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Multiple roles for time in short-term memory: Evidence from serial recall of order and timing

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Abstract

Three experiments are reported that examine the relationship between short-term memory for time and order information, and the more specific claim that order memory is driven by a timing signal. Participants were presented with digits spaced irregularly in time, and postcued (Experiments 1 and 2) or precued (Experiment 3) to recall the order or timing of the digits. The primary results of interest were: 1) Instructing participants to group lists had similar effects on serial and timing recall in inducing a pause in recall between suggested groups; 2) The timing of recall was predicted by the timing of the input lists in both serial recall and timing recall; and 3) When the recall task was precued, there was a tendency for temporally isolated items to be more accurately recalled than temporally crowded items. The results place constraints on models of serial recall that assume a timing signal generates positional representations, and suggest an additional role for information about individual durations in short-term memory.

Multiple roles for time in short-term memory: Evidence from serial recall of order and timing

How do we remember the temporal structure of sequences of events? This question has concerned short-term memory researchers for a number of decades, and has culminated in the formulation of a number of models specifically dedicated to explaining short-term memory for ordered sequences of information (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Estes, 1972; Farrell & Lewandowsky, 2002; Page & Norris, 1998). The interest in the principles underlying short-term memory for order has been supplemented by a concern with short-term memory for the timing of sequences (e.g., Collier & Logan, 2000; Farrell & McLaughlin, in press; Glenberg, Mann, Altman, Forman, & Procise, 1989; Watkins, LeCompte, Elliott, & Fish, 1992). This interest in time as the content of memories has been partly driven by the suggestion that the positional representations underlying memory for serial order have a general temporal basis (Brown et al., 2000; Burgess & Hitch, 1999; Glenberg & Swanson, 1986), and a more general belief in the importance of studying time as an object of memory (Crowder & Greene, 1987; Estes, 1985).

The purpose of this paper is to consider the role of timing information in short-term memory for the both the order and timing of sequences. Below, we consider the possibility that the same principles apply to memory for time and memory for order, and the stronger claim that memory for time and memory for order rely on the same mechanisms or representations is discussed. To examine this claim, three predictions from the involvement of a timing mechanism in serial recall are tested across three experiments: That grouping should have effects of recall of timing information, as well as order information; That input timing should be reflected in output timing for recall of both order and timing; and that temporally distinct items should receive an ordered recall advantage. The accuracy and dynamics of recall from the experiments suggest that time is represented in both a timing signal and at the level of individual durations, placing constraints on contemporary models of working memory.

The role of time in models of short-term memory

A popular class of serial recall models assumes that items are associated with some representation of position, such that a sequence can be recreated by cueing for items with successive positional cues. In some these models (Brown, Neath, & Chater, 2007; Brown et al., 2000), time can be identified as playing a fundamental role in the representation of position. For example, in the OSCAR model of Brown et al. (2000) it is assumed that each stimulus in a sequence is associated with the state of activation across a set of nodes representing temporal context. This timing signal is assumed to follow from the activity of neural oscillators, which have been suggested to play a role in timing behaviour (e.g., Treisman, Cook, Naish, & MacCrone, 1994), and gives a natural mechanism for the reinstatement of the timing context for each position by "rewinding the clock" (Brown et al., 2000). In a more recent and general time-based model, the SIMPLE model of Brown et al. (2007), the primary assumption is that items being retrieved from memory are discriminated on the basis of their temporal distance from the present. As in the OSCAR model, time plays a key role in determining the recall of the ordering of items. [1]

These time-based models make a strong prediction that distinguishes them from models assuming ordinal representations of position (e.g., Farrell & Lewandowsky, 2002): Items that are spaced further apart in time (leading to less overlap in the temporal contexts of the two items) are predicted to be less confusable in order memory tasks. Contrary to this prediction, a number of studies have failed to demonstrate any effects of the temporal isolation of items, whether the information to be remembered is auditory, visual or spatial in nature; whether recall or recognition is used as measure of memory;

and regardless of the range of temporal intervals used (Farrell & McLaughlin, in press; Lewandowsky & Brown, 2005; Lewandowsky, Brown, Wright, & Nimmo, 2006; Nimmo & Lewandowsky, 2005, 2005; Parmentier, King, & Dennis, 2006). There are two exceptions to this general failure to observe a temporal isolation effect. One is the observation that extending the duration following an item can enhance memory for that item (Lewandowsky & Brown, 2005). However, this has been argued to follow from the employment of other processes such as rehearsal and consolidation during these longer intervals; thus, time may only be a proxy in determining the application of time-dependent processes. Consistent with this is the observation that requiring participants to remember items under conditions of articulatory rehearsal negates these temporal isolation effects whilst leaving ordered recall relatively intact (Lewandowsky & Brown, 2005). A second form of evidence is less easily explained away. In a recent set of experiments Brown, Lewandowsky and colleagues have observed that temporal isolation effects are observed in free recall (Brown, Morin, & Lewandowsky, 2006), and may also be in order memory tasks when the output order is left unconstrained, even when participants cannot anticipate the nature of the memory test (Lewandowsky, Nimmo, & Brown, in press). On the basis of these results, it has been argued that both ordinal and temporal information are encoded, with these different sources of information being differentially weighted when retrieving items (Lewandowsky et al., in press). What is clear is that temporal information does not solely drive the sequencing of information in short-term order memory, but appears to be encoded by default in short-term order memory tasks.

Another set of studies has tested these models by examining the accuracy and dynamics of the recall of list items under grouping conditions. Imposing a grouped structure on lists (effectively forming "mini-lists") has a number of effects on serial recall performance (see Ng & Maybery, 2002a, for a review). Overall order recall accuracy is enhanced for grouped lists (e.g., Hitch, Burgess, Towse, & Culpin, 1996; Maybery, Parmentier, & Jones, 2002; Ryan, 1969a, 1969b), and grouping results in the appearance of miniature serial position functions (i.e., multiple bowings in the serial position function) corresponding to the groups (e.g., Hitch et al., 1996; Maybery et al., 2002). Grouping also has a qualitative effect on recall latencies: a pause is left in recall between groups, leading to discontinuous peaks in the latency serial position function (Anderson & Matessa, 1997; Farrell & Lewandowsky, 2004; Maybery et al., 2002; Parmentier, Andrés, Elford, & Jones, 2006). Usually, this grouping is accomplished by separating the groups in time (e.g., presenting a 6-item list with the temporal structure 1..2..3.....4..5..6; see Frick, 1989; Hitch et al., 1996; Maybery et al., 2002; Ryan, 1969a), which has led some to emphasise the temporal nature of the grouping effect (Hitch et al., 1996). That these grouping effects on accuracy and latency may also be obtained with other manipulations that leave the temporal organization of list items undisturbed, such as visual organization (Anderson & Matessa, 1997), playing auditory pips between groups (Ryan, 1969a), and simply instructing participants to group the lists without any stimulus manipulation (Ryan, 1969a), indicates that temporal variation is not critical to obtaining grouping effects. Nevertheless, time-based theories such as that of Brown et al. (2000) specify that grouped lists are represented by a hierarchy of temporal representations, with grouped lists recruiting an additional set of oscillators that repeat between groups. That is, these models assume that one component of the timing signal represents time in the sequence, and another represents time in the group. This assumption was tested in experiments by Ng and Maybery (2002a, 2005), who varied the timing of items within temporally separated groups. The time-based models predict that confusions of items between groups should occur on the basis of the time of the occurrence of items within the group; that is, items that occurred at the same time within their respective groups would be more likely to be confused at recall than otherwise. Instead, Ng and Maybery (2002a, 2005) observed that confusions between groups occured solely on the basis of shared in-group ordinal position. Furthermore, Maybery et al. (2002) observed that the dynamics of recall also failed to indicate a temporal synchronization between input and output: Although introducing a temporal gap between items at input led to a pause being introduced between the groups at output, the size of this pause did not vary with the size of the original temporal gap (see also Ng & Maybery, 2002b). Generally, these data have been argued to invalidate temporal models of order memory, and have instead been interpreted as evidence in favour of order-based theories (Ng & Maybery, 2005).

One attempt to resolve these findings with a belief in a primary role for time in short-term memory is found in the SIMPLE model of Brown et al. (2007). As mentioned, SIMPLE's primary assumption is that items being retrieved from memory are discriminated on the basis of their temporal distance from the present. An assumption critical to explaining the above results is that the relative weighting of the various dimensions along which items might be discriminated is not fixed but can be set at retrieval (Brown et al., 2007; Lewandowsky et al., in press). Together, these assumptions allow the SIMPLE model to explain many of the results above that appear problematic for a time-based model. The lack of temporal isolation effects in serial recall are accounted for by assuming that items are represented on both a temporal dimension and an ordinal dimension, with the ordinal dimension being given primary weighting in standard serial recall, whereas the temporal dimension may be more heavily weighted in cases where the order of output is unconstrained (Brown et al., 2006; Lewandowsky et al., in press). To explain the null effect of varying timing of items in groups (Ng & Maybery, 2002a, 2005), Brown et al. (2007) assume that items are discriminated along both a temporal dimension representing time since occurrence and an ordinal dimension representing the position of items in a group. Although the flexibility to allocate weights to temporal and ordinal dimensions gives the model additional freedom to account for these effects, it isn't clear under what situations the modeller can *a priori* determine when participants will recruit one or the other dimensions to guide responding. More germane to the issues here, the nature of the temporal dimension and its relation to temporal representations in other models and tasks is unclear, as Brown and colleagues deliberately abstract from such a level of instantiation. We next consider more direct approaches to the nature of temporal representations and how they might relate to sequence recall.

A common basis for timing and ordering in short-term memory?

The data reviewed in the previous section, in questioning the necessary involvement of temporal information in ordered recall, are quite surprising given that a wealth of evidence indicates a critical relationship between timing behaviour and short-term or working memory (e.g., Fortin & Massé, 1999; Neath & Fortin, 2005). Evidence for a specific relationship between short-term memory for order and timing comes from a study by Elvevåg, Brown, McCormack, Vousden, and Goldberg (2004), who tested schizophrenia patients and controls on a probed order recall task, a temporal estimation task, and a line length estimation task. Elvevåg et al. found that, compared to controls, the patients with schizophrenia were impaired on the order recall task and the temporal estimation task, but were not impaired on the line length estimation task. Elvevåg et al. concluded that this pattern of impairment suggested a specific dysfunction in the biopsychological mechanism(s) responsible for the processing of temporal information. Henson, Hartley, Burgess, Hitch, and Flude (2003) argued that these temporal mechanisms might also be disrupted in experimental situations. They showed that articulatory suppression, irrelevant speech and concurrent tapping all interfered with a short-term memory task that placed demands on order memory to a greater extent than one simply requiring the retention of the identity of list items. Along with the enhancing effects specifically for order recall, Henson et al. (2003) suggested that their results were consistent with the recruitment of a timing mechanism (or possibly more than one), to enable the short-term ordering of sequences.

Recent work has also considered the extent to which serial order memory might be related to processing and memory of the temporal structure of whole sequences. A number of studies have examined memory for the temporal schedule of items, with the majority of these considering the hypothesis that the modality effect in serial recall (e.g., Cowan, Saults, & Brown, 2004; Frankish, 1985) is due to a greater temporal resolution in the auditory modality. Most studies failed to find an effect of modality for timing tasks, or observed an auditory advantage only under specific conditions of rate of presentation, distractor activity and variability in the timing of stimuli (Collier & Logan, 2000; Glenberg & Jona, 1991; Watkins et al., 1992). A more direct investigation of the time-order relationship was conducted by Saito (2001), who examined individual differences in a number of short-term memory measures including visual and auditory digit span, and memory for rhythms (i.e., sequences of on-off beats). Saito found that both visual and auditory digit span correlated with rhythm recall performance, even when individual differences in reading speed (a measure of articulatory speed) were accounted for. Given the relationship was observed for both auditory and visual stimuli, Saito concluded that any common basis for timing and ordering extended beyond auditory or articulatory processes and was instead due to a shared reliance on a timing mechanism such as that assumed in the Burgess and Hitch (1999) model.

Together, the evidence for the role of a timing mechanism in short-term order memory, and the nature of a more general relationship between time and memory, is unclear. Although there is some evidence against the specific formalism of the time-order relationship in the Brown et al. (2000) model (see also Burgess & Hitch, 1999), further exploration of this relationship is warranted in light of the positive evidence discussed, and the abstract nature of more general models of the role of time in order memory (Brown et al., 2007). The remainder of this paper reports three experiments that examine the relationship between time and order memory in a single task that manipulates memory requirements (remembering order or timing) and otherwise equates experimental details. In exploring this relationship three questions are addressed:

1. *Does grouping have a similar effect on timing recall and order recall?* In accounting for the well-replicated effects of grouping on ordered recall Henson, Burgess, and Frith (2000) suggested that grouping has the effect of recruiting additional timing mechanisms (for example, some representation of rhythm; Saito, 2001) and additionally modulates the timing signal assumed to be at play in ungrouped lists. On the assumption that recalling the timing of a sequence also recruits this timing signal (see Farrell & McLaughlin, in press; Saito, 2001) we expect that grouping will similarly affect timing and order recall. In particular, given that people leave an extended pause at group boundaries in serial recall of grouped lists (Farrell & Lewandowsky, 2004; Maybery et al., 2002), we predict a pause to be left at group boundaries in recalling the timing of grouped lists.

2. *Does input timing drive output timing in timing and order recall?* Previous studies have demonstrated the ability of humans to store, retain, and recall or recognize sequence timing (Collier & Logan, 2000; Crowder & Greene, 1987; Farrell & McLaughlin, in press; Ross & Houtsma, 1994). Accordingly, we expect that participants will demonstrate some ability to reproduce the timing of sequences in output when this is the task demand. Of greater interest is the question of whether input timing is reflected in the dynamics of serial recall. Although previous studies have failed to demonstrate a mirroring of input times between groups in recall of grouped lists (Maybery et al., 2002; Ng & Maybery, 2002b), this has not been studied more generally. One prediction of timing signal models such as OSCAR and the Burgess and Hitch model is that, if the timing signal unfolds in real-time (or a scaled version of real-time), input timing on a list should predict output timing.

3. *Does input timing affect ordered recall accuracy?* In failing to systematically

demonstrate a temporal isolation effect in short-term order memory, the studies reviewed earlier indicate a non-critical role of timing in ordered recall (e.g., Farrell & McLaughlin, in press; Lewandowsky et al., 2006). Nevertheless, a temporal isolation effect is sometimes observed (Brown et al., 2006; Lewandowsky et al., in press), and the boundary conditions on this effect are still unclear. The data collected here provide further constraints on accounts of temporal isolation effects; on the basis of the conclusions of Lewandowsky and colleagues (in press) we predict no temporal isolation effects for the serial recall tasks employed here.

Experiment 1

To address the time-order relationship in a controlled design, Experiment 1 (and Experiment 2) used the experimental procedure schematically depicted in Figure 1 (cf. Farrell & McLaughlin, in press). Participants were presented with lists of 6 digits, the digits being presented with irregular timing. After presentation of the list, participants were presented with a cue indicating either a) recall of the digits on the list in order ("NUMBERS"); or b) recall of the timing of the digits, disregarding the identity of the digits themselves ("RHYTHM"). Use of this postcueing procedure meant that the two memory tasks were equated both on the content of the lists and on the processing of the lists at encoding, with the only possible difference being the information recalled at output. The grouping of the lists was also manipulated, by introducing grouping instructions halfway through the experiment. As reviewed earlier, instructing participants to think about list items as being in groups is sufficient to elicit grouping effects in serial recall (Ryan, 1969a). Temporal grouping was not employed as this was thought to be a less salient grouping cue given the irregularity of list timing, and to provide a stronger test of the grouping hypothesis: If grouping affects latencies in the absence of any objective timing manipulations, we can conclude that the effects of grouping on latencies in either task are not simply due to reading off of the posited temporal dimension like a tape (cf. Maybery et al., 2002).

Method

Participants and design

Participants were 40 undergraduate students from the University of Bristol, who participated in exchange for course credits. All participants were native or fluent English speakers. Each participant completed trials in all cells of the 2 (task type: order vs timing) x 2 (instructions: ungrouped vs grouped) x 6 (serial position: 1–6) design.

Materials and apparatus

Lists contained 6 digits that were randomly sampled without replacement from the set 1 through 9. Sixty lists were constructed for each recall task subject to two constraints: following Henson (1996), lists could not contain ascending or descending pairs of integers (e.g., "3 4," "7 6"); and an item could not appear in the same serial position on consecutive lists. This constraint also applied to all remaining experiments.

The presentation duration of each item on each list was varied pseudo-randomly using the following procedure. First, a raw duration was generated for each item by pseudo-randomly sampling from a uniform distribution with lower and upper limits of 0 and 1. The durations on each list were then scaled such that durations summed to a constant 3000ms; this equates to an average presentation rate of 2 digits per second, similar to other experiments requiring serial recall of visually presented digits (e.g., Farrell & Lewandowsky, 2004). Any lists that contained a presentation duration shorter than 200ms were entirely resampled, the resampling being repeated until the constraints were satisfied. A histogram of the resulting inter-stimulus intervals (ISIs) across all participants and serial positions is shown in the left panel of Figure 2.

The experiment was controlled by a PC that presented all stimuli (on a 15" monitor) and collected and scored all responses using the Psychophysics Toolbox for MATLAB (Brainard, 1997; Pelli, 1997). The same apparatus was used in the remaining experiments.

Procedure

Participants were tested individually in a laboratory. Each trial began with a fixation point (a cross) being presented in the centre of the screen for 1000ms. This was followed by a blank screen with duration 500ms, which was then followed by presentation of the memory list. List items were presented one by one on the screen, each item after the first immediately replacing the preceding item, and being presented for the time determined by the pseudo-random sampling procedure described above. Following presentation of the list there was another blank screen of 500ms, followed by presentation of one of the two cues "NUMBERS" and "RHYTHM". If "NUMBERS" appeared on the screen, the participant's task was to recall the digits from the list in the order they were presented by typing them on the numeric keypad of the keyboard (i.e., standard serial recall). If the "RHYTHM" cue appeared, the participants were instructed to ignore the identity of the digits, and instead to tap the '5' key on the numeric keypad in time with the remembered timing of the input list; that is, they should tap the key at the remembered onset of each item. In effect, the timing task required participants to reproduce the remembered durations of the items on the memory list in order. Demonstration trials were given to show exactly what was required of the participants in the timing task. The task cue remained on the screen throughout the recall period. When the participant had pressed 6 keys on the keypad, the cue was replaced by a blank screen for 1000ms before moving on to the next trial.

For the first half of the experiment (60 lists: 30 order recalls and 30 timing recalls) the participants carried out the experiment in line with the procedure as detailed. At the halfway point a message appeared on the screen with additional instructions. These instructions were to "think about the six numbers on each list as being in two groups of 3"; participants were given an example of such a grouping ("For example, if you got the list of numbers '1 7 4 8 3 2', you would remember '1 7 4' as one group, and '8 3 2' as another group"). The experimental task was otherwise unchanged. The grouping instruction was presented in the second half of the experiment for all participants. Although this leads to an order confound, this constant ordering of conditions was chosen because the grouping strategy was otherwise expected to continue once people had been presented with grouped lists, and thus contaminate the ungrouped condition (Farrell & Lewandowsky, 2004; Henson, 1999).

Four practice trials were presented before the experimental session began (2 order trials and 2 timing trials), in order to familiarise participants with the experiment. A self-paced break was presented after every 10 experimental trials; participants were presented with a message indicating that they should press the space bar to move to the next set of trials. The entire procedure lasted for around 40 minutes.

Results

Results for all experiments reported here are structured according to the questions posed in the introduction. Within each section we consider the order task and the timing task in succession, with the exception of the reporting of input-output timing relationships, for which we consider the timing task first given the essential nature of input-ouput timing for that task.

Ordering accuracy

The left panel of Figure 3 plots the accuracy serial position functions for the ungrouped and grouped conditions; repeated-measures error bars in this and all figures were calculated using the methods in Bakeman and McArthur (1996). A 2 (instruction:

ungrouped vs grouped) x 6 (serial position) repeated measures analysis of variance (ANOVA) confirmed an apparent main effect of grouping, with grouped lists being recalled more accurately than ungrouped lists [ungrouped mean = .81; grouped mean = .88; $F(1, 39) = 34.65$, $p < .001$, η^2_P=0.47],[2] and a main effect of serial position [$F(1.97, 76.68) = 27.86$, $p < .001$, η^2_P=0.42] reflecting the extended primacy and limited recency typical of serial recall. A significant interaction was also observed [$F(3.98, 155.26) = 5.89$, $p < .001$, η^2_P=0.13], confirming that the grouping manipulation changed the shape of the serial position function. Visual inspection of the functions in Figure 3 suggests "mini" serial position curves corresponding to each group (Hitch et al., 1996); however, there is some indication of spontaneous grouping even in the ostensibly ungrouped lists (cf. Henson, 1996). An analysis of repeated measures contrasts for this interaction revealed a quadratic trend relating serial position to the difference between grouping conditions [$F(1, 39) = 9.16$, $p = .004$, η^2_P=0.19], in replication of previous grouping experiments involving lists of verbal items (Maybery et al., 2002).

Output timing serial position functions

The left panel of Figure 4 plots the mean output time serial position functions for the order task separately for the ungrouped and grouped conditions. A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA revealed that response times were significantly longer in the ungrouped condition [ungrouped mean = 658.2 ms; grouped mean = 615.2 ms; $F(1, 39) = 18.75$, $p < .001$, η^2_P=0.36], and also indicated a main effect of serial position [$F(2.15, 83.77) = 299.0$, $p < .001$, η^2_P=0.86]. The majority of the latter effect came from noticeably longer latencies for the item first recalled. This pattern is generally observed in latency serial position functions (Anderson & Matessa, 1997; Farrell & Lewandowsky, 2004; Oberauer, 2003; Thomas, Milner, & Haberlandt, 2003), and can be attributed to preparatory processes (Farrell & Lewandowsky, 2002, 2004), particularly in the postcued task used here. Of greater interest was the observed significant interaction between grouping instruction and serial position [$F(2.75, 107.14) = 6.27$, $p = .001$, η^2_P=0.14]. Inspection of Figure 4 shows the expected effects of grouping in discontinuously elevating the latency of the fourth item (the first item in the second group), a marker of grouping of the list.

Though less pronounced, similar effects of grouping were observed for the timing task. Inspection of the left panel of Figure 5 reveals patterns of output times similar to those in the order task, in particular a discontinuous effect of grouping in elevating the output time for the fourth position. Consistent with this, a 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA revealed significant effects of serial position [$F(1.76, 68.64) = 82.92$, $p < .001$, η^2_P=0.68] and a significant interaction [$F(3.67, 142.97) = 5.36$, $p = .001$, η^2_P=0.12]; the main effect of grouping was not significant [$F(1, 39) < 1$, η^2_P=0.01].

Although the interaction between serial position and grouping instruction is indicative of the peak in latencies at position 4 consistent with the grouping strategy (Maybery et al., 2002), an analysis was desired to specifically test for the predicted discontinuity in latencies at the suggested group boundary. Previously, analyses have focussed on comparing the peak point to the surrounding points using, for example, t-tests (Maybery et al., 2002). Here a related approach was employed that uses information from the entire serial position function to determine a baseline with which to compare the peaked latencies. Inspection of a variety of reports of latency serial position functions for serial recall uncontaminated by grouping suggests that, after the first output position, the serial position function for ungrouped lists is either monotonic (approximately linear) or quadratic (Farrell & Lewandowsky, 2004; Maybery et al., 2002). Accordingly, for each participant a second-order polynomial was fit to the latencies from serial positions 2, 3, 5 and 6 separately for ungrouped and grouped conditions, and the deviation between the observed latency at the fourth serial position and that predicted from the polynomial fit was calculated. Statistics for the resulting grouping deviations are shown in Table 1. Paired samples t-tests comparing grouping deviations in the ungrouped and grouped conditions revealed significantly larger (more positive) differences for both the order task [$t(39)$=3.64, p = .001, Cohen's d=0.58] and the timing task [$t(39)$=3.77, p = .001, d=0.60] in the grouped condition. These results indicate that both tasks were sensitive to the instructions to group lists, and that such instructions led to a lengthening of the pause in output separating the groups in both tasks.

Does input timing predict output timing?

Input-output regression. To determine whether or not input timing predicts output timing, a mixed-effects linear regression model (see, e.g., Pinheiro & Bates, 2000) was fit to the data, with input durations for serial positions 1–5 as the predictor, and the times between keypresses at recall (which align with the input durations) as the dependent variable; random effects (variability between participants) were included for the intercept and slope parameters. A benefit of using mixed-effects models is that we can estimate relationships common to all the participants whilst accounting for variance due to individual differences. To maximise the power of the test, prior to application of the model the observed effects of output position on output times (Figures 4 and 5) were filtered from the output durations for each participant by subtracting from each indiviual response time the mean of all responses for that response's grouping condition and serial position (cf. Farrell & Lewandowsky, 2004).

The results of the analysis are shown in the left half of Table 2. We first look at the timing task, where reproduction of the input timings was the goal of the task. Table 2 shows that the estimated slope was positive and significantly above 0, indicating that participants were able to reproduce the input timings to some extent. This reproduction was not perfect, in that the estimated slopes are well below 1; if participants were exactly matching the input timings with their responses, the estimated slopes should be equal to 1. One possibility is that the output timing that participants produce is a speeded up version of the input timing, given that people can underestimate durations in time estimation and time reproduction tasks (see, e.g., (Fraisse, 1984; Wearden & Ferrara, 1993)). This is unlikely, as rerunning these analyses with rescaled input and output durations (such that input and output durations both had standard deviations of 1) gave similar slope estimates. Instead, the lower slope estimate is likely to be a consequence of regression towards the mean.

Table 2 also gives the parameter estimates when applying the mixed-effects linear regression to the output times from the order task. Recall that the order task required only ordered recall of the digits on the list, with the presentation durations being irrelevant. Table 2 shows that output times nonetheless significantly predicted the output times produced by the participants. The slope estimates indicate that this is only a weak dependence, with both slopes being below 0.1. Although theoretically these slopes would be equal to 1 for a perfect dependence, these slope estimates are better put in perspective by comparing them to the parameter estimates from the timing task. Such comparison reveals the order task estimates to be between roughly one quarter and one ninth of the values in the timing task.

Before moving on we consider one potential confound in these results. One strategy that participants may be employing in these experiments is to use any pauses that are longer than average as a basis to group lists (see, e.g., Lewandowsky & Brown, 2005). For example, if there happens to be a long pause after onset of the second item, participants may use the extra time during presentation of the item (or after the item, in later experiments) to group the list in a 2-4 structure. If participants then leave a longer pause at the resulting group boundary due to this grouping strategy, as was observed for the group structure suggested by the experimenter in the grouped condition (Figures 4 and 5), then we may see an artificial dependence between input and output times in the absence of any retention of temporal information[3]. To address this issue, the mixed-effects model was fit to the same set of data with the longest output time in each list recall excluded, on the assumption that the longest response would be a marker for any grouping effects. Note that the resulting inclusion criterion is conservative in that the longest pause was always assumed to be due to a grouping strategy, and there was no explicit test for grouping. Nevertheless, a significant relationship remained between input and output times in both the order and the timing task, though the slope estimates were generally reduced (right half of Table 2).

Migration errors. Additional information about the relationship between temporal information and order information can be obtained by examining the types of errors that participants make in the timing task. One marker of the ordering component underlying the serial recall task is referred to as the *locality constraint*: items that are not recalled in their correct position tend to be recalled in nearby positions (Henson, Norris, Page, & Baddeley, 1996; Nairne, 1990; Page & Norris, 1998; Parmentier & Jones, 2000). If, at some level above the representation of individual durations, timing recall is driven by the same ordering processes or representations that drive ordered recall of other types of information, we would expect that timing errors should obey the locality constraint; that is, if a particular duration is recalled at the wrong position, it should tend to be reproduced at a nearby position. One challenge in examining such migration errors is determining which durations in the output sequence map to which durations in the input sequence, given the continuous nature of the responses. This issue was addressed by ordering the input and output durations for each list, and designating an input–output mapping on the basis of a common ordinal code. For example, for the ordered set of input durations {300ms, 400ms, 500ms, 200ms, 100ms} and output durations {400ms, 300ms, 200ms, 100ms, 500ms}, the input codes would be {3, 4, 5, 2, 1}, and the output codes would be {4, 3, 2, 1, 5}, such that, for example, the first output duration would be taken to match the second input duration in the original list (both being the fourth–longest duration, '4', in their respective timing sequence). Using this procedure to discretize the stimuli and responses, a transposition gradient was constructed by tallying the frequency of migration errors committed over various distances (for example, recalling the fourth item at the second position would be a transposition distance of 2).

Before being interpreted, these transposition gradients should be corrected for the chance of conducting transpositions of various distances; for example, for an ordered list of 5 durations there are 2 ways for a transposition distance of 4 to occur (the first item being recalled at the fifth position, or the fifth item being recalled at the first position) and 8 ways of committing a transposition error of distance 1. To assess the deviation of these gradients from chance, and to specifically determine whether such deviations are in line with the locality constraint, two simple models were fit to the transposition data. The first, "random" model assumed that the only errors made on the timing task are due to confusions between items of similar duration. Given the random assignment of durations to positions, this was approximated by assuming that an item was recalled at the correct position with probability $1 - p_{it}$, and was otherwise recalled at a randomly selected position, with equal probability for all positions. As an alternative model characterising the locality constraint, a version of the perturbation model of serial order memory was fit to the data (Estes, 1972, 1997; Lee & Estes, 1977; Nairne, 1992). The perturbation model assumes that forgetting of serial order occurs over time due to the repeated perturbation of the position of items in memory. At each time step an item i migrates to an adjacent position ($i - 1$ or $i + 1$) with probability p_{ord}; otherwise, the item remains in the same position (see Nairne, 1992, for fully specified equations). Repeated application of the perturbation process leads to transposition gradients embodying the locality constraint:

transpositions over short distances are more frequent than those covering larger distances, above and beyond the different opportunities for making such transpositions completely at chance (Estes, 1972; Nairne, 1992). For application of the model here, and following precedent (Nairne, 1992), ten perturbation cycles were assumed to take place for all items prior to retrieval. On retrieval of each item there was an opportunity for the item to be confused with other durations on the basis of similarity as in the "random" model; again, such an item-based confusion occurred with probability p_{it}. This allowed for the determination of the relative contribution of item-based and position-based information to the transposition errors.

The models were fit to the aggregate data by minimizing the χ^2 deviation between each model and the data (including correct responses, of transposition distance 0); for a particular set of parameter values, predictions were determined from 100,000 model replications. For the "random" model, $p_{it} = .872$ for the ungrouped condition, and .897 for the grouped condition; for the perturbation model, the ungrouped and grouped conditions respectively gave parameter estimates of $p_{it} = .872$ and .86, and $p_{ord} = 0.001$ and .027. A χ^2 test comparing the two models indicated a non-significant difference between the two models for the ungrouped condition [$\chi^2(1) = 0.29$, $p = .59$]. For the grouped condition, a significant difference was observed [$\chi^2(1) = 5.58$, $p = .02$]. Figure 6 plots summary results of the modelling for Experiment 1 (top panels). Plotted in the figure are the deviation from chance (i.e., the predictions of the best-fitting chance model) for the data (triangles) and the best-fitting predictions of the perturbation model (circles); transpositions in the figure have been grouped into "local" (transposition distance 1) and "remote" (transposition distance > 1) transpositions. The right panel of Figure 6 shows a tendency for the "random" model to underpredict distance 1 transpositions and overpredict more remote transpositions. This pattern is captured by the order-based perturbation model, indicating some conformity of the data to the locality constraint. No such pattern is evident for the ungrouped condition (left panel).

Discussion

The numerous data provided by Experiment 1 provide a rich and complex picture of the relationship between time and order memory. The similar effects of the grouping manipulation on order recall and timing recall indicate some common basis for timing and order information in short-term memory. The close connection between the sequencing and dynamics of recall is also revealed by the mirroring of input timing in output timing, regardless of whether or not the task called for recall of such information. Finally, the slight but significant conformation of timing recall to the locality constraint in the grouped condition is suggestive of some higher-order ordering or timing mechanism at play above the level of individual durations.

A full consideration of the implications of these results is left to the *General Discussion*. First, two further experiments are presented that serve as replications of this initial experiment, as well as generalising the results to provide further constraints on the theories under consideration.

Experiment 2

Experiment 2 served as a basic replication of Experiment 1, but also extended the procedure in two ways (see Figure 1). First, digits were presented auditorily rather than visually. Some experiments have demonstrated an auditory advantage for recall of timing information, though this only appears to be the case in specific circumstances (e.g., Collier & Logan, 2000; Glenberg & Jona, 1991; Glenberg et al., 1989; Glenberg & Swanson, 1986; though see Nimmo & Lewandowsky, 2006; Schab & Crowder, 1989; Watkins et al., 1992). Although the empirical status of modality effects in temporal sequencing is unclear, the fact that a modality effect may sometimes be observed in rhythm memory, and may be observed for perception of single intervals (e.g., Wearden, Edwards, & Fakhri, 1998) suggests that this is an important variable to consider. Additionally, some researchers have suggested that timing of durations involves processes akin to the phonological loop in Baddeley's working memory model (Franssen, Vandierendonck, & Van Hiel, 2006; Saito & Ishio, 1998). Thus, it may be that different timing mechanisms are recruited for auditory and visual materials. In light of these concerns, it seemed appropriate to confirm that the results were replicated in the auditory modality.

Another change in Experiment 2 was to keep the duration of items constant, and instead vary the pauses between items to manipulate list timing. This was done first on pragmatic grounds, as lengthening auditory stimuli led to unnatural lists that were difficult to process and may have introduced acoustic artifacts. Second, this allowed for testing of the temporal isolation effect, which could not be examined in Experiment 1 given the constant pauses between items.

Method

Participants and design

Participants were 40 undergraduate students from the University of Bristol, who were recruited as part of an opportunity sample, and provided informed consent for participation. All participants were native or fluent English speakers. Each participant completed trials in all cells of the 2 (task type: order vs timing) x 2 (instructions: ungrouped vs grouped) x 6 (serial position: 1–6) design.

Materials and apparatus

Lists contained 6 digits that were randomly sampled without replacement from the set 1 through 9, subject to the same constraints as Experiment 1. The stimuli themselves were recorded from a male speaker with a neutral English accent, and digitised for storage on hard disk. The digits were pitch-flattened to a fundamental frequency of 113Hz using the phonetics software Praat (Boersma & Weenink, 2006)—to avoid any grouping effects arising from pitch variations (see Nicholls & Jones, 2002)—and normalised to a constant length of 500ms. The digits were additionally padded to give a regular sounding sequence for different permutations, as it is known (and was observed in pilot testing) that the subjective experience of the centre of an acoustic stimulus does not exactly relate to the onset of the stimulus (e.g., Scott, 1998). The average duration of this padding was 85.9ms (sd = 50ms).

In Experiment 1 the presentation schedule was made irregular by varying the durations of item presentations. Experimentation with shortening and lengthening the auditory stimuli suggested this would lead to unnatural sounding stimuli. Instead, the pauses between the digits were randomly varied using a similar sampling procedure to that of Experiment 1. Raw pause durations were generated by pseudo-randomly sampling from a uniform distribution, and the durations on each list were then scaled such that durations summed to a constant 3000ms. There was no minimum constraint on the pause durations. A histogram of the resulting inter-stimulus intervals (ISIs) across all participants and serial positions is shown in the right panel of Figure 2.

Procedure

The experimental procedure was similar to that of Experiment 1, with the following changes. List stimuli were played over headphones to participants at a comfortable volume determined prior to the experiment. Forty lists were presented under the standard instructions and grouping instructions, 20 each for the order task and timing task, respectively. The entire procedure lasted for around 45 minutes.

Results

Ordering accuracy

The middle panel of Figure 3 plots the accuracy serial position functions for the ungrouped and grouped conditions. A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA confirmed an apparent main effect of grouping instruction, with grouped lists being recalled more accurately [ungrouped mean = .88; grouped mean = .92; $F(1, 39) = 9.11, p = .004$, η_P^2=0.19], and a main effect of serial position [$F(2.37, 92.48) = 28.32$, $p < .001$, η_P^2=0.42] reflecting the bowed shape of the serial position functions. The interaction between grouping instruction and serial position failed to reach significance [$F(3.10, 120.76) = 1.95$, $p = .124$, η_P^2=0.05]; nevertheless, there is the visual suggestion of a scalloped serial position function for the grouped condition.

Output timing serial position functions

The centre panel of Figure 4 plots the mean latency of responses for the order task for Experiment 2. A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA revealed a main effect of serial position [$F(1.95, 76.07) = 168.76$, $p < .001$, η_P^2=0.81] and a significant interaction between grouping instruction and serial position [$F(3.69, 143.77) = 6.96$, $p < .001$, η_P^2=0.15]; the effect of grouping instruction was not significant [$F(1, 39) < 1$, $p = .68$, η_P^2 <0.01].

A similar pattern of effects was observed for the timing task (see middle panel of Figure 5). A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA revealed a significant effect of serial position [$F(1.63, 63.90) = 64.87$, $p < .001$, η_P^2=0.63], and a significant interaction [$F(4.09, 159.50) = 4.03$, $p = .004$, η_P^2=0.09]; the effect of grouping instruction was not significant [$F(1, 39) < 1$, η_P^2=0.001].

As for Experiment 1, a discontinuous peak was apparent in output times at the fourth serial position in the grouped condition; this effect was apparent in both the order task and the timing task. This was verified by examining grouping deviations as in Experiment 1 (Table 1). Paired samples t-tests comparing grouping deviations in the ungrouped and grouped conditions revealed larger (more positive) differences under grouping conditions for both the order task [$t(39)$=5.52, $p < .001$, d=0.87] and the timing task [$t(39)$=2.82, $p = .008$, d=0.44]. Replicating Experiment 1, the instruction to group specifically led to a lengthening of the pause in output separating the groups in both tasks.

Does input timing predict output timing?

Input-output regression. Fitting a mixed-effects linear regression model, with the pauses between items in the input as predictors and the times between keypresses at recall as the dependent variable, gave similar results to Experiment 1. The results presented in the left half of Table 2 show similar sized estimates of the regression slope relating input times to output times in the timing task, these estimates being highly significant. The significance values for the slopes for the order task were significant for the ungrouped condition, and failed to reach significance for the grouped condition; the slopes themselves were of similar size to those in Experiment 1. The results in the right half of Table 2 for the analyses on all data excluding (listwise) the longest response durations again show that this relationship between input and output was not attributable to confounding effects of grouping, with a similar pattern of results in both the order task and the timing task, with an additional marginally significant β for the grouped condition in the order task.

Migration errors. As for Experiment 1, the “chance” model and the perturbation model were fit to the frequencies of transpositions over various distances. For the “random” model, $p_{it} = .907$ for the ungrouped condition, and .910 for the grouped condition; for the perturbation model, the ungrouped and grouped conditions respectively gave parameter estimates of $p_{it} = .903$ and .913, and $p_{ord} < 0.001$ for both conditions. A χ^2 test comparing the two models showed a non-significant difference between the two models for the ungrouped condition [$\chi^2(1) = 0.601$, $p = .44$] and the grouped condition [$\chi^2(1) = 0.24$, $p = .72$]. The difference in frequencies between those predicted by the chance model, and those from the data and the perturbation model are shown in the middle row of Figure 6. Consistent with the modelling results, there is no evidence that transpositions in Experiment 2 conformed to the locality constraint.

Does input timing predict order accuracy?

The manipulation of the pauses between list items in Experiment 2 also allowed calculation of the extent to which the relative temporal isolation of items in the order task resulted in enhanced recall for those items (cf. Lewandowsky & Brown, 2005). To determine whether or not input timing predicts output timing, a mixed-effects logistic regression model (see, e.g., Pinheiro & Bates, 2000) was used to predict the accuracy (i.e., either correct or incorrect) of each individual response at serial positions 2, 3, 4, and 5 (serial positions 1 and 6 were excluded as these respectively have missing preceding and following pause durations). The predictors were the length of the pause preceding and following each item; random effects (variability between participants) were included for both predictors. One concern was that effects of temporal isolation might be observed due to grouping effects, as detailed in presentation of the preceding mixed-effects linear regression. In this case it may be that participants use a long pause for extra rehearsals or to construct a new group, and that there is therefore an advantage for the immediately preceding item (Lewandowsky & Brown, 2005). To address this possiblity, before the analysis was run the longest input duration, and the items preceding and following it, were removed from the data and not analysed.[4]

The maximum likelihood estimates and model tests are shown in Table 3. As can be seen, there was little evidence in the data from Experiment 2 that surrounding items by longer pauses led to more accurate ordered recall, with the parameter estimates (βs) for both preceding ("pre") and following ("post") durations being fairly close to, and not significantly different from, 0.

Discussion

The results of Experiment 2 were in line with those from Experiment 1: Grouping had effects on both order and timing recall, and input timing was reflected in output timing for both tasks. Additionally, investigation of the relationship between input timing and ordered recall failed to suggest that recall of items benefited from temporal isolation. This is consistent with previous failures to demonstrate a temporal isolation effect in serial recall (Lewandowsky & Brown, 2005; Nimmo & Lewandowsky, 2005, 2006; Parmentier, King, & Dennis, 2006).

These results provide clear evidence for some common basis for short-term memory for time and order information. The common effect of grouping on the dynamics of recall in the order and time recall tasks is consistent with suggestions that grouping has effects on the internal timing signal driving ordered recall (Brown et al., 2000; Burgess & Hitch, 1999). The lack of a temporal isolation effect also places constraints on such a relationship, in indicating that a time-based timing signal as assumed in in the OSCAR model (Brown et al., 2000) does not solely underpin sequential recall from short-term memory. The temporal isolation data are consistent with the generalization of OSCAR and the Burgess and Hitch (1999) model instantiated in the SIMPLE model (Brown et al., 2007), in which both temporal and ordinal information may be used at the time of retrieval, and may be differentially weighted based on task demands (Brown et al., 2007; Lewandowsky et al., in press); the lack of temporal isolation effects implies majority weighting of an ordinal dimension.

Nevertheless, a relationship was observed between input timing and the dynamics of output. If a single form of temporal representation, such as the suggested timing signal, was responsible for the effects of time on both ordering accuracy (temporal isolation effects) and latencies (input-output timing coupling), then these measures theoretically should not disscociate (though in practice differential sensitivity in the two effects could give rise to an apparent dissociation). Along with those of Brown et al. (2007) and Lewandowsky et al. (in press), these results suggest instead that time is represented at two levels in this task: at the level of sequencing of the entire list (equating to the timing signal or dimension in the models of Brown et al., 2000,Burgess & Hitch, 1999 and Brown et al., 2007, and accounting for the common effects of grouping on recall latencies), and at the level of individual durations (accounting for the relationship between individual input and output times in both tasks). Glenberg et al. (1989) (see also Glenberg & Jona, 1991 made a similar distinction in accounting for their observed modality effect on recall accuracy in a rhythm reproduction task, arguing that any observed modality effects follow from the influence of modality on the tuning of representation of the order of events, not of individual durations. The results here, particularly the common effects of grouping, suggest that the posited representation of sequence information is common to memory for order and time.

Before drawing some final conclusions, one final experiment is presented that addresses an issue suggested by the SIMPLE framework. The possibility that participants choose to weight different dimensions of evidence begs the question of the extent to which an artificial weighting of dimensions was induced by the postcued nature of Experiments 1 and 2. Experiment 3 examines the relationship between serial and temporal recall again, and also considers the extent to which these relationships are indicative of a basic relationship between these tasks.

Experiment 3

The postcueing procedure employed in Experiments 1 and 2 allowed comparison of order recall and timing recall under very similar conditions. This postcueing controls strategic processes at encoding that might otherwise be differentially employed for different types of information (see, e.g., Duncan & Murdock, 2000). One cost of such an approach is that these conditions, and the results they give rise to, will not necessarily generalise to typical order and timing recall experiments. Accordingly, Experiment 3 replicated the basic procedure of Experiments 1 and 2, with the primary exception that the recall task was precued and blocked, in line with typical short-term memory experiments.

Method

Participants and design

Participants were 57 undergraduate students from the University of Bristol, who were recruited as part of an opportunity sample, and provided informed consent for participation. This sample consisted of an original sample of 40 participants, plus an additional sample of 17 participants; the additional participants were run given an apparent failure to replicate the grouping effect for the order task from visual inspection of summary statistics.[5] All participants were native or fluent English speakers. Each participant completed trials in all cells of the 2 (task type: order vs timing) x 2 (instructions: ungrouped vs grouped) x 6 (serial position: 1–6) design.

Materials and apparatus

List construction and apparatus were identical to that in Experiment 2, with the exception that an alternative method was used to generate the random pauses between items. Following other studies on the effects of timing on order memory (e.g., Lewandowsky et al., 2006), for each list the pauses between items were sampled without replacement from the set of pauses {100ms, 200ms, 400ms, 800ms, 1200ms}, giving a summed pause duration of 2700ms. This guaranteed that durations on each list were all uniquely discriminable.

Procedure

The procedure was identical to that of Experiment 2 with the major exception that the cue for the task to be performed was presented prior to the list. Each trial began with the presentation of the visual cue ("NUMBERS" or "RHYTHM") for 1500ms, followed by list presentation as in Experiment 2. After presentation of the final list item there was a pause for 500ms, followed by the generic recall cue "RECALL". On appearance of this cue participants were to perform the recall task indicated at the beginning of the trial. To further disambiguate the task to be performed, trials of the same type were run in single blocks within each level of the grouping variable (i.e., 20 order trials followed by 20 timing trials in each grouping condition, or vice versa), with the order of the blocks approximately counterbalanced between participants.[6] The entire procedure lasted for around 45 minutes.

Results

Ordering accuracy

The rightmost panel of Figure 3 plots the accuracy serial position functions for the ungrouped and grouped conditions. A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA failed to show a significant effect of grouping [$F(1, 56) < 1$, η_P^2=0.002] or a significant interaction [$F(3.30, 184.56) < 1$, η_P^2=0.015]; this is likely due to ceiling effects given the overall very high accuracy. A significant effect of serial position was obtained [$F(2.94, 164.47) = 13.38$, $p < .001$, η_P^2=0.193].

Output timing serial position functions

The right panel of Figure 4 plots the mean latency of responses for the order recall task for Experiment 3. A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA revealed a practically significant effect of grouping instruction [$F(1, 56) = 3.99$, $p = .051$, η^2_P=0.066], indicating longer mean output times for the ungrouped condition (ungrouped mean = 556.3 ms; grouped mean = 531.0 ms), and a main effect of serial position [$F(1.94, 108.33) = 92.63$, $p < .001$, η^2_P=0.623]. The interaction between grouping instruction and serial position was also significant [$F(2.57, 143.73) = 3.52$, $p = .022$, η^2_P=0.059].

This pattern of results failed to replicate in the timing task (right panel of Figure 5). A 2 (instruction: ungrouped vs grouped) x 6 (serial position) ANOVA revealed a significant effect of grouping instruction [ungrouped mean = 963.8 ms; grouped mean = 912.8 ms; $F(1, 56) = 31.55$, $p < .001$, η^2_P=0.360] and serial position [$F(2.29, 128.41) = 6.91$, $p = .001$, η^2_P=0.110]; however, the interaction between grouping and serial position was not significant [$F(3.85, 215.57) = 1.72$, $p = .15$, η^2_P=0.030]. Inspection of Figure 5 (right panel) shows that output times were slightly slower in the ungrouped condition, but fails to suggest a discontinuous peak for output times at the group boundary; if anything, the serial position function for the grouped condition approximately resembles that for the ungrouped condition in the other experiments and task.

The different effects of instructed grouping on the order and timing task were confirmed by examining grouping deviations (Table 1). Paired samples t-tests comparing grouping deviations in the ungrouped and grouped conditions revealed larger (more positive) differences for the grouped condition in the order task [$t(56)$=3.02, $p = .004$, d = 0.40], despite evidence from Figure 4 and Table 1 that the grouping strategy was often being employed spontaneously even in the ungrouped condition. In contrast, the difference in grouping deviations between ungrouped and grouped conditions in the timing task was not found to be significant [$t(56) < 1$, $d = 0.13$].

Does input timing predict output timing?

Input-output regression. Fitting a mixed-effects linear regression model to the data from Experiment 3 revealed a similar pattern of effects to those in Experiments 1 and 2, with one exception. The left half of Table 2 shows that, for the timing task, slope parameter estimates were large and highly significant. For the order task the relationship was found to be significant for the ungrouped condition, with similar parameter estimates to those observed in the previous experiments. In contrast, the regression coefficient for the data in the grouped condition was not significantly different from 0. As shown in the right half of Table 2 these results remained unchanged, with the exception of a downwards shift in the slope estimates, when the possible contributions of time-based grouping were approximately controlled by removing the longest output times.

Migration errors. Best-fitting parameters were obtained for the models as before. For the "random" model, $p_{it} = .776$ for the ungrouped condition, and .811 for the grouped condition; for the perturbation model, the ungrouped and grouped conditions respectively gave parameter estimates of $p_{it} = .751$ and .776, and $p_{ord} = 0.010$ and .013). A χ^2 test comparing the two models revealed a difference approaching significance for the ungrouped condition [$\chi^2(1) = 3.39$, $p = .066$] and a significant difference for the grouped condition [$\chi^2(1) = 5.65$, $p = .018$]. Differences in transposition frequencies by migration distance for Experiment 3 are shown in the bottom row of Figure 6. The plotted results confirm the pattern implied by the model statistics, with a tendency for there to be greater frequencies of transpositions to adjacent positions (transposition displacement 1) in both the data and the perturbation model compared to those expected from the "random" model.

Does input timing predict order accuracy?

As for Experiment 2, a mixed-effects logistic regression model was applied to the data to determine whether or not input timing predicts order recall accuracy. The same model was applied here, including the removal of the longest pause and surrounding responses on each list prior to analysis. The maximum likelihood estimates and model tests are shown in the bottom half of Table 3. Although the "post" duration estimates did not differ significantly from 0, the effect of preceding ("pre") durations was found to be significant for the grouped condition, and marginal for the ungrouped condition. The parameter estimates for the ungrouped and grouped conditions indicate a respective increase (multiplication) in odds of recalling an item correctly of 1.34 and 1.82 with each unit (seconds) increase in the pause duration preceding an item. Thus, ordered recall benefited from temporal isolation, though in an apparently asymmetric fashion.

Discussion

Experiment 3, which employed a precueing procedure, showed some interesting similarities and contrasts with Experiments 1 and 2. In contrast to the preceding experiments, participants did not appear to group lists in the timing experiment as they did in Experiments 1 and 2, although a grouping strategy did appear to be employed on order trials. In line with previous experiments, input timing was reflected in output timing in both the order and timing tasks; in the order task, this was regardless of the experimental setup, which allowed timing information to be ignored throughout order recall blocks. Finally, there was some evidence of a temporal isolation effect in Experiment 3, where none was observed in Experiment 2. Together, these results reinforce the general picture emerging from Experiments 1 and 2 that timing and order information are not entirely independent in short-term memory, and places constraints on interpretations of the relationship between the two. In the *General Discussion* we consider the possible source and nature of the overlap between the two tasks, and what the differences between tasks might tell us about the function of the putative timing signal in short-term memory.

General Discussion

The results of the experiments can be summarised as follows. First, when participants were not precued about the nature of the information to be recalled, instructed grouping had effects on the dynamics of recall of both order and timing information: in grouping conditions, participants left an extended pause between groups in their output (cf. Farrell & Lewandowsky, 2004; Maybery et al., 2002). When the recall task was precued, grouping had this effect on the latencies of serial recall, but not recall of list timing. Second, it was generally the case that input timing was reflected in the timing of participants' output, even in the serial recall task where recall of timing was not explicitly required. Third, there was some inconsistent evidence for temporal isolation effects: for the precued experiment (Experiment 3), items preceded by a longer pause were more likely to be correctly recalled.

Along with other experiments examining the relationship between time and order in short-term memory (e.g., Elvevåg et al., 2004; Farrell & McLaughlin, in press; Lewandowsky et al., in press; Saito, 2001), these data are both suggestive and constraining with respect to models of short-term memory of order and temporal structure of sequences of information. The specific implications of each of the findings is considered in turn.

Grouping effects on recall timing

The common effects of instructed grouping on recall and timing in the postcued task (Experiments 1 and 2) are consistent with the notion that a common timing signal supports positional representations in serial recall. A peak in latencies at group boundaries has been previously demonstrated in serial recall using temporal and spatial grouping (Anderson & Matessa, 1997; Farrell & Lewandowsky, 2004; Maybery et al., 2002; Parmentier, Andrés, et al., 2006); the results here using instructed grouping, along with the lack of effect of the length of the pause in temporal grouping (Maybery et al., 2002), suggest that this effect follows from organizational strategies employed by participants. The novel finding from the experiments was the occurrence of a latency peak at the boundary between groups in the timing task. This latency peak is surprising in that it is contrary to task demands. Leaving a pause between groups disrupts the dynamics and may make the recall of the duration coinciding with the group boundary less accurate. This is one explanation for the failure to observe a latency peak on the timing task in the precued experiment (Experiment 3), where participants apparently chose not to use a grouping strategy despite being instructed to do so. Although others have noted a tendency for participants to segment longer sequences of intervals into subgroups in timing recall, this is assumed to occur on the basis of intervals themselves (Ross & Houtsma, 1994); for the short sequences here, where the suggested grouping structure would not always be consistent with the grouping structure suggested by the intervals, the 3-3 grouping would not have been a useful strategy.[7]

The suggestion of a common underlying timing signal that is affected by grouping is consistent with neuroscientific evidence on the mechanisms underlying grouping effects. In an fMRI experiment exploring the neural underpinnings of verbal short-term memory, Henson et al. (2000) observed that activity in left dorsolateral premotor cortex increased when placing an additional requirement on participants to remember order information. Henson et al. (2000) also observed that introducing a grouping structure decreased activation in this region and medial thalamus, whilst increasing activation in right inferior frontal gyrus (IFG). Henson et al. suggested that the change in activity in premotor cortex reflected the modulation by temporal grouping of the timing signal assumed in the models of Burgess and Hitch (1999) and Brown et al. (2000). In further support of this, Henson (2005) pointed to evidence of premotor cortex involvement in timing tasks such as enacting repetitive finger movements (e.g., Catalan, Honda, Weeks, Cohen, & Hallett, 1998). The increase in activity in the right IFG observed by Henson et al. (2000) in grouped lists is interesting in the light of carefully controlled fMRI work by Livesey, Wall, and Smith (2007), who identified the right IFG (specifically, its confluence with the anterior insula) as one of only three brain regions specifically involved in timing behaviour beyond more general processes. The results of Livesey et al. (2007) suggest that the premotor activity witnessed by Henson et al. reflects operation of more general working memory processes; one interpretation is that this activity reflects the operation of a timing mechanism subserved and driven by working memory, as suggested in the work of Fortin and others (Field & Groeger, 2004; Fortin & Breton, 1995; Fortin & Massé, 1999; Fortin & Rousseau, 1987; L. A. Jones & Wearden, 2004; Neath & Fortin, 2005; Wearden & Ferrara, 1993). Indeed, in the framework of the SIMPLE model this could be seen as a shift from the use of ordinal information (subserved by dorsolateral premotor cortex) in serial recall of ungrouped lists to using both ordinal (within-group) and temporal (within-list, supported by right IFG) information in grouped lists.

Despite this consistency with timing signal hypothesis, this account does not explain where the pause between groups comes from in the first place, especially in the experiments here where the grouping was only instructed and no temporal separation of the groups was explicitly indicated. Although Maybery et al. (2002) convincingly demonstrated that directly encoding the pause between groups using the timing signal could not account for the pause in participants' output, one possibility is that grouping (whether instructed or not) leads participants to implicitly insert a fixed pause along their internal representation of time regardless of the actual time separating groups (e.g., a list presented as 3.4..7..2.1..5 is internally represented as 3.4..7.....2.1..5 when a 3-3 grouping structure is suggested). An alternative explanation is that the common effects in the order and timing tasks do not point to the dynamics of a common timing signal but instead reflect the dynamics of retrieval, with the time between groups reflecting the time taken to retrieve a representation of the next group (Anderson & Matessa, 1997; Henson et al., 2003; Maybery et al., 2002). In other words, the same representations and processes may drive ordered sequence recall for both information about digits and information about their durations without the necessary involvement of a timing signal. We return to this possibility shortly.

Reflection of input timing in output timing

The finding that participants' output timing reflected the timing of presented sequences is consistent with previous demonstrations that information about the temporal structure of sequences (i.e., rhythm) is a type of information readily processed and retained in short-term memory (Collier & Logan, 2000; Farrell & McLaughlin, in press; Glenberg & Jona, 1991; Glenberg et al., 1989; Ross & Houtsma, 1994; Watkins et al., 1992). A more surprising observation was that input times were also reflected in output times in the order task; the only clear exception to this finding was a lack of relationship observed in the grouping condition in the precued task of Experiment 3. There are two possible explanations for this general relationship between the timing of list items and their output. This relationship is what would be expected from the real-time ticking forward of the timing signal assumed in models such as OSCAR and some interpretations of the Burgess and Hitch model (see, e.g., Ng & Maybery, 2002a, 2005). Under this assumption, the isolated lack of effect for grouped lists in Experiment 3 and other experiments (Maybery et al., 2002; Ng & Maybery, 2002b) might be explained by participants paying more attention to an ordinal position-in-group dimension in grouped lists, a strategy not allowed in Experiments 1 and 2 given the requirement to remember the timing of items. However, the relationship between the input and output timing was weak for the serial recall lists (several of the observed relationships were only marginally significant), suggesting that this timing was not driving recall in the order task, particularly given the overall high accuracy of ordered recall. Additionally, the use of a real-time signal also predicts a temporal isolation effect, which was not universally observed in the experiments (as discussed below).

An alternative explanation is that recall is not necessarily time-based, but that individuals nonetheless have immediate and compulsory access to the temporal information stored as part of the information of items. In such a framework it would be the durations of, or intervals between, items that would be the content of memory, and not the time of occurrence of items. The treatment of intervals as being the unit of information in remembering the temporal arrangement of sequences is consistent with the treatment of timing memory elsewhere (e.g., Glenberg et al., 1989; Glenberg & Jona, 1991; Sorkin, 1990). This would also explain the non-flat serial position functions in the timing task in the ungrouped condition in the timing task (Figure 5). These latency serial position functions from the serial recall task are usually considered to be measures of the time taken to retrieve, and initiate report of, successive items (Anderson & Matessa, 1997; Farrell & Lewandowsky, 2002, 2004; Maybery et al., 2002). The similar inverse U-shaped latency functions for the order task (Figure 4) and the timing task (Figure 5), though flatter in Experiment 3, suggests the same process of retrieving and reporting item information was used in both tasks. Finally, the assumption that durations form part of the content of memory is also suggested by the patterns of transpositions observed in the timing task in some of the conditions considered here (see Figure 6). For both grouping conditions in Experiment 3, and the ungrouped condition of Experiment 2, it was found that the transposition gradients were fit significantly (or marginally significantly) better by a model (the perturbation model; Estes, 1972) in which intervals presented closer together in the list would be more likely to be confused than those further apart in the list. Such a locality constraint on transpositions is a benchmark of serial recall performance and is taken to directly reflect the operation of the mechanism responsible for ordering in serial recall (Brown et al., 2000; Farrell & Lewandowsky, 2002; Page & Norris, 1998). The transposition data reported here must stand as suggestive, as the locality constraint did not apply to all conditions, and was only weakly observed in the conditions when the pattern of transpositions deviated significantly from chance. These weak effects are unsurprising given the implied high confusability of temporal durations implied by the p_{it} estimates in the modelling; future research might consider minimising these confusions by using a recognition task (cf. Farrell & McLaughlin, in press) and thus limiting the contribution of reproduction errors to the timing output.

Why is information about the temporal nature of items accessed and incorporated into the dynamics of serial recall of those items? Several possibilities immediately present themselves. One possibility is that durational information is useful information for distinguishing between items additional to other aspects of their identity. A common assumption in models of serial recall, and memory generally, is that the more detailed the available information about an event, the higher probability of recovery of any missing information (all other things being equal; e.g., Brown & Hulme, 1995; Lewandowsky & Farrell, 2000; Nairne, 1990). It may be then that by attempting to reinstate the timing of items, the participants in these experiments, particularly Experiment 3, are supplying temporal information as additional cues to the identities of items. The stronger claim that different types of information (including positional and temporal information) are bound together into integral short-term memory representations may also explain these results and the common effects of grouping on order and timing recall. One question is whether this binding occurs automatically, or was witnessed in Experiments 1 and 2 due to the requirement that both order and timing information be attended to.[8] If order and timing information are stored in an integrated fashion regardless of task demands, this predicts that manipulations of either type of information should have effects on recall of the other type of information. For example, in a paradigm in which recognition memory for a sequence of order or timing information is tested with a probe sequence (e.g., Farrell & McLaughlin, in press), if integrated representations are formed we would predict that varying the temporal arrangement of items between presentation and test (independent of order) would affect recognition of order, and vice versa. If the relationship between ordering and timing is more hierarchical in nature, with ordering giving access to timing information, then we would predict that varying timing information should have no effect on order recognition, whilst varying order should affect the recognition memory for timing information.

A second, alternative possibility is that the incorporation of timing information into the dynamics of serial recall reflects the deployment of an integrated "action plan". D. M. Jones, Macken, and Nicholls (2004) and Macken and Jones (2003) have argued that what appears to be a specialised system for short-term memory of phonological information is actually the co-opting of perceptual and motor processes to perform sequence production. From this perspective, many phenomena associated with short-term memory, such as the effects of phonological similarity, modality, and irrelevant speech, are all attributed to perception and motor planning. Recently, Tubau, Hommel, and López-Moliner (2007) have suggested that action plans formed in sequential learning tasks involve the integration of order information and relative timing; this follows from Tubau et al.'s observation that the performance of participants who appeared to be explicity learning action plans was adversely affected by disrupting the timing of the response sequence. The input-output timing coupling witnessed in the experiments here may reflect the partial integration of order and timing information in such action plans [9] . In any case, the significant coupling of input and output timing in the order task, along with the transposition gradients of temporal confusions, suggests a role for the information about individual durations.

Temporal isolation effects

A final finding of interest was a temporal isolation effect in Experiment 3. That a temporal isolation effect was observed at all is surprising, given repeated failures to find such an effect in the serial recall task (Lewandowsky & Brown, 2005; Nimmo & Lewandowsky, 2005, 2006; Parmentier, King, & Dennis, 2006). One possible explanation, in line with previous findings of apparent temporal isolation effects (Lewandowsky & Brown, 2005) might be that participants in Experiment 3 took advantage of the durations between items for additional rehearsal of the preceding item. However, this would not explain the enhanced performance for items preceded by longer durations, particularly in the grouped condition. Another explanation for the difference between these results and previous failures to observe temporal isolation effects might be that the context of the experiment, in which participants were sometimes required to attend to the timing of items, led participants to attend more to the timing of items than in previous experiments. This is an unlikely explanation as Experiment 2, in which attention to time was explicitly required, did not produce any evidence of a temporal isolation effect. Similarly, Farrell and McLaughlin (in press) failed to observe a temporal isolation effect in a recognition experiment in which the type of information on which the recognition decision was to be made, ordinal or temporal, was postcued. Indeed, the finding that a temporal isolation effect was not observed when requiring participants to attend to time, and was observed when attention to time was not required, reinforces the conclusion that there are several types of temporal information that might be drawn on in the various short-term memory tasks.

A plausible explanation for the difference in results between Experiments 2 and 3 is a trade-off between the dimensions of time (or position) in the list, and durations of items, such that in Experiment 3 participants were paying more attention to the ordinal or temporal placement of items, and less to duration or interval information relating to individual items. This would leave unexplained the reason for participants weighting the time-in-list dimension where others have failed to observe a temporal isolation effect. Lewandowsky et al. (in press) have argued that temporal isolation effects are observed when the order of recall of information in unconstrained, whether that information is about the identity of items or their placement in a sequence. The observation of a temporal isolation effect here in the serial recall task, in which output order is necessarily forward, questions the completeness of this account and suggests other factors might be at play in such tasks. A hint about one such factor is the observation that a temporal isolation effect in Experiment 3 was observed more strongly in grouped lists (see Table 3). One explanation for this grouping effect is that, in grouped lists, participants make use of two dimensions, a temporal dimension and a positional in-group dimension. Thus, grouping lists forces participants to rely on a time-based representation of position in the list, giving rise to a clear temporal isolation effect[10]; as suggested above, this may relate to shifting of reliance on a lateral premotor cortical timing mechanism to involvement of an additional timing mechanism associated with right IFG (cf. Henson et al., 2003).

Conclusions

Overall, the results call into question the notion of a single timing signal driving serial recall, and point to a variety of temporal representations at play in working memory (cf. Glenberg & Jona, 1991). Such a conclusion is not inconsistent with models such as those of Brown et al. (2000), Brown et al. (2007) and Burgess and Hitch (1999), which assume a hierarchical temporal signal drives ordered recall (see also Henson et al., 2003). However, the results here, along with others, suggest that ordinal information may be used to perform sequence ordering, and that participants may freely switch between the use of different types of information about the timing of a sequence (Brown et al., 2007, 2006; Lewandowsky et al., in press). In particular, the results suggest that time is represented both at the level of the entire sequence and at the level of individual durations (cf. Glenberg et al., 1989), and that this information may be incorporated into the dynamics of recall. The challenge for current models of short-term memory is to recognise such flexibility whilst specifying in detail the mechanisms and representations supporting such performance (cf., Lewandowsky et al., in press); in particular, the data here emphasise the importance of considering output times as constraining data on models of serial recall (see also Farrell & Lewandowsky, 2004).

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Footnotes

[1]One other model to which the label “time-based” has been applied is the phonological loop model of Burgess and Hitch (1999), a connectionist version of the phonological loop model of Baddeley (1986). In this model it is assumed that each stimulus in a sequence is associated with the state of activation across a set of nodes representing temporal context; as time passes, a window of activation slides across the context nodes. Given Burgess and Hitch (1999) have identified the timing signal as being the output of temporal oscillators as in the OSCAR models, some authors have justifiably identified this model as being time-based (e.g., Lewandowsky & Brown, 2005; Lewandowsky et al., 2006). However, in a recent paper Burgess and Hitch (2006) state that the “timing” signal was never intended to be taken as time-based, and that the intended assumption is that the “ticking over” of the timing signal is driven by events rather than time. We take the Burgess and Hitch (2006) interpretation of the model, but note the implications of the results reported here for a time-based interpretation of the model where appropriate.

[2]In cases where Mauchly’s test of sphericity was significant, ANOVA results are reported with the Greenhouse-Geisser correction applied

[3]I am indebted to Murray Maybery for pointing out this possibility

[4]The same model was also fit to the data including the removed responses and durations. A similar pattern was obtained for both Experiments 2 and 3, with the exception that the effect of “post” duration was significant for ungrouped lists in Experiment 3.

[5]Although in general running an experiment until significance is achieved will lead to problems in inference in the standard null hypothesis testing approach, in this case we are interested in the results on the order task conditionalised on the assumption of a grouping effect for the order task. If this assumption is not met, then an observation of (or failure

to observe) a grouping effect in the timing task is not diagnostic regarding the relation between the two tasks.

[6]Order of blocks was fully counterbalanced for all participants except participant 57, who received the same block order as participant 1

[7]One possible criticism, raised by a reviewer, is that the effect of grouping on the timing task demonstrates that participants are no longer performing this task accurately under grouping instructions. However, Table 2 reveals that grouping instructions did not grossly disrupt performance on the timing task, with similar regression estimates for the ungrouped and grouped conditions, with only slightly poorer performance in the grouped condition generally.

[8]I thank Fabrice Parmentier for raising this issue.

[9]Neither of these possibilities accounts for the failure to observe coupling of input-output times in the experiments of Ng and Maybery (2002b) and Maybery et al. (2002) and the grouped condition of Experiment 3 here, all of which involved presentation of grouped lists. One speculative explanation, again in the framework of the SIMPLE model (Brown et al., 2007), would be that weighting both a temporal within-list dimension and an ordinal within-group dimension would result in minimal weighting being given to duration information, except in cases where that information will later be required for recall (Experiments 1 and 2). This explanation is more speculative, however, as SIMPLE does not currently account for the dynamics of recall (Farrell & Lewandowsky, 2004).

[10]A planned experiment in our lab will test this suggestion by replicating the serial recall trials of Experiment 3 in conditions where recall of temporal information is never required.

Table 1

Mean deviations (in ms) between output times observed at the fourth output postion (the group boundary) and those predicted from a second-order polynomial fit to all other output times excluding the first. Standard deviations (in ms) are also given.

	Ungrouped		Grouped	
	Mean	SD	Mean	SD
Experiment 1				
Order	27.58	129.96	159.79	129.60
Timing	35.87	129.61	148.55	145.13
Experiment 2				
Order	-24.29	189.71	202.29	232.54
Timing	-27.54	154.97	77.50	235.72
Experiment 3				
Order	80.76	117.64	164.21	170.27
Timing	35.02	167.20	5.02	191.71

Table 2

Maximum likelihood slope parameter estimates and significance tests from the mixed-effects linear regression model predicting output timing from input timing

		All responses				Excluding longest response			
		β	SE	t	p	β	SE	t	p
					Experiment 1				
Order task									
	Ungrouped	0.07	0.015	5.12	0.00	0.03	0.010	2.73	0.01
	Grouped	0.03	0.011	2.58	0.01	0.02	0.007	2.75	0.01
Timing Task									
	Ungrouped	0.31	0.025	12.23	0.00	0.23	0.017	13.37	0.00
	Grouped	0.27	0.027	10.19	0.00	0.18	0.019	9.32	0.00
					Experiment 2				
Order task									
	Ungrouped	0.09	0.03	2.93	0.01	0.03	0.015	2.04	0.04
	Grouped	0.04	0.032	1.13	0.26	0.03	0.016	1.85	0.06
Timing Task									
	Ungrouped	0.41	0.032	12.86	0.00	0.29	0.027	10.68	0.00
	Grouped	0.32	0.033	10.02	0.00	0.22	0.024	8.92	0.00
					Experiment 3				
Order task									
	Ungrouped	0.06	0.018	3.39	0.00	0.02	0.007	2.56	0.00
	Grouped	0.01	0.015	0.34	0.74	-0.00	0.007	-0.24	0.80
Timing Task									
	Ungrouped	0.58	0.029	20.19	0.00	0.41	0.024	16.66	0.00
	Grouped	0.46	0.029	16.46	0.00	0.32	0.023	13.45	0.00

Table 3

Maximum likelihood slope parameter estimates and significance tests from the mixed-effects logistic regression model predicting ordered recall accuracy in Experiments 2 and 3 from temporal isolation (preceding, "pre", and following, "post", pause durations)

		β	SE	z	p
		Experiment 2			
Ungrouped					
	Pre	0.062	0.11	0.58	0.56
	Post	-0.004	0.11	-0.04	0.97
Grouped					
	Pre	0.13	0.11	1.19	0.24
	Post	0.13	0.11	1.18	0.24
		Experiment 3			
Ungrouped					
	Pre	0.29	0.16	1.74	0.08
	Post	0.25	0.17	1.48	0.14
Grouped					
	Pre	0.60	0.17	3.47	<.01
	Post	0.118	0.16	0.72	0.47

Figure Captions

Figure 1. A schematic depiction of the post-cueing trial structure for Experiments 1 and 2. See text for a description.

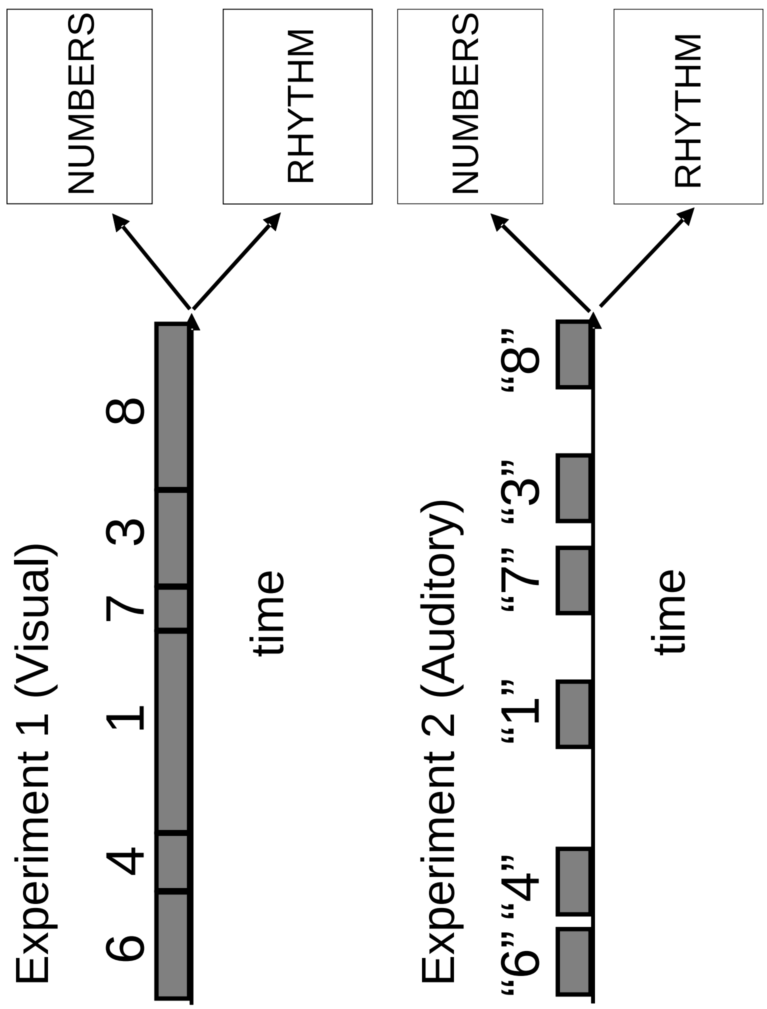
Figure 2. Histograms of the ISIs across all participants and conditions for Experiment 1 (left panel) and Experiment 2 (right panel).

Figure 3. Mean proportion correct ordered recall on the order task for ungrouped and grouped lists, plotted by serial position for the three experiments.

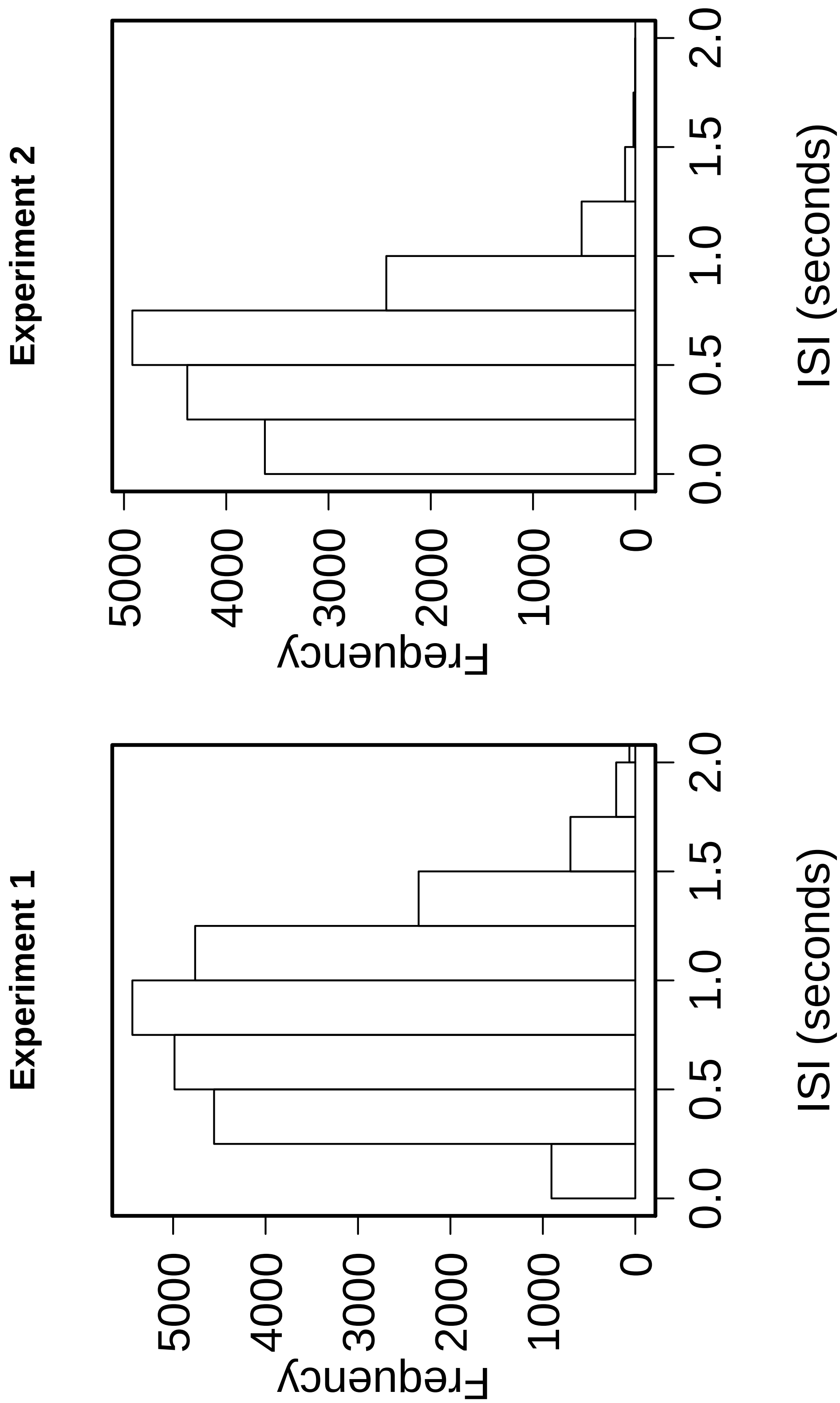
Figure 4. Mean output times on the order task for ungrouped and grouped lists, plotted by serial position for the three experiments.

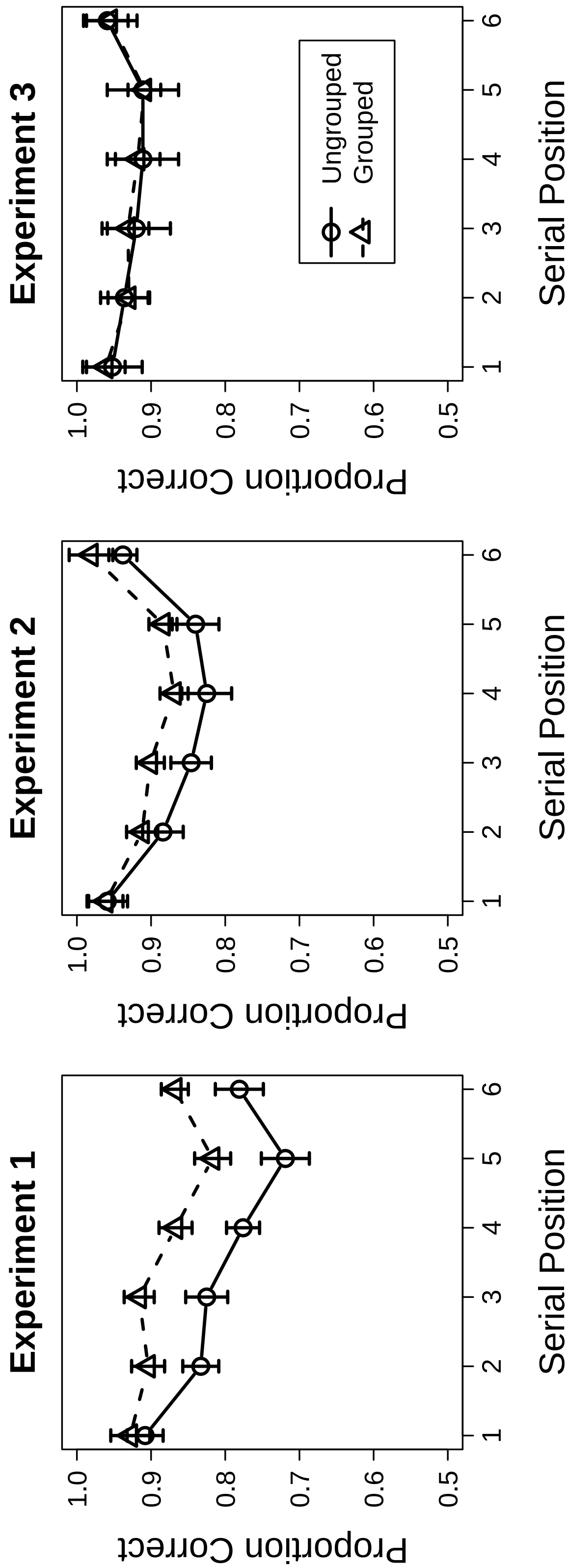
Figure 5. Mean output times on the timing task for ungrouped and grouped lists, plotted by serial position for the three experiments.

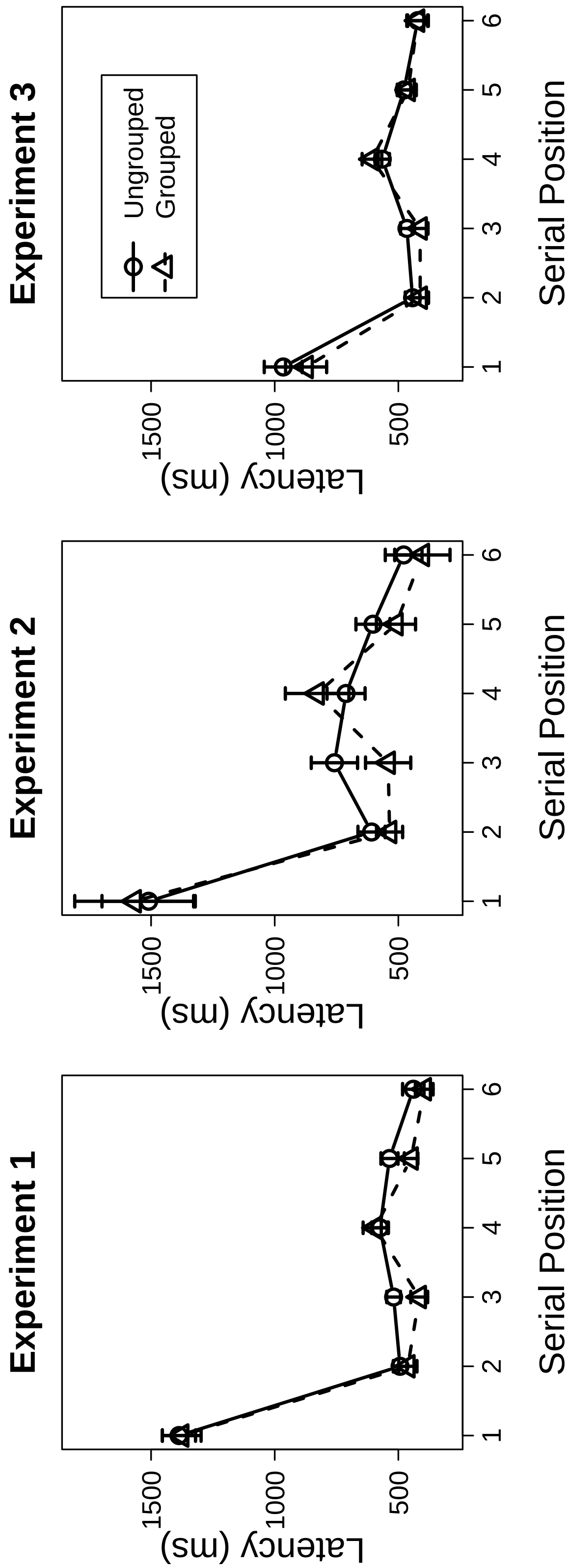
Figure 6. Difference between the frequency of transposition errors predicted by the "random" model and those observed in the data (triangles) and in the predictions of the perturbation model (circles) for the timing task. The transpositions are grouped into "local" transpositions (transposition distance = 1) and "remote" transpositions (transposition distance > 1). The rows respectively correspond to Experiments 1, 2, and 3, while the left and right columns show data from the ungrouped and grouped conditions, respectively. See text for details of the modelling.

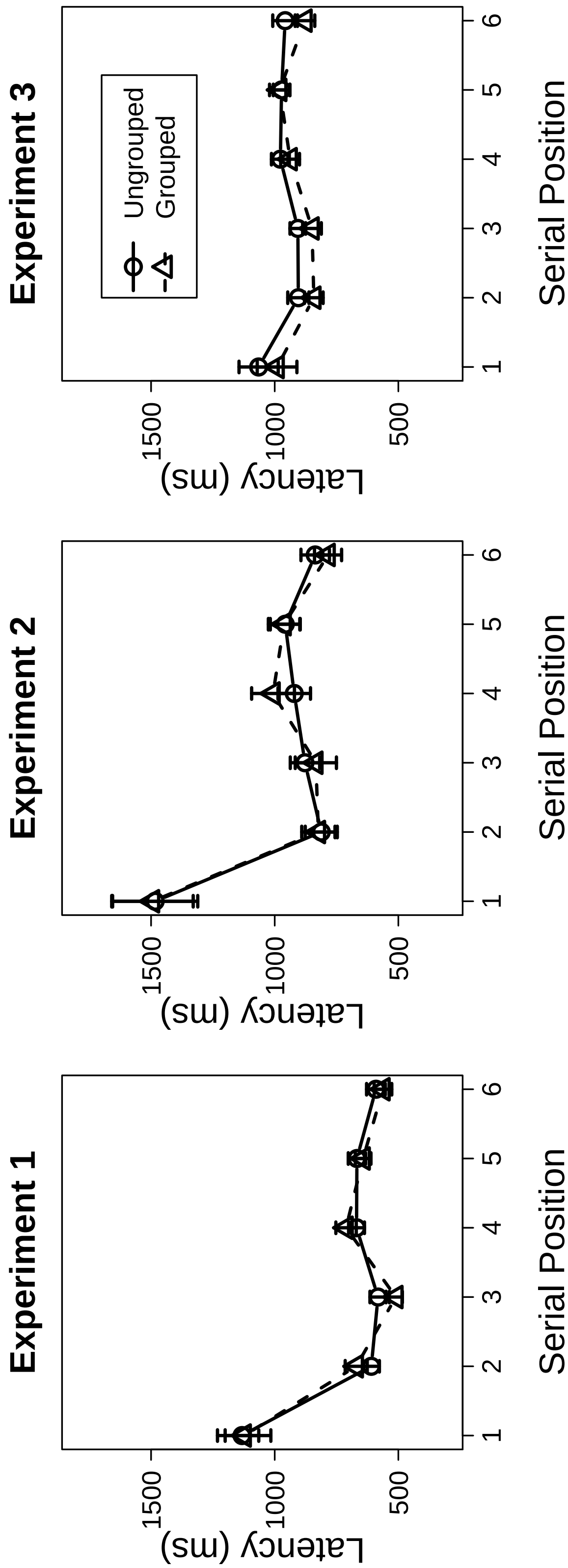


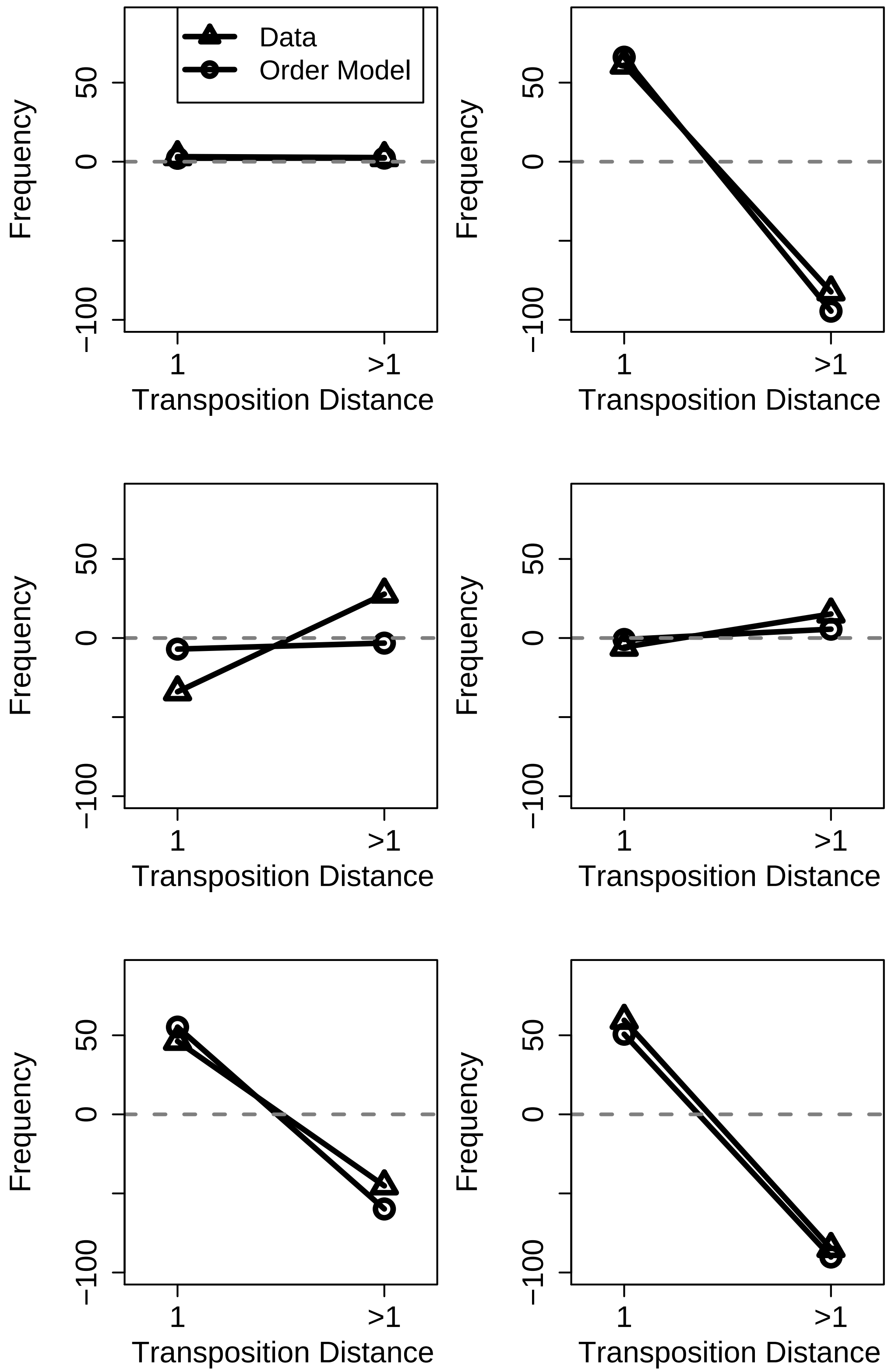
Experiment 1 (Visual)
6 4 1 7 3 8
time
NUMBERS
RHYTHM
Experiment 2 (Auditory)
“6” “4” “1” “7” “3” “8”
time
NUMBERS
RHYTHM


Experiment 1
Experiment 2
Frequency
0
1000
2000
3000
4000
5000
ISI (seconds)
0.0
0.5
1.0
1.5
2.0


Experiment 1
Experiment 2
Experiment 3
Proportion Correct
1.0
0.9
0.8
0.7
0.6
0.5
Serial Position
1
2
3
4
5
6
Ungrouped
Grouped


Experiment 1
Experiment 2
Experiment 3
Latency (ms)
1500
1000
500
Serial Position
1
2
3
4
5
6
Ungrouped
Grouped


Experiment 1
Experiment 2
Experiment 3
Latency (ms)
Serial Position
Ungrouped
Grouped
1500
1000
500
1
2
3
4
5
6



Data
Order Model
Frequency
50
0
−100
1
>1
Transposition Distance