process. It is assumed that the memories of to-be-recalled items become progressively less distinctive as recall proceeds due to interference caused by each successive recall. The output interference parameter, o, reduces the value of c for the nth item recalled by multiplying it by o^{n-1}. Thus, with $o = 1$, there is no output interference; as o reduces below 1 there is increasing output interference.

All simulations implemented the exact presentation regime of the experiment being modeled, using the experimental presentation duration, inter-item intervals, and retention intervals. The best-fitting parameter estimates and, where applicable, R^2 values are summarized in Table 1.

Predictions

For the time-based predictions, we estimated values for all parameters, including wt, by first fitting the model to an unpublished experiment from our laboratory that was virtually identical to the studies reported below but did not contain unpredictable inter-item intervals. For the event-based predictions, we set wt to zero, thus relying on positional encoding alone. The remaining parameter values were the same as for the time-based account except that c was set to 40% of its previous value to achieve comparable overall levels of performance.

Parameters were then held constant and predictions were generated by presenting SIMPLE with 7-item lists whose inter-item intervals summed to a constant total duration, but whose distribution across serial positions varied across simulation replications. The inter-item gaps were generated and administered in the same way as in Experiment 1 below. As a result, the combined temporal isolation of items in serial positions 2–6 varied from 150 to 2000 ms. (Those combined temporal isolation values reflect the sum of each item's pre- and post-intervals.) Serial positions 1 and 7 were omitted because they were surrounded by only one interval. The predictions are shown in Fig. 1, using a 3-D surface to show the effect of combined temporal isolation and serial position simultaneously. The panel on the left shows the time-based predictions and the panel on the right shows the event-based predictions.

The differences between the two panels are noteworthy: when the time-based account is used (left-hand panel), temporal isolation has a clear beneficial effect on recall performance, in particular at the earlier serial positions. When temporal information is ignored in favor of an event-based account (right), the absence of any benefit of temporal isolation is equally clear. The obvious contrast between the two sets of predictions confirms that their experimental adjudication should be straightforward.

Experiment 1

Experiment 1 used 7-item lists that were separated by unpredictable intervals ranging from 50 to 1200 ms. Across trials, all intervals occurred equally often between all item pairs, thus permitting an analysis at the level of individual serial positions. To examine the effects of pre- and post-item intervals independently, analysis focused on critical items in serial positions 2, 4, and 6. Participants in one condition studied the list quietly, whereas participants in another condition engaged in AS during study. The latter condition is of particular interest because it controls potential consolidation processes that might otherwise contribute to temporal isolation effects.

Method

Apparatus and participants

A PC presented all lists and collected and scored all responses. Twenty-four first-year undergraduate students participated in exchange for course credit or for reimbursement at the rate of A$10 per hour and were randomly allocated to condition. Four participants were excluded due to technical difficulties and one due to poor performance, which retained 9 participants in the quiet condition and 10 participants in the AS condition. Each participant completed three 1-h sessions.

Design and procedure

Lists were constructed from 19 letters (all consonants except Q and Y) and items were randomly sampled without replacement for each list. The lists contained 7 items and the total presentation duration was constant across all trials. Each list contained one of a possible 720 permutations of the six inter-item intervals 50, 100, 200, 400, 800, and 1200 ms.

Use of all possible permutations implied that across trials, the lists were balanced for repetitions of pre- and post-item interval combinations at each of the critical items in serial positions 2, 4, and 6.

As it was impractical for each participant to complete 720 trials, the ensemble of possible permutations was split into two sets of 360 with an equal number of repetitions of each interval pair at each critical position. For example, the pre-post interval pair of 100 and 200 ms occurred 12 times at critical item 2 across the 360 trials in a set, and the two sets differed only on the surrounding interval combinations. Sets were randomly assigned to participants within each condition.

Each trial commenced with a blank screen for 2000 ms, which was followed by the list, with each item presented centrally for 300 ms. Items were separated by a blank screen for the time determined by the interval manipulation. After the last item, a blank screen of 100 ms and a mask of three asterisks appeared for 300 ms, which were followed by a "_" cursor to prompt recall via the keyboard. Responses remained on the screen until all items were entered but correction was not possible. The computer also recorded the latency of responses.

Participants in the quiet condition quietly watched the presentation of the list, whereas participants in the AS condition repeated the word "sugar" aloud during list presentation but not during recall. Participants' verbalizations were recorded to ensure that AS continued throughout the session. Participants were instructed to recall all of the items in the list in their presented order as accurately and as quickly as possible. Participants were instructed to guess if necessary or alternatively use the spacebar to indicate an omission. Emphasis was placed on ensuring that items were recalled in the correct position.

Results

Serial position analysis

Correct-in-position performance for participants in both groups ranged from .29 to .85 (averaged across serial positions). Fig. 2 shows the serial position curves for both conditions.

A 2 × 7 (Condition × serial position) ANOVA confirmed the obvious effects of condition, $F(1,17) = 21.47$, $p < .0002$, $MSE = .084$, serial position, $F(6,102) = 60.69$, $p < .0001$, $MSE = .013$, and an interaction of both variables, $F(6,102) = 3.95$, $p < .002$, $MSE = .013$. These results confirm that the articulation manipulation had the expected effect.

Temporal isolation effects

An overall visual impression of the effects of temporal isolation can be provided by summing the pre- and post-item intervals at each serial position to compute an item's "combined isolation" from its immediate neighbors. Combined isolation ranged from 150 to 2000 ms. Fig. 3 shows the effect of combined isolation and serial position (excluding end items because they have only one neighbor) simultaneously. There is no suggestion in Fig. 3 that temporal separation had a beneficial effect on performance, irrespective of whether or not people articulated during study. To explore the apparent absence of a temporal separation effect further, the remaining analyses considered the effects of pre- and post-intervals separately and focused on critical serial positions 2, 4, and 6, thus ensuring statistical independence of all observations as any given interval contributes to performance on one item only.

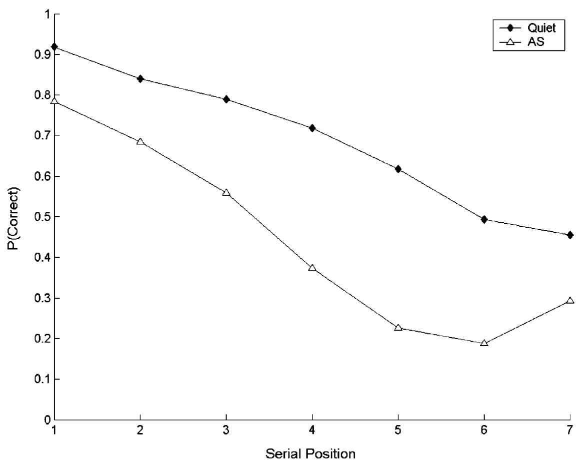

Fig. 2. Serial position curves for both conditions in Experiment 1.

Fig. 4 shows performance on the critical items as a function of pre- and post-intervals separately. The figure reveals a very strong overall serial position effect, as indicated by the vertical separation between the lines representing each critical position. The figure also shows that there is no discernable beneficial effect of the pre-item interval in any condition and at any of the critical positions. The same conclusion appears to hold for the post-item interval, albeit with a possible exception at critical position 4, for which there appears to be a beneficial effect.

The impact of temporal separation on each critical item was statistically examined with a hierarchical linear regression model. Hierarchical regression permits an aggregate analysis of data from all participants without confounding within- and between-participant variability and was also used by Lewandowsky and Brown (2005). Specifically, hierarchical regression permits estimates of the intercept term plus the predictors—in the present case, the duration of the pre and post intervals—to vary across participants, while at the same time computing the statistical significance of those parameter estimates

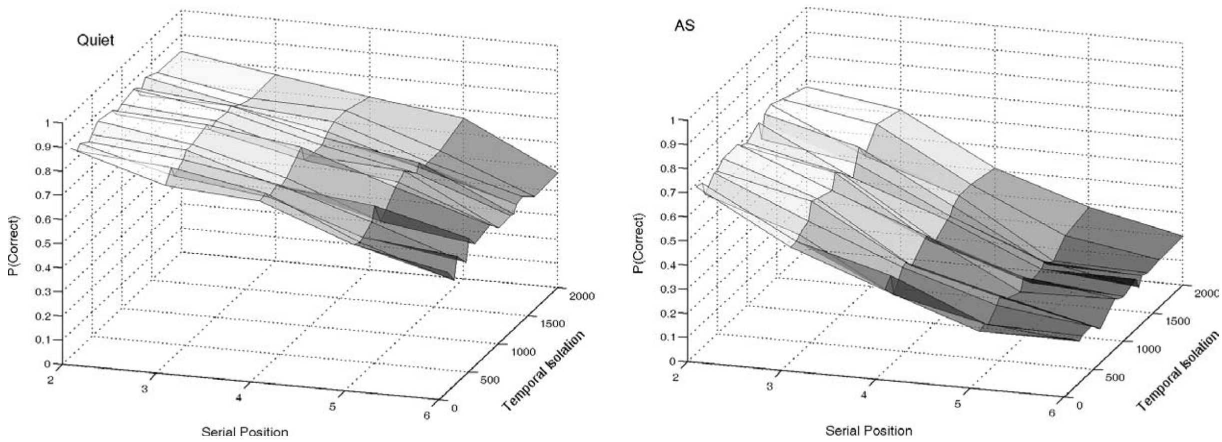

Fig. 3. The effects of combined isolation and serial position on performance in both conditions in Experiment 1.

across all participants.[1] We fitted a separate model to each critical item within each condition, using pre and post as the two independent variables and the proportion correct for each conjunction of pre and post as the dependent measure. The obtained parameter estimates are shown in Table 2.

To facilitate interpretation, note that the intercept term captures the baseline performance at each critical position before the effects of pre and post are included. The decline of the intercept estimates with critical item captures the extensive primacy in the data (cf. Fig. 2). Similarly, the difference in estimates between conditions captures the overall effect of AS on performance. Concerning temporal separation, it is noteworthy that neither post nor pre had any effect in any of the conditions at critical positions 2 and 6. Significant effects emerged only for critical position 4, with the post parameter being significant for the quiet condition and both pre and post being significant for the AS condition. The magnitude of these effects is best interpreted by comparing the data in Fig. 4 to the contrasting predictions in Fig. 1 generated by SIMPLE. The comparison clarifies that for all critical positions, including the one which gave rise to significant isolation effects, the data resemble the predictions of an event-based model more than the predictions associated with temporal distinctiveness. In the remaining analyses, we therefore explore a non-temporal explanation for why the effects of isolation were limited to serial position 4 and were so convincingly absent at the other critical positions. We then buttress this non-temporal explanation by fitting SIMPLE to our results and showing that a purely temporal model is inadequate.

Temporal isolation vs. subjective grouping

The temporal separation effect at critical position 4 may have reflected the participants' choice to divide the 7-item list into two subjective groups either before or after that item, thus creating a 3-item group followed by a 4-item group (3-4 strategy) or vice versa (4-3 strategy). Relative to an ungrouped baseline, performance is typically enhanced for both the first and the last item in a group (e.g., Henson, 1999a, 1999b; Hitch et al., 1996; Ng & Maybery, 2002; Ryan, 1969). It follows that if participants subjectively grouped the list either right before or after critical item 4, any performance increase at that position might reflect a subjective grouping process rather than temporal separation per se. Importantly, people can subjectively group a list that is temporally undifferentiated (e.g., Frankish, 1989), which identifies grouping as a non-temporal top-down process (for supporting evidence see Frankish, 1995; Reeves, Schmauder, & Morris, 2000). Accordingly, SIMPLE explains grouping effects without any reference to time but by using a separate dimension dedicated exclusively to the representation of groups.

Subjective grouping is accompanied by at least one of several characteristic features; namely, a scalloping of the serial position curve (e.g., Hitch et al., 1996), a tendency for between-group transpositions to maintain their position within the group (e.g., Henson, 1999b), and by

[1] There are several hierarchical regression models that could apply to the present data. The simplest model constrains the effects of pre and post to be identical for all participants but assumes that the intercept may vary between participants. The more complex random coefficient model allows all parameters (i.e., intercept, pre, and post) to vary between participants. Both models yielded nearly identical results and we therefore only report the results of the latter, more complex model. We explored several variants of this model, including some in which condition and serial position were coded as dummy variables in a single omnibus analysis, and found that all models converged on the same conclusions. For ease of interpretation, we present the analysis based on a separate regression for each serial position within each condition.

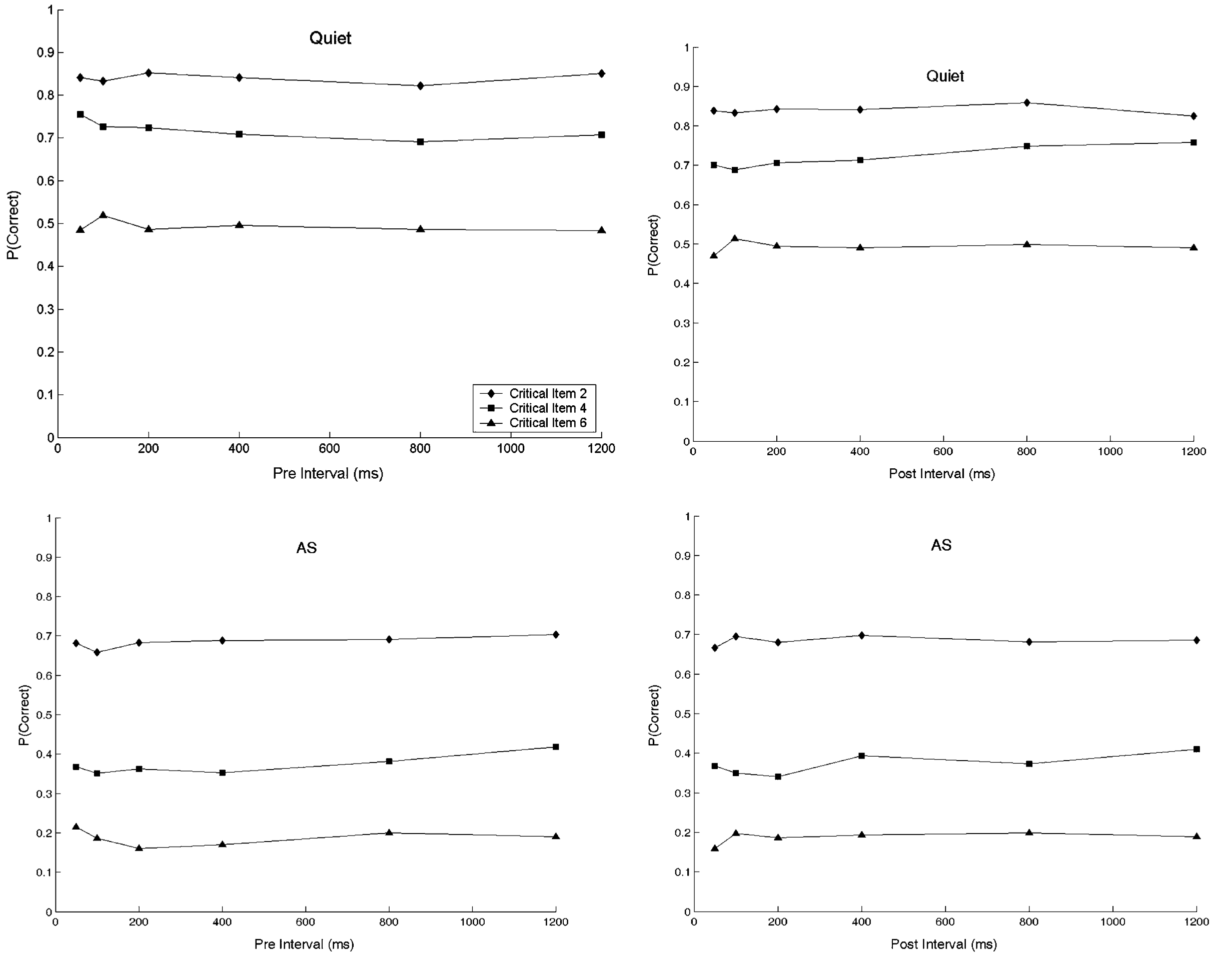

Fig. 4. Mean proportion of correct recall for each critical item as a function of pre (left panels) and post (right panels) intervals in Experiment 1. Top panels are for the quiet condition; bottom panels for the AS condition.

Table 2
Hierarchical regression parameters (intercept, pre, and post) and associated *t* values (all $df = 8$ for the quiet condition and $df = 9$ for the AS condition) for all critical items in both conditions in Experiment 1

Condition	Critical item	Intercept	*t*	Pre	*t*	Post	*t*
Quiet							
	2	**.84**	**29.44*****	−.0003	−.02	−.003	−.12
	4	**.71**	**18.37*****	−.025	−.89	**.054**	**2.73***
	6	**.50**	**6.13****	−.014	−.56	−.0008	−.04
AS							
	2	**.67**	**14.07*****	.028	1.48	.009	.46
	4	**.32**	**6.18****	**.060**	**2.91***	**.056**	**2.95***
	6	**.18**	**4.70***	.006	.27	.014	.78

Bold font indicates that effects are significant.
* $p < .05$.
** $p < .001$.
*** $p < .0001$.

strikingly slower response latencies for the first item within each group (e.g., Anderson & Matessa, 1997; Kahana & Jacobs, 2000; Maybery, Parmentier, & Jones, 2002). Following precedent (Kahana & Jacobs, 2000), we relied on the latter indicator to pinpoint each participant's preferred grouping strategy (this is possible because the average inter-item interval was equal across trials for all serial positions, hence canceling out the effects of temporal structure in the latency serial position curves). Collapsing across conditions, two judges independently identified 10 participants who grouped the list into a 4-3 pattern, whereas the remaining nine participants did not group the list at all.[2] We next repeated the hierarchical linear regression for each subgroup separately. As before, no effect of pre- or post-interval emerged for either group at critical positions 2 and 6 (largest $t(8) = 1.53$, $p > .10$). At critical position 4, a significant effect of post-emerged for the 4-3 subgroup, $t(9) = 3.86$, $p < .004$, but not for the non-grouping subgroup, $t(8) = 1.58$, $p > .10$. The effect of pre at serial position 4 was not significant for either group (largest $t(9) = 1.55, p > .10$). It follows that temporal isolation assisted only those participants who were identified, by independent means, as using a critical item as a group boundary, and then it only affected that critical item. Participants who did not subjectively group the list did not show sensitivity to temporal isolation.

Propagation of errors

If people commit an error early in recall, this tends to give rise to further errors later on in the sequence. For example, if item C is recalled prematurely in position 2 (instead of 3), then unless people immediately repeat the item a second time, the response in position 3 must necessarily be incorrect. This likely propagation of errors raises the possibility that the effects of the pre- and post-item intervals were swamped by errors committed earlier in the sequence and therefore escaped detection in this study.

We consider this possibility unlikely for two reasons: first, we detected an effect of isolation in participants who grouped the list at serial position 4, suggesting that whatever propagation of errors may have occurred, it did not necessarily prevent the detection of isolation effects. Second, isolation effects were clearly absent at serial position 2—where the opportunity for error propagation is virtually non-existent—and serial position 6—where the role of error propagation can be expected to be maximal. We therefore conclude that error propagation by itself cannot explain the absence or presence of temporal isolation effects.

Predictability vs. temporal separation

A final analysis sought to reconcile the absence of a temporal distinctiveness effect in Experiment 1 with the strong effect of presentation schedule observed in the experiments by Neath and Crowder (1996) and Welte and Laughery (1971). This analysis involved another experiment, not reported here, which used the same inter-item intervals as Experiment 1 but presented them to participants in an increasing (i.e., 50, 100, ..., 1200 ms) or decreasing (i.e., 1200, 800, ..., 50 ms) sequence in the same way as in Neath and Crowder's study. All procedural details of this experiment, such as presentation duration and recall regime, were identical to Experiment 1. This unpublished study obtained a strong interaction between increasing and decreasing presentation schedules, thus successfully replicating the Neath and Crowder effect.

The analysis considered only those responses from Experiment 1 at each serial position whose pre- and post-interval pair matched the presentation schedules from the unpublished replication of the Neath and Crowder methodology. For example, any responses at serial position 2 with pre- and post-intervals of 50 and 100 ms, respectively, were used for the increasing presentation schedule, whereas pre- and post-intervals of 1200 and 800 ms at the same serial position contributed to the decreasing presentation schedule. This process yielded composite serial position curves for both the increasing and decreasing presentation schedules for each participant, which were entered into a four-way ANOVA with Experiment (Experiment 1 vs. the unpublished study) and Condition (quiet vs. AS) as between-subjects variables, and presentation schedule (increasing vs. decreasing) and serial position as within-subjects variables. The ANOVA revealed a number of significant effects, three of which involved presentation schedule: the interaction between presentation schedule and serial position was significant, $F(6, 234) = 11.02$, $p < .0001$, $MSE = .009$, as was the interaction between experiment, condition, and presentation schedule, $F(1, 39) = 4.74$, $p < .05$, $MSE = .014$. Crucially, the three-way interaction involving experiment, presentation schedule, and serial position was also significant, $F(6, 234) = 2.69$, $p < .02$, $MSE = .009$. The latter interaction confirms that temporal separation had statistically different effects in Experiment 1 and in the unpublished study using predictably increasing and decreasing presentation schedules.

We conclude that the effects reported by Neath and Crowder (1996) and Welte and Laughery (1971) were tied to the within-list predictability of their presentation schedules. It follows that those effects are more likely to reflect the utility of a top-down encoding strategy rather than a general memory benefit arising from temporal isolation of the input material.

SIMPLE: A two-dimensional account

We explored the results further by fitting the two-dimensional version of SIMPLE to the data of Experiment 1. Quantitative application of the theory permits a more fine-grained interpretation of the results and it also affords an opportunity to examine whether the highly selective effects of isolation at serial position 4 require

[2] The set of non-grouping participants included one person who clearly preferred a 3-4 grouping plus several other participants whose grouping was highly idiosyncratic (e.g., 5-2 or 2-5). For parsimony, their data were not analyzed separately.

a temporal account or can be handled by appealing to grouping, as we suggested above.

Parameters were estimated using the exact experimental training regime. The attentional weight on the temporal dimension (which represented temporal distance in seconds) was allowed to vary freely, and the observed output times were used to model retention intervals for each serial position. The results are shown in Figs 5 and 6, using the same format as for the experimental results. The error term was minimised with respect to the 3-D surface plot. It is evident that a good overall fit was obtained ($R^2 > .95$ in both quiet and suppression conditions) and that there was no effect in the model of temporal isolation on the selected serial positions. Of particular interest were the estimated values of *wt*; these were close to zero in both conditions, consistent with the hypothesis that an event-based version of the model provides the best fit to the data when presentation schedule is unpredictable.

The fact that SIMPLE could handle the present data only by virtually eliminating any attention to time at encoding, and by representing items in memory exclusively on the basis of their ordinal position, challenges the claim that time is a necessary organizing principle of encoding into short-term memory as assumed by several models (e.g., Brown et al., 2000; Burgess & Hitch, 1999). At least in Experiment 1, people clearly did not retrieve items in terms of their position along a temporal dimension.

A further simulation examined the grouping explanation for the effect of temporal isolation on position 4. For this simulation, a ''grouping dimension'' was added into the model. On the assumption of a 4-3 grouping strategy, the seven items were given values {1 2 3 4 1 2 3} on that dimension. To incorporate the assumption that grouping would be more likely to occur when a relatively large temporal gap followed the fourth item, the attentional weighting on the grouping dimension was set to be one fifth of the temporal gap (measured in seconds) between items 4 and 5. The weight on the temporal dimension, *wt*, was set to zero thus ensuring that any temporal effect would be due to grouping alone. All other parameters were set to those used to fit the data from the ''quiet'' condition of Experiment 1. As expected, this addition of gap-dependent attention to a grouping dimension resulted in a small but clear effect of temporal isolation for item 4 but not items 2 or 6. We take this as convergent evidence for the grouping explanation of our results.

Discussion

The principal contribution of Experiment 1 was to show that when list items are separated by unpredictable intervals, temporal isolation does not benefit serial recall. Comparison of the obtained results (Figs 3 and 4) with the set of contrasting predictions provided by SIMPLE (Fig. 1) confirms that this conclusion can be drawn with some confidence. The data differ noticeably from the predictions of temporal distinctiveness models but are largely indistinguishable from the predictions of an event-based model.

One potential limitation of our conclusion is its reliance on a null result, which raises the possibility that the experiment simply lacked power to discover an effect of temporal isolation. Our response to this problem is threefold: first, the comparison with the unpublished replication of Neath and Crowder (1996) shows that a nearly identical methodology can replicate known isolation effects, which renders it highly likely that the present study would also have enough statistical power to detect similar effects, had they been present. Second, the results were in close agreement with the quantitative predictions of an event-based model and third, the isolated departures of the results from those predictions (i.e., the effects at serial position 4) could also be modeled at a quantitative level within the same event-based approach.

The conclusion that temporal isolation does not benefit serial recall is accompanied by a clear boundary con-

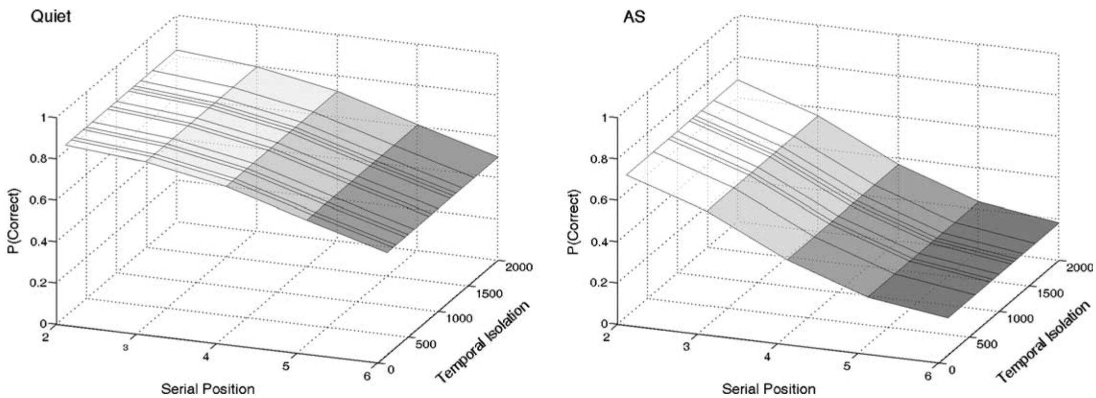

Fig. 5. SIMPLE fitted to Experiment 1. The 3-D surfaces show the effects of combined temporal isolation and serial position simultaneously (end items are omitted).

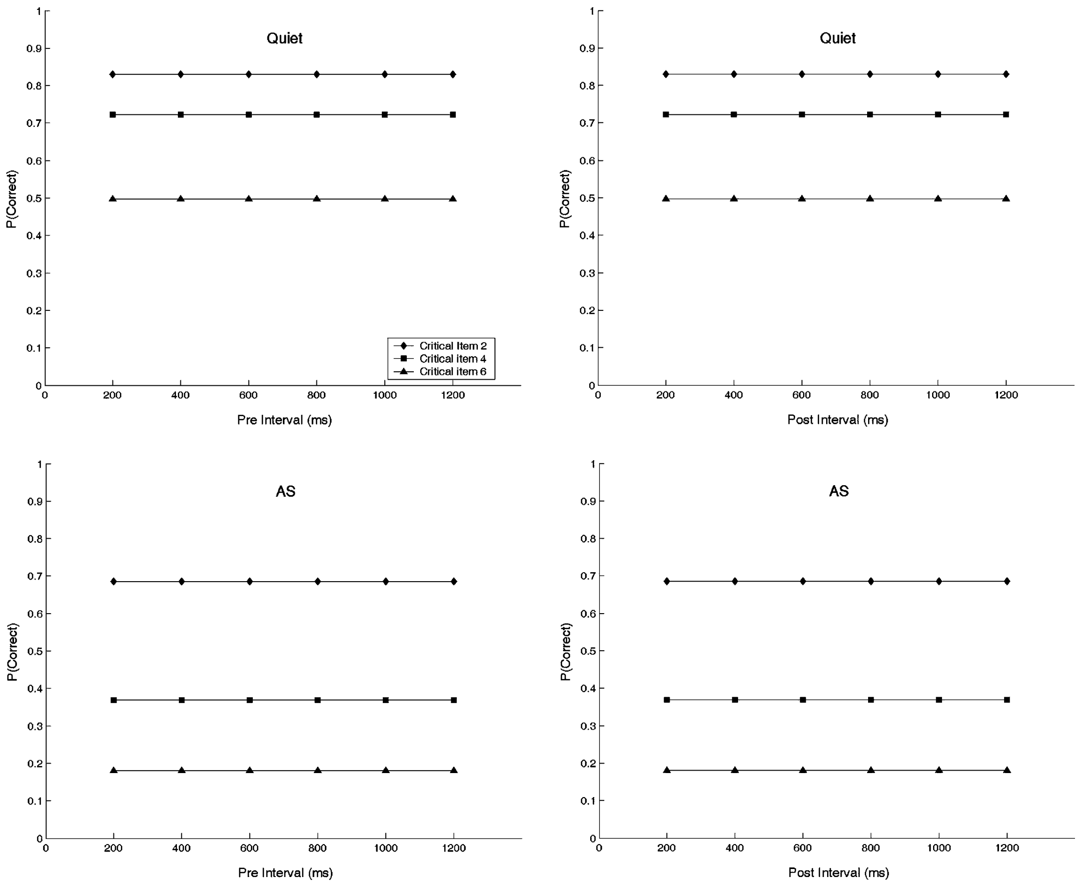

Fig. 6. SIMPLE fitted to Experiment 1. Mean predicted proportion correct recall is shown for each critical item as a function of pre (left panels) and post (right panels) intervals. Top panels are for the quiet condition; bottom panels for the AS condition.

dition: when people group the list, an item at a group boundary benefits from temporal isolation. In support of the tight link between subjective grouping and the apparent benefits of temporal isolation, no isolation effects were observed for items that were unlikely to be at the boundary of groups (e.g., items 2 and 6 in a 7-item list) and no isolation effects were observed at any serial position for participants who did not group the list. Importantly, these conclusions rest on an agreed independent assay of grouping strategies (i.e., latency serial position curves).

The results of Experiment 1 are therefore readily reconciled with the findings of Lewandowsky and Brown (2005), who reported an overall effect of the post-interval under quiet conditions that was abolished by AS. Given that people in their quiet condition grouped the list while grouping was absent under AS, the results of Lewandowsky and Brown therefore exactly parallel the present results if their data are presented with respect to the presence and absence of grouping rather than the (correlated) presence or absence of AS.

There are several possible criticisms that can be levelled at Experiment 1: first, it used whole-report serial recall which, by definition, involves output interference for all but the first reported item. Output interference is known to play a major role in serial recall (e.g., Lewandowsky et al., 2004), and in consequence it may have swamped any effects of temporal isolation. Second, participants may have recoded the list during presentation into a "motor program" for subsequent keyboard recall. Perhaps this motor sequence was insensitive to the temporal list structure and isolation effects may yet emerge if motor-based re-coding is precluded. Finally, the serial position curve in Experiment 1 exhibited very little recency. Although little recency is expected in forward serial recall following visual presentation, its absence may be of concern because accounting for extensive recency is a signature capability of temporal distinctiveness models (e.g., Glenberg & Swanson, 1986). Experiment 2 was designed to overcome all those limitations by using a probed partial-report task.

Experiment 2

The act of recalling any one list item is known to reduce a participant's ability to recall the remaining items, either by delaying those subsequent reports (within a time-based framework) or by interfering with yet-to-be-reported items (within an event-based framework). The phenomenon is often known as output interference (Anderson & Neely, 1996), although in the present context we prefer the theoretically neutral term output *effects* to refer to the indisputably detrimental effects of one memory retrieval on another. One way of eliminating or reducing the role of output effects is to use a partial-report probed recall task (e.g., Waugh & Norman, 1965; Woodward & Murdock, 1968). In this task, list presentation is followed by recall of a single item from the list, at a random serial position, in response to a probe. In addition to eliminating output effects, probe tasks also prevent recoding of the list into a motor program for subsequent recall because the probed position is randomly chosen. Finally, unlike the limited single-item recency typically observed with forward serial recall with visual list presentation, partial-report tasks tend to give rise to substantial recency that extends back for as many as 3 or 4 items (Penney, 1982).

Experiment 2 used the same combinations of pre- and post-item durations as the first study but replaced serial recall with a sequential probe task. On each partial-report trial, people were presented with the list item from position $N - 1$ and had to respond by reporting the item from list position N.

Method

Participants

One hundred and five third-year students at the University of Western Australia participated in compliance with a course requirement. Participants were aware of the broad theoretical background (i.e., time- vs. event-based theories) but were unaware of the outcome of previous investigations along those lines.

Apparatus and design

A computer running a Matlab program, designed using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), was used to display stimuli and record responses.

Lists were constructed in the same manner as for Experiment 1 except that the 720 unique permutations of intervals were divided into 6 sets of 120 trials subject to the constraint that within each set, each inter-item interval occurred the same number of times (20) at each serial position. Because each trial involved only a single memory test, each set was replicated six times, using a different test position for each replication, to ensure a roughly equal number of tests (approximately 3–4) of each interval at each serial position across replications. This procedure yielded an array of 36 unique sequences of 120 trials that were randomly assigned to participants.

Procedure

Participants were tested in groups of three and were seated in front of computers that were separated by privacy screens. Each participant was presented with four practice trials (two probed and two whole report) before the experimental session began.

Each list took a constant 7750 ms to present, with the time divided as follows: first, a 1200 ms fixation symbol ('+') signalled the beginning of a trial in the centre of the screen. Each list item was then presented centrally for 400 ms, with the gap between items determined by the inter-item interval for that trial and position. A 1000 ms pause separated the final list item from the response cue.

The experiment involved 120 probed trials and 20 whole-report lists. The probed trials consisted of a random ordering of the trials within the replication assigned to that participant, and the whole-report trials consisted of a subset of lists within that set. Probed trials and whole-report trials were randomly interleaved.

For the probed trials, a letter and a question mark (e.g., 'B–?') were used to prompt recall of the letter that followed the probe on the list. For instance, given the list D, X, V, F, B, G, H, the probe 'B-?' cued recall of 'G.' For whole-report trials, the cue 'ALL:' signalled participants that they had to recall all of the list items. Responses were entered on the keyboard without possibility of correction. The last whole-report response (or the only response for probed trials) remained visible for 300 ms before the screen was cleared and the next trial commenced.

A self-paced break was provided after every 35 trials. The instructions emphasized both accuracy and latency and a space bar was used to indicate an omission. The experiment lasted approximately 35 min.

Results

Whole report

Analysis of the whole-report trials was used to identify participants whose performance level fell below that typically expected for 7-item lists. Using the average correct-in-position score across all serial positions, one participant was identified as a clear outlier with a performance level of .086. This individual was removed from all analyses. The performance of a further 9 participants fell below .25, which is lower than expected on the basis of the first study; however, analysis of the distribution of the entire sample suggested that those nine participants should not be considered outliers. They were therefore retained for the analyses.

Whole-report showed standard primacy and a one-item recency effect, with correct-in-position recall of .71, .61, .54, .48, .41, .33, and .37 across positions 1–7, respectively. Not surprisingly, the effect of serial position was highly significant, $F(6, 618) = 156.26$, $MSE = .012$, $p < .0001$. All remaining analyses, including the focal analysis of temporal isolation, focused on the partial-report trials.

Partial report

The serial position curve in Fig. 7 confirms that partial report gave rise to the expected extended recency and limited primacy. Serial position 1 could not be probed and therefore does not appear in the figure or in any of the analyses. A one-way within-subjects ANOVA confirmed the obvious effect of serial position, $F(5, 515) = 23.88$, $MSE = .019$, $p < .0001$.

Fig. 8 shows the effect of combined temporal isolation, computed in the same manner as for the first study, and serial position simultaneously. Although the omission of the last position (because it is not followed by a variable post-interval) reduces the magnitude of the serial position effect, the figure clearly shows that temporal isolation had no overall visible effect on performance.

Statistical exploration of the role of temporal isolation had to consider the fact that most participants contributed at most one observation to each possible combination of pre- and post-intervals at each serial position. Accordingly, to achieve the required level of aggregation, responses at each level of combined temporal isolation were aggregated across the critical serial positions 2, 4, and 6. At this level of aggregation, each participant contributed between 3.9 and 4.3 observations on average (range 0–9) to each of the 15 combined temporal isolation values, which was considered sufficient given the large sample size.

Temporal isolation was entered as the sole independent variable into a multi-level hierarchical regression, which yielded a highly significant intercept estimate of .56, $t(103) = 27.83$, $p < .0001$, but a non-significant estimate for temporal isolation of .005, $t(103) = .38$. That is, average performance across the three critical serial positions was estimated to be 56%, with each second of temporal isolation adding a negligible (and non-significant) one-half of one percentage point. Fig. 9 illustrates the lack of a temporal distinctiveness effect by showing performance as a function of combined isolation; it is clear that temporal isolation did not benefit memory.

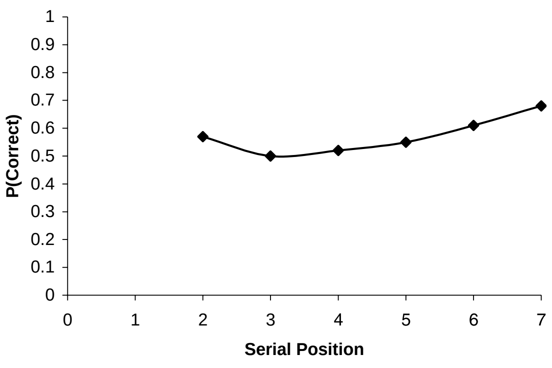

Fig. 7. Partial-report serial position curve for Experiment 2.

SIMPLE: Choosing the relevant dimension

Our primary aim in applying SIMPLE to the results from Experiment 2 was to examine whether a purely temporal model could fit the data adequately, or whether a purely positional model would provide a better account. We therefore created two versions of the model—time-only and position-only—and fit each to the data.

The most straightforward model of probed serial recall within the SIMPLE framework, and the one we adopt here, assumes that the probability of recalling a probed item is simply the discriminability of the target item. In this case, the probability of correct item recall is given by Eq. (3). (This account assumes that the main performance-limiting factor is the discriminability in memory of the target item and ignores complexities such as the memorability of the probe item and the associative relationship in memory between the probe and the target item.) An advantage of this account, which we believe outweighs its obvious simplicity, is its consistency with the earlier modeling: the principal difference between serial and probed recall is the absence of output interference in the latter task.

As in the earlier modelling, the temporal schedule of list presentation exactly mirrored the experimental procedure. It was assumed that the retention interval was the same for every item, and was equal to the interval between last-item offset and the response cue (1 s) plus an additional 1 s to allow for processing of the response cue. Parameter estimates were again obtained by minimising the summed squared error between the model's predictions and the data involving critical positions (i.e., in Fig. 9).

The serial position curves and temporal isolation effects shown by the model were then derived (corresponding to data shown in Figs. 7 and 8), but no attempt was made to optimise the fit to those data directly. Because omissions are not possible in the probed serial recall task, and because each model had only a single dimension along which items were represented (i.e., temporal or positional) there was only a single parameter, c, to be estimated.

The results obtained with the purely temporal model are shown in Fig. 10, with the combined effect of serial position and temporal isolation in the top panel; the serial position curve in the middle panel; and the tempo-

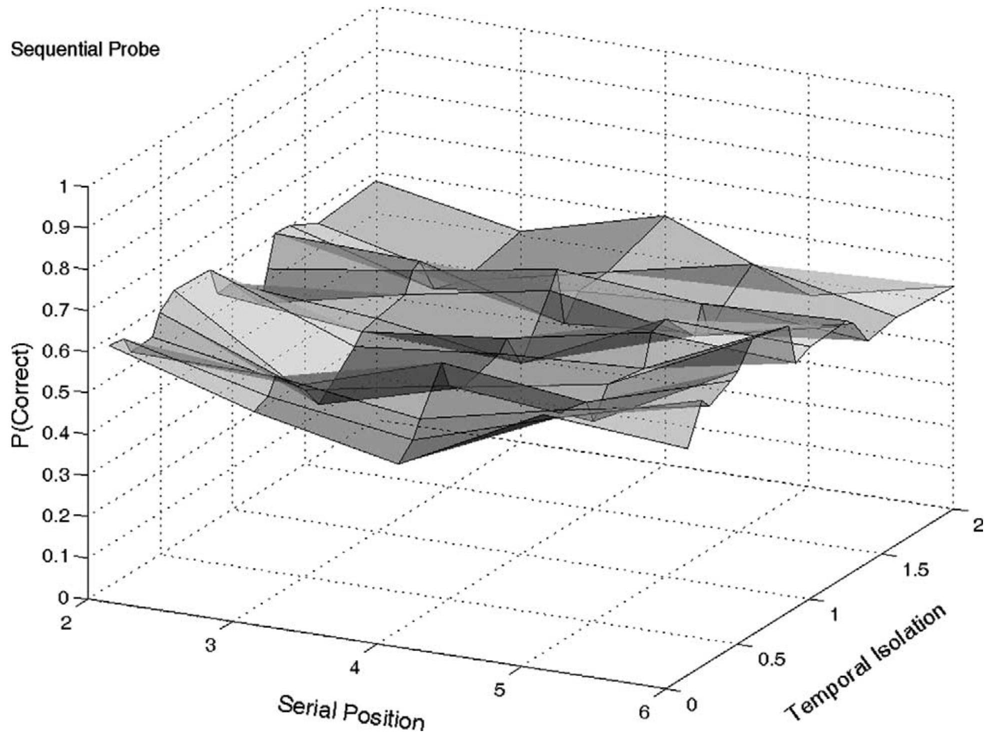

Fig. 8. The effects of combined temporal isolation and serial position on performance in Experiment 2.

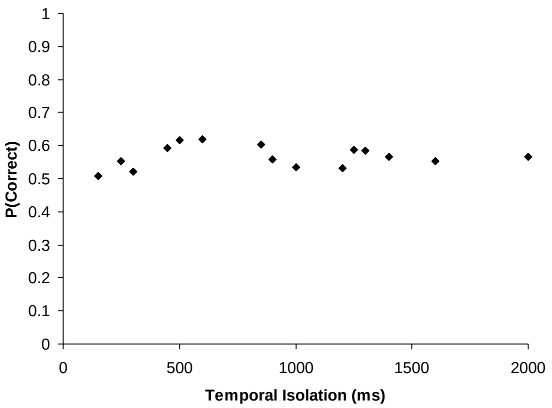

Fig. 9. Average performance on three critical items as a function of their combined temporal isolation in Experiment 2.

ral isolation effect for critical items in the bottom panel. (The discontinuity in the bottom panel arises because performance is slightly better when the gaps surrounding an item are 400 and 800 ms than when the gaps are 50 and 1200 ms and reflects the basic non-linearity of temporal isolation; see, e.g., Eq. (2).) The corresponding panels of Fig. 11 show the predictions of the purely positional model. Note that in both cases, the single free parameter (c) is estimated from the data shown in Fig. 9. The best-fitting estimate of c was 6.4 (time-only model; time measured in seconds) and 1.2 (position-only model), respectively.

It is clear that the purely temporal model predicts a large effect of recency and of temporal isolation–much larger effects than are seen in the data. The predictions of the purely positional model, by contrast, match the data very closely. The conclusion mandated by the modeling is, therefore, entirely consistent with the modeling of the first experiment—a temporal model does not provide an adequate account of our results.

Further modeling, not reported in detail here, examined the ability of a two-dimensional model to account for the data. The best-fitting parameters did give some weight to the temporal dimension, but the overall fit was not noticeably better than that of the positional model. This reinforces the conclusion that a purely temporal model is not sustainable, although a small contribution from a temporal dimension remains a possibility.

Discussion

Experiment 2 replicated and extended the principal finding obtained with whole-report serial recall in Experiment 1: a general effect of temporal isolation was absent, and performance on items that were temporally crowded on the list was generally indistinguishable from

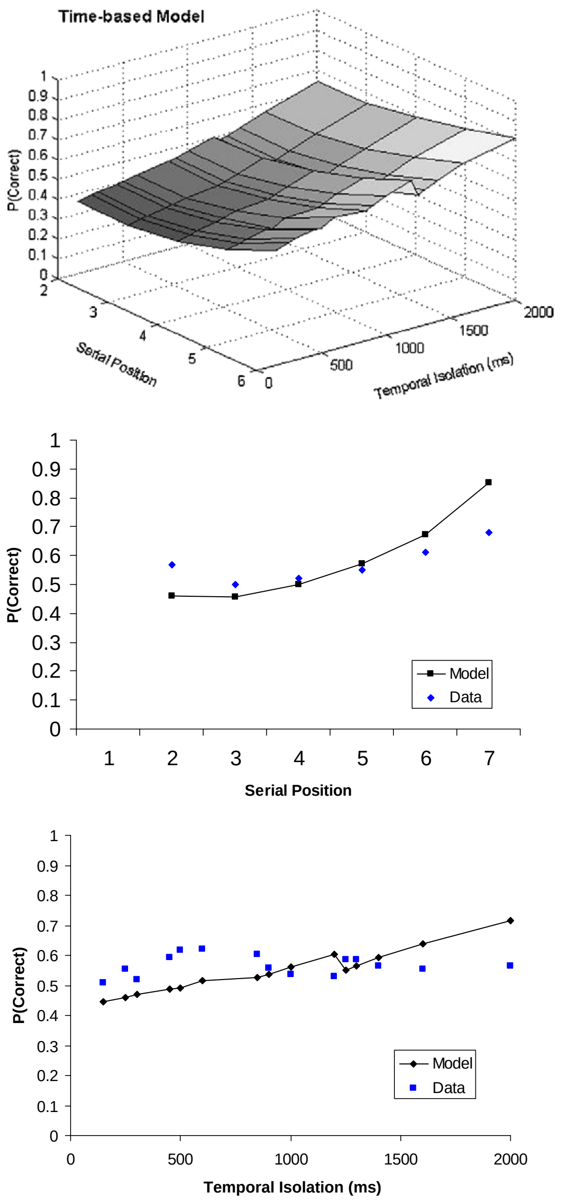

Fig. 10. SIMPLE predictions from a purely temporal model for Experiment 2 with the combined effects of temporal isolation and serial position in the top panel; the serial position curve in the middle panel; and the temporal isolation effect for critical items in the bottom panel.

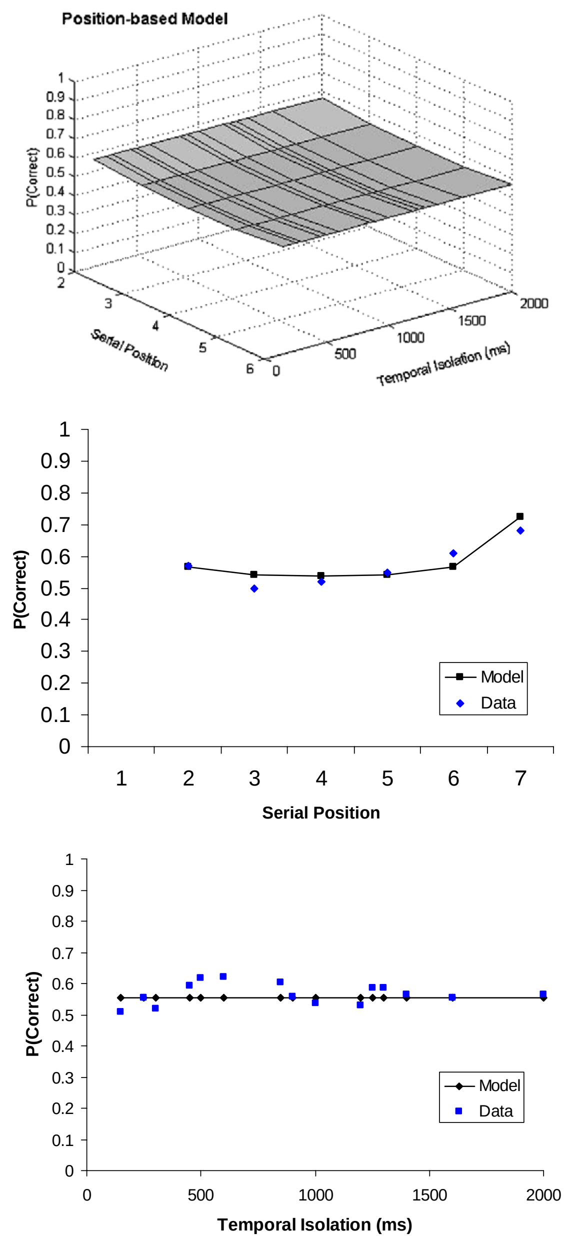

Fig. 11. SIMPLE predictions from a purely positional model for Experiment 2 with the combined effects of temporal isolation and serial position in the top panel; the serial position curve in the middle panel; and the temporal isolation effect for critical items in the bottom panel.

performance on items that were well separated from their neighbors. We conclude that temporal isolation has no effect on recall from short-term memory, even if the role of output effects is eliminated by selective recall of single items.

The modeling using SIMPLE confirms the conclusion that temporal distinctiveness need not be a major contributor to partial-report performance.

General discussion

Limitations

Before considering the theoretical implications of this finding, several limitations of the current studies deserve to be considered. First, one might argue that the range of intervals used here (from 50 to 1200 ms) was too small for distinctiveness effects to emerge. This appears unlikely because the replication of the Neath and Crowder methodology mentioned in the context of Experiment 1 yielded strong effects of presentation schedule with identical intervals. In addition, Nimmo and Lewandowsky (in press-b) recently reported a study in which (unpredictable) inter-item intervals were as long as 4 s and no isolation effects were observed.

Another potential limitation of the studies is the exclusive use of visual presentation. Temporal distinctiveness effects in free recall are arguably larger with auditory than visual presentation (Glenberg & Swanson, 1986), and it is therefore possible that auditory list presentation might give rise to qualitatively different results. This possibility was ruled out by two studies reported by Nimmo and Lewandowsky (in press-a) which used auditory presentation and also did not find an effect of temporal isolation with unpredictably varying intervals.

A final limitation concerns the scope of our studies. In particular we emphasize the fact that our conclusions regarding the role of temporal distinctiveness are confined to short-term memory for serial order. It follows that our results do not cause difficulty for models that ascribe a central role to time in other tasks, such as long-term free recall, where there is additional evidence apparently supportive of temporal distinctiveness approaches (e.g., Bjork & Whitten, 1974; Turvey, Brick, & Osborn, 1970).

Empirical contribution and theoretical implications

The idea that temporal distinctiveness contributes to the quality of our memories has a longstanding history, great intuitive appeal, and much empirical support. The absence of temporal isolation effects in our studies is thus particularly noteworthy, and we suggest that our data constrain the notion of temporal distinctiveness and the surrounding experimentation in several ways. In particular, the present article makes the following unique contributions.

First, we showed that whenever temporal isolation effects are experimentally observed, care must be taken to ascertain that they did not arise from non-temporal processes. For example, seemingly temporal effects can actually reflect subjective grouping processes: in the present data, and arguably also in the studies of Lewandowsky and Brown (2005), when grouping was absent, so were the effects of temporal isolation. In confirmation, one of our SIMPLE simulations provided an event-based account of those selective seemingly temporal effects.

Second, we showed that our results can be reconciled with those reported by Neath and Crowder (1996) and Welte and Laughery (1971) because the latter effects can be replicated without difficulty when intervals were predictable. It follows that those earlier findings either did not reflect a true temporal effect (e.g., instead arose from selective encoding of the list), or reflected an effect that was temporal but was linked to the use of predictable presentation schedules. Perhaps, then, people choose to pay attention to temporal cues only when their predictability renders them useful but not otherwise. This controlled trade-off is entirely compatible with the weighted two-dimensional version of SIMPLE presented in this article.

Third, on the basis of the present results it appears inadvisable to claim that time necessarily plays a role in short-term memory for serial order. The simulations confirm that the data cannot be handled by the temporal version of SIMPLE and instead mandate an event-based approach. An additional contribution of the modeling is that it helps allay fears about the interpretation of a null effect. While it is possible in principle that a small effect of time in the data may fail to reach statistical significance, the modeling is less affected by issues of statistical power. In particular, the small estimates of *wt* reported in Table 1 are not affected by the statistical power associated with the corresponding behavioral data; in principle, the values of *wt* might have been large enough to suggest an important role of time even in the absence of a statistically significant effect of temporal isolation in the data. The fact that this did not happen supports our interpretation of the null effect.

Fourth, although we focused on positional coding in our event-driven simulations, other event-based representations are equally compatible with the results. For example, any of the theories for serial order developed within the TODAM framework (Lewandowsky & Murdock, 1989; Murdock, 1987, 1992, 1995) could readily handle the data despite the variety of representations—ranging from pairwise inter-item associations to chunks of items—they embody. The same applies to a positional-coding theory such as Henson's (1998) SEM, although the situation there is complicated by the facts that Henson (1) acknowledges a possible role of time in the evolution of context and (2) postulates the existence of temporally decaying phonological representations, although the latter only exist for a subset of simulations and when they do, are discretized to decay across episodes rather than time per se. Finally, even a non-associative theory that relies on a time-independent primacy gradient, such as SOB (Farrell & Lewandowsky, 2002), could potentially accommodate the data without difficulty, as could the Primacy Model in which encoding (but not retrieval) is event-based (Page & Norris, 1998).

Finally, our conclusions regarding temporal isolation must be placed into a wider context by considering other instances in which recent research has led to a re-evaluation of the role of time in memory. An inevitable implication of time-based views, whether instantiated as a decay model (e.g., Baddeley, 1986) or as a temporal distinctiveness theory (Brown et al., 2002), is that the passage of time will entail forgetting. Lewandowsky et al. (2004) recently provided some evidence against this notion. In their studies, participants were trained to recall lists at different speeds, thus manipulating the amount of time that elapsed between encoding and retrieval of an item. Irrespective of whether serial recall was oral or by key press, and irrespective of whether or not people engaged in AS during recall, time had no effect on performance. Lewandowsky et al. suggested that these data provided evidence against a decay-based view of forgetting, and they additionally showed by simulation that the results were at odds with the temporal version of SIMPLE (Cowan et al., in press, recently provided converging evidence). The present studies thus report another instance in which findings that had previously been taken to support a causal role of time in memory had to be re-interpreted upon further empirical scrutiny.

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