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Temporal isolation does not facilitate forward serial recall—or does it?

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In numerous recent studies in short-term memory, it has been established that forward serial recall is unaffected by the temporal isolation of to-be-remembered items. These findings contradict the temporal distinctiveness view of memory, which expects items that are temporally isolated from their neighbors to be more distinct and hence remembered better. To date, isolation effects have only been found with tests that do not constrain output order, such as free recall. This article reports two experiments that, for the first time, report a temporal isolation effect with forward serial recall, using a running memory task in which the end of the list is unpredictable. The results suggest that people are able to encode and use temporal information in situations in which positional information is of little value. We conclude that the overall pattern of findings concerning temporal isolation supports models of short-term memory that postulate multidimensional representations of items.

In trying to explain people's ability to recall items in the short term, two main classes of theory have been proposed that can be differentiated according to their appreciation of time as a causal variable in memory. One the one hand, in time-based theories of memory, it has been argued that time is inseparably linked to memory. In the present article, we will focus on temporal distinctiveness models, which are based on the notion that temporally isolated items—for example, where you parked your car during your annual visit to the local cricket ground—are recalled better than temporally crowded items—for example, where you parked your car on campus after today's regular commute (see, e.g., Brown, Neath, & Chater, 2007; Brown, Preece, & Hulme, 2000; Brown, Vousden, McCormack, & Hulme, 1999; Glenberg & Swanson, 1986; Murdock, 1960; Neath, 1993; Neath, Brown, McCormack, Chater, & Freeman, 2006; Neath & Crowder, 1996; Roennberg, 1980). Proponents of a temporal distinctiveness view have suggested that items are encoded and retrieved along a temporal dimension and thus benefit from isolation on this dimension, akin to the beneficial effect of isolation on memory in general that was established by von Restorff (1933).

On the other hand, in event-based theories (see, e.g., Botvinick & Plaut, 2006; Farrell & Lewandowsky, 2002; Henson, 1998; Lewandowsky & Farrell, in press), time is considered to play merely an epiphenomenal role. Instead of time, those theories consider definable events—such as additional study items or covert rehearsal—to constitute the causal agents of memory. Accordingly, temporal isolation in between items is assumed to exert a beneficial effect only insofar as it allows for other processes—such as selective encoding or rehearsal—to take place. If these additional processes are prevented—for example, by randomizing the temporal intervals between items (to prevent the former) or by overt articulation of irrelevant words (to prevent the latter)—then beneficial effects of temporal isolation should be absent.

As we will show later, the preponderance of evidence in short-term memory to date has favored event-based views over temporal-distinctiveness theories. There are now numerous studies that have shown forward serial recall to be entirely unaffected by temporal isolation (Lewandowsky, Brown, Wright, & Nimmo, 2006; Nimmo & Lewandowsky, 2005, 2006; Parmentier, King, & Dennis, 2006). That is, given the list *A.B....C.....D..E* (where each "." represents a unit of time), people recall *C* no more accurately than they would if they had been given the list *A.....B.C.D...E*. This occurrence runs counter to the expectation of distinctiveness theories, which would expect the recall of *C* to be considerably better in the former case.

To date, only two exceptions to this pervasive absence of temporal isolation effects in short-term memory have been reported. Isolation has been shown to be beneficial with free recall (Brown, Morin, & Lewandowsky, 2006; Glenberg & Swanson, 1986; Neath & Crowder, 1990; Roennberg, 1980) and with unconstrained reconstruction-of-order tasks (Lewandowsky, Nimmo, & Brown, 2008). In an unconstrained reconstruction task, list items are represented in random order at test, and people must place them into their original input sequence, but, crucially, people are free to fill the positions in any order of their choosing. It follows that both instances in which isolation effects have occurred are characterized by people being able to choose the order of report of the to-be-recalled items (the reasons why this might affect isolation effects will be discussed later). This article reports another excep-

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tion to the pervasive absence of isolation effects in short-term memory; however, unlike the existing exceptions, we report the first instance in which temporal isolation was found to affect forward serial recall, when people have no choice about output order.

We will proceed as follows: We will first outline the assumptions of the temporal distinctiveness view in more detail and summarize predictions derived from the leading computational instantiation of this view (scale independent memory, perception, and learning, or SIMPLE; Brown et al., 2007). We will then summarize existing research into temporal isolation effects in short-term memory with particular emphasis on its presence in free and unconstrained recall and its absence in forward serial recall. We will explain how SIMPLE can account for both of these findings. We will then present two experiments that explore the implications of SIMPLE's explanation and that reveal the first case of an isolation effect for forward serial recall.

SIMPLE

A recent instantiation of the temporal distinctiveness view—SIMPLE (Brown et al., 2007)—assumes that people represent items according to their positions in a multidimensional space. One of those dimensions necessarily is time, but other dimensions—such as ordinal list position or phonological similarity—may be relevant as well. The ability to recall an item is determined by the proximity—and, hence, confusability—of items in this psychological space. The closer two items are in psychological space, the more readily they are confused and the less well they are recalled.

The temporal dimension plays an important role in two ways. First, it can contribute to an item's isolation if two items are temporally far apart. Second, because of a presumed logarithmic transformation of time, the temporal dimension in SIMPLE also changes the confusability of items as time elapses. This forgetting mechanism is illustrated in the well-known telephone pole analogy (first proposed in all but name by Bjork & Whitten, 1974): In the same way in which telephone poles become less discriminable to an observer as they recede into the distance when viewed from the window of a moving train, so items become increasingly crowded in time as they recede into the past. The temporal dimension in SIMPLE thus naturally gives rise to a recency advantage as well as to an isolation advantage.

In addition to time, other dimensions that determine the proximity of two items in psychological space include similarity between items, the grouping structure of the list, or—crucially for tasks requiring memory for serial order—the ordinal position in which an item occurred on a list (see, e.g., Lewandowsky, Duncan, & Brown, 2004). In this article, consideration is restricted to the temporal and positional dimensions.

As a consequence of the existence of multiple dimensions, an important determinant of an item's isolation in psychological space is the attentional weight that is placed on a specific dimension. That is, according to SIMPLE, people can choose the extent to which they pay attention to time versus some of the other dimensions. When all attention is placed on the temporal dimension, recall is governed exclusively by the temporal properties of the items—including, in particular, their recency and their temporal isolation. Conversely, when all attention is shifted away from time to the positional dimension, memory retrieval is governed by nontemporal properties of the items. To illustrate, consider a study by Lewandowsky et al. (2004) that varied delay at retrieval in a serial recall task by either training the participants to recall items at varying speeds (Experiment 1) or by manipulating interretrieval durations by varying the number of to-be-articulated distractor words between the retrieval of each item (Experiment 2). In a purely temporal distinctiveness view, it would be predicted that delaying recall should be detrimental to performance, because of the increased confusability of items with more elapsed time. In actual fact, the data showed that recall was unaffected by delay—a result that could be accommodated by SIMPLE only by assuming that people disregarded time and focused their attention on the positional dimension instead. It turns out that a similar attentional focus on position at the expense of the temporal dimension is also observed when the timing of list items is manipulated at encoding.

Temporal Isolation Effects in Short-Term Memory

In the bulk of recent research on the effects of temporal isolation in short-term memory, virtually no evidence has been found that isolation benefits performance when items are separated by unpredictable intervals and when people have to retrieve the list in a prescribed order (see, e.g., Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2005, 2006; Parmentier et al., 2006). Isolation effects were absent across a broad range of circumstances. For example, Nimmo and Lewandowsky (2005) varied the isolation of items from 450 msec up to 7,000 msec and found forward serial recall performance to be unaffected. Likewise, the absence of an isolation effect has been observed with both visual and auditory stimuli (Nimmo & Lewandowsky, 2006; Parmentier et al., 2006), and it has been observed with single-item probed recall as well as with whole-report forward serial recall (Lewandowsky et al., 2006). Even with serial recognition, no isolation effects are observed under conditions that are thought to be most favorable to their emergence (e.g., because on some trials, participants are asked to retain timing information, which they are demonstrably able to do; Farrell & McLaughlin, 2007).

We provide an overview of the conditions under which short-term memory has been found to be unaffected by temporal isolation in the left column of Table 1. The overall mean of the regression parameter for the effect of temporal isolation—computed from 15 separate conditions involving six different studies—is nearly indistinguishable from 0—namely, 0.005. (The final entry in that column previews the main contribution of this article and is best ignored for now.)

There are two known exceptions to the pervasive absence of temporal isolation effects in short-term memory. Both exceptions involve tasks in which the report order of items

Table 1
Overview of Findings From All Recent Studies Employing Temporal Isolation Manipulations on Serial and Unconstrained Recall

Study	Experiment Number/Condition	Range of Combined Isolation (msec)	Isolation Parameter Estimate[a]	Isolation Parameter Estimate[a]
Forward Serial (or Probed) Recall (or Reconstruction)				
Nimmo & Lewandowsky (2005)	Quiet	450–7,000	−0.002	
	AS	450–7,000	0.009	
Lewandowsky, Brown, Wright, & Nimmo (2006)	1/Serial recall			
	Quiet	150–2,000	0.001	
	AS	150–2,000	0.029	
	2/Probed recall	150–2,000	0.005	
Nimmo & Lewandowsky (2006)	1/Serial recall			
	Auditory short	950–2,800	0.017	
	Auditory long	1,250–7,800	0.007	
	2/Serial recall			
	Auditory	375–6,000	0.006	
	Visual	375–6,000	0.003	
Parmentier, King, & Dennis (2006)	Auditory verbal	100–1,900[b]	−0.031[c]	
	Spatial nonverbal	100–1,900[b]	−0.036[c]	
Lewandowsky, Nimmo, & Brown (2008)	1/Forward reconstruction	150–2,000	0.016	
	2/Forward reconstruction	150–2,000	0.005	
	Serial order recall	150–2,000	0.016	
Lewandowsky (unpublished)	Probed recall by position	150–2,000	0.020	
Free Recall and Unconstrained Reconstruction				
Brown, Morin, & Lewandowsky (2006)	2 item filled gaps			0.065**
	Free recall	0–7,000 (approx.)		
Lewandowsky, Nimmo, & Brown (2008)	1/Unconstrained reconstruction	150–2,000		0.048***
	2/Unconstrained reconstruction	150–2,000		0.045**
	Intermixed with other recall tasks	150–2,000		0.034**
Overall Mean			**0.005**	**0.048**
Present study, Experiment 2	AS, running memory span	250–1,800	0.054***	

Note—The parameter estimates refer to the results of multilevel regression analyses, with correct-in-position recall as the dependent variable and temporal isolation (i.e., pre- and postinterval or the combined isolation of pre+post) as predictor(s). [a]None of the reported studies found a temporal isolation effect due to the postitem interval alone, thus ruling out an alternative explanation based on rehearsal or other strategies assumed by event-based approaches. To simplify exposition, we report the means of the estimates obtained from the pre- and postitem intervals in those cases in which they were estimated separately. Estimates are also averaged across serial positions in cases in which they were reported separately. [b]Parmentier et al. (2006) randomized intervals and reported the range of each interval (50–950 msec) but not total isolation. These values are therefore approximate only. [c]Parmentier et al. (2006) reported parameter estimates from a logistic rather than a linear regression. To be comparable to the other table entries, the values reported here were converted to an approximately linear scale using the "divide by 4 rule" (Gelman & Hill, 2007, p. 82). $^{**}p < .01$. $^{***}p < .001$.

is unconstrained.[1] As shown in the right-hand column of Table 1, a substantial isolation effect has been observed in free recall (Brown et al., 2006), as well as in an unconstrained reconstruction-of-order task (Lewandowsky et al., 2008). The fact that unconstrained reconstruction gave rise to a substantial temporal isolation effect suggests that it is not the requirement to retain order per se that is responsible for eliminating isolation effects: In unconstrained reconstruction—unlike in free recall—people must remember order information, and Lewandowsky et al. (2008) nonetheless found a large isolation effect. Instead, it is the requirement to report in a strictly prescribed forward order that has thus far uniformly abolished isolation effects. In support of this conclusion, Lewandowsky et al. (2008) showed that the benefits of isolation disappear with a constrained reconstruction task, in which people must click on the (reshuffled) list items in the order in which they appeared on the list. Why, then, would the requirement to report items in forward order eliminate isolation effects that emerge with unconstrained report?

Attentional Shifts Between Dimensions

Lewandowsky et al. (2008) provided an explanation of this pattern within SIMPLE. Lewandowsky et al. (2008) argued that both relevant dimensions (time and ordinal list position) are necessarily encoded and that people choose the more beneficial dimension at the time of recall. Accordingly, in an experiment that randomly intermixed unconstrained reconstruction trials with forward serial recall trials, and in which people were unaware of the type of test until after list presentation, isolation effects nonetheless selectively occurred with the former but not with the latter test. (In support of the notion that people can shift attention after encoding, Farrell & McLaughlin, 2007, reported a similarly selective use of time between two variants of a recognition test.) Thus, whenever forward serial retrieval is required, people will rely on the positional dimension at recall and thus do not show a temporal isolation effect (see Table 1), notwithstanding the fact that they have demonstrably encoded information about the temporal properties of the list. Conversely, during free recall or in an unconstrained reconstruction task, people evidently make use of the temporal dimension, as revealed by the more accurate report of isolated items.

This observation suggests that the temporal dimension for representing items in memory prevails when the task requirements permit the advantages of a temporal representation to be exploited. Unconstrained report order confers an advantage to the temporal dimension because the most recent items can be reported first, thus exploiting their recency-based isolation before they have receded into the (more crowded) past. The extensive recency that would be associated with early report of recent items, in turn, may maximize overall performance level. In confirmation, Lewandowsky et al. (2008) found substantial recency in the unconstrained task in addition to the isolation effect already mentioned (recency was absent, together with the isolation effect, in constrained strictly forward reconstruction).

In summary, there is evidence to suggest that (1) people can selectively place dimensional attention onto time or onto some other, perhaps ordinal, dimension; (2) they focus attention on time when the recall task renders this advantageous; and (3) attention can be shifted *after* encoding on a trial-by-trial basis. To date, an attentional focus on time has been observed only with tasks that permit arbitrary report order, and it remains to be seen whether people can be induced to focus attention on time even when items must be serially recalled. It is theoretically important to show that attention *can* be focused on time even in forward serial recall, because this would support the flexible dimensional representation postulated by SIMPLE without any potentially confounding effects of output order.

What might induce people to focus attention on time in forward serial recall? We argue that this may occur when reliance on positional information is difficult or impossible and, concomitantly, when the temporal dimension offers a better means of representing and cuing memory.

Discouraging Reliance on Positional Information

One memory task in which positional information is of limited utility is the *running memory span* task (see, e.g., Pollack, Johnson, & Knaff, 1959).[2] In a running memory span task, people are shown lists of unknown and unpredictable lengths. When the list suddenly terminates, people must recall either as many items as possible (open-span procedure) or a fixed number of the most recent items (closed-span procedure). For example, people may be asked to recall the last four items in forward order, in which case, a sequence such as "K F J M P S T X" translates into the to-be-recalled target list "P S T X" (with serial positions of the target items coded as 1–4 for the remainder of this article).

When list lengths exceed memory span (as they do on most trials in a running memory span task), this task requires that the content of short-term memory be updated continuously. People must continuously be "dropping the 'oldest' item and adding the most recent item to the string" (Morris & Jones, 1990, p. 113; see also Postle, 2003). Since this updating operation also shifts the functional serial position of the to-be-remembered item with each new item that is displayed, positional information is of little value in this task. Accordingly, Ruiz, Elosùa, and Lechuga (2005) proposed that in a running memory span task, "subjects seemed to be simply trying to retrieve the last items of the presented list from their episodic memory with a pure recency criterion—that is, based on some temporal contextual cue" (p. 906). This assertion that the running memory span task involves temporal cuing is supported by the large recency effects that typically emerge for any list length exceeding the number of to-be-reported items—even when recall is in forward order (see, e.g., Bunting, Cowan, & Saults, 2006; Morris & Jones, 1990; Ruiz et al., 2005). For example, in the study by Ruiz et al., recall accuracy in one of their experiments was .38, .61, .70, and .73 across the four to-be-remembered serial positions; this extensive recency stands in striking contrast with the extensive primacy and the slight upturn for the last one or two items that are typical of forward serial recall with fixed list lengths.

Given the close linkage between recency and isolation effects observed by Lewandowsky et al. (2008)—who found that both occurred with unconstrained reconstruction, whereas both were absent or reduced with forward report order—and, given our analysis of the limited utility of the positional dimension in a running memory span task, it follows that the latter task may induce people to focus attention on the temporal dimension at the expense of positional information. In consequence, we expect a temporal isolation effect to emerge in a running memory span task even during forward recall. We will now present two experiments that tested this hypothesis.

EXPERIMENT 1

The first experiment employed a closed-span procedure involving forward serial recall of the last four items of each list. The study was based on the methodology of Ruiz et al. (2005). Unlike in the Ruiz et al. study, Experiment 1 varied the interstimulus intervals (ISIs) during list presentation. In addition, participants engaged in articulatory suppression throughout in order to prevent rehearsal-based encoding strategies that might artifactually give rise to an isolation effect (see Lewandowsky et al., 2006; Lewandowsky, Wright, & Brown, 2007, for a detailed discussion).

Method

Participants. Participants were 46 third-year psychology students at the University of Western Australia who participated voluntarily in exchange for course credit.

Materials and Procedure. The running memory task involved lists of consonants that varied in length between 4 and 19 items. List items were sampled randomly without replacement from a set of 19 letters (all consonants except Q and Y). 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.

Participants were presented with 84 experimental lists of seven different lengths (4, 5, 6, 8, 10, 14, and 19 letters). Regardless of list length, people had to report the last four items (coded as Serial Positions 1–4) in forward order. There were 12 trials for each of the seven list lengths.

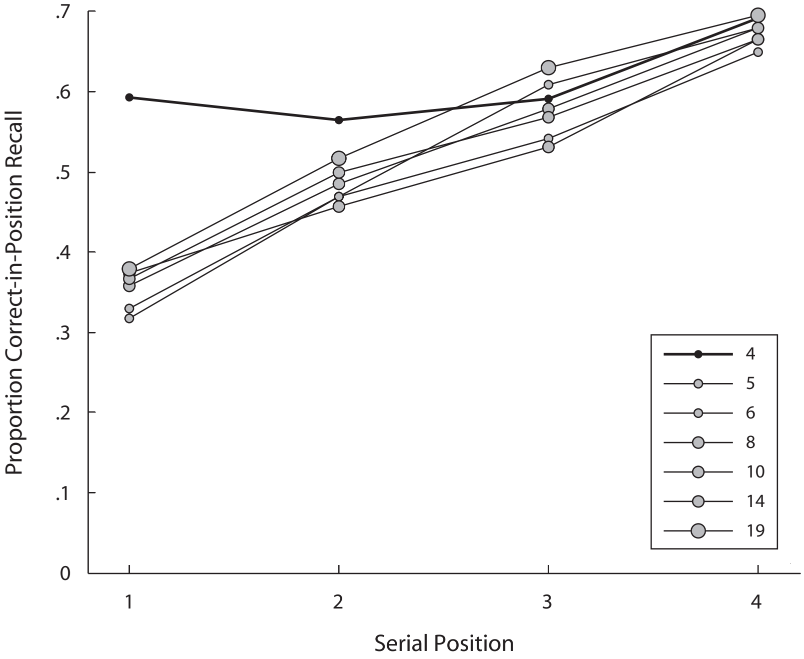

Figure 1. Serial position curves obtained in Experiment 1 using proportion correct-in-position recall for the four to-be-remembered items for all list lengths. Numbers in the legend refer to list lengths.

The intervals between the four to-be-recalled items were formed by using all six possible permutations of the intervals 50, 600, and 1,200 msec. Across the 12 lists of each length, the six permutations were repeated twice. The intervals between the remaining (filler) items that preceded the to-be-recalled items were of little interest and were chosen randomly and uniformly from the range 0–1,200 msec with a 1-msec time base, subject to the constraints that one interval was exactly 50 msec and another one was exactly 1,200 msec. (This constraint precluded participants from identifying the onset of the critical portion of the list by recognizing one of the intervals used for the last four items.)

Participants were told that the experiment consisted of lists of unpredictably varying lengths. They were instructed to passively observe the items and to use the keyboard to recall the last four items in forward order once the prompt to recall appeared.

The 84 experimental lists were preceded by 10 practice trials constructed in an identical manner (with list length chosen randomly and with replacement from the set of lengths). Each trial commenced with the presentation of a fixation cross for 0.9 sec in the center of the screen, which was followed by a sequential presentation of the list at a rate of 900 msec per item, with the ISI determined by the intervals as just described. Items were displayed centrally in black on a white background. The end of each list was followed by the prompt “last 4,” whereupon participants had to recall the last four items in the order presented using the keyboard. As soon as the fourth item had been entered, the next trial commenced 3.5 sec later.

During list presentation and recall, participants were required to continuously articulate a suppressor word (i.e., “sugar”). After every 21 trials, there was an optional self-paced break. The experiment took approximately 45 min, and testing was performed in groups of 3 to 4 participants, with computers separated by sound-attenuating dividers.

Results and Discussion

Individual differences. Examination of the data at an individual level identified 3 participants whose overall performance level fell below 10% correct. These participants were excluded from further consideration, and all reported analyses were based on the data of the remaining 43 participants.

Serial position analysis. Correct-in-position performance was first analyzed by aggregating across all temporal isolation intervals and examining the effects of list length and serial position. The serial position curves for the four to-be-recalled items are shown in Figure 1. The figure shows the pattern typically observed in a forward running memory span task, with extensive recency and no primacy for list lengths exceeding the number of to-be-recalled items, and with a more symmetrical serial position curve for list length 4 (see, e.g., Bunting et al., 2006; Morris & Jones, 1990; Ruiz et al., 2005).

In confirmation of the obvious pattern in the figure, a 4 (serial position: 1–4) × 7 (list length: 4, 5, 6, 8, 10, 14, and 19) within-subjects ANOVA revealed a main effect of list length [$F(6,252) = 5.73$, $MS_e = 0.04$, $p < .0001$], a main effect of serial position [$F(3,126) = 88.9$, $MS_e = 0.05$, $p < .0001$], and an interaction between both variables [$F(18,756) = 6.42$, $MS_e = 0.01$, $p < .0001$].

Temporal isolation analysis. The remaining analyses examined the effects of temporal isolation. List length 4 was omitted because the first item on that list was not preceded by an isolation interval. In order to compute the combined temporal isolation of each to-be-recalled item, the temporal intervals preceding (called *pre* from here on) and following (*post*) each item were added together, which yielded three categories: short (650 msec), medium (1,250 msec), and long (1,800 msec). For the item in Serial Position 1, which was preceded by a randomly varying interval, the combined

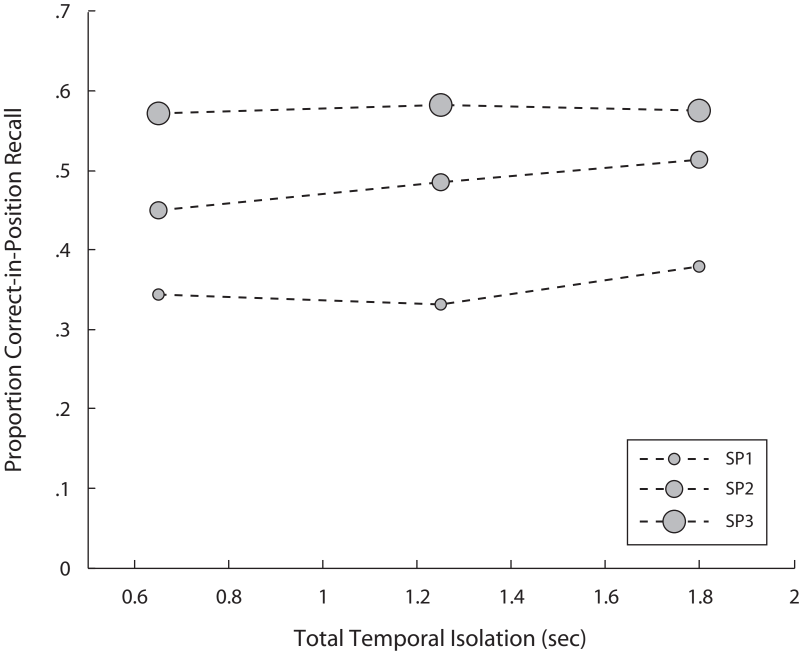

Figure 2. The combined effects of serial position and total temporal isolation for the three critical serial positions (SP1, SP2, and SP3) in Experiment 1. Note that the isolation values for SP1 are only approximate because of binning; see the text for details.

durations were binned into three categories with mean durations of 552, 1,248, and 1,873 msec for short, medium, and long, respectively. These particular bins represented the closest possible match with the three total isolation values for the other serial positions.

Because preliminary analyses revealed that list length did not interact with the effects of isolation, we report the data collapsed across list lengths. Performance for items in Serial Positions 1, 2, and 3 (the fourth item is omitted because it is not bracketed by two temporal intervals) is shown in Figure 2 as a function of combined temporal isolation.

A 3 × 3 within-subjects ANOVA, with the variables serial position (1, 2, and 3) and temporal isolation (short, medium, and long), revealed a large effect of serial position [$F(2,84) = 82.9$, $MS_e = 0.02$, $p < .0001$] and an effect of temporal isolation [$F(2,84) = 4.9$, $MS_e = 0.01$, $p < .01$]. This effect provides statistical confirmation of the small beneficial effect of isolation that is evident in Figure 2. There was no interaction between the two variables [$F(4,168) = 1.7$, $p > .1$].

The temporal isolation effect observed in this experiment is new and surprising. Unlike the bulk of studies reported at the outset (see Table 1), combined temporal isolation exerted a positive—if small—effect on forward serial recall performance. Before we discuss the implications of this finding further, we will report a second study with an improved design that sought to reproduce the isolation effect and enhance its magnitude.

EXPERIMENT 2

In Experiment 1, we employed the running memory procedure of Ruiz et al. (2005) to examine whether a temporal isolation effect would occur in a task in which positional information is unlikely to be of much use. Although this attempt was successful, there is at least one procedural limitation that may have militated against obtaining a larger isolation effect. Specifically, with an equal number of trials at each list length, the probability that any given item would be the last one was highly uneven across serial positions. For example, no lists ever terminated after the presentation of the 7th or 9th item, and, once list length exceeded 10, it would not terminate until at least another three items were presented. It is possible that participants picked up on the distribution of list lengths and thus could anticipate when a list was unlikely to end; for example, when the 10th item appeared without the list terminating, at least 4 more items were guaranteed to be forthcoming. It follows that a useful strategy at that point would have been to clear all information from memory and recommence encoding. (It is noteworthy that list lengths 14 and 19 gave rise to slightly better performance in Experiment 1—.52 and .56, respectively—than the average of the remaining list lengths >4—namely, .51.) A crucial attribute of these types of encoding strategies is that they rely on the knowledge of list position; by implication, if people used those strategies, then they were unlikely to rely on a purely temporal dimension alone. The relatively small size of the temporal isolation effect observed in Experiment 1 is compatible with this possibility.

We therefore employed a different method to generate lists in Experiment 2 that ensured that any item on the list (after the fourth one) was equally likely to be the last one. This prevented participants from guessing the number of

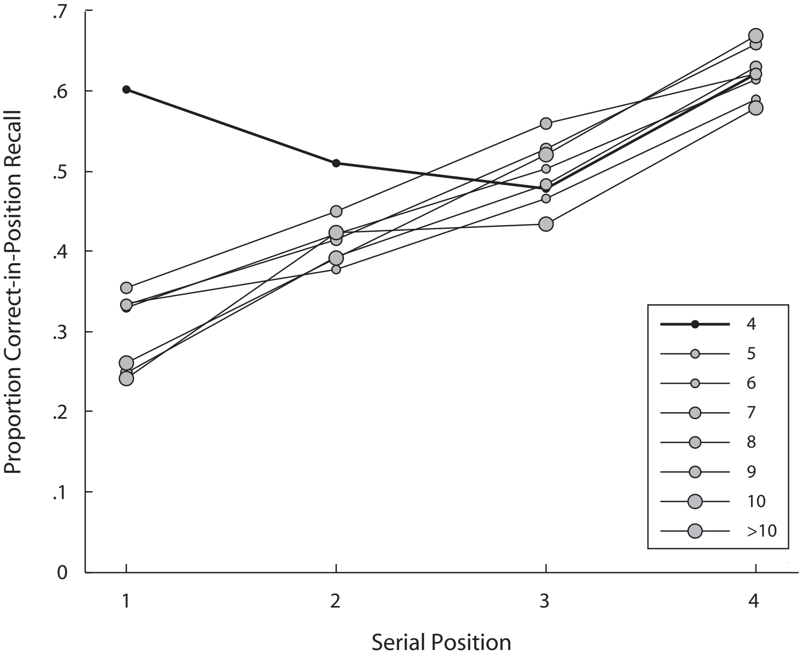

Figure 3. Serial position curves obtained in Experiment 2 using proportion correct-in-position recall for the four to-be-remembered items for all list lengths. Numbers in the legend refer to list lengths.

remaining items at any point during list presentation. In addition, as a further possible measure to discourage reliance on positional information, people were instructed to process the items in a passive manner (see Cowan et al., 2005; Hockey, 1973). These instructions have been used previously to enhance a strategy in which participants recall items from "the automatically activated memory stream" (Cowan et al., 2005, p. 56) without updating every single item during representation.

Method

Participants. Participants were 31 members of the University of Western Australia campus community who were reimbursed $10 (Australian) for their participation.

Materials and Procedure. The procedure was identical to that of Experiment 1, with four exceptions. First, instead of distributing the number of trials evenly across list lengths, 72 lists were randomly generated for each participant, with a constant probability of .2 at each position >4 for the list to terminate (subject to a maximum list length of 19). The precise distribution of list lengths was thus uniquely determined for each participant, but it followed an exponentially declining pattern. This manipulation ensured that people could not anticipate the end of the list, thus preventing possible strategies based on clearing memory and recommencing encoding.

The second change concerned the isolation intervals, which were now 50, 200, 600, or 1,200 msec. All 24 possible permutations of these intervals were used to form the intervals for the four to-be-recalled items (including the interval preceding the first to-be-recalled item if list length was greater than 4), providing three replications of each permutation across the 72 trials. All lists of length 4 were constructed from one replication of those 24 permutations, leaving two replications for lists longer than four items; all temporal isolation analyses were based on that set of 48 fully counterbalanced trials. All intervals between filler items were randomly sampled from the same set of durations.

Third, participants were tested individually in a sound-attenuating booth in the experimenter's presence. The final change involved the instructions. Participant were told to passively observe the items and to try to recall as many as possible of the last four in forward order once the recall prompt was presented.

After every 18 trials, there was an optional self-paced break. Due to the smaller number of trials, the experiment only took 35 min.

Results and Discussion

Individual differences. Examination of the data at the individual level identified 1 participant who failed to exceed 10% correct recall overall. This person was excluded from the analyses, which were therefore based on the data of the remaining 30 participants (the conclusions are not altered if this participant is included in the analysis).

Serial position analysis. Figure 3 shows the correct-in-position serial position curves obtained in Experiment 2. As in Experiment 1—and in replication of the standard pattern for a running memory task—the serial position curves exhibit both primacy and recency for list length 4, and only recency for list lengths greater than four items.

In confirmation of the obvious pattern in the figure, a 4 (serial position: 1–4) × 8 (list length: 4–10, and all lengths >10 combined) within-subjects ANOVA revealed a main effect of list length [$F(7,203) = 2.76$, $MS_e = 0.08$, $p < .01$], a main effect of serial position [$F(3,87) = 46.09$, $MS_e = 0.08$, $p < .0001$], and an interaction between both variables [$F(21,609) = 3.71$, $MS_e = 0.03$, $p < .0001$].

Temporal isolation analysis. As in Experiment 1, the overall temporal isolation of an item was computed as the sum of the temporal interval preceding and following the target item. Because no interitem intervals were repeated within the set of to-be-recalled items, the four

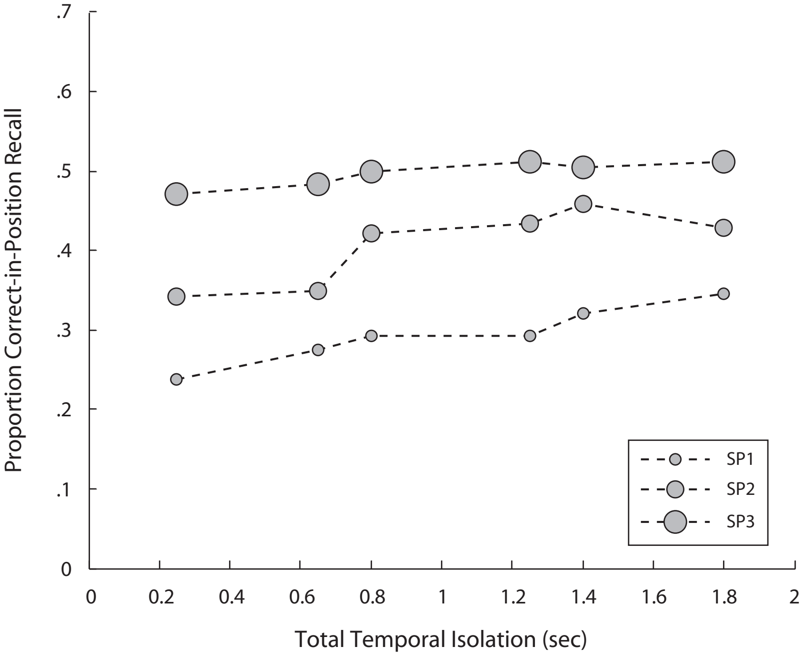

Figure 4. The combined effects of serial position and total temporal isolation for the three critical serial positions (SP1, SP2, and SP3) in Experiment 2.

intervals added up to six total durations: 250, 650, 800, 1,250, 1,400, and 1,800 msec for Serial Positions 1–3 (as in Experiment 1, the fourth item could not be considered because it did not have an interval following it).

Because an initial analysis showed that list length did not interact with any of the remaining variables, responses were again collapsed over all list lengths >4. The effects of combined temporal isolation (i.e., summing pre- and postintervals for each item) and serial position are presented in Figure 4. The data were analyzed using a 3 (serial position: 1, 2, 3) × 6 (total temporal isolation: 250, 650, 800, 1,250, 1,400, and 1,800 msec) within-subjects ANOVA. There was a large effect of serial position [$F(2,58) = 61.90$, $MS_e = 0.03$, $p < .0001$], reflecting the large recency in the data. We also obtained a temporal isolation effect [$F(5,145) = 3.99$, $MS_e = 0.02$, $p < .005$], providing statistical confirmation of the obvious isolation effect in Figure 4. There was no interaction between serial position and temporal isolation [$F(10,290) < 1$].[3]

We additionally conducted a multilevel regression analysis to obtain a quantitative estimate of the effect of isolation on performance. Multilevel regression aggregates data from all subjects while deconfounding within- and between-subjects variability by fitting each participant's data separately before aggregating the parameter estimates; this approach has been used in numerous studies to quantify temporal isolation effects (e.g., Lewandowsky & Brown, 2005; Lewandowsky et al., 2006; Lewandowsky et al., 2008). Table 2 shows the summary of the parameter estimates, consisting of separate intercepts for the three serial positions (to accommodate the obvious recency) and an overall parameter for the estimated slope of the combined temporal isolation effect (i.e., the sum of the pre- and postintervals). The size of the temporal isolation effect ($b = .054$) is considerably larger than any other temporal isolation effect demonstrated to date with forward serial recall (cf. last row in Table 1 with the other entries in the left column).[4]

With the enhanced design that prevented participants from guessing the number of remaining list items, we obtained a notable temporal isolation effect, equivalent to roughly 5%–6% improvement in performance per additional second isolation. We will now discuss the implications of the findings from both experiments.

GENERAL DISCUSSION

In Experiment 1, we demonstrated a temporal isolation effect in forward serial recall. The second experiment also obtained a temporal isolation effect, but of even larger magnitude and with an improved design that prevented strategic dismissal and re-encoding of items. These findings stand in striking contrast to previous research on forward serial recall that manipulated temporal isolation and did not find any beneficial effects (Table 1). Until now, the data clearly showed that temporal information is ignored in virtually all circumstances involving forward serial re-

Table 2
Results of the Multilevel Regression Analysis Conducted for Experiment 2

Effect	Estimate	*t*(29)	*p*
Combined isolation	.054	3.85	<.001
Serial Position 1	.239	7.01	<.0001
Serial Position 2	.351	10.76	<.0001
Serial Position 3	.442	13.66	<.0001

call. The only circumstances in which people were found to use temporal information had hitherto been confined to tasks in which report order was unconstrained.

Our experiments identified a new condition under which temporal information is used for the retrieval of memory content. This condition involved a memory task in which positional information is of limited utility to retrieve an item. In our running memory span task, once list lengths exceed span, serial positions must be constantly recoded and updated, which renders ordinal positions less straightforwardly informative than those in short lists of fixed lengths. In consequence, people demonstrably focused attention on the temporal dimension. This is the first time temporal information has been shown to be important during forward serial recall.

Because the present studies required forward serial recall, unlike the only previous demonstrations of isolation effects in short-term memory, a complete account of the role of isolation in short-term memory cannot rely on report order alone to differentiate between situations in which isolation effects are or are not observed. What are the implications of our findings for existing theories?

Implications for Event-Based Theories

Purely event-based theories, such as SOB (see, e.g., Farrell & Lewandowsky, 2002; Lewandowsky & Farrell, in press) or various other models (e.g., Botvinick & Plaut, 2006; Henson, 1998; TODAM, see, e.g., Lewandowsky & Murdock, 1989; Murdock, 1995) have no difficulty accommodating the preponderance of results that show forward serial recall to be immune to temporal isolation manipulations. However, those theories cannot handle the benefits of isolation that have emerged for free recall, unconstrained reconstruction, and, now, forward recall in the running memory span task.

Those models could accommodate an effect of temporal isolation only if the effect identifiably resulted from additional processing—such as rehearsal—in between item presentations. In all relevant studies to date, including our experiments, rehearsal during encoding has been prevented by articulatory suppression. Similarly, selective encoding strategies were ruled out by (virtual) randomization of the interitem intervals (see Lewandowsky et al., 2007). It follows that alternative event-based explanations of the observed isolation effects are difficult to conceive: Once rehearsal or selective encoding strategies have been ruled out, purely event-based approaches have no mechanism to explain the present data.

Implications for Time-Based Theories

Conversely, approaches that are entirely and exclusively time based cannot overcome the challenge of why temporal isolation effects are present in some recall conditions (free recall, unconstrained reconstruction, and the running memory task) but absent in others (forward serial recall, probed recall for order, forward reconstruction). Among the theories that are compromised by the overall pattern of isolation effects are the models of Burgess and Hitch (1999, 2006) and OSCAR (Brown et al., 2000). Although these models differ in other respects, both assume a temporally based encoding of items into short-term memory. This assumption should predict the same effects of temporal isolation, regardless of recall variation. Because there is no mechanism in either of the models that allows the role of time at encoding to vary, the absence of temporal isolation effects in some recall tasks but not in others presents a serious challenge to these models.

This conclusion also applies to a hybrid theory, such as the primacy model (Page & Norris, 1998), which proposes that although forgetting arises from time-based decay, time plays no role at encoding. If isolation has no effect at encoding, then this should again apply under all conditions of recall, and the primacy model—despite postulating temporal decay—is thus challenged whenever temporal isolation effects do occur, as in the present experiments.

Multiple Dimensions of Representation

When considering all available data on isolation effects, the overall pattern appears to mandate an approach that combines both temporal and nontemporal (e.g., positional) sources of information. This approach is perhaps most readily embodied in SIMPLE, which acknowledges that dimensions other than time play a role in memory and that people can decide how to divide their attention among all potential dimensions. From the bulk of studies summarized in Table 1, it is fairly clear that people shift their attention away from time and toward position (or some other nontemporal mode of representation) in all but (so far) two clearly defined circumstances. The first of those involves situations in which output order is arbitrary, which, for the reasons cited earlier, permits the temporal dimension to be exploited to raise overall performance. The second involves situations in which positional information is of limited utility, as in the present running memory span task. Both situations produce substantial isolation effects of around 5% or more per second.

Two attributes of this preferred multidimensional explanation deserve to be emphasized. First, the fact that random cuing *after* study can either elicit or prevent isolation effects (Lewandowsky et al., 2008) suggests that the encoding of temporal information is mandatory, but its use is not. The selective sensitivity to temporal information that is observed with an unconstrained reconstruction task (even if people remain unaware of the type of test until after encoding) and the simultaneous absence of any effects with serial recall or constrained reconstruction appear impossible to reconcile with any view that does not propose obligatory encoding of both temporal and ordinal information. Second, although within the SIMPLE framework, nontemporal information has so far been invariably represented by a positional dimension (see, e.g., Lewandowsky et al., 2006; Lewandowsky et al., 2008), we are not committed to this instantiation. For example, other event-driven representations, such as Botvinick and Plaut's (2006) recurrent network, may turn out to provide a powerful alternative instantiation of event-based aspects of memorial representations.

Finally, we must anticipate a potential criticism of our theorizing; we appear to explain the phenomenon of interest—namely, temporal isolation—by appealing to a construct—namely, the distribution of attention—that is in turn revealed by the same phenomenon. In response, we note that the conditions under which isolation effects arise were not identified serendipitously, but on the basis of a principled analysis of task demands. Thus, Lewandowsky et al. (2008) analyzed the reasons why free report order might encourage people to pay attention to time (we summarized their analysis earlier in this article), and we likewise predicted at the outset that isolation effects would emerge in the running memory span paradigm because it reduces the value of positional information.

We therefore conclude that an approach that combines information about time and position into a multidimensional representation of information in memory provides a testable account of all isolation effects observed in short-term memory to date.

Conclusions

Until now, temporal isolation effects have not been found in forward serial recall. The present studies showed that temporal information is encoded and can be used even in forward serial recall. People rely on temporal information when the use of positional information is discouraged by task demands, as in the case of a running memory span task. The present results pose a challenge to purely event-based and purely time-based approaches to short-term memory alike.

AUTHOR NOTE

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NOTES

1. There is some empirical evidence (Neath & Crowder, 1996; Welte & Laughery, 1971) of a positive effect of increased temporal isolation on immediate serial recall, which seems to support a temporal distinctiveness view. However, those effects only arise with a predictable temporal structure of the list and are therefore subject to an alternative explanation based on selective encoding strategies (for a detailed explanation, see Lewandowsky, Wright, & Brown, 2007).

Relatedly, Farrell (2008) recently reported an isolation effect in forward serial recall in one experiment (but not in another similar one) in which people had to explicitly group the list on some trials and to recall the timing of input items (rather than their identity) on some other trials. This finding is consistent with the account advanced here—namely, that isolation effects can emerge on the basis of how much attention people pay to temporal information.

2. Running memory span tasks have been designed to resemble real-life situations—for example, when industrial operators have to track a number of variables for which they must know the most recent values (Blankenship, 1938). Running memory span tasks have been of particular theoretical interest to investigate the interplay between storage and central executive processes (i.e., involved in updating) in working memory (Conway et al., 2005; Morris & Jones, 1990).

3. Although the interaction failed to approach significance, there is a slight suggestion in the figure that the isolation effect for Serial Position 3 is compressed, as opposed to its state in the other two positions. One may be tempted to link this compression with the fact that greater isolation of the penultimate item necessarily corresponds to a slightly greater retention interval; in consequence, the greater opportunity for forgetting may have counteracted the benefits of isolation. (No such compression is observed for the other serial positions because, owing to the presumed logarithmic scale of the temporal dimension, the relatively small changes in retention interval have no effect for those earlier items.)

4. The data from Experiment 1 were less amenable to a regression analysis because total isolation only had three levels (as opposed to six in the present study), and those levels were not exactly equal across serial positions because of the binning required for the first serial position (this problem also did not arise in the second experiment).

For the sake of completeness, we nonetheless conducted a multilevel regression for Experiment 1 and found a small but significant effect of temporal isolation [$b = .029$; $t(42) = 2.93$, $p < .006$], thus confirming the results of the earlier ANOVA-based analysis.

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