When Temporal Isolation Benefits Memory for Serial Order

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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. Contrary to that expectation of distinctiveness views, much recent evidence has shown that forward short-term serial recall is unaffected by temporal isolation. We report two experiments using reconstruction of order tasks that confirmed that when report order is strictly forward, temporal isolation does not benefit performance. However, both experiments also showed that when report order is unconstrained, temporal isolation does benefit performance. The differences between forward and unconstrained report were found to be independent of whether or not people can anticipate the type of test at encoding. The presence *and* absence of isolation effects under two different conditions, both requiring memory for order, challenges many existing theories of memory but is compatible with the idea that multiple differentially weighted types of information contribute to memory retrieval.

When Temporal Isolation Benefits Memory for Serial Order

The notion that items are represented in memory according to their position along a continuously-evolving temporal axis has a long history and great intuitive appeal. According to these views, which we collectively refer to as "temporal distinctiveness" theories in this article, 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. Hence, given the list structure A….B....C, where the letters A, B, and C refer to arbitrary list items and each "." represents a unit of time, item B would be expected to be recalled more accurately than if it had been presented on the list A.B.C.

A recent computational instantiation of the temporal distinctiveness hypothesis is the SIMPLE (*S*cale *I*nvariant *M*emory, *P*erception, and *LE*arning) model of Brown, Neath, and Chater (2002). Like all such distinctiveness theories, SIMPLE predicts a beneficial effect of temporal separation on memory. In addition, because chronological times are logarithmically transformed, the model predicts an advantage for recent items over temporally distant events (the larger values representing longer elapsed times are more crowded along a logarithmic scale than small values). An intuitive foundation for this core assumption of SIMPLE can be found in the well-known "telephone pole" analogy (Bjork & Whitten, 1974; Crowder, 1976). According to this analogy, memories become less discriminable from one another (and hence less retrievable) as they recede into the temporal distance just as evenly spaced telephone poles will become less visually distinctive to a stationary observer as they recede into the spatial distance.

Unlike earlier distinctiveness models, SIMPLE acknowledges that memorial representations are likely to be multi-dimensional and may involve variables in addition to time, such as similarity among list items, the grouping structure of the list, or, most important in the present context, time-independent positional information (Lewandowsky, Brown, Wright, & Nimmo, 2006; Lewandowsky, Duncan, & Brown, 2004). Retrieval from memory is assumed to be determined by the separation of items from each other within this multi-dimensional space, such that widely separated items are recalled more accurately than items that are crowded close together. Separation, in turn, is modulated by the amount of attention that is devoted to each of the multiple dimensions. To illustrate, consider the case of a two-dimensional space consisting of positional and temporal information: If people pay attention to temporal but not positional information, then temporal separation necessarily leads to better recall. Conversely, if people were to pay attention to positional but not temporal information, then temporal isolation effects would necessarily be absent.

An examination of the available evidence suggests that temporal isolation effects are far from universal: Although they are sometimes strikingly present, there are other situations in which they do not arise at all, suggesting that people sometimes do and sometimes do not pay attention to a temporal dimension in memory. Little is known about when temporal isolation effects do or do not occur and the primary purpose of this article is to reconcile those conflicting outcomes.

Despite initial suggestions that temporal isolation has a beneficial effect on short-term memory for serial order (Neath & Crowder, 1996), there has been a considerable amount of recent evidence showing that serial retrieval from short-term memory is immune to the effects of temporal separation (Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2005, in press). Specifically, it is now known that when list items are separated by unpredictably varying intervals, and when encoding strategies such as subjective grouping are adequately controlled, temporal isolation does not facilitate forward serial recall from short-term memory. That is, contrary to the expectations of temporal distinctiveness, the lists A….B....C and A.B.C give rise to equal recall of item B (e.g., Lewandowsky et al., 2006).

It thus appears that during forward serial recall, people encode and retrieve items from short-term memory using some form of non-temporal representation, such as a positional or ordinal dimension (see also, Henson, 1999; Ng & Maybery, 2002). This finding is obtained irrespective of whether lists are presented visually or auditorily (Nimmo & Lewandowsky, in press); it is obtained irrespective of whether or not rehearsal is prevented during encoding (Lewandowsky et al., 2006); it is obtained not only with verbal stimuli but also with auditory spatial stimuli (Parmentier, King, & Dennis, in press); it arises when a single item is probed for recall by its predecessor on the list (Lewandowsky et al., 2006); and it holds even when list items are separated by up to 4 s (Nimmo & Lewandowsky, 2005). A traditional distinctiveness view that relies exclusively on temporal representations cannot accommodate this pervasive absence of temporal separation effects in serial recall (see Lewandowsky, Wright, & Brown, in press, for a review and meta-analysis of isolation effects). Instead, the sum total of available data suggests that temporal representations play no role in serial recall, either because time is generally irrelevant to memory or because people choose not to pay attention to time at encoding under those circumstances. (One exception to this conclusion involves situations in which all temporal intervals are completely predictable, in which case isolation effects can emerge for strategic reasons; see Lewandowsky et al., in press, for a detailed examination.)

By contrast, there is a considerable body of evidence that temporal isolation assists *free* recall. Some early evidence includes a study by Glenberg and Swanson (1986), who found that increasing the temporal gap before the last of 5 word pairs improved memory for that pair, although the effect was limited to auditory presentation. Using 10-word lists whose temporal structure was manipulated in a variety of ways, Rönnberg (1980) observed a clear tendency for items in the more temporally crowded regions of the lists to be less well recalled than on a control list in which all intervals were held constant (see also Rönnberg, 1981).

More recently, Brown, Morin, and Lewandowsky (2006) examined the effects of temporal isolation on free recall in a situation that was more comparable to the earlier serial recall studies by Lewandowsky and colleagues. Specifically, Brown et al. presented people with 17-word lists on which the items were separated by randomly varying temporal gaps. The duration of the gaps ranged from 0 through 3.5 s and gaps were filled with digits (at 500 ms/digit) that had to be read aloud. In stark contrast to the results obtained with serial recall, Brown et al. found a strong temporal isolation effect, with recall improving by some 5-10% for each additional second of isolation. These findings were more in line with the expectations of temporal distinctiveness theories, but of course they raise the question why and under what circumstances do temporal separation effects occur. Putting aside minor variables such as list length or means by which rehearsal was prevented, we identify the type of memory test as the most likely candidate for determining whether or not a temporal isolation effect will arise. All studies that have shown isolation effects under properly controlled conditions have used free recall (e.g., Brown et al., 2006) whereas all studies in which an isolation effect was absent have used serial recall.

What, then, are the factors that are responsible for the conflicting outcomes between free and serial recall? We focus on two principal differences between the two types of test: First, and most obvious, unlike in serial recall there is no requirement to retain the order among items in free recall. If this difference were responsible for producing the conflicting outcomes, then any task that requires retention of order among items should abolish the temporal isolation effect that is present in free recall.

Second, it may not be the requirement to retain order information per se that abolishes isolation effects in standard serial recall, but rather the requirement to report that information ordinally. Temporal isolation effects could potentially arise even when order information is retained provided that *report* order is unconstrained—as is the case when items can be recalled in any order but must be placed into their correct serial position. Indeed, there are good theoretical reasons why unconstrained report order may engender isolation effects: By the earlier telephone pole analogy, reliance on the temporal dimension is most beneficial with unconstrained report order because items in later serial positions can then benefit from their lateness—and hence distinctiveness—by being retrieved first. By contrast, when report order is in a forward direction, late items lose their temporal advantage because by the time they can be recalled, the telephone poles will have receded into the past with an attendant loss of discriminability even for the most recent items.

According to this second possibility, temporal isolation effects could emerge even in a serial order task if report order is unconstrained. How might this occur? We consider two potential contributing factors. First, isolated items, like late-list items, might be recalled ahead of temporally crowded items, thus protecting isolated items against the detrimental effects of output interference or output delay. Second, irrespective of report order, isolated items may be more discriminable—and are therefore recalled more accurately—if people rely on the temporal dimension when order of recall is unconstrained.

We now report two experiments that examined the factors underlying temporal isolation effects in short-term memory. The first experiment tested the possibility that any requirement for order retention, irrespective of type of report, will eliminate temporal isolation effects. The experiment compared two reconstruction methodologies, both of which required memory for the order among items, but only one of which required report of the items in their original input order. The other, unconstrained, reconstruction task permitted report of items in any order. To foreshadow the results, temporal isolation effects were found with unconstrained reconstruction but not forward reconstruction. Because both tasks require memory for order, we conclude that isolation effects are not tied to the requirement to retain order per se.

The second experiment extended the first study by including two conditions in which participants remained unaware of report order requirements until after list presentation. The second study again revealed an isolation effect whenever report order was unconstrained, implying that people can choose whether or not to use the temporal dimension after list presentation. We conclude that temporal information is always encoded into short-term memory but is only used upon demand. The second study additionally showed that temporal isolation causes preferentially early report of isolated items when unconstrained report is possible, but that when output order is statistically controlled, isolated items retain their recall advantage over crowded items. Taken together, the fact that isolation effects can be both present or absent under two clearly defined but highly comparable conditions challenges many existing theories of memory and is compatible with the idea that multiple differentially weighted types of information can contribute to memory retrieval.

Experiment 1

The purpose of the first experiment was to examine whether isolation effects necessarily disappear when people must retain information about the order among items. In line with several recent studies, Experiment 1 separated items by unpredictable inter-item intervals during list presentation. Memory was tested through a reconstruction of order task. In a reconstruction task, all list items are shown in a random sequence at retrieval and the participant's task is to place the items in their correct order. One advantage of the reconstruction task is that it is commonly considered to be a particularly pure measure of memory for serial order because the identity of the items need not be remembered (e.g., Neath, 1997; Whiteman, Nairne, & Serra, 1994).

Although the literature to date has considered all reconstruction-of-order (ROO) tasks interchangeably (but see Tan & Ward, in press), we find it necessary to differentiate between two variants of reconstruction. We refer to these variants here as "forward ROO" and "unconstrained ROO", respectively. Forward ROO resembles forward serial recall and requires participants to identify the list items in forward serial order, for example by clicking on them in the order in which they were presented. Forward ROO was used by the studies that pioneered the reconstruction methodology (Healy, 1982; Healy, Fendrich, Cunningham, & Till, 1987). Unconstrained ROO, by contrast, places no constraints on retrieval order and allows people to choose any item for report, for example by placing a chosen list item, via mouse click, into a specific list position (Nairne, 1991, 1992; Nairne & Neumann, 1993; Neath, 1997).

It follows that in forward ROO, people have no choice over the output order, similar to serial recall, whereas in unconstrained ROO, participants can select list items for retrieval in any order they choose. Except for that potentially important difference, the two variants of the reconstruction task are identical, thus permitting a controlled examination of the role of output order in producing temporal isolation effects.

Experiment 1A used forward ROO, whereas participants in Experiment 1B performed unconstrained ROO.[1] In both studies, people engaged in articulatory suppression (AS) throughout encoding and retrieval. The extension of AS to retrieval (as opposed to limiting it to study alone) represents a slight deviation from previous related studies and was introduced to reduce the likelihood that isolation effects might be masked by retrieval strategies such as post-encoding grouping of the list.

Method

Experiment 1A: Participants. Twenty-four undergraduate psychology students from the University of Western Australia participated voluntarily in exchange for course credit.

Experiment 1B: Participants. Twenty-four members of the University of Western Australia campus community participated voluntarily in exchange for reimbursement of travel expenses (A$10 for a single 1-hr session).

Stimuli and Apparatus. For both experiments, a set of 19 letters (all consonants except Q and Y) were used to construct 7-item lists that were sampled randomly without replacement. Eash list contained six inter-item intervals of 50, 100, 200, 400, 800, and 1200 ms duration. All possible permutations of these intervals resulted in 720 unique trials. That is, each trial represented one possible ordering of intervals. The complete set of 720 interval permutations was split into 6 sets of 120 each, subject to the constraint that within each set, each inter-item interval was presented the same number of times (i.e., 20) in each possible position. Participants were randomly assigned to one of the sets and the order of the 120 trials was randomized anew for each participant.

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

Experiment 1A: Procedure. 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 inter-item interval determined by the permutation of intervals for that particular trial. The forward ROO task commenced 1 s after offset of the last item, with the display of the list items in random order, using black letters in a row of white boxes at the top of the screen. Simultaneously, a row of 7 initially empty response boxes (subtending approximately 20° of visual angle) was presented at the bottom of the screen.

Participants were required to reconstruct the list in order of presentation by clicking on the items at the top of the screen in the order in which they had been presented. Once an item had been clicked, it automatically appeared in the corresponding response box at the bottom of the screen. Items could not be selected again and each filled response box became unavailable for the remaining responses. The next trial commenced 3.5 s after completion of the reconstruction task.

All participants repeated the word "Kalbarri" aloud during list presentation and reconstruction. Participants' verbalizations were recorded to ensure that AS continued throughout each trial. The experiment commenced with 4 practice trials during which the experimenter remained present. Every 30 experimental trials were followed by a self-paced break.

Experiment 1B: Procedure. The procedure was identical to Experiment 1A, with the exception that participants performed an unconstrained ROO task. As in Experiment 1A, a test was initiated by displaying the list items at the top of the screen in random order. Participants used the mouse to select a list item from that array (by clicking inside its box, which highlighted the item), and then placed the item into one of the response positions by clicking the corresponding empty response box at the bottom. Unlike in Experiment 1A, participants could select and place list items in any order. Once an item had been placed into a response box, it could not be selected again and the filled response box became unavailable for the remaining responses.

Experiment 1A (Forward ROO): Results and Discussion

Serial position analysis. Correct-in-position performance ranged from .24 to .68 across participants (averaged across serial positions). All participants were retained for the analysis. Figure 1 shows the serial position curve which exhibits the extended primacy and one-item recency that is typical of forward-retrieval tasks.

Temporal isolation effects. An overall visual impression of the effect of temporal isolation can be provided by summing the intervals surrounding a given item to form the combined temporal isolation (ranging from 150 msec to 2 sec). The top panel of Figure 2 shows the effects of combined temporal isolation averaged across all but the terminal serial positions (because the first and last positions only have one adjacent interval). The figure shows that temporal isolation had little if any effect on ordered reconstruction performance, with the linear trend showing an increase of only about 2% as combined temporal isolation increased by an order of magnitude (from 0.2 to 2 s).

To further explore what appears to be the (near) absence of a temporal isolation effect, the subsequent analysis considered the effects of temporal isolation by focusing on three critical items in serial positions 2, 4, and 6. Focus on these items ensures that any given interval is examined with respect to performance on one item only (because the interval following item 2 is not also contributing to the next critical item in position 4). The proportions of correct responses to those items were entered into a hierarchical linear regression analysis (e.g., Busing, Meijer, & van der Leeden, 1994) with the combined isolation of each critical item as the predictor and a separate intercept for each of the serial positions. Different intercepts were required to accommodate the strong serial position effects.[2]

Hierarchical regression permits an aggregate analysis of data from all participants without confounding within- and between-subject variability, and has been used previously to examine isolation effects (e.g., Lewandowsky & Brown, 2005; Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2005, in press). The parameter estimates and associated *t*-tests are shown in the top panel of Table 1. The small value of the combined isolation parameter and lack of statistical significance confirms that temporal isolation had little if any beneficial effect on forward ROO performance.

This finding is consistent with the set of recent studies that have failed to find a benefit of temporal isolation with unpredictable intervals in forward serial recall (Lewandowsky & Brown, 2005; Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2005, in press). Experiment 1A extends the generality of these findings to situations where participants, (a) performed forward ROO, and (b) where articulatory suppression extended throughout retrieval.

Although the top panel of Figure 2 arguably hints at an effect of isolation, the small magnitude of the corresponding regression parameter in Table 1 not only fails to reach significance but it is also commensurate with the values observed in the earlier studies. Moreover, as shown through a meta-analysis by Lewandowsky et al. (in press), it is unlikely that these repeated null effects of temporal isolation reflect a lack of statistical power; by now there have been more than a dozen published experiments from different laboratories involving hundreds of participants, all of which have failed to find a reliable effect of isolation in forward serial recall when inter-item intervals are unpredictable.

Experiment 1B (Unconstrained ROO): Results and Discussion

Serial position analysis. Correct-in-position performance ranged from .26 to .84 across participants (averaged across serial positions). All participants were retained for analysis. Figure 1 shows the serial position curve, which exhibits the extended recency and near-symmetry that is typical of unconstrained reconstruction data and other paradigms in which people can choose order of report (Tan & Ward, in press).

Output order. To examine the extent to which people deviated from forward report, a response position × input position matrix was constructed by classifying, for each response, the item chosen for report according to its serial position. For example, if people first placed an item into the last response box, this would be counted as an entry in the "first response-7th

list item" cell. The matrix was not conditionalized on whether or not a response was correct (i.e., whether or not the item placed in the 7th response box was actually 7th on the list).

One way in which report order can be quantified is by examining the proportion of responses on the diagonal of this input-output matrix which corresponds to the proportion of items that were reported in their input position. The proportion of responses on the diagonal was 28%, suggesting that people frequently departed from strict forward report. To illustrate, the first response involved placing an item into the response box for serial positions 1 through 7, respectively, 33, 2, 4, 6, 14, 14, and 27% of the time. Thus, people chose the first or last item for initial report with almost equal frequency, confirming that they exploited the possibility of unconstrained report to maximize their performance, in line with the predictions of temporal distinctiveness theories discussed at the outset. Nonetheless, people retained a considerable preference for forward report, with 531 lists (of a total of 2880 across participants and trials) being reported in strict forward order and another 310 lists being reported in forward order bar the last item which was reported first.

Temporal isolation effects. The bottom panel of Figure 2 shows the effects of combined temporal isolation on performance. Unlike in Experiment 1A, there is a clear visual indication that temporal isolation benefited unconstrained ROO performance. Responses to the critical positions (2, 4, and 6) were again entered into a hierarchical linear regression analysis with combined isolation as the predictor. The parameter estimates and associated *t*-values are shown in the center panel of Table 1. The comparatively large and statistically significant value of the combined isolation parameter confirms the presence of a temporal isolation effect.

The fact that a significant isolation effect was observed in a situation in which people were required to retain the order among items eliminates one of the possibilities discussed at the outset; namely, that isolation effects arise in free recall only because information about the order among items does not need to be retained. We therefore do not consider that possibility further and instead focus on the alternative possibility; namely, that the constraints concerning output order are a crucial determinant of isolation effects. When output order is unconstrained, as in free recall or in unconstrained ROO, isolation benefits memory. When output order is constrained to be in strict forward order, as in Experiment 1A, temporal isolation does not benefit memory.

To provide further statistical support for this conclusion, we compared the effects of temporal isolation between Experiments 1A and 1B. An ANOVA that used each participant's individual regression estimates for combined isolation (obtained by fitting a separate linear regression to each participant's data) as dependent observations revealed a significant difference between the two experiments, $F(1, 46) = 6.91$, MSE = .0017, $p < .02$. This result confirms that the effects of temporal isolation are significantly greater when report order is unconstrained than when report is in forward order.

Temporal isolation and output order. We next differentiated between the two ways in which unconstrained report order can give rise to temporal isolation effects. As noted at the outset, temporal isolation may cause the earlier report of isolated items, thus protecting them from the harmful effects of delayed report. In addition, isolation may render items more distinctive in memory, thus providing them with a further memorial advantage that is independent of output order.

The first mechanism implies that an item's output order should be predictable from its temporal isolation. Specifically, its migration to a report position ahead of its actual input serial position should be predicted by its isolation. The second possibility implies that once output order is statistically controlled, temporal isolation effects should remain, albeit perhaps in reduced magnitude.

We defined the migration of a response as the difference between the actual serial position of a response box and the ordinal response position during which it was filled. Thus, a negative migration refers to the early report of an item whereas positive values refer to delayed report. Migrations turned out to be predictable from an item's temporal isolation. A hierarchical linear regression with combined isolation as the only predictor (besides the intercept) revealed that greater isolation contributed to early report of an item (parameter estimate for isolation: –.25, $t(23) = –6.91$, $p < .0001$). This suggests that temporal isolation at least partially determined output order, a finding that is compatible with any temporal distinctiveness model that suggests that people adjust their output order to maximize performance. What remains to be examined is whether isolation effects persist once output order is controlled.

We repeated the hierarchical regression analysis of performance on the critical items as a function of temporal isolation but with migration entered as another predictor. The results are shown in the bottom panel of Table 1. The highly significant effect of migration, with a negative parameter estimate, is not entirely unexpected and shows that accuracy declines if report of an item is withheld beyond its expected output position. The persistence of a strong isolation effect, despite controlling for output position, suggests that temporal isolation has an effect above and beyond causing earlier report of items. This outcome supports the hypothesis that when report order is unconstrained, temporal isolation is directly and causally responsible for improved memory above and beyond preferentially early report of isolated items.

Implications of Experiment 1

An immediate empirical implication of the first experiment is that it is unwise to consider all variants of reconstruction tasks interchangeably. We have shown that the two variants of reconstruction considered here can give rise to very different outcomes for theoretically interesting reasons. It therefore appears advisable to differentiate between constrained and unconstrained variants of reconstruction in future research.

At a theoretical level, the results of the first experiment provide a strong challenge to many theories of memory: While the absence of temporal isolation effects with forward reconstruction is compatible with event-based theories such as the feature model (Nairne, 1990) or SOB (Farrell & Lewandowsky, 2002), and also with the Primacy model (Page & Norris, 1998) which despite being largely time-based does not predict isolation effects at encoding (see Lewandowsky et al., 2006, for a discussion), the emergence of isolation effects with unconstrained reconstruction is difficult to accommodate by those models.

Conversely, while the isolation effect can be accommodated by various time-based models such as OSCAR (Brown, Preece, & Hulme, 2000) or the model by Burgess and Hitch (Burgess & Hitch, 1996, 1999), its absence with forward reconstruction presents a strong challenge for those models. A principal conclusion from Experiment 1 therefore is that the presence *and* absence of isolation effects within the same study under two clearly defined but highly comparable conditions challenges most existing theories of memory.

Instead, the data appear to be compatible with views that acknowledge the contribution of multiple types of information that can be differentially weighted. For example, SIMPLE could accommodate the results if lists are thought to be represented along two dimensions, one representing time and the other one representing ordinal list position (cf. Lewandowsky et al., 2004). On this view, the results imply that when retrieval was constrained to be in forward order, people paid no attention to the temporal dimension (and instead focused on positional information or some other event-based representation) whereas when retrieval was unconstrained, people paid more attention to time (and presumably correspondingly less to position). Experiment 1 did not however specify when that attention shift took place: Although it may have occurred at the time of test, the fact that people could anticipate the type of test at encoding renders it equally possible that attention was shifted before or during list presentation. In other words, it is possible that encoding strategies differed between the forward and unconstrained conditions, and that use of the temporal dimension with unconstrained report order was a result of temporal encoding strategies. The next experiment examines the role of encoding strategies and, by implication, determines when people can shift attention between dimensions.

Experiment 2

The purpose of the second experiment was twofold. First, the study sought to provide a further within-experiment comparison of the differences between constrained and unconstrained ROO. The second purpose was to examine the link between a temporal isolation effect and people's test expectation and possible associated encoding strategies.

Experiment 2 included one condition in which all tests involved unconstrained ROO, thus replicating Experiment 1B. In the remaining two conditions, unconstrained ROO was randomly intermixed with either serial ordered recall (SOR from here on) or forward ROO, and participants were only made aware of the required retrieval task after list presentation. By post-cueing retrieval, participants in those conditions could not reliably alter their encoding strategies to accommodate a particular memory test. If people must choose between relying on a temporal or a positional dimension at encoding, then in those mixed conditions one would expect temporal isolation to be uniformly absent (or present) for both tasks. By contrast, if people can choose which type of information to rely on after encoding, then the differences between unconstrained and constrained ROO that were observed in Experiment 1 should transfer to the mixed conditions in Experiment 2.

Method

Apparatus and Participants. Thirty-six members of the University of Western Australia campus community participated voluntarily. Participants were remunerated at a rate of A$10 per hour. Each participant completed two 1-hour sessions.

An equal number of participants were randomly assigned to each of the three conditions. In the pure-unconstrained condition, all trials for all participants involved unconstrained ROO. This condition provided a virtual replication of Experiment 1B. In the unconstrained-and-SOR condition, a random half of all trials involved standard forward serial recall whereas the remaining half involved unconstrained ROO. Finally, in the unconstrained-and-forward condition, all trials involved a reconstruction task, which on a random half of trials was unconstrained and on the other half of trials involved forward reconstruction. Retrieval task was cued after list presentation in the latter two conditions.

Design and Procedure. Lists were constructed in the same manner as in Experiment 1. Participants were randomly assigned to one of the 6 sets of 120 lists which were used anew in each of a participant's two sessions. The pure-unconstrained condition involved 240 unconstrained ROO trials; the unconstrained-and-SOR condition involved 120 unconstrained ROO trials and 120 serial recall trials (60 of each type per session); and the unconstrained-and-forward condition involved 120 unconstrained ROO and 120 forward ROO trials (60 of each type per session). In all conditions, the order of trials was randomized separately for each session and subject. This ensured that within each set, and across tasks within each condition, each inter-item interval was presented the same number of times in each possible serial position.

In the two mixed conditions (unconstrained-and-SOR and unconstrained-and-forward), the final list item was followed 1 s later by a test cue. The test cue was "All:" when forward SOR was required. Participants then entered responses on the keyboard, using the space bar to indicate an omission. Responses could not be corrected once entered. The test cue was "any order" for the unconstrained ROO task, and "serial order" for forward ROO. In all other respects, both reconstruction tasks were identical to those used in Experiment 1.

In all conditions, the last response remained visible for 300 ms before the screen was cleared and the next trial commenced 3.5 s later. As in Experiment 1, all participants repeated the word "Kalbarri" aloud during list presentation and retrieval and a self-paced break was interspersed between every 30 experimental trials.

Results and Discussion

Serial position analysis. Correct-in-position performance (averaged across serial positions) ranged from .15 to .75 across participants in the pure-unconstrained condition. In the two mixed conditions, performance ranged from and .11 to .56 (for SOR) and .38 to .68 (for forward ROO), whereas performance on the unconstrained ROO in the mixed conditions ranged from .25 to .82. Performance on unconstrained ROO was found to be highly similar between the two mixed conditions, and all remaining analyses therefore considered unconstrained ROO performance jointly for the two mixed conditions.

Analysis of the distribution of individual differences identified two participants (one from the pure-unconstrained and one from the unconstrained-and-SOR condition) who were clear outliers, with their performance being around .20 below the mean of their condition-task cell. Those two participants were eliminated and all remaining analyses were based on 34 participants.

The top panel of Figure 3 shows the serial position curves for all tasks and conditions. In replication of Experiment 1B, performance in the pure-unconstrained condition exhibited the extended recency and near-symmetry that is typical of unconstrained ROO. The extent of that recency effect was attenuated in the mixed conditions, when unconstrained ROO was paired with another retrieval task that required strict forward report. A similar attenuation of recency as a function of post-cuing was observed by Tan and Ward (in press). A series of ANOVA's confirmed the obvious patterns in the figure (e.g., serial position effects and interactions between tasks and serial position) but are not reported in detail here because the effects were exactly as expected.

Temporal isolation effects. As in Experiment 1, analysis considered the effects of combined temporal isolation for the three critical items in serial positions 2, 4, and 6. Hierarchical linear regression models were computed separately for pure-unconstrained ROO, unconstrained ROO in the two mixed conditions, SOR, and forward ROO. The parameter estimates and associated *t*-values are shown in Table 2.

In replication of Experiment 1A, the analysis revealed that when participants were required to reconstruct list items in forward order, temporal isolation did not benefit memory. Similarly, in replication of a number of recent studies, temporal isolation did not benefit SOR.

By contrast, in replication of Experiment 1B, when participants were free to retrieve list items in any order, temporal isolation benefited memory. Crucially, this temporal isolation effect appeared to be of roughly equal magnitude for the pure-unconstrained condition and the unconstrained ROO trials from the two mixed conditions. The latter result suggests that the two retrieval tasks in the mixed conditions did not interfere with each other: When report order was forward, temporal isolation effects were absent, and when report order was unconstrained, isolation benefited memory, each outcome being unaffected by the presence of the other task.

The results imply that people need not be aware of what type of test is forthcoming when encoding a list: People appear able to choose their favored dimension with which to pursue retrieval after list presentation is complete. We defer discussion of the implications of this finding to the General Discussion.

It should also be noted that the average intercept across the critical serial positions was nearly identical between forward ROO (.45) and the unconstrained ROO trials from the mixed conditions (.44). This allays fears that absolute differences in performance may have been responsible for the differences in outcome between forward and unconstrained ROO.

Output order. As in Experiment 1B, response position × input position matrices were constructed for the pure-unconstrained condition and the unconstrained ROO trials from the two mixed conditions. For the mixed conditions, a relatively large proportion of responses fell on the diagonal (54.1%). For the pure-unconstrained condition, by contrast, only 29.1% of all responses were on the diagonal, which closely mirrored the value observed for Experiment 1B. This comparison suggests that people in the pure-unconstrained condition were less likely to retrieve the list in forward order than in the two mixed conditions.

To illustrate, the first response in the pure unconstrained condition involved items from positions 1-7, respectively, 33, 1.2, 1.6, 4, 15, 18, and 27% of the time. This pattern again closely mirrored the outcome of Experiment 1B. By contrast, those values were 59, 1, 2.1, 2.7, 7.5, 10, and 17% for the two mixed conditions, suggesting that the twinning of an unconstrained task with another task requiring forward report reduced, but did not eliminate, deviation from forward report.

Output order and temporal isolation effects. As in Experiment 1B, we examined whether report order, represented by an item’s migration from report in its serial position, was determined by temporal isolation. We conducted separate hierarchical linear regressions for the pure-unconstrained condition and the unconstrained ROO trials from the mixed conditions. In both cases, temporal isolation contributed to early report of an item, although the effect was numerically larger for the pure-unconstrained condition (parameter estimate for migration: –.17, $t(10) = -4.44$, $p < .002$) than for the mixed conditions (–.09, $t(22) = -3.25$, $p < .005$). As in Experiment 1B, temporal isolation was a determinant of report order.

We next examined the extent to which the manifestations of temporal isolation in Experiment 2 were due to report order. We first considered the serial position curves for the unconstrained ROO task. As noted at the outset, by a temporal distinctiveness account, extensive recency is a result of temporal isolation that can manifest itself only if late-list items are reported early. By implication, the recency observed with unconstrained ROO should be reduced or eliminated if responses based on early reports of terminal list items are excluded. The bottom panel of Figure 3 shows the serial position curves for unconstrained ROO conditionalized on considering those responses that were made in the ordinal position expected on the basis of forward recall (i.e., by including only responses on the diagonal of the input × output position matrices described earlier). As expected on a distinctiveness account, this conditionalization abolished recency (see Tan & Ward, in press, for a related result).

We next examined the extent to which the temporal isolation effect was a consequence of the demonstrably early report of isolated items. To maximize power for this analysis, we combined all unconstrained ROO trials across both experiments (i.e., Experiment 1B and the pure-unconstrained condition of Experiment 2 plus the unconstrained ROO trials from the mixed conditions in Experiment 2). We then fitted three different hierarchical regression models to this combined data set, with the results shown in Table 3.

The first regression model, in the top panel of the table, merely confirms that if all unconstrained ROO data are considered together, there is a significant and large effect of temporal isolation. The second model, in the center panel, shows that the effect persists, albeit in somewhat attenuated magnitude, when migration is entered as another independent variable into the regression. This replicates the parallel observation made with Experiment 1B.

The final regression model, shown in the bottom panel of the table, examined the effects of output order not by controlling migration statistically, but by conditionalizing on responses made in their expected serial position, as for the preceding serial position analysis.[3] As shown in the table, there was a clear benefit of temporal isolation on unconstrained reconstruction, despite the fact that only those responses were considered that were reported in their original serial position.

We showed in two ways that when temporal isolation benefits performance, this effect is not entirely due to the preferentially early report of isolated items. Instead, when people choose to rely on the temporal dimension at retrieval, temporal isolation causes better memory irrespective of report order.

Comparing unconstrained ROO and forward ROO. For this final analysis, we again maximized power by combining the data from Experiment 1A with the forward ROO responses in Experiment 2, and compared the effects of temporal isolation under those conditions to the effects in the preceding unconditional analysis combining Experiment 1B and all unconstrained ROO trials in Experiment 2. An ANOVA on each participant's individual regression estimate for combined isolation revealed a significant difference between the two combined data sets, $F(1, 92) = 11.0$, MSE = .0017, $p < .002$. This result confirms once more that the effects of temporal isolation are significantly greater when report order is unconstrained than when report is in forward order.

General Discussion

Summary of Results

The results are readily summarized: The presence of temporal isolation effects in short-term memory is contingent upon the type of memory test. If the test requires report in strict forward order, temporal isolation has little benefit, if any, on memory (see top panel of

Figure 1). By contrast, if report order is unconstrained, then temporal isolation clearly and considerably benefits memory (bottom panel of Figure 1). Crucially, as shown by comparing the pure unconstrained condition against the mixed conditions in Experiment 2, this pattern arises irrespective of whether or not people can anticipate the type of test during list presentation.

Because all tasks used in the present studies required people to remember the order among items, the data rule out the possibility that temporal isolation can only benefit performance when order information is irrelevant (as it might potentially be in free recall). Instead, it appears that people always encode ordinal as well as temporal information, and that they can choose after encoding of a list which dimension to rely on for retrieval. If people rely on temporal information, this has two distinct consequences: First, temporally distinct items are preferentially reported early. This early-report strategy applies both to items that are temporally distinct because of their recency and to those that—independent of recency—are distinct because of their temporal isolation from list neighbors. Second, above and beyond early report, temporally isolated items are recalled better, provided they remain isolated—relative to their list neighbors—until the time at which they are retrieved.

An important corrollary of the latter statement is that items that are distinct solely because of their temporal recency should lose their advantage if recall is delayed. In confirmation, the extent of recency with unconstrained ROO was tied to the extent to which late list items were recalled early: Recency was largest in the pure unconstrained ROO conditions (Experiment 1B and pure unconstrained ROO condition in Experiment 2) where report order demonstrably deviated most from forward retrieval. Recency was somewhat smaller in the mixed conditions of Experiment 2 (where report order deviated less from forward retrieval), and it was virtually completely absent when analysis was conditionalized on items being recalled in their input position (bottom panel of Figure 3).

By contrast, items that are temporally distinct because of their separation from list neighbors should retain their relative advantage irrespective of output delays. In confirmation, unlike recency, conditionalizing on forward response order did not eliminate the isolation effect—although it was diminished numerically, exactly as expected from a distinctiveness view with a logarithmic compression of elapsed time.

Implications for Event-Based Theories

Up until now, the repeated recent findings that temporal isolation does not benefit serial recall (Lewandowsky & Brown, 2005; Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2005, in press) were entirely compatible with event-based theories of memory; that is, theories that negate that time plays a role in short-term memory and that instead rely on events, such as presentation or retrieval of an item, to build or retrieve representations. For example, any of the theories for serial order developed within the TODAM framework (Lewandowsky & Murdock, 1989; Murdock, 1987, 1992, 1995) could handle the null effect of isolation notwithstanding the variety of representations—ranging from pairwise inter-item associations to chunks of items that those models embody. Similarly, a non-associative theory that relies on a time-independent primacy gradient, such as SOB (Farrell & Lewandowsky, 2002), could accommodate the lack of isolation effect without difficulty, as could the Primacy Model in which encoding (but not retrieval) is also event-based (Page & Norris, 1998).

However, the present finding that temporal isolation can, under certain circumstances, benefit memory provides a novel challenge to those pure event-based theories. Neither SOB, nor the Primacy Model, nor any of the variants developed within the TODAM framework can in their present instantiations handle the isolation effects observed here. None of these models contain the type of multi-dimensional representations that, together with attention shifting, appear necessary to handle the presence and absence of isolation effects when retrieval is unconstrained or strictly forward, respectively. We therefore prefer to discuss our results within a distinctiveness framework.

Implications for Temporal Distinctiveness Theories

The present data are compatible with a distinctiveness view that (1) acknowledges the possibility that dimensions other than time are relevant in memory and (2) assumes that people are able to shift attention between the various dimensions and (3) can do so at the time of test. The SIMPLE theory of Brown et al. (2002) fulfills all three criteria.

On two previous occasions, a version of SIMPLE with two representational dimensions (position and time) was applied to data from experiments that examined the role of time during retrieval and encoding, respectively. Lewandowsky et al. (2004) manipulated the time in between retrievals during forward serial recall. SIMPLE was found to handle the data—which showed that performance was largely unaffected by delaying retrieval—only when attention was exclusively focused on positional information, without any weight being given to the temporal dimension. Lewandowsky et al. (2006) separated items on the study list by unpredictably varying intervals, similar to the present experiments but using forward serial recall, and again found that SIMPLE was able to handle the data by ignoring the temporal dimension and focusing on positional information. Both applications showed that a temporal distinctiveness view must be augmented by also including positional information (or perhaps some other non-temporal representation), and that temporal information is often entirely irrelevant in serial recall.

The present data are compatible with those earlier applications of SIMPLE but additionally show that items are necessarily encoded using *both* dimensions, even when one or the other is ignored, and that the selection of information with which to guide retrieval can be made at the time of test. To date, SIMPLE has not specified when attention is shifted between dimensions—that is, whether it occurs at encoding or at retrieval—so the present data place a further constraint on the theory by suggesting that attention can be shifted after items have been encoded.

However, there is at least one aspect of our results that, to our knowledge, no existing distinctiveness theory can explain: Distinctiveness offers no mechanism by which isolated items are preferentially reported early and it thus fails to capture the fact that isolation determines report order. Although SIMPLE can predict memory performance for items quite well on the basis of the time that has lapsed since their encoding (plus positional information), the theory is mute on the variables that determine that time. Specifically, retrieval is probed by using elapsed time as a cue for each item, but that elapsed time is taken as a given rather than being computed by the model. Our results therefore identify the need for development of a theory of output order; that is, an explanation of how people choose items for report in unconstrained (but serial) memory tasks.

Towards a Theory of Output Order

Theories of output order already exist for free recall (e.g., Howard & Kahana, 2002), but those theories do not apply to situations in which report order is unconstrained but memory for order is nonetheless important. Although development of a full theory of output order is beyond the scope of this paper, we can at least provide three strong constraints for its development.

First of all, the present data support many others in suggesting that recency effects may emerge in serial recall memory tasks when the late-presented items may be recalled first (Beaman, 2002; Beaman & Morton, 2000; Cowan, Saults, & Brown, 2004; Cowan, Saults, Elliott, & Moreno, 2002; Tan & Ward, in press). Thus, one factor influencing report order is recency: Recent items tend to be recalled early. Second, the present paper adds the observation that temporally isolated items tend to be recalled early as well. Although both constraints could be plausibly accommodated by temporal distinctiveness models by specifying that more distinctive items tend to be recalled earlier, such an account would be incomplete because our data provide a third constraint; namely, a strong preference for items to be recalled in forward order independently of the effects of temporal isolation and recency (see also, Tan & Ward, in press). Indeed, when reconstruction was unconstrained, participants still chose to retrieve the list in perfect or almost-perfect forward order nearly 30% of the time. This tendency was even stronger when recall order was post-cued as in the mixed conditions of Experiment 2. The observed forward-recall preference resembled that observed in free recall (Kahana, 1996; Laming, 1999) and is difficult to accommodate by temporal distinctiveness models which predict a bias towards backwards retrieval because this would maximally exploit recency-based distinctiveness.

In summary, our results identified three constraints that must be accommodated by any theory of output order during unconstrained serial recall. Two of those constraints, viz. recency-first and isolated-first, appear to be at least in principle compatible with existing distinctiveness views. The third constraint, viz. a supervening forward bias, is not readily compatible with a distinctiveness view. Indeed, the reconciliation of the forward-preference with a recency-first strategy under a single explanatory umbrella constitutes a formidable challenge for future models of serial order memory.

Conclusions

We have uncovered clear boundary conditions on the occurrence of temporal isolation effects in short-term memory. Temporal isolation benefits memory when report order is unconstrained whereas it has no effect when report is in forward order. When isolation benefits memory, the effect is partially—but not wholly—due to preferential early report of isolated items.

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Footnotes

[1] Note that these experiments were run separately and have been reported accordingly.

[2] This analysis represents a slight departure from previous work in which the intervals preceding and following a critical item were examined separately (Lewandowsky et al., 2006). Having shown repeatedly that the two types of interval typically give rise to identical effects (e.g., Nimmo & Lewandowsky, 2005, in press), a combined temporal isolation analysis is reported here for ease of exposition.

[3] One difficulty with this conditionalization is that the number of observations per subject-cell may become very small, in which case it is likely that a single error in a later serial position may result in performance being recorded at 0%, thus contributing to the emergence of floor effects. We guarded against this problem by examining the conditionalized serial position curves for each participant individually. Five participants with more than one zero entry in their serial position curve were removed from the analysis, thus retaining 52 participants for this conditionalized hierarchical regression analysis.

Table 1. Hierarchical regression parameters (intercept and combined isolation) and associated t-values (*df* = 23) for both types of reconstruction task in Experiment 1.

Reconstruction task (Experiment)	Critical Item	Intercept	*t*[a]	Isolation	*t*	Migration	*t*
Forward ROO (1A)							
	2	.53	14.27	.016	1.53		
	4	.30	10.83				
	6	.27	13.19				
Unconstrained ROO (1B)							
	2	.57	15.95	.048	4.32***		
	4	.41	12.37				
	6	.51	14.15				
Unconstrained ROO (1B) with migration							
	2	.69	19.26	.031	2.86**	–.063	–7.96***
	4	.48	14.77				
	6	.41	12.50				

[a] All intercepts are significantly different from zero with $p < .0001$

*** $p < .001$

** $p < .01$

Table 2. Hierarchical regression parameters (intercept and combined isolation) for all conditions and tasks in Experiment 2.

Task	Critical Item	Intercept	t^a	Isolation	*t*
Forward ROO					
(*df* = 11)	2	.61	12.70	.005	<1
	4	.39	11.32		
	6	.35	9.50		
SOR					
(*df* = 10)	2	.52	9.69	.016	1.10
	4	.25	4.89		
	6	.12	5.24		
Pure Unconstrained					
(*df* = 10)	2	.55	9.32	.045	4.19**
	4	.36	7.06		
	6	.52	9.77		
Unconstrained ROO mixed conditions					
(*df* = 22)	2	.57	17.71	.034	3.26**
	4	.37	12.49		
	6	.38	11.52		

[a] All intercepts are significantly different from zero with $p < .0001$

*** p < .001

** p < .01

Table 3. Hierarchical regression parameters (intercept and combined isolation) and associated *t*-values for combined analysis of all unconstrained ROO results in Experiments 1B and 2.

Model	Critical Item	Intercept	t^a	Isolation	*t*	Migration	*t*
Unconditionalized							
(*df* = 57)	2	.57	26.34	.042	6.61***		
	4	.38	18.97				
	6	.46	19.90				
Unconditionalized with migration							
(*df* = 57)	2	.56	19.24	.027	4.40***	–.075	–15.36***
	4	.40	14.25				
	6	.51	17.49				
Conditionalized							
(*df* = 51)	2	.72	31.57	.028	2.26*		
	4	.44	14.94				
	6	.32	11.24				

[a] All intercepts are significantly different from zero with $p < .0001$

*** $p < .001$
* $p < .05$

Figure Captions

Figure 1 Serial position curves for both conditions in Experiment 1.

Figure 2 The effects of combined isolation averaged across serial positions on forward ROO (top panel) and unconstrained ROO (bottom panel) in Experiment 1. Plotting symbols represent means across participants and solid lines are best-fitting regression lines.

Figure 3 Serial position curves for all conditions and tasks in Experiment 2. The top panel shows the results when all responses are considered and the bottom panel shows the same data when only those responses are considered that were reported in their original serial position.

Figure 1.

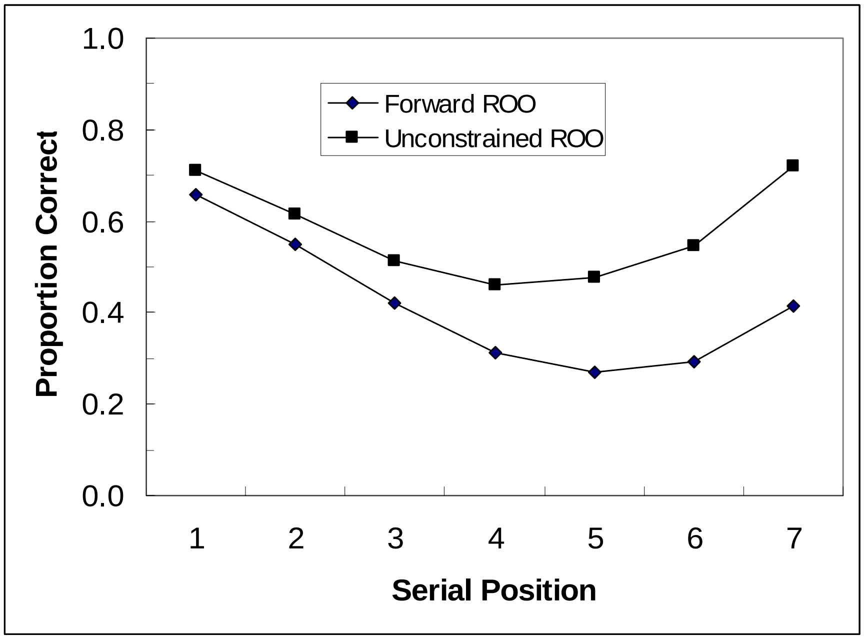
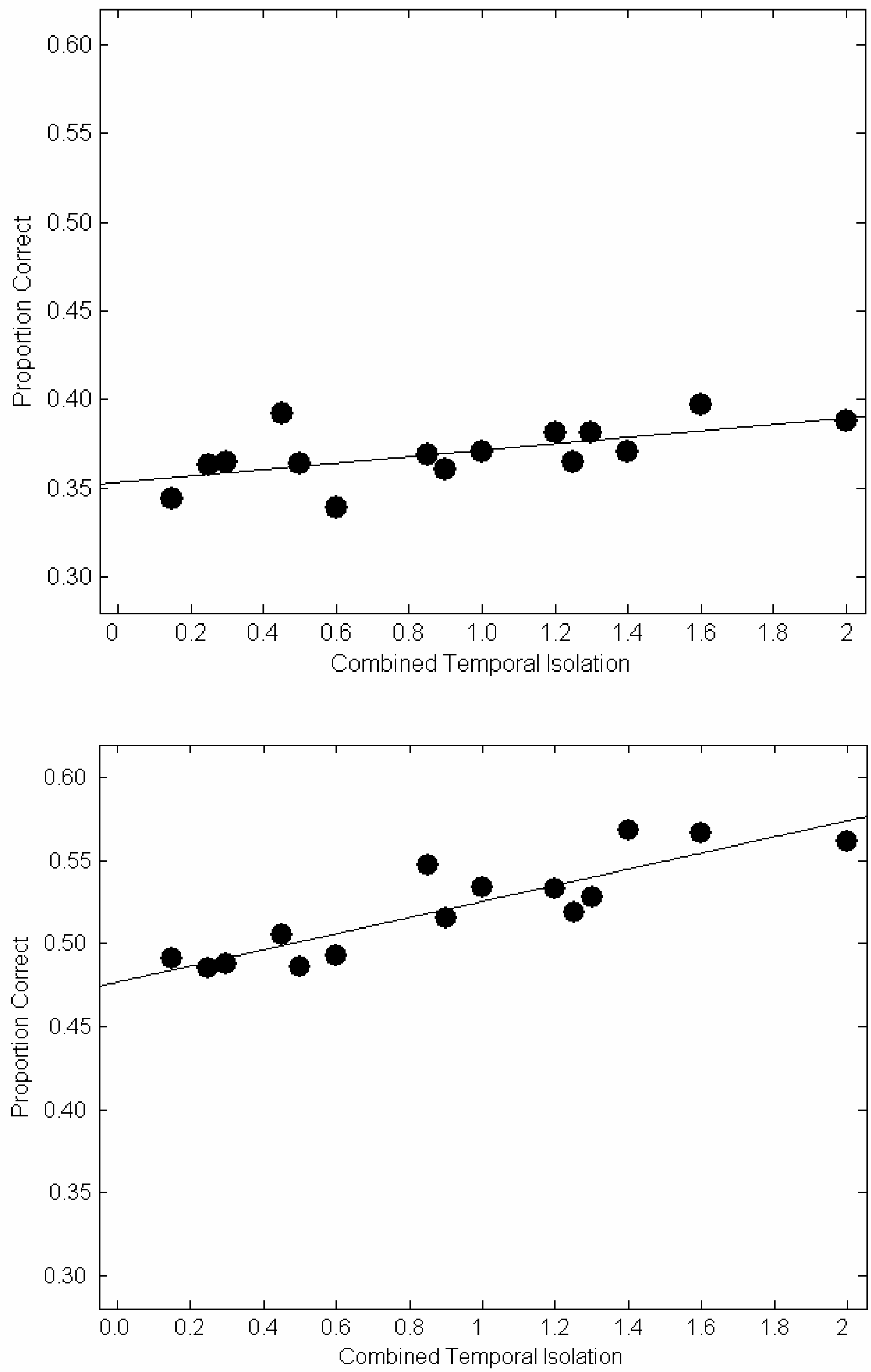
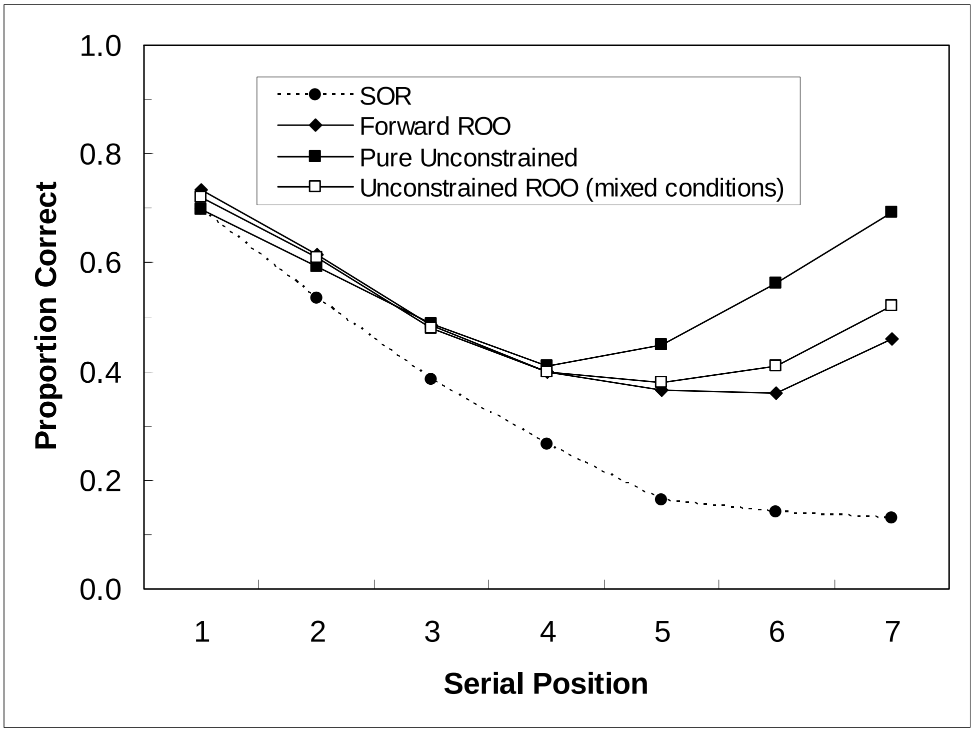

1.0
0.8
0.6
0.4
0.2
0.0
Proportion Correct
Forward ROO
Unconstrained ROO
1
2
3
4
5
6
7
Serial Position

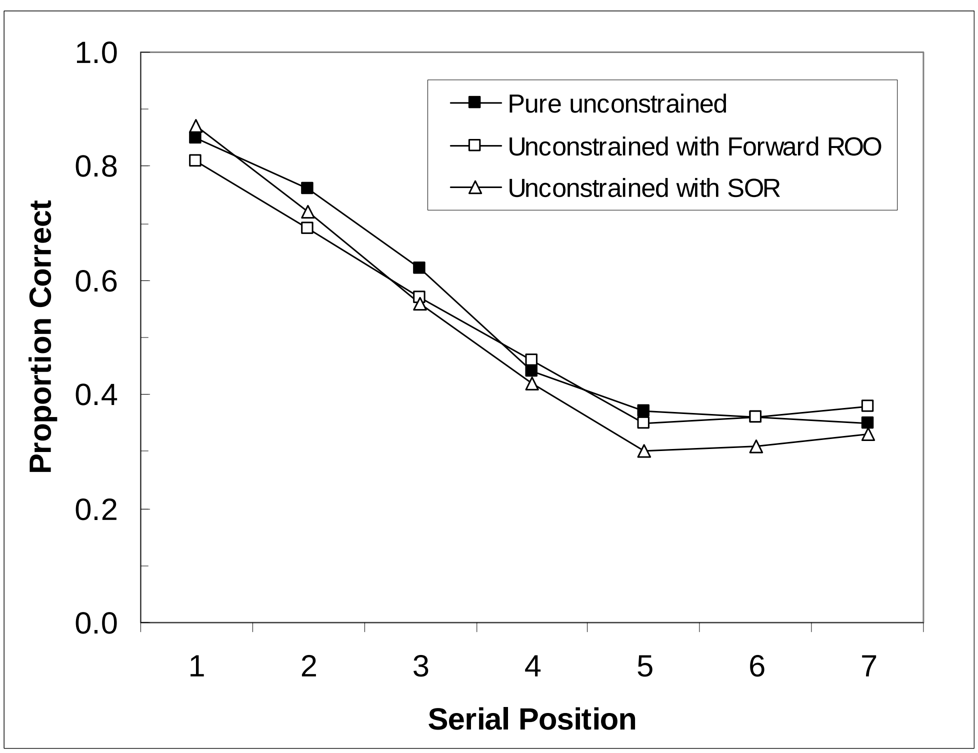
Figure 2.



0.60
0.55
0.50
0.45
0.40
0.35
0.30
Proportion Correct
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2
Combined Temporal Isolation
0.60
0.55
0.50
0.45
0.40
0.35
0.30
Proportion Correct
0.0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Combined Temporal Isolation

Figure 3


1.0
0.8
0.6
0.4
0.2
0.0
Proportion Correct
SOR
Forward ROO
Pure Unconstrained
Unconstrained ROO (mixed conditions)
1
2
3
4
5
6
7
Serial Position


1.0
0.8
0.6
0.4
0.2
0.0
Proportion Correct
Pure unconstrained
Unconstrained with Forward ROO
Unconstrained with SOR
1
2
3
4
5
6
7
Serial Position