Evaluating models of verbal serial short-term memory using temporal grouping phenomena

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Abstract

Various capabilities such as the ability to read or conduct a conversation rely on our ability to maintain and recall information in the correct order. Research spanning more than a century has been devoted to understanding how units of information are retained in order in short-term memory.

The nature of the mechanisms that code the positions of items in serial short-term verbal recall can be investigated by examining a set of phenomena that can be termed temporal grouping effects. Inserting extended pauses to break a list of verbal items into sub-lists (e.g. SHD-QNR-BJF, where the dashes represents the pauses) improves the accuracy of serial recall relative to performance observed without this temporal grouping. In addition, two other effects are linked to temporal grouping. One of these effects is a shift in the shape of the serial position function, which changes from a single bowed function to a multiple-bowed function. That is, the serial position curve for ungrouped sequences is typically characterized by better performance for the beginning and ending items compared to the mid-list items. For grouped lists, the multiple-bowed function comprises better recall for the beginning and ending items within each group. Another effect associated with temporal grouping is a change in the patterns of order errors. For ungrouped sequences (e.g. SHDQNRBJF), order errors often involve the swapping of items in neighbouring positions, such as exchanging D for Q or R for B. By contrast, grouped sequences (such as SHD-QNR-BJF) show a reduction in order errors that cross group boundaries such as exchanging items D and Q or R and B; instead, there tend to be an increased incidence of exchanging items that share similar within-group positions such as swapping H and N or Q and B.

According to several current models of short-term memory, items are retained by associating them with extra-list information such as contextual information. However, these models disagree on the nature of this contextual information. A critical division splits these models into two categories: those that rely on temporal oscillators and those that do not. Among the models relying on temporal oscillators, there is a further division as to whether serial position is coded with reference to absolute or relative time. This thesis examined whether serial recall relies on temporal information to code the positions of items in verbal sequences, and a subsidiary issue addressed was whether any reliance on temporal information is dependent on absolute time or relative time. A series of experiments was conducted to investigate these issues by varying the timing of the presentation of items both within and between groups in temporally structured lists.

The first experiment in the series (unpublished, but presented in Chapter 1) was pragmatic in its major aim, which was to compare the effects of temporal grouping in the Singaporean and Australian populations. Since the intention was to draw participants from the two populations in subsequent experiments, it was necessary to investigate whether temporal-grouping effects vary qualitatively between the two populations. Undergraduate students of the two nationalities were asked to recall, in order, grouped and ungrouped sequences of visually presented consonants. Grouping was imposed using an extended pause between items 3 and 4 and items 6 and 7 in presenting the 9-item sequences. The data showed elevated accuracy for grouped compared to ungrouped lists, and a scalloped serial position function for grouped lists. In addition, for grouped lists, order errors showed high rates of transpositions of items across groups but so that the items retained their within-group serial positions, whereas for ungrouped lists, errors favoured items migrating to adjacent positions in the sequence. Protrusion errors—items from the previous trial recalled for the current trial—also showed evidence of the

influence of grouping. Importantly, each of these temporal grouping effects was exhibited for each sample of students, consistent with there being no qualitative population-based differences in these phenomena.

The first major series of experiments (published in the *Quarterly Journal of Experimental Psychology* and reproduced in Chapter 2) examined whether the coding of serial position is dependent on absolute time. The critical manipulation was to vary the item-to-item stimulus-onset asynchrony (SOA) from one group to the next in the same list. In three experiments, lists of consonants (6 to 9) were presented (1) visually, but with vocalization, (2) auditorily, or (3) auditorily with articulatory suppression, for serial recall by undergraduate participants. The main focus was to examine order and protrusion errors to evaluate the contrasting predictions of models that depend on absolute time and models that do not. Across the three experiments, the pattern of order errors consistently favoured the predictions of the models that do not code position with reference to absolute time, in that across-group transposition errors reflected within-group serial position rather than time from group onset. Errors involving intrusions from previous lists (protrusions) also demonstrated high rates of intrusion of items sharing similar within-group serial position, thereby extending support for models that are not based on absolute time.

The previous series of experiments presented evidence inconsistent with oscillator-based models that code serial position with reference to absolute time. However, the results of these experiments can be accommodated by oscillator models that code serial position with reference to relative time, as well as by context models that do not incorporate oscillators. Therefore, two additional experiments were conducted to evaluate these two classes of model. The first of these experiments (published in full in the conference proceedings of the *Sixth Conference of the Australasian Cognitive Science*

Society, and reproduced in Chapter 3) investigated whether the timing of list presentation would be preserved in the timing of recall. The critical manipulation was to vary the within-group and between-group intervals separating consonants in six-item lists formed into two groups of three items. There was no change in the inter-response latencies across these variations in the timing of presentation, thus providing support for models that do not incorporate oscillators and are time-independent.

The next experiment (published in the *Journal of Experimental Psychology: Learning, memory and Cognition,* reproduced in Chapter 4) examined error patterns in evaluating the contrasting predictions of, on the one hand, all classes of existing oscillator-based models (i.e. those that code absolute time and those that code relative time), and, on the other hand, context models that do not incorporate oscillators. This was done by unconfounding temporal position (time from group onset) and ordinal position (number of items from group onset) for certain key items in sequences comprising two groups of four consonants. The critical manipulation was to vary the SOAs within and across the two groups. Errors that involve items migrating across groups should preserve within-group temporal position according to oscillator models, but should preserve within-group ordinal position according to non-oscillator models. Results from the inter-group errors strongly favored preservation of ordinal rather than temporal position.

Finally, the Appendix reports an unpublished experiment that examined patterns of errors in recalling sequences of nine visually presented letters, where the letters were grouped into threes using temporal gaps. A critical manipulation was the insertion of a to-be-ignored item (an asterisk) between the first and second letters of selected groups. Inclusion of this item failed to alter the patterns of errors observed, indicating that the coding of serial position is based on only those events represented for recall.

The central conclusion based on all the studies is that serial order for verbal items is retained using contextual positional codes that change with each presentation of a to-be-remembered item, are influenced by large temporal gaps that lead to grouping, but otherwise are not dependent on the timing of events.

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See the listing of components of the thesis, and signatures, in the following Preface section.

Signature 13/7/07

Preface

This thesis describes a series of studies conducted to examine whether the order of information represented in verbal short-term memory is coded with reference to the timing of presentation of the to-be-remembered information. The research is presented as a collection of five papers. Three of the papers have been subjected to peer-review and published, two in journals and the other in conference proceedings. The papers comprising the thesis are as follows:

Chapter 1 presents an unpublished study that compared critical effects in short-term memory for samples of participants drawn from the Singaporean and Australian populations.

Chapter 2 presents the published manuscript Ng L. H. H. & Maybery, M.T. (2002). Grouping in short-term verbal memory: Is position coded temporally? Quarterly Journal of Experimental Psychology, 55A, 391-424. Three experiments are reported in this paper.

Chapter 3 contains the manuscript Ng L. H. H. & Maybery M.T. (2002). Grouping in verbal short-term memory: Does latency of recall bear any resemblance to presentation rate? Refereed Proceedings of the Sixth Conference of the Australian Cognitive Science Society, Fremantle, Australia, April. A single experiment is reported in this paper.

Chapter 4 comprises the published manuscript Ng L. H. H. & Maybery M.T. (2005). Grouping in verbal short-term memory: Do oscillators code the positions of items? Journal of Experimental Psychology: Learning, Memory & Cognition, 31(1), 175-181. This paper also reports a single experiment.

The **Appendix** reports an unpublished experiment addressed to an issue somewhat tangential to the rest of the thesis: whether the occurrence of an irrelevant item alters the coding of the positions of items in a sequence.

Contribution of the candidate to publications

The design of studies, development of tasks, recruitment and testing of participants, data entry and analysis, and preparation and revision of manuscripts was conducted by the candidate, Ms Ng, with advice provided by her supervisor, Dr Murray Maybery. We estimate that the weighting of contributions to the publications arising from this thesis would be approximately 80% for Ms Ng and 20% for Dr Maybery.

Signed:

13/7/07

Honey Ng Li Huang (Candidate) Date

Murray Maybery (Supervisor) Date

Acknowledgements

The genesis of this thesis began as a first year student attending a lecture on memory. In response to my query, the lecturer on that day inspired me to probe and develop the idea further. It was that day that the seed of inquisition was planted; it then grew with confidence through my years as a student at UWA and thereafter.

It was of no coincidence that the lecturer that inspired me that day eventually became my supervisor for this thesis. I would like to thank Murray Maybery, my supervisor for his confidence, support, gentle reminders and invaluable advice. His patient tolerance of all my shortcomings is beyond my understanding. I am indebted to him for his generosity and kindness. Without his input, this piece of work would remain in pieces.

As an external student, I sorely missed being on the campus. But the efforts of many have helped me through the years. I would like to thank the staff in the School of Psychology, University of Western Australia, for all their assistance, whether in programming, setting up an email account or countless issues that I presented to them over the years while completing my PhD. In addition, my gratitude goes out to the numerous students who sat through my experiments both at UWA and the National Institute of Education, Singapore.

In my journey during the preparation of this thesis, I have also relied extensively on my family for both emotional and physical support. I would like to thank Lyndon for his patience and to my girls, for the joy of their endless questions, smiles and tears. They have made this journey extra special.

Chapter 1

A demonstration of central temporal grouping phenomena in two populations

A demonstration of central temporal grouping phenomena in two populations

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Running head: Temporal grouping phenomena in two populations

Abstract

The main aim of this experiment was to establish that effects of temporal grouping are found in both the Singaporean and Australian populations, and that these effects do not vary qualitatively between the two populations. Undergraduate students of the two nationalities were given grouped and ungrouped sequences of consonants for immediate serial recall using visual presentation. Grouping was imposed using an extended interval between items 3 and 4 and items 6 and 7 in presenting the 9-item sequences. The data were analyzed for correct recall at each serial position and showed elevated accuracy for grouped compared to ungrouped lists. There was also evidence of a scalloped serial position function for grouped lists. In addition, for grouped lists, order errors showed high rates of transpositions of items across groups but so that the items retained their within-group serial positions, whereas for ungrouped lists, inter-group errors favoured items migrating to adjacent positions in the sequence. Protrusion errors—items from the previous trial recalled for the current trial—were also analyzed and showed evidence of the influence of grouping. Each of these temporal grouping phenomena was exhibited for both populations.

What are the central temporal grouping effects and are they consistent across different populations? This experiment compared temporal grouping phenomena for two populations, Singaporeans and Australians. Temporal grouping effects are frequently found when extended pauses break up a list into smaller chunks of items (see Ryan, 1969a, 1969b). These effects are an increase in accuracy for grouped lists compared to ungrouped lists (Henson, 1998; Hitch, Burgess, Towse & Culpin, 1996; Ryan 1969a; 1969b), a qualitative change in the serial position function from a single U-shaped curve to a multiple U-shaped curve (Frankish, 1985; Hitch et al. 1996; Ryan 1969a, 1969b), and a qualitative change in the pattern of transposition (i.e. order) errors (Henson, 1998; Hitch et al., 1996; Ryan 1969a, 1969b). Specifically, for grouped lists (compared to corresponding errors for ungrouped lists) there is an increase in the incidence of across-group transpositions of items that share the same serial position within their groups (e.g. R taking the position of S in CRB-GSP, or vice versa). By contrast, there is a reduction in the number of transpositions of adjacent items between groups (e.g., B taking the place of G in the above example, or vice versa; see Ryan, 1969a, 1969b). Also examined are items recalled for the previous list that are also recalled (erroneously) for the current list. These protrusions from the previous list are examined to identify if they also respect within-group serial position. For example, if an item was recalled in the middle of a group on the previous trial, if it is erroneously recalled on the current trial, does it occupy the middle position of one of the recalled groups? This analysis of protrusion errors focuses on the reported items for the previous trial rather than the presented items because previous research with ungrouped lists has shown that a higher proportion of these inter-trial errors come from the previously reported rather than the previously presented list

(Henson, 1996). An analysis of possible effects of grouping in relation to protrusion errors has not been reported prior to the series of experiments reported in this thesis.

The temporal grouping effects relating to overall accuracy, shape of the serial position function and transposition (order) errors are phenomena that have been consistently observed for British participants (Frankish, 1985; Hitch et al. 1996; Ryan 1969a, 1969b). The central aim of this paper was to examine whether these effects are found in Australian and Singaporean samples. There is no reason to expect that these effects should be qualitatively different across the two populations. However, if any effect associated with grouping is substantially different for the two populations, the implications for the proposed programme of research would be substantial, since it is intended that these two populations will be used in different experiments in the research programme.

Method

Participants

Thirty undergraduate students took part in the experiment. Of the 30, 15 were volunteer trainee teachers from the National Institute of Education, Singapore, and 15 were studying first-year psychology at the University of Western Australia, Australia, and participated to fulfill a course requirement. The former were all Chinese and the latter Australian born. All participants were aged between 16 and 36 years.

Apparatus

An IBM compatible Hyundai super 386i computer and keyboard with a 36 cm monitor were used to present the stimulus sequences and record the participants' answers at the University of Western Australia. An MMX Pentium CD notebook was used at the National Institute of Education.

Stimuli

The 20 consonants, after excluding w (which comprises three syllables) were used to construct 80 lists, each of 9 letters. Each list was randomly generated and no consonant was repeated. Any obvious patterns were excluded (i.e. there were no alphabetically adjacent letters or sequences that made words, e.g. FRY).

For each participant, 46 of the 80 lists were selected at random, but without replacement. They were assigned at random to the different ungrouped and grouped trials, which are described below.

Procedure

Participants were tested individually in a small room. Each received 4 ungrouped practice trials, 10 ungrouped test trials, then 2 practice grouped trials and 20 grouped test trials, and finally a further 10 ungrouped test trials. The 46 lists were presented in one continuous block.

The procedure for each test trial was as follows. A fixation point denoted by a cross preceded each sequence by 1,500 ms. Each letter of the list was presented in Times New

Roman font, size 36, in the centre of the screen and for 250 ms. The SOAs were 500 ms for all list items with the following exceptions. For grouped lists, the SOAs between the 3rd and 4th item, and the 6th and 7th item were 1000 ms. Recall was initiated by the appearance of nine boxes across the bottom of the screen. These boxes appeared 500 ms after the onset of the last item for the ungrouped and grouped lists. These boxes occupied 200 mm by 20 mm of the screen. An asterisk marker was shown under the leftmost box. This box signified the first serial position, and when the participant typed a letter on the keyboard, that letter was printed in the box in Times New Roman font, size 36. The marker then moved to a position under the next box to the right. Thus the boxes were filled from left to right while the letters were typed. After filling all nine boxes (which was necessary to proceed), the participant pressed the down arrow key to signal the end of the response. To proceed to the next list, the participant pressed any key when ready.

Participants were instructed that sequences of letters would be presented on the screen and they would be required to recall the items in the correct order at the end of each list. The method of recording responses using the keyboard and the display of boxes was also explained. It was also emphasized that each letter had to be said aloud as it was presented. This was to ensure phonological registration of the items, and to standardize the strategy used by the participants. It took approximately 25 minutes to complete the experiment.

Analytic methods for order errors

For the calculation of order errors, direct tabulation of the different types of error is inapt, as there are more possibilities for making some types of errors rather than others. For instance, there are more possible inter-group errors that involve the same within-group serial position (such as item 1 taking the place of item 4, or vice versa, item 2 taking the place of item 5, and so on) than there are possible inter-group errors that involve adjacent items in the sequence (the four possibilities are item 3 taking the place of item 4, or vice versa, and item 6 replacing item 7, or vice versa). Therefore, a corrective method was formulated to account for differential opportunity. This consisted of calculating the ratio of the actual number of errors of a particular type divided by the number of errors expected of that type if the total errors had been distributed equally. That is, if there are n cases forming a type (e.g. there are 4 cases of the adjacent inter-group error) and Σe errors observed for that type, then using N to refer to the total number of error cases (e.g.72 for interpositions, which is derived from 9 serial positions with 8 possible errors at each position) and ΣE to refer to the total errors observed (e.g. all interposition errors), the ratio would be:

$$R = \frac{\sum e}{n \sum E / N}$$

Alternatively, the ratio is the mean error rate for a particular type (Σe/n) divided by the overall mean rate (ΣE/N). Hence, an error type occurred with above-average frequency if the ratio is greater than one. Conversely, a below average frequency is implied when the error ratio is less than one. This ensures that the error ratio is not reliant on either the total numbers of errors made (ΣE) or the opportunities available for each type of error (n).

Results

In attempting to confirm effects of temporal grouping, we first compared performance on the grouped and ungrouped lists for recall accuracy. Next, we conducted analyses of interposition errors. This was done to check for a reduction of adjacent inter-group errors and an increase in same serial position errors for grouped lists compared to ungrouped lists. In addition, we examined protrusion errors to examine if previously reported list items intruded on recall of the current list in ways that respected within-group serial position. The Appendix contains additional analyses of accuracy, which compared performance on the ungrouped lists for Phases 1 and 3. It should be noted that as no qualitative differences in the shape of the serial position curve were found between the two phases for the ungrouped lists, the data from these two phases were pooled in the analyses reported in this section. Analyses were conducted using Pearlman's (1986) Unix-Stat Data Analysis programs.

Of critical interest in all analyses is whether there are any qualitative differences for the two participant groups when performance on grouped and ungrouped lists are compared. Thus the participant's country was included as a between-subjects factor in all analyses.

Accuracy for Grouped versus ungrouped lists

Accuracy of recall was scored using a position-respecting scoring method, that is, an item was scored as recalled correctly only if it was recalled in its correct serial position. The accuracy scores are expressed as number correct per 10 trials. A 2 (country—Australia vs. Singapore) x 2 (list type—grouped vs. ungrouped) x 9 (serial position) ANOVA was conducted. The main effects of list type and serial position were significant with F (1, 28) = 82.80, MSE = 4.19, $p < .01$, and F (8, 224) = 59.32, MSE = 2.90, $p < .01$, respectively. There were also interactions between list type and serial position, and country and serial position with F (8, 224) = 6.30, MSE = 2.01, $p < .01$, and F (8, 224) = 5.12, MSE = 2.90, $p < .01$, respectively.

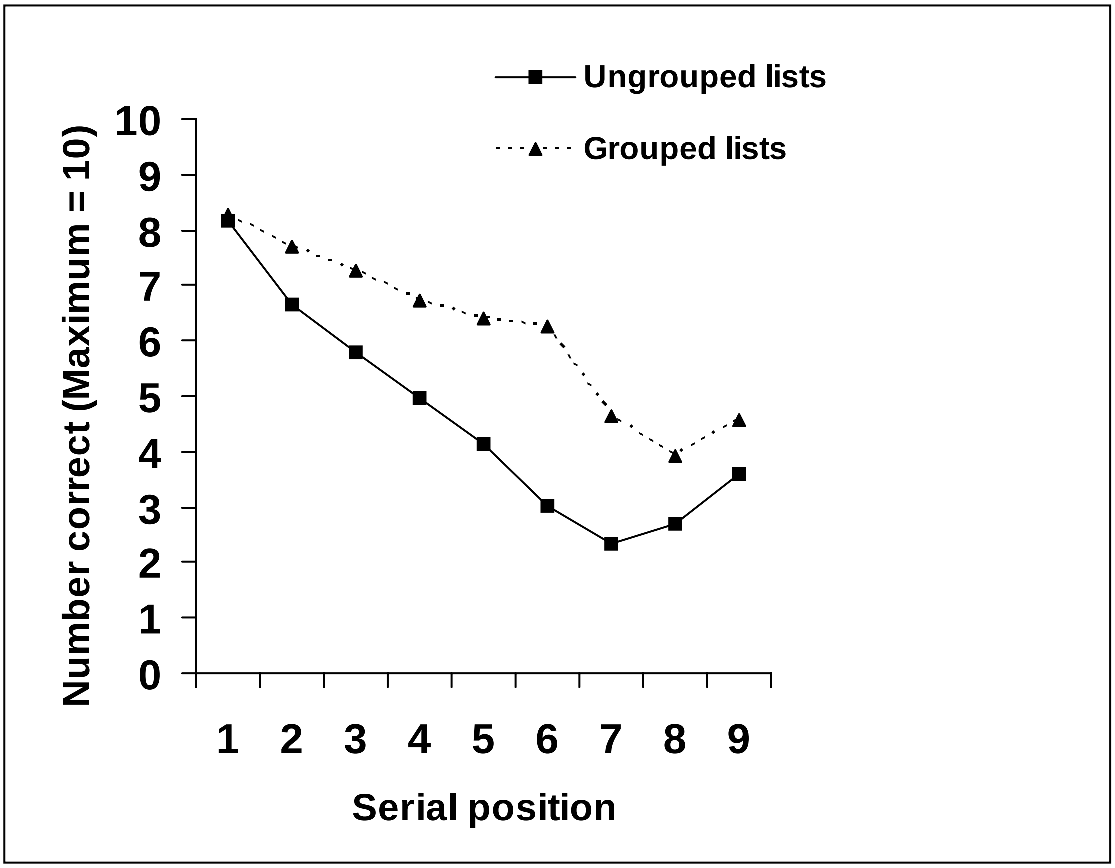

Figure 1. Mean number of correct responses at each serial position as a function of list type.

At each serial position, accuracy was higher for the grouped compared to the ungrouped lists (see Figure 1). Also, the serial position curves for the ungrouped and grouped lists both exhibit strong primacy together with weaker recency (Figure 1). However, there also appears to be some evidence of multiple bowing for the grouped lists (Figure 1; cf. Hitch et al, 1996; Ryan, 1969a, 1969b). These observations were supported when the quadratic trend over serial position was calculated (Ferguson, 1976). This trend was significant overall, F (1, 224) = 31.04, MSE = 2.01, $p < .01$, and also interacted with list type, F (1, 224) = 35.49, MSE = 2.01, $p < .01$. The quadratic trend is more pronounced for the ungrouped lists compared to the grouped lists, in part because there is more pronounced scalloping in the function for grouped lists.

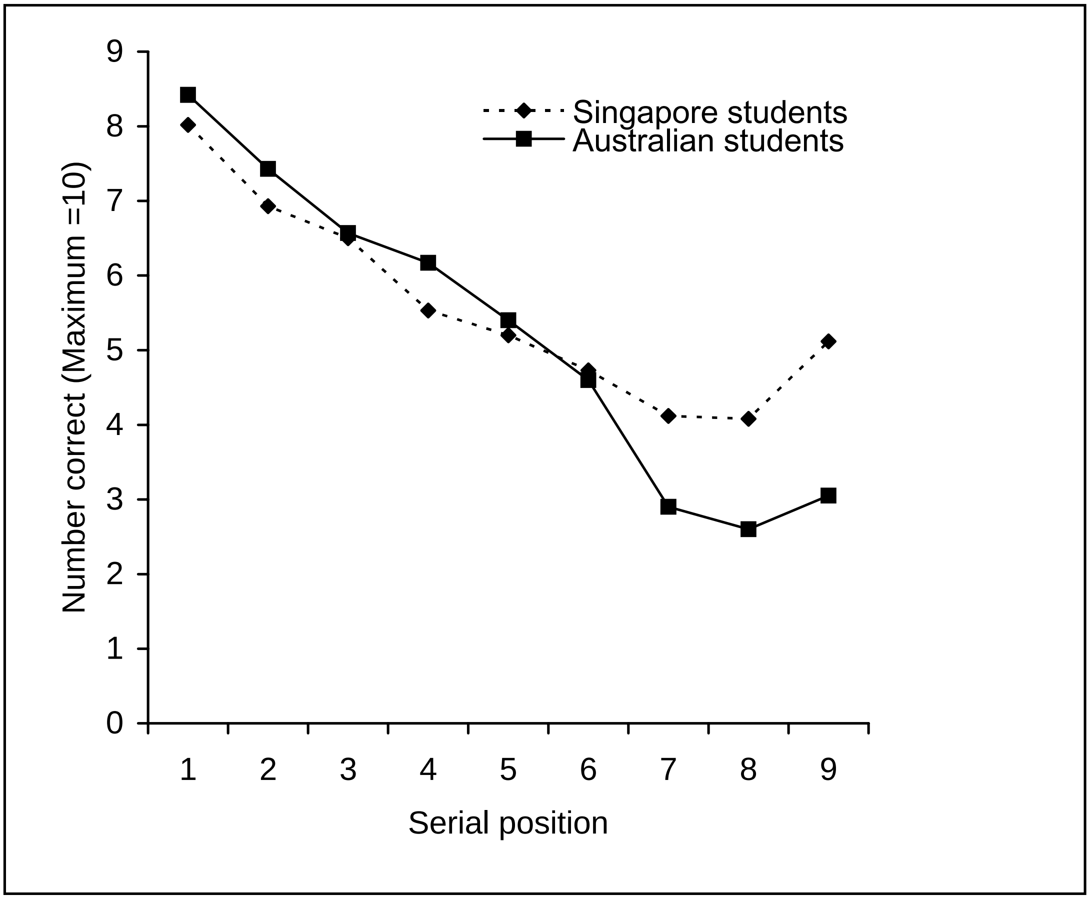

Figure 2. Mean number of correct responses at each serial position as a function of country.

The interaction between country and serial position was further explored by examining the simple effect of country for each serial position. This effect was significant for serial positions 7, 8, and 9, with t (29) values of 3.14, 3.03 and 3.36 respectively, and all with $p < .05$. Accuracy was lower at serial positions 7, 8, and 9 for Australian participants compared to Singaporean participants. In essence, the Singaporean students showed more pronounced recency than did the Australian students (see Figure 2). The higher-order interaction of country x list type x serial position was not significant, so the effect of grouping on the serial position function did not differ across country.

A separate 2 (list type—grouped vs. ungrouped) x 9 (serial position) ANOVA for each participant group was conducted. For the Australian group, the main effects of list type and serial position were significant, with F (1, 14) = 47.12, MSE = 3.70, p < .01, and F (8,112) = 48.95, MSE = 2.73, p < .01, respectively. The interaction was also significant, with F (8, 112) = 2.23, MSE =2.316, p < .05. Similarly for the Singaporean group, the main effect of list type and serial position were significant, with F (1, 14) = 36.88, MSE = 4.69, p < .01, and F (8, 112) = 17.27, MSE = 3.06, p < .01, respectively. The interaction was also significant, with F (8, 112) = 5.93, MSE = 1.66, p < .01. The effect of grouping on the serial position function appeared to be common to the two nationalities. There was no evidence that grouping has a qualitatively different effect for Singapore students compared to Australian students.

This section has shown that two effects associated with temporal grouping were attained, namely the superior recall overall for grouped compared to ungrouped lists, and multiple bowing of the serial position function for the grouped lists compared to single bowing for the ungrouped lists. These two effects were present for both the Singaporean and Australian samples.

Order errors for grouped and ungrouped lists

This analysis compared the grouped and ungrouped lists in relation to two types of order error. These error types were defined with reference to grouped lists; however error ratios were calculated for the same errors on ungrouped lists, for comparison. The first error type involves adjacent positions, but across a group boundary, such as 3→4, 4→3, etc. These will be labeled adjacent inter-group errors. The second type of order error involves the shift of an item across groups, but so as to retain the same within-group serial position. These errors include 1→4, 4→1, 4→7, 7→4, 2→5, 5→2, and so on. They will be labeled same serial position inter-group errors. A 2 (country—Australia vs. Singapore) x 2 (list type—grouped vs. ungrouped) x 2 (error type—adjacent inter-group vs. same serial position inter-group) ANOVA was conducted on the error ratio measure. There were significant main effects of country and list type, with F (1, 28) = 8.55, MSE = 0.28, $p < .05$, and F (1, 28) = 36.23, MSE = 0.18, $p < .01$, respectively. The list by error type interaction was also significant, F (1, 28) = 50.70, MSE = 0.41, $p < .01$, indicating that the pattern of order errors differed for grouped and ungrouped lists. There was also an interaction between country and list type with F (1, 28) = 7.92, MSE = 0.18, $p < .05$.

The interaction between error type and list type was explored further by examining the effect of list type for each error type. The effect of list type was significant for the same serial position inter-group errors and also for the adjacent inter-group errors, with t (29) = 3.04, $p < .005$, and t (29) = 7.51, $p < .001$, respectively. The error ratio for the same serial position inter-group errors was higher for the grouped than for the ungrouped lists. In contrast, the error ratio for the adjacent inter-group case was higher for the ungrouped than for the grouped lists (see Figure 3). Therefore, when errors involve movement of items across groups, within-group serial position tends to be preserved for grouped lists, and there is a reduced incidence of exchanging adjacent items.

To examine the interaction between country and list type, the simple effect of list type was explored for each country. For Singaporean students, the mean error ratio was lower for grouped lists (M = 0.79, SE = 0.06) compared to ungrouped lists (M = 1.47, SE = 0.09). For Australian students, the mean error ratio also was lower for grouped lists (M = 1.30, SE = 0.08) compared to ungrouped lists (M = 1.50, SE = 0.07).

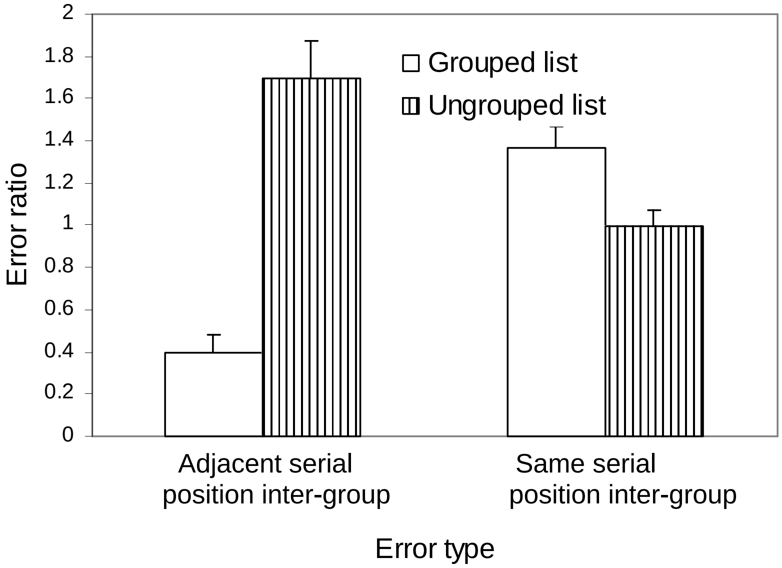

Figure 3: Mean error ratio for two types of interposition error as a function of list type

The list type effect was significant for both countries, with t (14) = 11.92, p < .01, for Singaporean students and t (14) = 3.24, p < .01, for Australian students. The interaction has arisen because of a more pronounced difference in means for the two types of lists for Singaporean students. Note that this country x list type interaction is not subsumed under a higher-order interaction involving error type. There is no evidence of a difference for the two student samples in the crucial list type x error type interaction. Thus both samples show evidence of the shift towards same serial position inter-group errors for temporally grouped lists compared to ungrouped lists.

Protrusions from the previously reported list

Errors were also scored with reference to protrusions from the previously reported list. Two types of error were considered. Again they were defined with reference to the grouped lists, but were also scored for the ungrouped lists. The errors were protrusions from: (1) the same serial position in a different group, 1→4, 4→1, 2→5, 5→2,3→6, 6→3, 4→7, 7→4, 5→8, 8→5, 6→9, 9→6, 8→2, 2→8, 9→3, and 3→9; and (2) adjacent serial positions but across groups, specifically, 3→4, 4→3, 6→7, and 7→6. Given that the analysis of inter-group order errors (reported above) revealed an elevated rate of exchange of items in the same within-group serial position for grouped lists, a similar pattern of results is expected to occur for intrusions from previously-reported lists.

A 2 (country: Australia vs. Singapore) x 2 (list type: grouped vs. ungrouped) x 2 (error type: same serial position inter-group vs. adjacent serial positions inter-group) ANOVA was conducted on the error ratios. The main effect of error type was significant, F (1, 28) = 8.76, MSE = 0.69, p < .01. There was also a significant interaction between list type and error type, with F (1, 28) = 8.62, MSE = 0.49, p < .01 (see Figure 4). No other effects were significant. The list type by error type interaction was explored further by testing the simple effect of list type for each error type. This simple effect was significant for errors involving the same serial position inter-group, with t (29) = 1.99, p < .05. This error ratio was higher for grouped lists than ungrouped lists. The simple effect was not significant for adjacent serial positions inter-group errors. Thus there is evidence from this analysis that temporal grouping influenced the pattern of protrusion errors in that it elevated the rate of protrusions that preserved the within-group serial position of the protruding item. This effect was not modified by the participant's nationality.

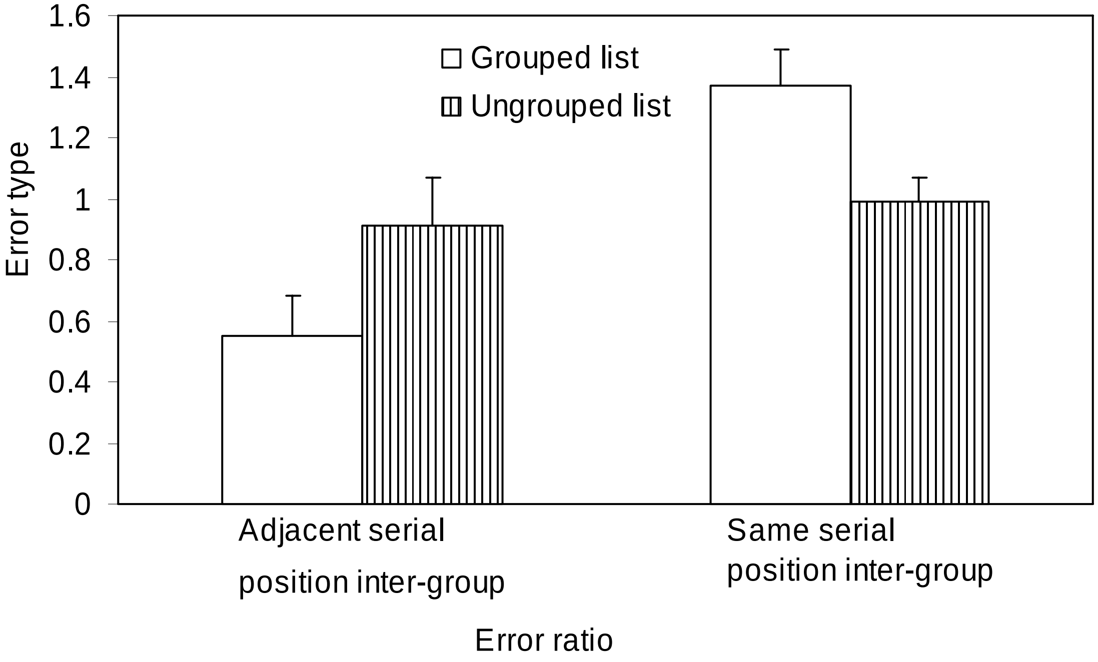

Figure 4: Mean error ratio for two types of protrusion error as a function of list type.

Discussion

This experiment set out to examine if the Singaporean and Australian student populations are qualitatively similar in their serial recall of temporally grouped lists. Comparisons made on accuracy of grouped and ungrouped lists and the types of errors that were made suggest that the two populations are qualitatively similar in the influence of temporal grouping.

Overall accuracy was higher for grouped than ungrouped lists. Similarly, there was multiple bowing of the serial position curves for the grouped lists but not for the ungrouped lists. These differences were present for both groups of students.

There was one effect on accuracy that did differentiate the two nationalities. This was the effect of serial position, which interacted with country. It is difficult to explain this interaction, which reflected a higher level of accuracy for the last three serial positions for Singaporean participants compared to Australian participants. The Singaporean students were training to be teachers whereas the Australian students were enrolled primarily in science and arts degrees. Perhaps a more significant difference is that the Singaporean students volunteered freely, whereas the Australian students participated to fulfill a course requirement. It is possible that the Australian students were less motivated to perform well, and sometimes did not pay as much attention to the last three items of the list, compared to their Singaporean counterparts. However it should be noted that the country x serial position interaction does not represent a difference in the influence of grouping for the two student populations.

In addition, the order error analyses demonstrated that the two populations showed similar trends in the pattern of order errors committed. In ungrouped lists, it is very common that order errors occur as a result of recalling adjacent items in transposed serial positions (Conrad, 1960; Ryan, 1969a, 1969b). This pattern is changed when items are grouped (Ryan, 1969a, 1969b). The transposition of adjacent items is reduced for grouped lists, especially when the relevant serial positions span two groups (Ryan, 1969a, 1969b). In addition, across-group transpositions show a higher frequency of errors that preserved within-group serial position for grouped lists compared to corresponding errors for ungrouped lists (see Ryan, 1969a, 1969b). In the present study, this shift in the pattern of order errors was found for both populations.

For the protrusion of items from the immediately preceding reported list, there appear again to be similar effects for the two student groups. A novel result reported was that items intruding from previously reported lists tended to maintain the same within-group serial position for grouped lists, more so than for comparable protrusions for ungrouped lists.

It would appear that there are no major qualitative differences in performance when comparing the two populations for temporal grouping effects. The Appendix section of this chapter also presents results of comparisons of performance across the two phases for the ungrouped lists. It reports an increase in accuracy for the ungrouped lists for Australian participants from the first to the third phase. However, this difference does not affect the comparison of the two samples on grouping phenomena and therefore will not be pursued further.

Conclusions

In summary, key phenomena associated with temporal grouping—namely higher accuracy overall, a change to the shape of the serial position function, and qualitative changes in the patterns of both transposition and protrusion errors—were identified in this experiment for the two populations. Since the two samples did not differ in the nature of these key phenomena, it is reasonable to use the Australian and Singaporean students where convenient in the research that follows.

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Appendix

Additional analyses were conducted for accuracy and order errors to check for possible differences in performance for the ungrouped lists as a function of phase.

Accuracy

For ungrouped lists, the number of items correct was scored separately for the first and third phases. A 2 (country—Australia vs. Singapore) x 2 (phase—first vs. third) x 9 (serial position) ANOVA was conducted. There were significant main effects of phase and serial position, with F (1, 28) = 5.28, MSE = 4.09, p < .05, and F (8, 224) = 37.43, MSE = 6.22, p < .01, respectively. There were also significant interactions between country and phase, and country and serial position, with F (1, 28) = 4.71, MSE = 4.09, p < .05, and F (8, 224) = 3.64, MSE = 6.22, p < .01, respectively. The interaction between country and serial position is very similar to the corresponding interaction reported earlier in the overall analysis for grouped and ungrouped lists (see Results, Figure 2) and so is not considered further. To examine the country x phase interaction, the simple effect of phase was examined for each country. There was a significant simple effect of phase for Australian participants, with t (29) = 3.09, p < .01. Australian participants appear to have improved their accuracy for ungrouped lists (in Phase 1, M = 4.03, SE = 0.26) following presentation of the grouped lists (in Phase 3, M = 4.81, SE = 0.27). On the other hand, recall accuracy for ungrouped lists for the Singaporean participants did not differ significantly across the phases (in Phase 1, M = 4.77, SE = 0.23 and in Phase 3, M = 4.79, SE = 0.24). It could be that experiencing the grouped lists for some reason improved the Australians' recall accuracy in the third phase; however, there is no evidence of any strategic shift in the Australian students. Other extraneous factors may also explain the results, such as differences in susceptibility to fatigue across the test session.

Order errors

This analysis compared the first and third phases for ungrouped lists to identify any qualitative differences in the pattern of order errors possibly attributable to exposure to the grouped lists in the second phase. A 2 (country-Australia vs. Singapore) x 2 (phase: first vs. third) x 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted on the error ratio measure. There was a significant effect of error type, F (3, 96) = 9.60, MSE = 0.76, $p < 0.001$. No other effects were significant. There appears to be no qualitative differences between the two nationalities for these error measures for ungrouped lists in the first or third phases. The means for the main effect of error type conform to the pattern described earlier for the ungrouped lists (see Figure 3 in the main body of this chapter).

Thus the additional analyses reported in this appendix provided no evidence of qualitatively different patterns of performance for the two student populations.

Chapter 2

Grouping in short-term verbal memory:

Is position coded temporally?

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Grouping in short-term verbal memory: Is position coded temporally?

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The nature of the mechanisms that code item position in serial short-term verbal recall was investigated with reference to temporal grouping phenomena—effects that arise when additional pauses are inserted in a presented list to form groups of items. Several recent models attempt to explain these phenomena by assuming that positional information is retained by associating items with contextual information. According to two of the models—the Phonological Loop model (Hitch, Burgess, Towse, & Culpin, 1996) and the OSCAR model (Brown, Preece, & Hulme, 2000)—contextual information depends critically on the timing of item presentation with reference to group onset. By contrast, according to the Start–End model (Henson, 1998) and a development from it, which we label the Oscillator-Revised Start–End model (Henson & Burgess, 1997), contextual information is independent of time from group onset. Three experiments examined whether coding of position is time dependent. The critical manipulation was to vary stimulus-onset asynchrony from one group to the next in the same list. Lists of consonants were presented visually, but with vocalization in Experiment 1, auditorily in Experiment 2, and auditorily with articulatory suppression in Experiment 3. The pattern of order errors consistently favoured the predictions of the time-independent models over those of the time-dependent models in that across-group transpositions reflected within-group serial position rather than time from group onset. Errors involving intrusions from previous lists also reflected within-group serial position, thereby extending support for the time-independent models.

Extensive research has been invested in the study of verbal short-term memory, typically using a paradigm that involves the sequential presentation of a list of verbal items for immediate serial recall (for reviews, see Baddeley, 1986, 1990; Brown, Preece, & Hulme, 2000). The nature of the mechanisms that code the positions of items for serial recall is currently being debated with reference to temporal grouping effects (Brown et al., 2000; Burgess & Hitch, 1992, 1999; Henson, 1998, 1999a, b; Henson & Burgess, 1997; Hitch, Burgess, Towse, & Culpin, 1996). These effects are observed when additional pauses are inserted between verbal items presented for serial recall—for example, when additional pauses occur between the 3rd

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and 4th and between the 6th and 7th items of a 9-item list to form three 3-item groups. Three central effects are illustrated in Table 1. First, recall from grouped lists is superior to recall from ungrouped lists (Frankish, 1985; Frick, 1989; Hitch et al., 1996; Ryan, 1969a, b). Second, serial position curves for grouped lists display multiple U-shaped bowing—that is, there is primacy and recency for each group—instead of the single bowed pattern observed for ungrouped lists (Frick, 1989; Hitch et al., 1996; Ryan, 1969a, b). Third, temporal grouping modifies the pattern of order errors (Ryan, 1969a, b). In ungrouped lists, there is a high rate of migration of items to neighbouring serial positions (Aaronson, 1968). Grouped lists show a reduction in these adjacent errors, especially across group boundaries; instead, there is transposition of items sharing the same serial position in different groups within the list (Table 1: Ryan, 1969a, b). These errors have been labelled interpositions (Henson, 1996). An additional possible effect of grouping, examined in our research, pertains to across-list intrusions (Table 1). For ungrouped lists, errors sometimes consist of the intrusion of items from previous lists that maintain within-list serial position (Conrad, 1960; Estes, 1991; Henson, 1999b). Henson (1996) labelled these errors protrusions. For grouped lists, it is possible that protrusions will tend to maintain within-group serial position—that is, there may be a higher intrusion frequency for items sharing the same within-group serial position even after any list-wise effect is taken into account.

Typically, research on verbal short-term memory has been interpreted within the theoretical framework of the working-memory model (Baddeley, 1990; Baddeley & Hitch, 1974). The phonological loop component of the model is postulated to be responsible for verbal short-term memory. Although this component can be used to account for limitations in verbal span (see Baddeley, 1990; Hulme, Thomson, Muir, & Lawrence, 1984; Naveh-Benjamin & Ayres, 1986; Schweickert & Boruff, 1986; but also see Brown & Hulme, 1995; Cowan, 1994; Cowan & Kail, 1996), it fails to provide a detailed account of the maintenance of serial order.

TABLE 1
Temporal grouping effects

		Ungrouped lists	*Temporally grouped lists*
	Example[a]	RGZFTNVMB	SHD–QNR–BJF
	Schematic description	123456789	123–456–789
Effects	1. Absolute accuracy of recall	Low	High
	2. Serial position curve on accuracy	Single U-shaped bowing, i.e., overall primacy and recency	Multiple bowing, i.e., primacy and recency for each group
	3. Typical order errors	Neighbouring items, e.g., 1 → 2, 2 → 1, 2 → 3, 3 → 2	Items sharing same position in different groups, e.g., 1 → 4, 4 → 1, 4 → 7, 7 → 4, 2 → 5
	4. Possible intrusions from previous list	Items from same absolute position, e.g., Item 3 on previous list with Item 3 on current list	Items from same position within a group, e.g., Item 3 from a previous list with Item 6 from current list

[a] Dash represents a pause.

Accordingly, temporal grouping effects are not easily handled by the Baddeley and Hitch model (Brown et al., 2000; Henson, 1996, 1998; Henson & Burgess, 1997; Hitch et al., 1996).

Recently, several connectionist models have been developed to address the mechanisms underlying the retention of serial-order information. There are three main classes of model—chaining, ordinal, and positional (Henson, 1998). Chaining models, which have a long history (Ebbinghaus, 1913), view the construction of serial order as associating neighbouring items (Lewandowsky & Murdock, 1989; Murdock, 1995). The recall of successive items typically results from cues provided by the retrieval of earlier items. However, several verbal short-term memory phenomena are difficult to accommodate under accounts based on inter-item associations (Brown et al., 2000; Henson, 1998; Henson, Norris, Page, & Baddeley, 1996). These include list-wise protrusion errors and the effects of temporal grouping summarized earlier. Ordinal models propose that the serial order of items is represented on a single dimension. For instance, in the Page and Norris (1998) model, the relative strength of items in the list provides the serial order information. However, this class of model also cannot explain protrusion errors and grouping effects (Henson, 1998).

Positional models are better equipped to explain protrusion errors and temporal grouping phenomena (Brown et al., 2000; Burgess, 1995; Burgess & Hitch, 1996; Henson, 1998). These models assume that associations between items and contextual information provide position in a sequence. Four prominent positional models are the Phonological Loop (PL) model (Burgess, 1995; Burgess & Hitch, 1992, 1996, 1999; Hitch et al., 1996), the OSCillator-based Associative Recall model (OSCAR; Brown et al., 2000), the Start–End (SE) model (Henson, 1998), and a substantial development from the latter, which we label the Oscillator-Revised Start-End (ORSE) model (Henson & Burgess, 1997[1]). These models are described in critical detail later; however, in prospect, we show that the PL and OSCAR models are sensitive to the timing of item presentation in a way that the SE and ORSE models are not. We then show that the two pairs of models generate contrasting sets of predictions for interposition and protrusion errors when inter-item SOA is varied across the groups within a single list. The three reported experiments evaluate these predictions and thereby establish the extent to which positional coding is time dependent.

The Phonological Loop (PL) model

The PL model (Burgess, 1995; Burgess & Hitch, 1992, 1996, 1999; Hitch et al., 1996) is an extension of the working-memory model (Baddeley, 1990; Baddeley & Hitch, 1974). Under the PL model, three types of information are coded in different sets of nodes—item information, phonological information, and contextual information deriving from a repeatable timing signal. As list presentation advances, similar steps occur for each item whereby phoneme–item, context–item, and item–phoneme associations are formed. The context signal is analogous to a "moving window" with each node activated temporarily (Figure 1). The mechanism underlying the context nodes is presumed to be sets of temporal oscillators, each set varying

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[1] In conflict with year of publication, the Henson and Burgess (1997) model was developed after the Start–End model (Henson, 1998). The Henson and Burgess model was developed acknowledging a preliminary (unpublished) report of one of the experiments we report here.

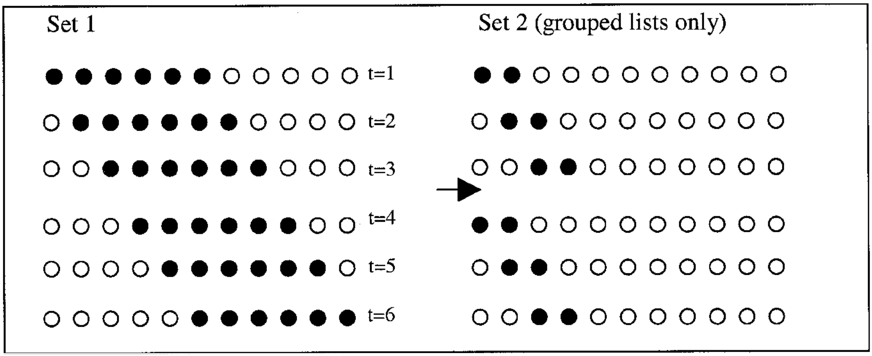

Figure 1. The "context timing" signal of the PL model (taken from Hitch et al., 1996, Figure 13). Activation of temporal oscillators is represented using filled circles. For ungrouped lists, a single set of oscillators (Set 1) is activated at the start of list presentation and reactivated at the start of recall. The second set of oscillators (Set 2) is activated at the start of list presentation and reactivated following each pause (indicated by the arrow).

around a modal frequency. For ungrouped lists, one set of oscillators is implicated. The beginning of list presentation triggers the initial phase of a wave of activation, which passes across the set of oscillators as the list is presented sequentially. Because the activation shifts over time, there is overlapping, but nevertheless discriminately different, contextual information encoded for adjacent items (see Set 1, Figure 1). This allows for order information to be encoded by the context signal. During recall or rehearsal, the wave of activation of the set of temporal oscillators is reinitiated and used to cue the retrieval of successive items. Context–item associations and item–phoneme associations form the cues for retrieval.

The PL model accommodates grouping phenomena by assuming that "a second set of oscillators become entrained such that they are reset after every pause" (Hitch et al., 1996, p. 134). Thus the PL model explains "temporal grouping effects by assuming that the context signal becomes entrained to the inter-group frequency" (Hitch et al., p. 133). Therefore, there are two sets of temporal oscillators used to encode contextual information for grouped lists. One set is triggered at the start of the list and operates as described earlier for ungrouped lists. The second set of oscillators becomes entrained to the interval from onset of one group to onset of the next. The onset of each group causes a resetting of the cycle of activation in this second set of nodes (Set 2, Figure 1). This means that there are similar patterns of activation in this set of oscillators for items that occupy the same temporal position within different groups. During recall or rehearsal, the activation of the two sets of oscillators is used to cue item retrieval.

The contextual information encoded from the oscillators is critical to the PL model's account of list-wise protrusion errors and group-wise interposition errors. The first set of oscillators, which are reset at the start of each list, provide similar contextual information for items occupying the same temporal position in successive lists. Therefore, if presentation rate is held constant across lists, protrusion errors should respect list-wise serial position. Similarly, the second set of oscillators, which are reset at the start of each group, provide similar contextual information for items occupying the same temporal position in different groups. Therefore, if presentation rate is held constant across groups, interposition errors should respect group-wise serial position. Because the contextual information is time dependent, critical tests of the PL model can be provided by manipulating item presentation rate across groups but so as to maintain a constant intergroup frequency, as we detail later.

The OSCillator-based Associative Recall (OSCAR) model

The OSCAR model of Brown et al. (2000) shares critical features with the PL model. In particular, OSCAR also assumes that temporal oscillators provide a context signal that is associated with items at encoding and then reinstated at recall to cue the retrieval of successive items. The context signal is composed of a number of vectors, with each vector representing the outputs of oscillators of different frequencies. For ungrouped sequences, the arbitrary state of the context vectors at the start of list presentation is retained and used to reset the context at recall. These context vectors are similar to the first set of oscillators of the PL model (Set 1, Figure 1) in that both encode list-wise temporal position. However, one difference is that, for OSCAR, the context signal is not reset at the start of each list—it simply continues to evolve, providing non-repeating information. For the simulations of performance on grouped lists, the OSCAR model adopts similar assumptions to the PL model in accounting for temporal-grouping effects. Two context signals are described with reference to a clock analogy (see Brown et al., p. 162). Some of the oscillators (the "hour hand") encode list-wise position and never repeat their output throughout list presentation. However, other oscillators (the "minute hand") repeat their cycles of output in phase with the groups—"a hand that repeats (completes a revolution of the clock face) in the time taken for each group to be presented"—and encode within-group position. These oscillators must reach the same state at the start of each group (i.e., they must evolve in phase with the inter-group frequency) if across-group interposition errors are to be explained. This repeating context signal is therefore much like the signal provided by the second set of oscillators of the PL model in that both encode within-group temporal position (see Set 2, Figure 1). Finally, a general feature of OSCAR is that the rate of evolution of the temporal oscillators is assumed to be under strategic control, both at encoding and at recall (Brown et al.).

The context signals that repeat in phase with group onset provide OSCAR with predictions of interposition errors that match the predictions of the PL model. However, in assuming that list-wise position is encoded by vectors that provide non-repeating information from one list to the next, it is difficult for OSCAR to predict protrusion errors that respect list-wise serial position. This deficiency could be overcome with a simple extension to the versions of OSCAR used by Brown et al. (2000) to simulate grouping phenomena. The extension would be to include some context vectors that repeat in phase with list onset (see the simulation of data from Nairne, 1991, in Brown et al., 2000). Therefore, for the phenomena of critical interest here—interposition and protrusion errors as a function of temporal grouping—OSCAR can provide an account that matches the account provided by the PL model. Because the context signal of OSCAR is based on temporal oscillators, its predictions also depend critically on the rate of item presentation, and so manipulation of this rate across the groups within a list represents a conjoint test of the OSCAR and PL models.[2]

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[2] We argue in the General Discussion that OSCAR cannot easily escape time-dependent predictions through allowing for strategic variation in the rate of evolution of the temporal oscillators.

The Start–End (SE) model

In the SE model (Henson, 1998), representations of items are associated with start and end markers. As items occur, the strength of the start marker reduces while the strength of the end marker increases. The markers therefore encode position information. For grouped lists, two sets of markers apply. One set provides information regarding position within the list, and the other set provides position within a group. The set that encodes position within the list provides predictions of protrusion errors that respect list-wise serial position. Similarly, the set that encodes position within a group provides predictions of interposition errors that respect group-wise serial position. These predictions are invariant of the rate of presentation of items within groups because changes in the coding provided by the markers are event driven.

The Oscillator-Revised Start–End (ORSE) model

The acknowledged weakness of the SE model is the anticipatory nature of the end markers: It is not easy for distance from the end of the list (in terms of number of items) to be encoded before the list has actually terminated (Henson & Burgess, 1997). To overcome this problem, the ORSE model (Henson & Burgess) assumes that position markers are encoded using sets of temporal oscillators. These are organized in frequency-matched pairs. Different oscillator pairs have different frequencies, and these compete to best represent positional information for each list and for each group within a list. The winning oscillator pair for the list is the one with a half-cycle closest to the duration of the list. Similarly, the winning oscillator pair for each group has a half-cycle closest to the duration of the group. This means that the critical oscillator pairs encoding position information are assigned at the end of each group and each list. It is by this means that the ORSE model solves the problem of the anticipatory nature of the end markers in the SE model.

One critical feature of the ORSE model is that each winning pair of oscillators moves through half its cycle for the duration of the group or list it represents. This means that the oscillators do not code absolute temporal position. Instead they code relative temporal position within the group or list. For instance, if one item occurs 1 s after the onset of a 2-s group, and another item occurs 2 s after the onset of a 4-s group, the two items will be associated with very similar information from the oscillators that code intra-group position. In both cases the oscillators will be a quarter of the way through their cycles.

This feature means that the predictions of the ORSE model are aligned with those of the SE model for the presentation conditions we employ. We present items in groups of three, and although the item-to-item SOAs sometimes vary from one group to another, SOA is constant within any single group. In other words, SOAs are simply scaled by a constant (e.g., doubled) when there is a change from one group to another. Under these conditions, the oscillators of the ORSE model that encode position within a group provide predictions of interposition errors that respect group-wise serial position. Two items occupying the same serial position in different groups will be associated with similar information from these oscillators even if the rate of presentation of items in one group is half the rate in another group. Because the predictions of the ORSE model are not modified by shifts in the rate of presentation of items across groups, they are aligned with the predictions of the SE model, but contrast with the predictions of the time-dependent PL and OSCAR models.

Is position information time dependent?

A critical feature shared by the PL and OSCAR models is that position within a list and position within a group are coded with respect to absolute time. This feature is not part of the SE and ORSE models. It should be noted that the ORSE model does encode positional information with respect to time. However, the predictions of the model are independent of the critical manipulation of timing we employ, so it is only with reference to these manipulations that we label the ORSE model (along with the SE model) time independent. The PL and OSCAR models are time dependent with respect to our manipulations of timing. Because they differ on this feature, the two pairs of models make contrasting predictions when item-to-item stimulus-onset asynchrony (SOA) is varied across the groups that compose a list.

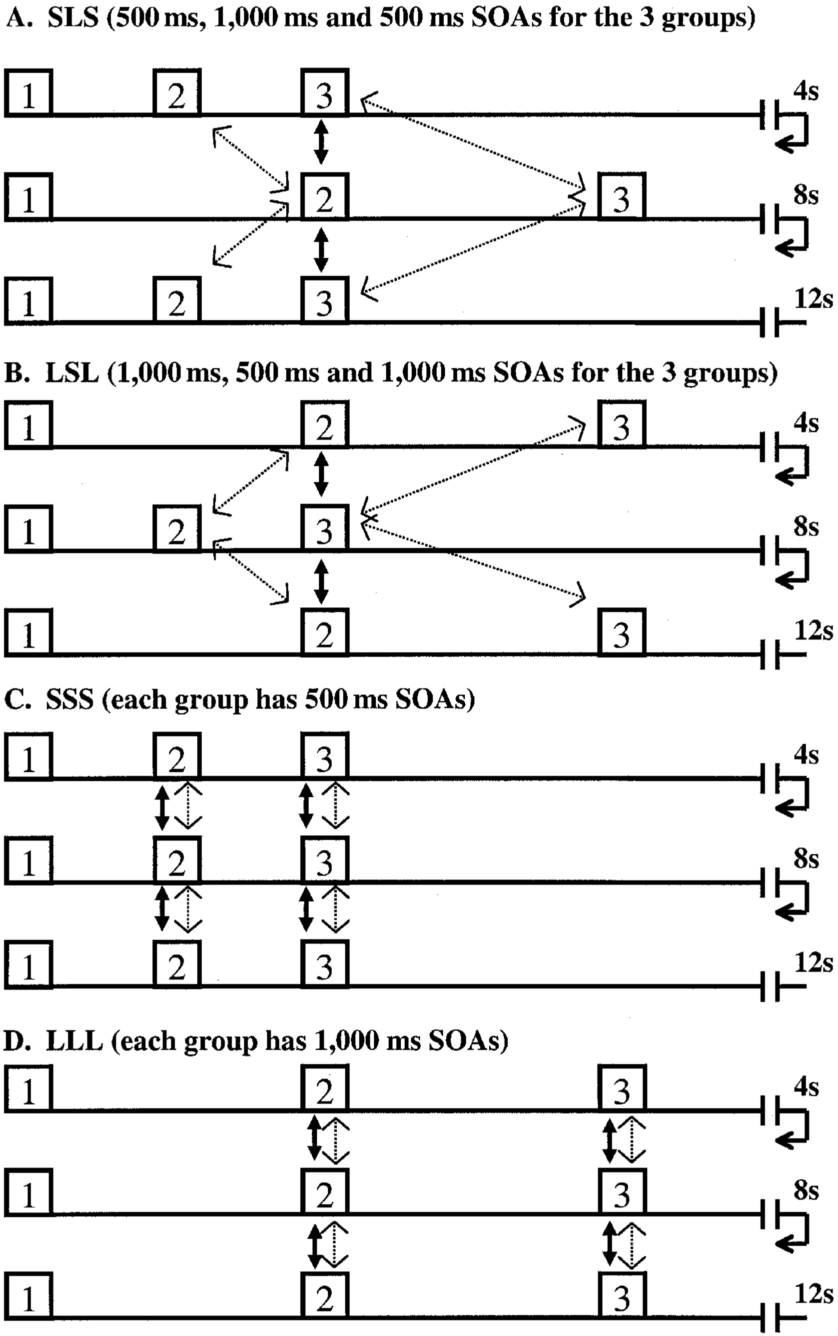
The first two experiments in the present series used 9-item lists. For each grouped list, extended pauses between the 3rd and 4th, and 6th and 7th items divided the list into three 3-item temporal groups. The critical manipulation was that each group used an item-to-item SOA of either 500 ms (the short, S, group) or 1000 ms (the long, L, group). Four types of grouped list were then constructed by combining the S and L groups. These were labelled the SSS, LLL, SLS, and LSL lists (see Figure 2). To illustrate, the SOAs of the SLS lists were 500 ms for Items 1 to 3, 1000 ms for Items 4 to 6, and 500 ms for Items 7 to 9.

The time-dependent (PL, OSCAR) and time-independent (SE, ORSE) models make contrasting predictions for interposition errors for the SLS and LSL lists. For the time-dependent models, any transposition of items across groups should depend on the absolute time since the onset of each group. So considering the SLS list (see Figure 2A), interpositions expected to occur with high frequencies are for Item 3 of the first group to take the place of Item 2 of the second group (or vice versa), or for Item 2 of the second group to take the place of Item 3 of the third group (or vice versa). This is because all of these items occur 1000 ms after group onset. These interpositions, which we collectively label 3–2–3, should occur with higher frequencies than the interpositions that we label 2–2–2/3–3–3 (Figure 2). This is because the 2–2–2/3–3–3 transpositions do not maintain within-group temporal position (despite maintaining within-list serial position). Turning to the LSL list, the time-dependent PL and OSCAR models predict high frequencies of the interposition errors 2–3–2 (see Figure 2B). These errors should be more common than the interpositions 2–2–2/3–3–3.

The time-independent SE and ORSE models make the reverse predictions. For these models, interpositions should respect within-group serial position rather than within-group temporal position. Therefore interpositions 2–2–2/3–3–3 should occur more frequently than interpositions 3–2–3 for the SLS list, and more frequently than interpositions 2–3–2 for the LSL, list (Figure 2).

The SSS and LLL lists were included for comparison. In these cases, within-group temporal position and within-group serial position are confounded, so all models predict a predominance of 2–2–2/3–3–3 transpositions.

Protrusion errors can also be used to contrast the time-dependent and time-independent models. These errors can be made from any “donor” group on the previous list to any “recipient” group on the current list. The critical cases are where the SOAs differ for donor and recipient. One case, which we label L to S, is exemplified by the two middle groups in an SLS list followed by an LSL list. For the time-dependent PL and OSCAR models, the second item of the long SOA group is expected to intrude on the third item of the short SOA group (see



A. SLS (500 ms, 1,000 ms and 500 ms SOAs for the 3 groups)

B. LSL (1,000 ms, 500 ms and 1,000 ms SOAs for the 3 groups)

C. SSS (each group has 500 ms SOAs)

D. LLL (each group has 1,000 ms SOAs)

Figure 2. The timing of stimulus sequences for the different grouped lists. Numbers represent within-group serial position. Solid arrows depict errors predicted by the time-dependent PL and OSCAR models. Broken arrows depict errors predicted by the time-independent SE and SEM models.

Figure 3A). This is because the context signal encoded for these items—both of which occur 1000 ms after group onset—should be quite similar. This protrusion, which we label 2 → 3, should occur more frequently than the protrusions 2 → 2 and 3 → 3 if absolute time is encoded. (Note that we use the arrow symbol to emphasize the directional nature of protrusion errors and also to differentiate these errors from interposition errors.) The second critical case (S to L) is exemplified by the two middle groups in an LSL list followed by an SLS list. Here the time-dependent models predict, based on concurrence of temporal position, that the third item of the short SOA group should intrude on the second item of the long SOA group (Figure 3B). This protrusion (3 → 2) should occur more frequently than the protrusions 2 → 2/3 → 3 according to the time-dependent PL and OSCAR models.

The time-independent SE and ORSE models make the reverse predictions concerning L to S and S to L protrusions. For these models, protrusions, like interpositions, should respect within-group serial position rather than within-group temporal position. Therefore the protrusions 2 → 2/3 → 3 should occur more frequently than the protrusion 2 → 3 for the L to S case, and more frequently than the protrusion 3 → 2 for the S to L case (see Figure 3).

When groups from the previous and current lists have the same SOAs (i.e., S to S or L to L), within-group temporal position and within-group serial position are confounded, so all models predict a predominance of 2 → 2/3 → 3 protrusions (Figure 3).

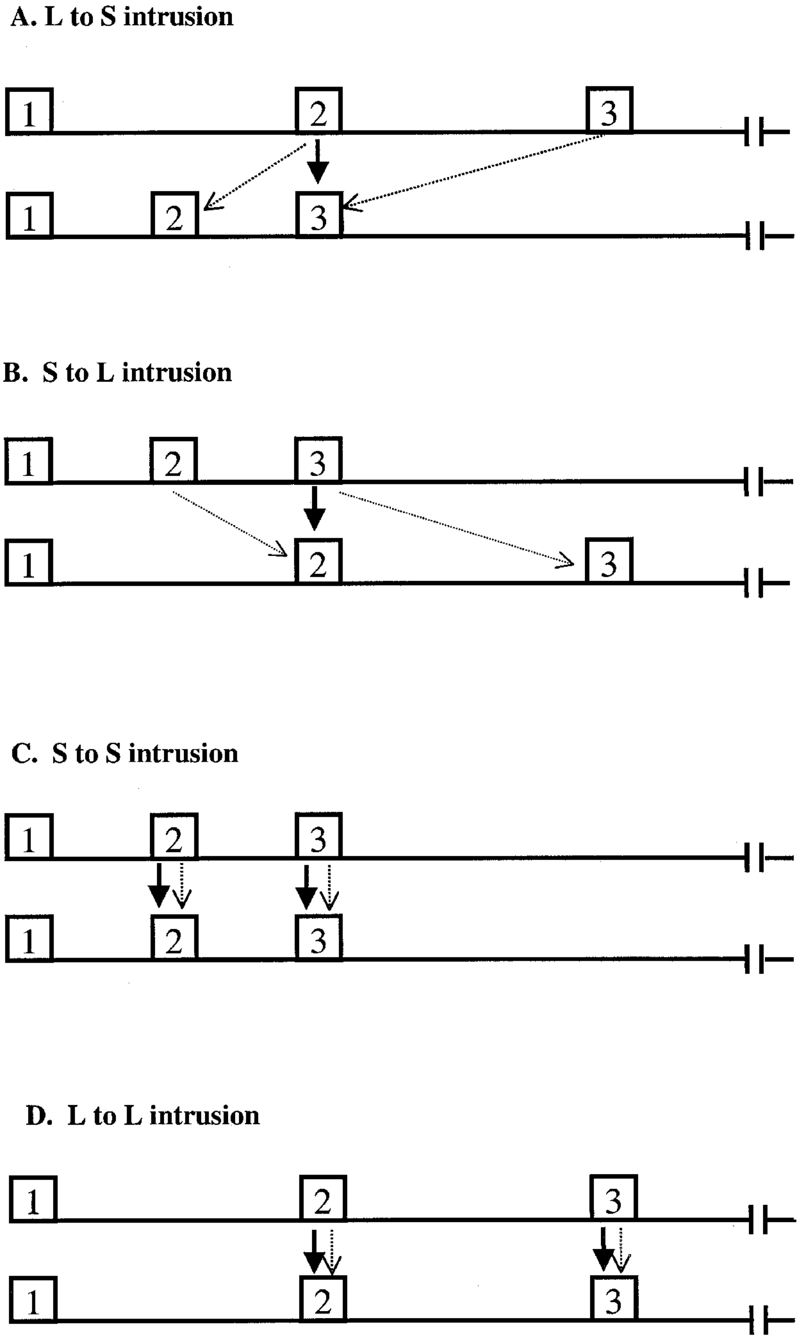
Overview of the three experiments

The major aim of the three reported experiments was to evaluate the predictions of the time-dependent and time-independent models in respect of interposition and protrusion errors. However, other temporal grouping effects summarized in Table 1 were also examined. These include the superior recall for grouped versus ungrouped lists and the multiple bowing of the serial position curve for grouped lists compared to the single bowing for ungrouped lists.

The first two experiments adopted the same basic design. There were three test phases: The first and last phases used ungrouped lists, whereas the middle phase used grouped lists. For the grouped lists, the SOAs between the 3rd and 4th, and 6th and 7th items were considerably longer than the other SOAs, thereby effectively dividing the 9-item list into three 3-item temporal groups. The temporal separation of the onsets of the three groups was held constant at 4 s for all of the grouped lists. (According to the PL model, this should enable entrainment of the second set of temporal oscillators—see Hitch et al., 1996.) As described earlier, each group had an item-to-item SOA of either 500 ms (S), or 1000 ms (L), and the four combinations of short and long groups were SSS, LLL, SLS, and LSL (Figure 2).

EXPERIMENT 1

The major difference between the three experiments was in the method of list presentation. For the first experiment, the consonants were presented visually, but the participant was asked to say each aloud as it was presented. This was to ensure phonological registration of the items and to standardize the strategy used by the participants.


A. L to S intrusion

B. S to L intrusion

C. S to S intrusion

D. L to L intrusion

Figure 3. Protrusion errors predicted by time-dependent (solid arrows) and time-independent (broken arrows) models for four combinations of timing for donor and recipient groups. The horizontal distances between the boxes represent temporal separation approximately.

Method

Participants

The 40 participants (31 female) were undergraduates at the University of Western Australia and were aged between 16 and 38 years.

Apparatus

An IBM-compatible Hyundai super 386i computer and keyboard with a 36-cm Hyundai monitor were used to present the stimulus sequences and record answers.

Stimuli

The 20 consonants, after excluding w (which comprises three syllables), were used to construct 80 lists, each of nine letters. Each list was randomly generated except that no consonant was repeated and any obvious patterns were excluded (i.e., there were no alphabetically adjacent letters or sequences that made words, e.g., SLY).

For each participant, 65 of the 80 lists were selected at random, but without replacement. They were used to form 5 practice and 10 test trials using ungrouped lists, 40 test trials using grouped lists, and an additional 10 test trials using ungrouped lists. There were 10 trials for each type of grouped list—SSS, LLL, SLS, and LSL (Figure 2). These 40 grouped trials were presented in random order with the restriction that every set of 4 consecutive trials contained one list of each type.

Procedure

Participants were tested individually in a small room. There were two presentation rate conditions, depending on whether the ungrouped lists were constructed with a 500-ms or a 1000-ms SOA, and 20 participants were randomly allocated to each. As indicated earlier, each participant received 5 ungrouped practice trials, 10 ungrouped test trials, then 40 grouped test trials, and finally a further 10 ungrouped test trials. The 65 lists were presented in one continuous block.

The procedure for each test trial was as follows. A warning signal (brief tone) preceded each sequence by 1500 ms. During this interval, a fixation point denoted by an asterisk was displayed at the centre of the screen. Each letter of the list was presented in Times New Roman font, size 36, in the centre of the screen for 250 ms. The SOAs depended on the types of sequence, as described earlier (and see Figure 2). However, to repeat, a 500-ms or 1000-ms SOA was used for each ungrouped list. For each grouped list, the onsets of the three groups were separated by 4 s, and the items within groups were separated by an SOA of either 500 ms (S) or 1000 ms (L). The four types of grouped list were formed through four combinations of these SOAs: SSS, LLL, SLS, and LSL (Figure 2). Recall was initiated by the appearance of nine boxes across the bottom of the screen. These boxes appeared 4 s after the onset of the last group for the grouped lists, and either 500 ms or 1000 ms after the onset of the last item for the ungrouped lists. An asterisk marker was shown under the left-most box. This box signified the first serial position, and when the participant typed a letter on the keyboard, that letter was printed in the box. The marker was then moved to a position under the next box to the right. Thus the boxes were filled from left to right while the letters were typed. The left and right arrow keys enabled movement across the boxes, with the left arrow key used when the participant needed to make changes to the response. After filling all nine boxes (which was necessary to proceed), the participant pressed the down-arrow key to signal the end of the response. To proceed to the next list, the participant pressed any key when ready.

Participants were instructed that sequences of letters would be presented on the screen and they would be required to recall the items in the correct order at the end of each list. The method of recording responses was also explained. It was emphasized that each letter had to be said aloud as it was presented.

Analytic methods for interposition and protrusion errors

For analyses of interposition (order) errors and protrusion (intrusion) errors, raw counts of the different types of error are inappropriate, as there are more opportunities to make some types of error rather than others. The measure adopted to correct for differential opportunity is the ratio of the actual number of errors of a particular type divided by the number of errors expected of that type if the total errors had been distributed equally. More precisely, if there are n cases forming a type (e.g., there are four cases of the 3–2–3 type—Serial Position 3 transposing with Serial Position 5, and vice versa, and Serial Position 5 transposing with Serial Position 9 and vice versa) and Σe errors observed for that type, then using N to refer to the total number of cases (e.g., 72 for interpositions, which is derived from 9 serial positions with 8 possible errors at each position) and ΣE to refer to the total errors observed (e.g., all interposition errors), the ratio would be:

$$R = \frac{\Sigma e}{n\Sigma E / N}$$

Equivalently, the ratio is the mean error rate for a particular type ($\Sigma E/n$) divided by the overall mean rate ($\Sigma E/N$). So a ratio greater than one implies that the error type occurred with above-average frequency, whereas a ratio less than one implies that it occurred with below-average frequency. The error ratio has the advantage that it is independent of both the total numbers of errors made (ΣE) and the opportunities available for each type of error (n). However, because the ratio is novel, we also report nonparametric analyses to confirm some of the critical outcomes from the analyses of ratios.

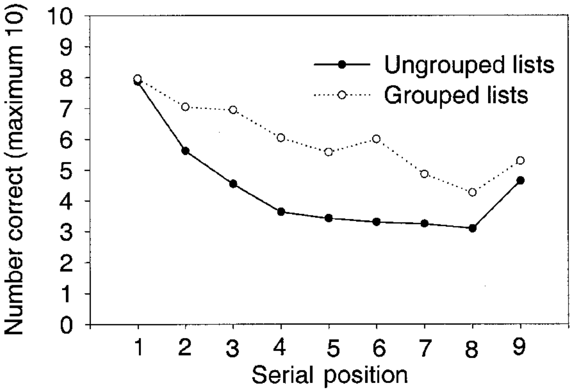
Results

We first compare performance on the grouped lists with performance on the ungrouped lists. This is done for accuracy. We then report analyses of the interposition and protrusion errors for the different types of grouped list. These analyses address the predictions that differentiate the time-dependent and time-independent models. This is followed by broader analyses of both interposition errors (where typical effects of temporal grouping reported elsewhere are confirmed) and protrusion errors (where we report some novel effects of grouping). The Appendix contains additional analyses of accuracy, which compare the different types of grouped list and the different types of ungrouped list.

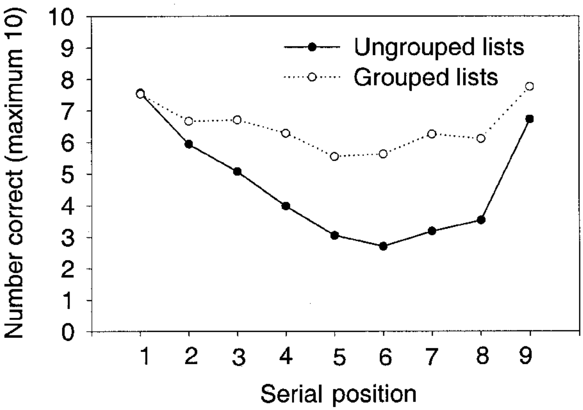
Accuracy for grouped vs. ungrouped lists

The mean number of items correct at each serial position (maximum 10) was calculated separately for the ungrouped and grouped lists for each participant. A 2 (list type: grouped vs. ungrouped) × 9 (serial position) repeated measures analysis of variance (ANOVA) was then conducted. The main effects of list type and serial position were significant, with $F(1, 39) = 96.00$, $MSE = 4.93$, $p < .001$, and $F(8, 312) = 48.73$, $MSE = 2.79$, $p < .001$, respectively. There was also a significant interaction, $F(8, 312) = 13.57$, $MSE = 1.14$, $p < .001$. At each serial position excluding the first, accuracy was higher for the grouped than for the ungrouped lists (Figure 4A). The serial position curves show strong primacy together with weaker recency for both list types; however, there also appears to be multiple bowing for the grouped lists (Figure 4A;

A) Experiment 1



B) Experiment 2



C) Experiment 3

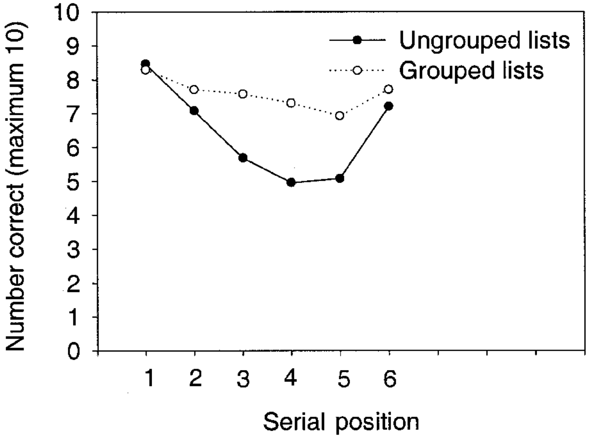


Figure 4. Mean number of correct responses at each serial position as a function of list type for Experiments 1–3.

cf., Hitch et al., 1996; Ryan, 1969a, b). These observations were supported when the quadratic trend over serial position was calculated (Ferguson, 1976). This trend was significant overall, $F(1, 312) = 259.53$, $MSE = 1.14$, $p < .001$, and also interacted with list type, $F(1, 312) = 95.61$, $MSE = 1.14$, $p < .001$. The quadratic trend is more pronounced for the ungrouped lists than for the grouped lists, in part because there is more pronounced scalloping in the function for grouped lists.

Interposition errors for grouped lists: Evaluation of time-dependent and time-independent predictions

The aim of this analysis was to evaluate the contrasting predictions of the time-dependent (PL and OSCAR) and time-independent (SE and ORSE) models in relation to the transposition of items across groups. Recall that the time-dependent models predict higher frequencies of interpositions 2–3–2 than of interpositions 2–2–2/3–3–3 for the LSL lists, and higher frequencies of interpositions 3–2–3 than of interpositions 2–2–2/3–3–3 for the SLS lists. The opposite predictions hold for the time-independent models. To test these predictions, the error ratio was used in a 4 (type of grouped list: LLL vs. SSS vs. LSL vs. SLS) × 3 (error type: 3–2–3 vs. 2–3–2 vs. 2–2–2/3–3–3) repeated measures ANOVA.[3] The main effect of error type was significant, with $F(2, 78) = 75.97$, $MSE = 0.77$, $p < .001$. However, the main effect of type of grouped list and the interaction were not significant. Post hoc *t* tests were conducted to examine the differences between the types of error. The error ratio was significantly higher for 2–2–2/3–3–3 interpositions than for either 3–2–3 interpositions or 2–3–2 interpositions (see Table 2). The last two means did not differ significantly.

Thus, consistent with the time-independent models, there was a higher rate of 2–2–2/3–3–3 interpositions than of 2–3–2 and 3–2–3 interpositions for all four list types. There was no support for the time-dependent models as the error ratios showed significant differences in the reverse direction to these models' predictions for the SLS and LSL lists.

TABLE 2
Mean ratios for 222/333, 232, and 323 interposition errors of grouped lists for each experiment

	222/333 error		*232 error*		*323 error*	
Experiment	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	1.74	0.05	0.62	0.06	0.80	0.07
2	1.57	0.06	0.76	0.08	0.70	0.07
3	1.32	0.12	0.39	0.13	0.67	0.14

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[3] Note that there are eight particular errors included in the 222/333 category and four included in each of the 232 and 323 categories. Therefore the three error ratios are based on 16 of the 72 possible transposition errors. This means that interdependence between the 3 ratios should not be a problem. In fact the Pearson *r* correlation coefficients between error ratios calculated separately for each grouped list type (12 correlations in all) provided significant correlations in only two cases, and these were of opposite sign ($r = -.331$, $p < .05$, and $r = .347$, $p < .05$). Therefore, a high ratio for one error category does not necessarily imply low ratios for the other two categories.

As a check on the validity of the results reported from the analyses of the error ratio, a simpler alternative analysis was conducted on the transposition errors. This analysis focused on the predictions of the time-dependent models for the SLS and LSL grouped lists. We started with the number of errors that each participant made in each cell of the matrix of possible order errors. Then, for each of the three critical categories of error (2–3–2, 3–2–3, 2–2–2/3–3–3), we calculated the mean number of errors for the cells included in that category. Finally, we compared these means for individual participants. Recall that for the SLS lists the prediction for the time-dependent models is that 3–2–3 interpositions should occur more frequently than 2–2–2/3–3–3 interpositions. However, when the mean number of errors was compared for these two categories of error, only 3 participants showed a difference in the predicted direction, whereas 31 participants showed the contrary ordering of means: $\chi^2(1) = 23.06$, $p < .001$, for the comparison of these frequencies. For the LSL lists the critical prediction for the time-dependent models is that 2–3–2 interpositions should occur more frequently than 2–2–2/3–3–3 interpositions. However, only 2 participants showed a difference in the predicted direction, whereas 37 participants showed the contrary ordering of means: $\chi^2(1) = 31.42$, $p < .001$. For both list types, the predictions of the time-dependent models were not supported, consistent with the previous analysis. The predominance of 2–2–2/3–3–3 transpositions supports the time-independent SE and ORSE models.

Protrusion errors for grouped lists: Evaluation of time-dependent and time-independent predictions

This section examines errors consisting of the protrusion of items from the list presented on the immediately preceding trial. A recalled letter was counted as a protrusion if it had not been an item in the presented list for the scored trial, but had been an item in the presented list on the preceding trial. The errors predicted from the time-dependent PL and OSCAR models depend on the relative timing of the donor and recipient groups (see Figure 3). Recall that these models predict higher frequencies of 2 → 3 protrusions than of 2 → 2/3 → 3 protrusions for the L to S case, and higher frequencies of 3 → 2 protrusions than of 2 → 2/3 → 3 protrusions for the S to L case. The converse predictions are made from the time-independent SE and ORSE models. To evaluate these predictions, a combined error ratio labelled 2 → 3/3 → 2 was calculated based on 2 → 3 protrusions for the L to S case and 3 → 2 protrusions for the S to L case. This ration was then compared with a ratio based on protrusions 2 → 2 and 3 → 3 for either L to S or S to L. We also calculated two similar ratios for the remaining cases, S to S and L to L.[4] There were therefore two types of protrusion (2 → 3/3 → 2 and 2 → 2/3 → 3), for which ratios were calculated for two types of group timing (same, S to S and L to L, and different, S to L and L to S). Also, ratios were computed separately for protrusions that came from a group in the same position (e.g., middle group to middle group) as contrasted to a different position (e.g., first group to middle group).

A 2 (group position: same vs. different) × 2 (timing: same vs. different) × 2 (type of protrusion: 2 → 3/3 → 2 vs. 2 → 2/3 → 3) repeated measures ANOVA was conducted. There were

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[4] In this instance the 2 → 3/3 → 2 ratio was calculated by looking for either type of protrusion with each of the S to S and L to L cases.

significant main effects of group position, $F(1, 39) = 6.16$, $MSE = 0.66$, $p < .05$, and type of protrusion, $F(1, 39) = 18.78$, $MSE = 1.10$, $p < .001$. However, the main effect of timing was not significant, nor were any of the interactions. The error ratio was higher for protrusions from the same group position ($M = 1.10$, $SE = 0.09$) than for those from a different group position ($M = 0.88$, $SE = 0.05$). The ratio was also higher for protrusion type 2 → 2/3 → 3 ($M = 1.24$, $SE = 0.07$) than for protrusion type 2 → 3/3 → 2 ($M = 0.74$, $SE = 0.08$).

The predictions from the time-dependent models—higher frequencies of 2 → 3 protrusions than of 2 → 2/3 → 3 protrusions for the L to S case, and higher frequencies of 3 → 2 protrusions than of 2 → 2/3 → 3 protrusions for the S to L case—were therefore not confirmed. Instead, irrespective of the timing of donor and recipient groups (S to L, L to S, S to S or L to L), the predominant class of protrusion error was 2 → 2/3 → 3. This outcome is consistent with the time-independent SE and ORSE models. In sum, irrespective of the timing of the groups, protrusions were more frequent when both the position of the group in the list and the serial position of the item within the group were the same for the previous and current trials.

Interposition errors for grouped vs. ungrouped lists

This analysis compared the grouped and ungrouped lists in relation to two types of interposition error. These error types were defined with reference to grouped lists; however, error ratios were calculated for the same errors on ungrouped lists, for comparison. The first error type concerns adjacent positions that span a group boundary—that is, 3–4 and 6–7. We call these adjacent inter-group errors. The second type of order error also involves the shift of an item across groups, but so as to retain the same within-group serial position, such as 1–4, 2–5, and 6–9. We label these same serial position inter-group errors. A 2 (list type: grouped vs. ungrouped) × 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted on the error ratio measure. There were significant main effects of error type, $F(1, 39) = 11.06$, $MSE = 0.46$, $p < .01$, and list type, $\mathrm{F}(1, 39) = 9.01$, $MSE = 0.23$, $p < .01$. The list type by error type interaction was also significant, $F(1, 39) = 66.21$, $MSE = 0.47$, $p < .001$, indicating that the pattern of order errors differed for grouped and ungrouped lists (see Figure 5A). The interaction between error type and list type was explored further by examining the effect of list type for each type of error. For the adjacent inter-group errors, the error ratio was lower for the grouped lists than for the ungrouped lists, $t(39) = 6.65$, $p < .001$. However, this difference was reversed for the same serial position inter-group errors, $t(39) = 7.84$, $p < .001$ (Figure 5A). Thus, when errors involved movement of items across groups, within-group serial position tended to be preserved for grouped lists, and there was a reduced incidence of items being displaced across group boundaries.

Protrusion errors for grouped vs. ungrouped lists

Similar types of error can be examined for protrusions. Adjacent inter-group protrusions are where an item on a group boundary on the previous list intrudes onto the current list, but switches across the boundary (e.g., 3 → 4). Same serial position inter-group protrusions are where an intruding item also swaps groups, but so as to preserve within-group serial position (e.g., 3 → 6). However, one extra complication is that these protrusions can come from either

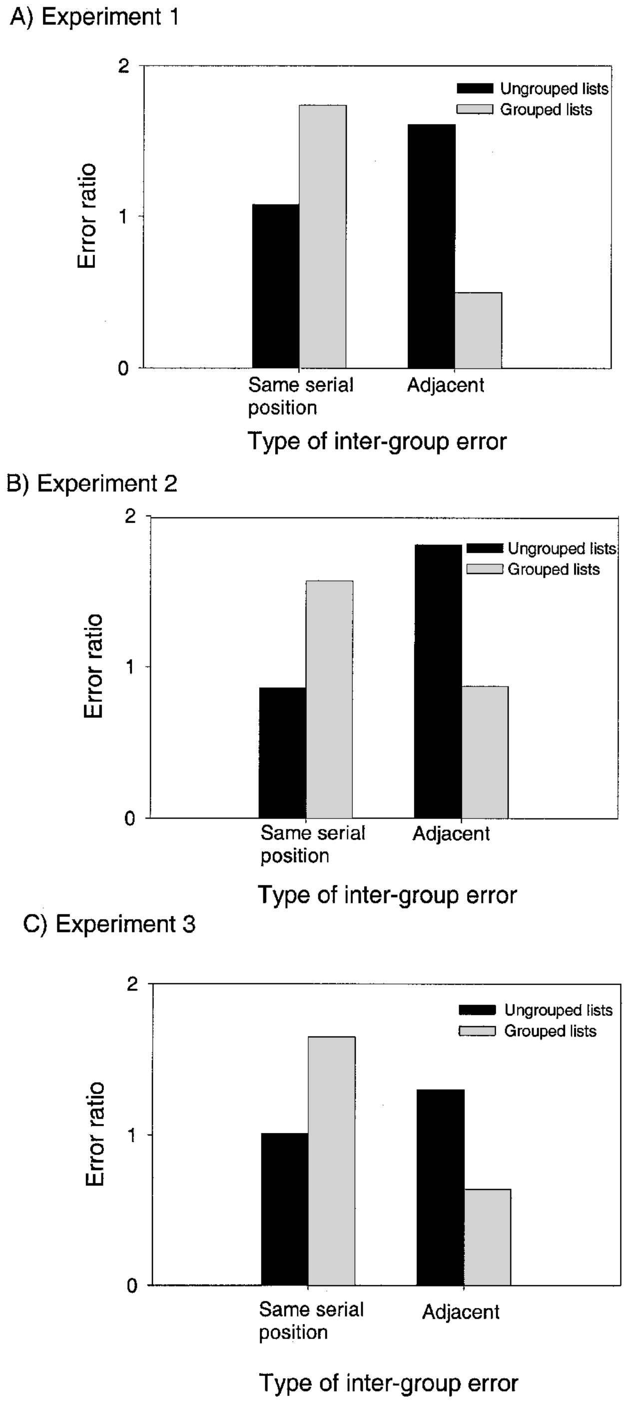

Figure 5. Mean error ratio for two types of interposition error as a function of list type for Experiments 1–3.

the presented list or the recalled list of the previous trial.[5] Intrusions arising from these two sources showed similar patterns of effects in each of the three experiments. However, the effects were more pronounced, and more often significant, in the analyses of protrusions from the previously recalled list, so our reporting is restricted to these protrusions.

Error ratios were calculated for protrusions from the previously recalled list, and a 2 (list type: grouped vs. ungrouped) × 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted. There was a significant error type by list type interaction, $F(1, 39) = 26.34$, $MSE = 0.44$, $p < .001$ (see Figure 6A), but no other effects were significant. To explore the interaction further, the simple effect of list type was calculated for each error type. Intrusions involving adjacent inter-group positions showed a lower error ratio for grouped than for ungrouped lists, $t(39) = 3.47$, $p < .001$ (Figure 6A). On the other hand, intrusions involving the same serial position in a different group showed a higher error ratio for grouped than for ungrouped lists, $t(39) = 4.71$, $p < .001$ (Figure 6A). Intrusions from the previously recalled list therefore show a shift in pattern from ungrouped to grouped lists, which reflects the influence of an item's within-group serial position.

Discussion

Whether position coding is time dependent or time independent was addressed by focusing on the pattern of order errors of grouped lists when the temporal separation of items was varied within groups. This variation effectively dissociated serial order and temporal information. Order errors in which items were transposed across groups were of critical interest because the time-dependent (PL and OSCAR) models predict that these errors should reflect coincidence in timing from the onsets of the groups. On the other hand, time-independent (SE and ORSE) models predict that these errors should depend on serial position. Time-dependent models predict a higher frequency of 2–3–2 interpositions than of 2–2–2/3–3–3 interpositions for the LSL lists, and a higher frequency of 3–2–3 interpositions than of 2–2–2/3–3–3 interpositions for the SLS lists. The time-independent (SE and ORSE) models predict the reverse. Both classes of model predict 2–2–2/3–3–3 interpositions for the SSS and LLL lists. The analysis of order errors did not provide any evidence of an increased incidence of either 2–3–2 interpositions for the LSL lists, or 3–2–3 interpositions for the SLS lists. Instead, these lists were undifferentiated from the SSS and LLL lists in showing elevated levels of the 2–2–2/3–3–3 interpositions, therefore providing support for time-independent models. It therefore appears that order errors involving transposition across groups reflect within-group serial position rather than within-group temporal position.

Further support for the time-independent models over the time-dependent models came from the analysis of protrusions. Across all combinations of group timing, the error ratio was higher for 2 → 2/3 → 3 protrusions than for 2 → 3 and 3 → 2 protrusions. There was no evidence of an elevated incidence of error 2 → 3 for an L to S protrusion, nor of the error 3 → 2 for an S to L protrusion. Thus items from the immediately preceding list intruded on the recall of

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[5] Note that when protrusions were analysed earlier in tests of the time-dependent and time-independent models, with analyses restricted to intrusions across the grouped lists, we considered only intrusions from the previously presented list. It is not possible to conduct tests of the models using intrusions from the previously reported list because it is nonsensical to consider whether temporal information has been preserved for intrusions that were errors on the preceding list.

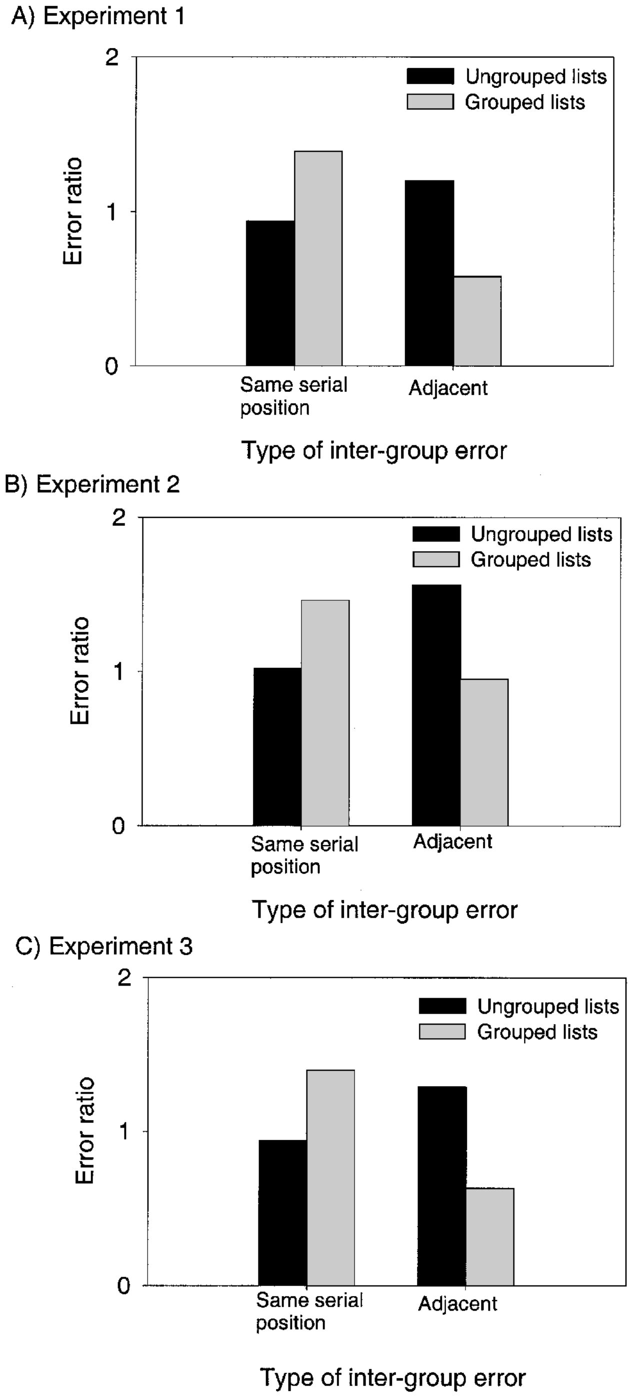

Figure 6. Mean error ratio for two types of protrusion error as a function of list type for Experiments 1–3.

the current list in a manner that did not reflect within-group temporal position. These errors tended to maintain within-group serial position.

One possible argument is that the present experiment failed to support the predictions of the time-dependent models because the variations in within-group temporal position adversely affected the entrainment of the set of temporal oscillators expected to encode intra-group contextual information. However, our presentation conditions did yield a number of effects consistent with grouping having been induced. First, accuracy was higher overall for grouped than for ungrouped lists. Second, the serial position function for grouped lists showed evidence of multiple scalloping whereas the function for ungrouped lists took the typical U-shaped form (Figure 4A). These serial position functions are consistent with the results of other studies of grouping, for which within-group SOAs had been held constant (Frankish, 1989; Hitch et al., 1996; Ryan, 1969a, b). Third, order errors showed a different pattern for grouped lists compared to ungrouped lists: Grouped lists showed lower frequencies of the migration of adjacent items across group boundaries, but higher frequencies of items swapping groups in a way that maintained within-group serial position. These shifts in order errors as a function of grouping are consistent with reports by Ryan (1969a, b) and Wickelgren (1967). The final source of evidence that the procedures of the current experiment were sufficient to induce grouping comes from the analysis of protrusions from the previously reported list. Protrusions that involved a shift of group but retention of within-group serial position were higher for grouped lists than for the corresponding protrusions for ungrouped lists. By contrast, protrusions involving adjacent inter-group positions were lower for grouped lists compared to the corresponding errors for ungrouped lists. This effect of grouping, whereby intrusions from previously reported lists tend to respect within-group serial position, is consistent with reports for ungrouped lists where intrusions respect within-list serial position (Estes, 1991; Henson, 1999b).

Thus effects concerning overall accuracy, serial position functions, order errors, and protrusion errors indicate that participants were grouping items into triplets in the grouped lists. It therefore appears that the procedures of Experiment 1 did not interfere with the operation of whatever mechanism encodes within-group positional information. However, the use of vocalized visual presentation of the letter sequences introduces two other complications to interpreting the results of Experiment 1 in relation to the time-dependent models. These complications are addressed in Experiments 2 and 3.

EXPERIMENT 2

According to the working-memory model, verbal information gains direct access to the phonological store if presented auditorily, but can enter the store only indirectly—by way of recoding through an articulatory rehearsal mechanism—if presented visually (Baddeley, 1986). The PL model appears to carry these assumptions of the working-memory model, but further assumes that information in the phonological store is associated with contextual information provided by the temporal oscillators (see Figure 1). So the timing of information entering the phonological store would appear to be crucial to grouping under the PL model. With vocalized visual presentation (as used in Experiment 1), it is possible that the intervals between the items of each group were “regularized” when the articulatory rehearsal mechanism converted the visually presented consonants into their phonological representations. The aim of

Experiment 2 was to address this possibility by using auditory presentation, which is assumed to provide direct entry of verbal information to the phonological loop. Experiment 2 mimicked Experiment 1 except for the use of auditory lists, so the predictions of the models are as described for Experiment 1.

Method

Participants

The participants were 32 undergraduates (23 female) at the University of Western Australia. They were aged between 17 and 36 years.

Apparatus

The apparatus consisted of a 486 IBM-compatible personal computer with a 36-cm Hitachi monitor, a Sound Blaster AWT 32 card, and Arista FS 300 fully enclosed headphones.

Stimuli

The practice and test trials were constructed in the manner described for Experiment 1. However, in preparation for auditory presentation of the consonant sequences, the 20 consonants excluding W were recorded using Goldwave audio software. They were spoken by an adult Australian male in English, his first language. Each consonant was recorded in 16-bit wave format and then trimmed and converted to an 8-bit au format. Each fitted a 400-ms envelope.

Analytic methods for interposition and protrusion errors

Methods described in Experiment 1 were used; however, a few participants did not make errors of the type addressed in some analyses, so error ratios could not be calculated for them. This was the case for one participant in all the analyses of interposition errors, one participant in the analysis of protrusion errors directed at evaluating the models, and five participants for the analysis of protrusion errors that compared grouped and ungrouped lists.

Procedure

The procedure was as for Experiment 1, with four exceptions. First, the consonants were presented auditorily through the headphones, rather than visually. Second, the warning signal that preceded each sequence consisted of a cross centred on the screen, accompanied by a short tone. Third, participants used the mouse to move from one box to another in attempting to recall each sequence, and to indicate the end of recall and readiness for the next trial. Fourth, the instructions were changed to reflect these differences.

Results

Accuracy for grouped vs. ungrouped lists

The serial position curves are similar in form to those reported in Experiment 1 although the differences between the grouped and ungrouped lists appear to be more pronounced for the auditory presentation of the current experiment (see Figure 4B). Once again, accuracy is higher for grouped than for ungrouped lists. Also, primacy and recency trends are present for both types of list but are more pronounced for the ungrouped lists, for which performance is very much suppressed at Serial Positions 4 through 8. Finally, for the grouped lists, there is the multiple bowing characteristic of temporal grouping. Consistent with these observations, a 2 (list type: grouped vs. ungrouped) × 9 (serial position) repeated measures ANOVA yielded significant main effects of list type and serial position, with $F(1, 31) = 147.23$, $MSE = 3.13$, $p < .001$, and $F(8, 248) = 40.41$, $MSE = 2.34$, $p < .001$, respectively. There was also an interaction between list type and serial position, $F(8, 248) = 13.39$, $MSE = 1.27$, $p < .001$. The quadratic trend over serial position was significant overall, $F(1, 248) = 124.84$, $p < .001$, and interacted with list type, $F(1, 248) = 70.90$, $MSE = 1.27$, $p < .001$.

Interposition errors for grouped lists: Evaluation of time-dependent and time-independent predictions

A 4 (type of grouped list: LLL vs. SSS vs. LSL vs. SLS) × 3 (error type: 3–2–3 vs. 2–3–2 vs. 2–2–2/3–3–3) repeated measures ANOVA was conducted on the error ratios for interposition errors. Outcomes were very similar to those reported in Experiment 1. The main effect of error type was significant, $F(2, 60) = 36.27$, $MSE = 0.80$, $p < .001$, but neither the main effect of type of grouped list nor the interaction was significant. Post hoc *t* tests showed, as for Experiment 1, that the error ratio was higher for 2–2–2/3–3–3 interpositions than for either the 2–3–2 interpositions or the 3–2–3 interpositions (see Table 2). The pattern of interpositions errors reported in Experiment 1 was therefore replicated for auditory presentation in the present experiment. Interposition errors were sensitive only to within-group serial position, as predicted by the time-independent models.

The chi-square analyses described in Experiment 1 were also conducted for Experiment 2 as a check on the results from the analyses of the error ratio. For the SLS lists, the prediction for the time-dependent models is that 3–2–3 interpositions should occur more frequently than 2–2–2/3–3–3 interpositions. This was the case for 6 participants, with 25 participants showing a difference in the contrary direction, $\chi^2(1) = 11.64$, $p < .001$. For the LSL lists, the critical prediction for the time-dependent models is that 2–3–2 interpositions should occur more frequently than 2–2–2/3–3–3 interpositions. However, only 8 participants showed a difference in the predicted direction, whereas 23 participants showed a difference in the opposite direction, $\chi^2(1) = 7.26$, $p < 0.01$. So for both list types, the predictions of the time-dependent models are not supported. Instead, the time-independent SE and ORSE models are favoured by the predominance of 2–2–2/3–3–3 transpositions.

Protrusion errors for grouped lists: Evaluation of time-dependent and time-independent predictions

As in the previous experiment, a 2 (group position: same vs. different) × 2 (timing: same vs. different) × 2 (type of error: $2 \rightarrow 3, 3 \rightarrow 2$ vs. $2 \rightarrow 2, 3 \rightarrow 3$) repeated measures ANOVA was conducted on error ratios calculated for the protrusions from the previously presented list. The main effect of type of error was significant, $F(1, 30) = 25.09$, $MSE = 1.08$, $p < .001$. The error ratio for $2 \rightarrow 2, 3 \rightarrow 3$ protrusions ($M = 1.28$, $SE = 0.11$) was higher than the ratio for $2 \rightarrow 3, 3 \rightarrow 2$ protrusions ($M = 0.62$, $SE = 0.07$). There were no other significant effects. Thus, similar to Experiment 1, there is no support for the contention, developed from the time-dependent models, that the timing of presentation of the previous and current lists should affect the intrusions that are made. Instead, these intrusions simply preserve within-group serial position as predicted by the time-independent models.

Interposition errors for grouped vs. ungrouped lists

Similar to Experiment 1, a 2 (list type: grouped vs. ungrouped) × 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted. The only significant effect was the list type by error type interaction, $F(1, 30) = 115.24$, $MSE = 0.18$, $p < .001$. This was further explored by examining the effect of list type for each error type. For same serial position inter-group errors, the ratio was higher for grouped than for ungrouped lists: Figure 5B; $t(30) = 12.05$, $p < .001$. On the other hand, for adjacent inter-group errors, the ratio was lower for grouped than for ungrouped lists: Figure 5B; $t(30) = 5.99$, $p < .01$. Thus in this experiment, which used auditory presentation, there was again strong preservation of within-group serial position in transposition errors for grouped lists.

Protrusion errors for grouped vs. ungrouped lists

A 2 (list type: grouped vs. ungrouped) × 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was limited in outcome to one effect of marginal statistical significance, that of the interaction between list type and error type, $F(1, 26) = 3.83$, $MSE = 1.94$, $p = .061$. The simple effect of list type was significant for the same serial position inter-group error, with $t(26) = 3.13$, $p < .01$. The mean ratio for this error type was greater for grouped lists than for ungrouped lists (see Figure 6B). This pattern of errors is consistent with Experiment 1 and with the conclusion that protrusion errors favour retention of within-group position for grouped lists.

Discussion

Given that auditory presentation is said to enable direct entry of verbal information to the phonological loop, this experiment provided a more direct test of time-dependent models. Nevertheless, consistent with Experiment 1, there was no evidence of increased frequencies of 2–3–2 interpositions for LSL lists and 3–2–3 interpositions for SLS lists, compared to 2–2–2/3–3–3 interpositions. Rather, 2–2–2/3–3–3 interpositions occurred with higher frequencies for all list types. These results provide further support for the time-independent models over the time-dependent models. In reference to protrusions, the errors 3 → 2 for S to L and 2 → 3 for L to S were not prominent. Instead, protrusions that preserved within-group serial position (2 → 2 and 3 → 3) occurred with elevated frequencies for all grouped lists. Again, these results favour the time-independent models. Thus the interposition and protrusion errors, in showing no sensitivity to the relative timing of items from group onset, provide evidence against the simple use of time in encoding within-group position, as advocated by the time-dependent PL and OSCAR models.

Recall was more accurate for the auditorily presented lists of Experiment 2 than for the visually presented lists of Experiment 1. Nevertheless, an advantage in accuracy was still present for grouped compared to ungrouped lists in Experiment 2, and differences in the serial position functions, with multiple scalloping for the grouped lists, were also observed. Effects of grouping were also present in the analysis of interposition errors: Same serial position inter-group errors provided a higher error ratio whereas adjacent inter-group errors provided a lower error ratio for grouped compared to ungrouped lists. In relation to the intrusion of items from the previously reported list, the error ratio for same serial position inter-group protrusions in grouped lists was higher than the error ratio calculated for comparable protrusions in ungrouped lists. Experiment 2 therefore replicated major effects associated with grouping that were reported in Experiment 1.

Although Experiment 2 provided conditions expected to result in the direct entry of information to the phonological loop, the intervals between groups provided opportunities for rehearsal. Rehearsal may modify the temporal separation of items and this may be why support was not found for the time-dependent models. Experiment 3 examined this possibility.

EXPERIMENT 3

Under the working-memory model, representations held in the phonological store decay below threshold in approximately 2 s unless "refreshed" by subvocal rehearsal (Baddeley, 1986). The interval of 4 s from onset of one group to onset of the next, as used in Experiments 1 and 2, exceeds the estimated 2-s life of representations held in the phonological store. This suggests that retention of the grouped lists may have required rehearsal during list presentation. Such maintenance rehearsal may have occurred in the intervals between groups. It could be argued that this rehearsal is the means by which the intervals between items are "regularized". That is, a constant rate of rehearsal could eliminate differences in timing for the items of the S and L groups, and this could invalidate our test of the time-dependent PL and OSCAR models.

In addition, in the description of OSCAR, a potential role for rehearsal is identified in modifying the contextual information provided by temporal oscillators. Brown et al. (2000) argued that very fast or very slow presentation rates may provide sub-optimal temporal codes, but that subsequent rehearsal at an intermediate rate may allow more discriminable context signals to be formed. A role for rehearsal in grouping is also suggested from Wickelgren's (1964) work in which instructions to rehearse temporally uniform lists in groups provided effects consistent with those found for lists with temporally demarcated groups. Measurement taken of changes in pupil size by Kahneman, Onuska, and Wolman (1968) has also led to the suggestion that pauses between groups allow participants to rehearse items without having to attend to new items.

There are some complications in assuming that rehearsal can be used to modify information encoded from temporal oscillators, as we shall discuss later, but nevertheless it seemed sensible to examine the predictions generated for the time-dependent models under conditions designed to suppress rehearsal. Brown et al. (2000) suggested that articulatory suppression could be used to examine the influence of variations in presentation rate uncontaminated by rehearsal. Accordingly, Experiment 3 was similar in design to Experiment 2 except that participants rehearsed "the the the" rapidly and continuously throughout list presentation and recall.

Articulatory suppression throughout list presentation and recall was expected to inhibit rehearsal. However, given that we were using auditory presentation, we did not expect articulatory suppression to eliminate the typical temporal grouping effects. Hitch et al. (1996) reported that articulatory suppression throughout auditory list presentation and recall did not modify the advantage that temporally grouped lists showed over ungrouped lists, nor did it affect the serial position functions these lists provided (see similar results reported by Frick, 1989, where articulatory suppression was limited to list presentation). For the present experiment, critical interest centred on whether support might be forthcoming for the particular interposition and protrusion errors predicted for the time-dependent models under conditions in which articulatory suppression inhibited rehearsal.

As indicated earlier, articulatory suppression was expected to suppress recall accuracy (Baddeley, 1986; Hitch et al., 1996). Therefore, 6- rather than 9-item lists were used in the present experiment. The four types of grouped list were SS, SL, LS, and LL. Predictions for the time-dependent models for these 6-item lists are analogous to those described in Experiment 1 for 9-item lists. In respect of interposition errors, the 3rd item of the first group and 2nd item of the second group are predicted to exchange positions for SL lists, whereas the 2nd item of the first group and the 3rd item of the second group are expected to exchange positions for LS lists. In respect of protrusions, the second item from an L group is expected to intrude on the 3rd item from an S group, and vice versa. These predictions follow from consideration of the elapsed time from group onset.

Method

Participants

The participants were 28 undergraduates (21 female) at the National Institute of Education of Singapore. They were aged between 18 and 31 years.

Apparatus

The apparatus consisted of a MMX Pentium CD notebook, a Sound Blaster compatible full duplex sound card, and headphones.

Stimuli

The practice and test trials were constructed in the manner described for Experiment 2, with one exception: There were six instead of nine letters in each sequence.

Procedure

The procedure was as that for Experiment 2, with three exceptions. First, the participants were instructed to say "the, the, the" rapidly and repeatedly from the start of the trial to the completion of recall. Second, the warning signal that preceded each sequence consisted of an instruction to start saying "the", and the end of each trial was followed by an instruction to stop saying "the". Conformity to this instruction was monitored closely by the experimenter. Third, recall consisted of filling six rather than nine boxes with letter responses.

Analytic methods for interposition and protrusion errors

Again, a few participants made no errors of the type addressed in some analyses, and so error ratios could not be calculated for them. This was the case for three participants in analyses of interposition and protrusion errors that evaluated the models, and for four participants in the analysis of interposition errors for grouped and ungrouped lists.

Results

Accuracy for grouped vs. ungrouped lists

Accuracy was generally higher than that in the previous experiments (Figure 4C), and once again accuracy was higher for grouped than for ungrouped lists. Thus the characteristic multiple bowing of the serial position curve often found in grouped lists was probably obscured by the ceiling performance level. A 2 (list type: grouped vs. ungrouped) × 6 (serial position) repeated measures ANOVA yielded significant main effects of list type and serial position, with $F(1, 27) = 75.81$, $MSE = 1.52$, $p < .001$, and $F(5, 135) = 26.53$, $MSE = 1.75$, $p < .001$, respectively. There was also an interaction of list type and serial position, $F(5, 135) = 19.48$, $MSE = 0.72$, $p < .001$ (Figure 4C). The quadratic trend over serial position was significant overall, $F(1, 135) = 197.51$, $MSE = 0.72$, $p < .001$, and also interacted with list type, $F(1, 135) = 73.26$, $MSE = 0.72$, $p < .001$.

Interposition errors for grouped lists: Evaluation of time-dependent and time-independent predictions

Errors were less frequent than for the previous experiments (which used 9-item lists), so data from SS and LL lists were combined, as the same pattern of order errors is predicted for the two. A 3 (type of grouped list: SS/LL vs. SL vs. LS) × 3 (error type: 3–2 vs. 2–3 vs. 2–2/3–3) repeated measures ANOVA was conducted on the error ratios. The only significant effect was the main effect of error type, $F(2, 46) = 11.16$, $MSE = 1.50$, $p < .001$. The error ratios display a pattern consistent with Experiments 1 and 2: Post hoc *t* tests showed that the 2–2/3–3 interpositions had a higher error ratio than either the 3–2 interpositions or the 2–3 interpositions (see Table 2). Therefore support is retained for the time-independent models even when articulatory suppression is employed.

Chi-square analyses were also conducted. For the SL lists, the prediction for the time-dependent models is that 3–2 interpositions should occur more frequently than 2–2/3–3 interpositions. This was the case for only 4 participants, with 14 participants showing a difference in the contrary direction, $\chi^2(1) = 5.55$, $p < .05$. For the LS lists, the prediction for the time-dependent models is that 2–3 interpositions should occur more frequently than 2–2/3–3 interpositions. However only 3 participants showed a difference in the predicted direction, whereas 15 showed a difference in the opposite direction, $\chi^2(1) = 8.00$, $p < .01$. So once again there is evidence of a predominance of 2–2/3–3 transpositions, which favours the time-independent models.

Protrusion errors for grouped lists: Evaluation of time-dependent and time-independent predictions

As in the earlier experiments, a 2 (group position: same vs. different) × 2 (timing: same vs. different) × 2 (type of error: $2 \rightarrow 3, 3 \rightarrow 2$ vs. $2 \rightarrow 2, 3 \rightarrow 3$) repeated measures ANOVA was conducted on the intrusion error ratios. There was a significant main effect of group position, $F(1, 24) = 6.11$, $MSE = 1.73$, $p < .05$, but no other effects were significant. Intrusions were more frequent from the same group position ($M = 1.20$, $SE = 0.16$) than from a different group position ($M = 0.74$, $SE = 0.10$).

Interposition errors for grouped vs. ungrouped lists

A 2 (list type: grouped vs. ungrouped) × 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted. The main effect of list type was significant, $F(1, 23) = 11.47$, $MSE = 0.57$, $p < .01$, as was the list type by error type interaction, $F(1, 23) = 37.48$, $MSE = 0.83$, $p < .001$. In following up the interaction, the simple effect of list type was found to be significant for both same serial position inter-group interpositions, $t(23) = 3.56$, $p < .001$, and adjacent inter-group interpositions, $t(23) = 5.63$, $p < .001$. As for Experiments 1 and 2, the error ratio was higher for grouped than for ungrouped lists with same serial position interpositions, whereas the difference was reversed with adjacent inter-group interpositions (Figure 5C).

Protrusion errors for grouped vs. ungrouped lists

A 2 (list type: grouped vs. ungrouped) × 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted on protrusions from the previously reported list. Neither main effect was significant, but there was a significant interaction between error type and list type, $F(1, 27) = 6.28$, $MSE = 1.40$, $p < .05$. The simple effect of list type was significant for both adjacent inter-group protrusions, $t(27) = 1.66$, $p < .05$, and same serial position inter-group protrusions, $t(27) = 2.07$, $p < .05$. For adjacent inter-group protrusions, there was a lower ratio for grouped lists than for ungrouped lists (see Figure 6C). For protrusions involving the same serial position in different groups, the error ratio was higher for grouped lists than for ungrouped lists (Figure 6C).

Discussion

Experiment 3 examined the possibility that participants in the previous experiments may have used rehearsal to render more regular the within-group intervals between items. It was suggested that a uniform rate of rehearsal could eliminate differences in timing for the items of the S and L groups, and this could invalidate our tests of the time-dependent models. With this possibility in mind, Experiment 3 used articulatory suppression to prevent rehearsal.

However, under conditions of articulatory suppression during presentation and recall, no support was found for the particular interpositions and protrusions predicted from the time-dependent models. The interpositions again showed a predominance of errors that respected within group serial position for all types of grouped list (i.e., SL and LS as well as SS and LL). That is, in all cases higher error ratios were observed for 2-2/3-3 interpositions than for 2–3/3–2 interpositions, which lends support to the time-independent models. There was no evidence of a shift towards order errors that respected within-group timing—that is, 3–2 interpositions for SL or 2–3 interpositions for LS, as predicted by time-dependent models. Also, in further analyses of data from the grouped lists, protrusions from the previously presented list again showed no evidence of error $2 \rightarrow 3$ for an L to S intrusion, nor of the error $3 \rightarrow 2$ for an S to L intrusion. (Note however, that $2 \rightarrow 2, 3 \rightarrow 3$ protrusions did not occur significantly more frequently than $2 \rightarrow 3, 3 \rightarrow 2$ intrusions, as had been observed in the first two experiments. This may reflect the lower rates of error for the 6-item lists of the present experiment.)

Other facets of performance consistent with grouping were observed: Accuracy was higher for grouped than for ungrouped lists, although the serial position curve did not show evidence of strong multiple scalloping as in Experiment 1 and 2, as performance was reaching ceiling level. Grouped lists also provided more same serial position inter-group interpositions and fewer adjacent inter-group interpositions than did ungrouped lists. A similar pattern of effects was observed when protrusions from the previously reported list were examined. Observing these differences under conditions of articulatory suppression reinforces the claim made by Hitch et al. (1996) that the rehearsal process is not critical to effects on recall due to temporal grouping (see also Frick, 1989).

GENERAL DISCUSSION

Three experiments were conducted to evaluate the nature of position coding: Whether it is time dependent as advocated by the PL and OSCAR models or time independent as advocated by the SEM and ORSE models. Results consistently supported the time-independent models. The within-group temporal separation of items during presentation did not affect the pattern of transposition errors across all three experiments. These errors consistently reflected within-group serial position. Errors on grouped lists involving the intrusion of items from the previously presented lists also tended to respect within-group serial position. Again there was no evidence that differences in the timing of presentation of the items within groups affected the errors observed. These results held for vocalized visual presentation (Experiment 1), auditory presentation (Experiment 2), and auditory presentation with articulatory suppression (Experiment 3). Therefore any mechanism that encodes positional information does not appear to faithfully preserve the intervals that separate the items comprising groups (at least over the range of intervals examined in this study, which are similar to those used by Hitch et al., 1996). Time-dependent models cannot accommodate these results.

Further, the results obtained cannot be attributed to participants having not encoded the structure of the grouped lists. Recall for grouped and ungrouped lists differed in overall level of accuracy, shape of the serial position function, and the pattern of interposition errors, consistent with results reported by Henson (1996, 1999b), Hitch et al. (1996), Frankish (1985, 1989), Ryan (1969a, b), and Wickelgren (1967). Our experiments also established an additional effect of temporal grouping obtained when errors were examined for the intrusion of items from the previously reported list. These protrusion errors favoured maintenance of within-group serial position. Therefore, given that comparisons between the grouped and ungrouped lists revealed several coherent and consistent differences in performance, it appears that the structure of the grouped lists was encoded in the present series of experiments.

One possibility raised in the review of this manuscript is that the use of keyboard responses may have affected the memory processes employed. For example, participants may have shifted away from phonological representations of the memory items and relied instead on visuospatial representations. One way to assess whether participants relied on phonological representations is to examine if intrusions consisted of items phonologically similar to the items they displaced from the presented list. We divided the consonant stimuli into rhyming (B, C, D, G, P, T, V) and non-rhyming (F, H, J, K, L, M, N, Q, R, S, X, Z) sets. If letters are remembered in phonological form, then the proportion of intrusions that come from the rhyming set should be higher when the letter misremembered is itself from the rhyming set rather than from the non-rhyming set. For each participant, the ratio of the number of rhyming set intrusions to the total number of intrusions was calculated separately for misremembered items from the rhyming set and misremembered items from the non-rhyming set.[6] In each experiment, the proportion of intrusions consisting of rhyming set items was significantly higher when the misremembered item was from the rhyming set rather than from the non-rhyming set (see Table 3 for descriptive statistics and *t* tests). This finding is consistent with other research showing that intrusions tend to be similar in phonology to the items they displace (Ellis, 1980; Wickelgren, 1965). These subsidiary analyses appear to indicate that items were held in the phonological loop and that the use of keyboard responses did not substantially distort memory processes. Note that a direct comparison of keyboard and spoken responses in the serial recall of ungrouped lists has shown similar effects on accuracy and response latency for the two modes of response (Dosher & Ma, 1998).

Our central conclusion—that memory for serial order does not depend on the retention of precise temporal information—is based primarily on the reported analyses of errors. However, evidence from a recent study of the timing of recall (Maybery, Parmentier, & Jones, in press) is also pertinent to this conclusion. In their first experiment, Maybery et al. showed that the latencies separating the recall of successive items were sensitive to temporal grouping at presentation. A peak in latency occurred as recall shifted from the last item in one group to the first item in the next. Furthermore, the profile of latencies over serial position bore some similarity to the profile of SOAs (short within group and long between group) that had governed presentation of the grouped lists. However, this apparent sensitivity of recall to the timing of item presentation was not maintained in Maybery et al.'s second experiment in which "tight-bunched" and "loose-bunched" grouping conditions were employed. The ratio of within-group SOA to between-group SOA was 1:5 for the tight-bunched condition, which contrasted with a 1:2 ratio for the loose-bunched condition. Despite these differences in timing of presentation, the two conditions yielded almost identical latency profiles as a function of serial position. This finding is difficult to reconcile with the assumption of the time-dependent PL and

TABLE 3
Mean proportion of intrusion errors consisting of an item from the rhyming set as a function of whether the displaced item was part of the rhyming set or part of the non-rhyming set

	Displaced item part of rhyming set[a]		*Displaced item part of non-rhyming set*[b]		
Experiment	*M*	*SD*	*M*	*SD*	*t test*
1	.441	.076	.333	.037	$t(39) = 7.15, p < .001$
2	.488	.099	.332	.055	$t(31) = 6.46, p < .001$
3	.639	.246	.185	.121	$t(26) = 8.46, p < .001$

[a] B, C, D, G, P, T, V.
[b] F, H, J, K, L, M, N, Q, R, S, X, Y, Z.

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[6] We recognize that some letters in the "non-rhyming" set actually rhyme (e.g., J & K). This is not a problem for our argument, which depends on similarity in phonology being lower across sets than within sets. For the analyses, intrusions consisting of items from outside the stimulus pool (e.g., vowels) were not included, and counts were accumulated across all lists. The misremembered item for each intrusion was the item that had been presented in the serial position occupied by the intrusion.

OSCAR models that oscillators used at encoding are rerun to cue recall. If this were the case, variation in the ratio of within-group SOA to between-group SOA should have been reflected in variation in the latency profile over serial position, with the tight-bunched condition showing a more pronounced peak in latency at the transition from one group to the next. The absence of this difference confirms that precise temporal information is not retained when a sequence of verbal items is memorized.

Whereas the timing of items within groups does not appear to be important, other aspects of the timing of list presentation clearly are important. First, the extended temporal gaps between the 3rd and 4th and 6th and 7th items for the grouped lists led to both quantitative and qualitative changes in recall when compared to recall from the ungrouped lists. Part of the improved accuracy for the grouped lists may reflect extra time available to encode and consolidate items during presentation. For the 9-item lists of Experiments 1 and 2, the interval from onset of the first item to onset of the recall display was 12 s for the grouped lists, 9 s for the 1000-ms SOA ungrouped lists, and 4.5 s for the 500-ms SOA ungrouped lists. If the critical factor is the duration of the presentation interval per se, then differences in accuracy might also be expected when comparing the 500-ms SOA and 1000-ms SOA ungrouped lists. Subsidiary analyses (see Appendix) did show a significantly higher level of accuracy for the 1000-ms SOA than for the 500-ms SOA ungrouped lists in Experiment 1; however, this comparison did not approach significance in Experiments 2 and 3 (see Appendix). Any general advantage provided by a slower rate of presentation appears to have been restricted to the vocalized visual presentation conditions of Experiment 1. It is also worth noting that no qualitative differences, such as in the shape of serial position functions or the patterns of order and protrusion errors, were apparent in the comparisons of the 500-ms SOA and 1000-ms SOA ungrouped lists. A final reason why it is unlikely that presentation interval per se accounts for the differences we report in comparing grouped and ungrouped lists is that most of these differences have been reported in other studies. The magnitude of these effects does not appear to depend on whether the presentation interval was equated across grouped and ungrouped lists (e.g., Hitch et al., 1996, Experiment 1; Ryan, 1969a, b) or whether it was not (e.g., Frankish, 1985, 1989; Hitch et al., 1996, Experiments 2–4).

Although the total duration of presentation may not be critical (at least within the range used here), it is possible that the discontinuous presentation for the grouped lists provided advantages in recall in offering opportunities for rehearsal or other means of consolidation in the inter-group intervals. Pertinent to this possibility are subsidiary analyses of accuracy for the four types of grouped list (see Appendix). A significant effect of list type was present in Experiments 1 and 2, but not in Experiment 3. The SSS lists yielded more accurate performance than the LLL lists in Experiment 1 and more accurate performance than the LSL lists in Experiment 2. This could have been because the SSS lists had the longest inter-group intervals, which provided the greatest opportunity for rehearsal and consolidation of early groups of items unencumbered by the encoding of subsequent items. With this possibility in mind, it is not surprising that when articulatory suppression limited the use of rehearsal in Experiment 3, no differences in accuracy were observed among the grouped lists.

Brown et al. (2000) described a role for rehearsal in the OSCAR model in arguing that control over the timing of rehearsal could be used to provide more optimal contextual cues for items. However, the results of Experiment 3 would appear to eliminate the possibility that the pattern of order errors arises because rehearsal is used to “regularize” the temporal contextual information encoded for S and L groups. Rehearsal was restricted by articulatory suppression in Experiment 3, yet order errors still respected within-group serial position rather than within-group timing. Another problem in trying to extend OSCAR using rehearsal to account for order errors is that before items could be associated with "sharper" contextual codes provided by a regular and more optimal rate of rehearsal, the items would first need to be re-established using the contextual information with which they had been associated during their presentation. At this point the time-dependent errors (3–2–3 for SLS lists and 2–3–2 for LSL, lists) would be expected. Errors might be expected to depend more heavily on this re-coding phase (where the contextual codes are sub-optimal) than on later phases that involve rehearsal (where the contextual codes are optimal). Therefore it is difficult for the OSCAR model to escape time-dependent predictions for order errors. (Note that the SIMPLE model developed more recently by Brown and his colleagues offers more promise in accounting for the effects we report—see Brown, Neath, & Chater, 2001.)

Processes of consolidation, such as rehearsal, may also be implicated in intrusion errors (see Henson, 1999b, for related arguments). We reported new evidence of particular intrusions associated with grouping. For grouped lists, when an item from the previously reported list intruded on the recall of the current list, the item tended to retain its within-group serial position even when switching from one group to another. However, it is worth noting that Experiments 1 and 2 showed significantly different patterns of intrusion errors for grouped and ungrouped lists only when the intrusions were scored with reference to the previously reported list and not to the previously presented list. Experiment 3 was the exception in that differences between grouped and ungrouped lists were present for intrusions from the previously presented list as well as for intrusions from the previously reported list.[7] One speculative interpretation of the intrusion data is that processes like rehearsal consolidate associations between positional codes and items that represent errors in recall. These errors are then perpetuated on later trials when the same positional codes are used to cue recall. In preventing rehearsal, Experiment 3 may have limited the consolidation of the associations between positional codes and errors and therefore provided more opportunity for previously presented items to compete as intrusion errors.

Although these differences across experiments invite speculation as to the influence of processes of consolidation, it is worth remembering that in Experiment 3, where articulatory suppression was used, recall remained substantially more accurate for grouped than for ungrouped lists. (Similar results under conditions of articulatory suppression are reported by Hitch et al., 1996.) Therefore temporal segmentation of lists appears to provide an advantage in recall even when rehearsal is suppressed. This advantage probably relates to more differentiated coding of positional information. It is also worth noting that despite differences in accuracy among the four types of grouped list in Experiments 1 and 2 (see Appendix), no differences were observed in the pattern of order errors. This is consistent with findings by Ryan (1969b) and Frankish (1985, 1989) that changes in the length of pauses between groups do not affect the quality of recall.

The analyses of interposition and protrusion errors consistently supported the time-independent SE and ORSE models, so we conclude with some observations concerning the more

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[7] Note that the results sections reported only the analyses of intrusions from the previously reported list.

recent of these models, the ORSE model (Henson & Burgess, 1997). It is appropriate to characterize this model as time independent only with reference to insensitivity to the manipulation of SOA in the present study. Timing of item presentation is important to the ORSE model in two ways. First, the relative intervals between the items within a group are preserved. Imagine presenting a 6-item list with a substantial interval between the 3rd and 4th items to encourage the encoding of two 3-item groups, but in addition, the two SOAs separating the items within each group are such that the first is double the second, or vice versa. If this resulted in the encoding of two 3-item groups (verified by serial position functions and patterns of error), then according to the ORSE model, the timing of responses should reflect the 1:2 or 2:1 ratio of the two within-group SOAs. This prediction is as yet untested.

The second way in which time matters to the ORSE model is that the intervals separating the items determine how a list is parsed into groups—any extended interval will define a boundary between groups. However a limitation of the ORSE model (shared with the PL and OSCAR models) is that it is restricted to differentiating groups in this way—that is, based on a temporal discontinuity in list presentation. The existing model cannot explain the effects of grouping observed when groups are demarcated by a shift in pitch (Frankish, 1989, 1995). Also problematic to the model is Wickelgren's (1964, 1967) success in inducing participants to subjectively group items presented under uniform timing. Nevertheless, the ORSE model provides an elegant account of the effects associated with temporal grouping, including the effects present in order and intrusion errors that we report. Therefore, it may be fruitful to look for ways to extend the model to account for subjective grouping and grouping by pitch.

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APPENDIX

Differences in accuracy among the grouped lists

For Experiment 1, a 4 (type of grouped list: LLL, SSS, LSL, SLS) × 9 (serial position) repeated measures ANOVA was conducted on number correct (maximum 10). The two main effects were significant, with $F(8, 312) = 39.39$, $MSE = 5.50$, $p < .001$, for the effect of serial position, and $F(3, 117) = 2.95$, $MSE = 4.22$, $p < .05$, for the effect of type of grouped list. The interaction was not significant. The significant main effect of type of grouped list was further explored by conducting post hoc *t* tests. The means for the LLL ($M = 5.82$, $SE = 0.13$) and SSS ($M = 6.25$, $SE = 0.12$) lists differed significantly, but neither differed significantly from the means for the SLS ($M = 5.91$, $SE = 0.12$) and LSL ($M = 5.97$, $SE = 0.12$) lists.

The same analysis was conducted for Experiment 2. Once again, there were significant main effects of type of grouped list and serial position, with $F(3, 93) = 3.84$, $MSE = 4.57$, $p < .05$, and $F(8, 248) = 16.23$, $MSE = 4.27$, $p < .001$, respectively, but the interaction was not significant. When post hoc *t* tests were used to compare the means of 6.83 for SSS ($SE = 0.11$), 6.43 for LLL ($SE = 0.13$), 6.32 for SLS ($SE = 0.12$), and 6.29 for LSL ($SE = 0.13$), only the two extreme means differed significantly.

For Experiment 3, a 4 (type of grouped list: LL vs. SS vs. SL vs. LS) × 6 (serial position) repeated measures ANOVA conducted on number correct yielded a significant main effect of serial position, with $F(5, 130) = 5.07$, $MSE = 3.89$, $p < .001$. Neither the main effect of list type nor the interaction of list type and serial position was significant.

The nonsignificant interactions in these analyses indicate no differences in the shape of the serial position function for the different types of grouped list. There is some evidence from Experiments 1 and 2 that the more pronounced temporal differentiation of the groups in the SSS lists led to higher levels of accuracy.

Differences in accuracy among the ungrouped lists

For Experiment 1, differences among the ungrouped lists were examined in a 2 (SOA: 500 ms vs. 1000 ms) × 2 (phase: first vs. last) × 9 (serial position) ANOVA, with the first factor between subjects and the other factors repeated measures. There were significant main effects of SOA and serial position, with $F(1, 38) = 9.97$, $MSE = 37.05$, $p < .01$, and $F(8, 304) = 39.57$, $MSE = 4.91$, $p < .001$, respectively. There was also a significant interaction of SOA and serial position, $F(8, 304) = 2.49$, $MSE = 4.91$, $p < .05$. The simple effect of SOA was significant for each of the Serial Positions 2 to 8. Recall was more accurate for the slower 1000-ms SOA presentation condition, especially for the middle serial positions.

An ANOVA of the same form for Experiment 2 yielded a significant main effect of serial position, $F(8, 240) = 38.78$, $MSE = 4.92$, $p < .001$, and a significant interaction of SOA and serial position, $F(8, 240) = 2.143$, $MSE = 4.92$, $p < .05$. This time the simple effect of SOA was significant only for Serial Position 5. Once again recall was more accurate for the slower 1000-ms SOA presentation condition.

The same ANOVA for Experiment 3 yielded significant main effects of serial position and phase, with $F(5, 125) = 35.95$, $MSE = 2.74$, $p < .001$, and $F(1, 25) = 20.25$, $MSE = 4.10$, $p < .001$, respectively. The interaction of SOA and serial position provided $F(5, 125) = 2.80$, $MSE = 2.74$, $p < .05$. The means showed higher accuracy for the 500-ms SOA condition than for the 1000-ms SOA condition at Serial Positions 1 and 2, but the reverse difference at Serial Positions 3-6. However, none of these differences was significant when tested as a simple effect. There was also an interaction of serial position and phase, $F(5, 125) = 2.31$, $MSE = 1.58$, $p < .05$. The simple effect of phase was significant at Serial Positions 3–6. Accuracy was generally greater for the last phase than for the first.

These analyses for the ungrouped lists show an advantage in recall for the slower 1000-ms SOA rate of presentation, particularly for the middle list items. The only effect of phase was in Experiment 3, where the superior performance in the last phase may reflect adjustment to the demands of concurrent articulation with practice.

Chapter 3

Grouping in verbal short-term memory: Does latency of recall bear any resemblance to presentation rate?

Grouping in verbal short-term memory:

Does latency of recall bear any resemblance to presentation rate?

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Running head: Latency of recall

Abstract

Inserting an extended pause to break a list of verbal items into sub-lists improves serial recall of the list. Additional effects associated with temporal grouping include a multiple-bowed serial position function and changes in order errors. These effects favour computational models in which items are associated with extra-list information that provides position in the list. For three of these positional models, temporal oscillators provide this extra-list information. They differ in their predictions concerning which aspects of the timing of list presentation should be preserved in the timing of recall. Other positional models do not include oscillators and precise aspects of the timing of list presentation are not expected to be reflected in the timing of recall. A test of these predictions was conducted by varying both the within-group and between-group intervals separating consonants in six-item lists formed into two groups of three items. Similar profiles of inter-response latencies were observed across these variations in the timing of lists at presentation, supporting models that do not incorporate oscillators. An analysis of order errors confirmed that a frequent type of error for grouped lists is where items swap across groups in a way that preserves within-group serial position.

The immediate recall of lists of verbal items is facilitated by temporal grouping for both auditory (Frankish, 1985, 1989; Henson, 1998; Hitch, Burgess, Towse & Culpin, 1996; Ng & Maybery, 2002) and visual (Hitch, et al., 1996; Ng & Maybery, 2002) presentation. Temporal grouping consists of using one or more extended pauses to effectively break a list of items into sub-lists (e.g. inserting an extended pause between the third and fourth items to split a six-item list into two three-item sub-lists). The improved performance on grouped compared to ungrouped lists is due largely to the better recall of mid-list items, particularly items on the ends of sub-lists. Thus temporal grouping typically results in multiple bowing of the serial position function. The pattern of order errors also changes with temporal grouping. One feature of this change is a reduction in the transposition of neighbouring items, especially between groups (e.g. exchanging Q for B in SNQ—BXH; see Henson, 1998; Ng & Maybery, 2002; Ryan, 1969a, 1969b). Conjointly, there is an increase in the transposition across groups of items that share the same within-group serial position (e.g. exchanging N for X in the previous example; Henson, 1998; Ng & Maybery, 2002; Ryan, 1969a, 1969b). Another phenomenon associated with temporal grouping is that items from the previous list which intrude on the recall of the current list also respect within-group serial position (Ng & Maybery, 2002).

Current computational models incorporating mechanisms for serial recall are chaining (e.g. Lewandowsky & Murdock, 1989; Murdock, 1995), ordinal (e.g. Page & Norris, 1998) and positional (Anderson & Matessa, 1997; Brown, et al., 2000; Henson, 1998; Henson & Burgess, 1997; Hitch et al., 1996) models. However, the chaining and ordinal models encounter problems explaining phenomena such as the changes in order errors with temporal grouping (see Henson, 1998, for a comprehensive review).

Positional models are better able to explain these phenomena. These models associate items with extra-list information that codes position in the sequence. A major division within this class of model is whether or not temporal oscillators provide this extra-list information. The Start-End (SE) model (Henson, 1998) and the Adaptive Character of Thought-Rational (ACT-R) model (Anderson & Matessa, 1997) do not incorporate temporal oscillators, whereas oscillators are central to the Phonological Loop (PL) model (Burgess & Hitch, 1992, 1996, 1999; Hitch et al., 1996), the OSCillator-based Associative Recall (OSCAR) model (Brown, Preece & Hulme, 2000), and a model we label the Oscillator-Revised Start-End (ORSE) model (Henson & Burgess, 1997).

Temporal oscillators have been used in theories developed for several areas of cognition, including the perception of rhythm in music and speech (Large & Kolen, 1995), time expectancies (Desain, 1992), time estimation (Church & Broadbent, 1990; Treisman, Cook, Naish & Maclone, 1994), tempo discrimination (McAuley, 1994) and, more generally, tracking time-varying events (Large, & Jones, 1999). Given their broad application elsewhere, it is therefore plausible to explore the use of temporal oscillators in the serial recall of verbal lists. In the following section, the different models relying on temporal oscillators, or alternatively on non oscillator-based positional codes, will be described and contrasted. The primary objective of the current study is to evaluate the predictions of these two classes of positional model.

Models relying on positional codes not derived from temporal oscillators

Start-End (SE) model. According to the SE model (Henson, 1998), representations of items are associated with a pair of start and end markers. The start marker is strongest at the first list item and weakest at the last item, whereas the end marker is weakest at the first item and strongest at the last. The markers therefore encode positional information. For grouped lists, two sets of markers are applied. One set provides information regarding position within the list and the other set provides position within a group. At recall, positional cues are gathered from the two sets of markers, as at encoding. However, this time the positional information is used to cue item retrieval. The markers that encode position within a group provide similar strength values for items from different groups that occupying the same within-group positions. This explains the higher transposition errors for these particular items. The timing of item presentation is inconsequential to this model (except that an extended gap demarcates groups) because changes in the coding provided by the markers are event-driven. Thus predictions concerning transposition errors depend simply on within-group serial position and are invariant of the timing of items. Because positional codes used at encoding and at retrieval are unrelated to temporal information, no predictions are made concerning the timing of recall.

Adaptive Character of Thought-Rational (ACT-R) model. Like the SE model, the ACT-R model (Anderson & Matessa, 1997; Anderson et al., 1998) assumes that positional codes are influenced by the rate of presentation of items only to the extent that any extended gap will demarcate groups. The model's representation of grouped lists relies on a hierarchy of positional coding provided by semantic memory. It assumes, like the SE model, that items are coded for position in their groups, but for ACT-R the codes are in essence labels like 1st and 2nd. Similar positional labeling applies at the superordinate level in the hierarchy where the positions of groups in the list are coded. According to this model, positional confusion arises because of partial matching. There can be two forms of partial matching, resulting in two predominant types of error: An item can be retrieved from the same position in a different group or, alternatively, from another position in the same group. This mismatching is dependent on distance from the targeted item—there is a higher chance of confusing nearby items than distant items. Again, like the SE model, positional cues are independent of the timing of items at list presentation. The transposition errors observed, and also the timing of responses, are not influenced by timing at input. Nevertheless, the ACT-R model does make explicit predictions about the latency of recall (Anderson & Matessa, 1997; Anderson et al., 1998; Maybery, Parmentier & Jones, in press) based on the semantic structure used to represent the sequence. It is assumed that retrieval proceeds "down the hierarchy" in that a list node is retrieved first, followed by group nodes, and then the item nodes within each group. All item nodes must be retrieved for each group prior to output of the first item in the group. So a pronounced delay is expected in recalling the first item in a group (relative to recalling the subsequent items in the group). That is, for grouped lists, the inter-response intervals are expected to show peaks at the onsets of groups.

Temporal oscillator models

In contrast to the SE and ACT-R models, three models incorporating temporal oscillators predict that transposition errors and the timing of recall depend on the timing of items at presentation. However, the oscillator models—PL, OSCAR and ORSE—vary in the particular aspects of presentation timing presumed to be preserved in information encoded from oscillators (see Table 1).

	PL	OSCAR	ORSE
Preserves absolute intervals	YES	NO	NO
Preserves ratios of within-group to between-group intervals	YES	YES	NO
Preserves ratios among the within-group intervals	YES	YES	YES

Table 1. Aspects of the timing of list presentation persevered in recall according to the PL, OSCAR and ORSE oscillator-based models.

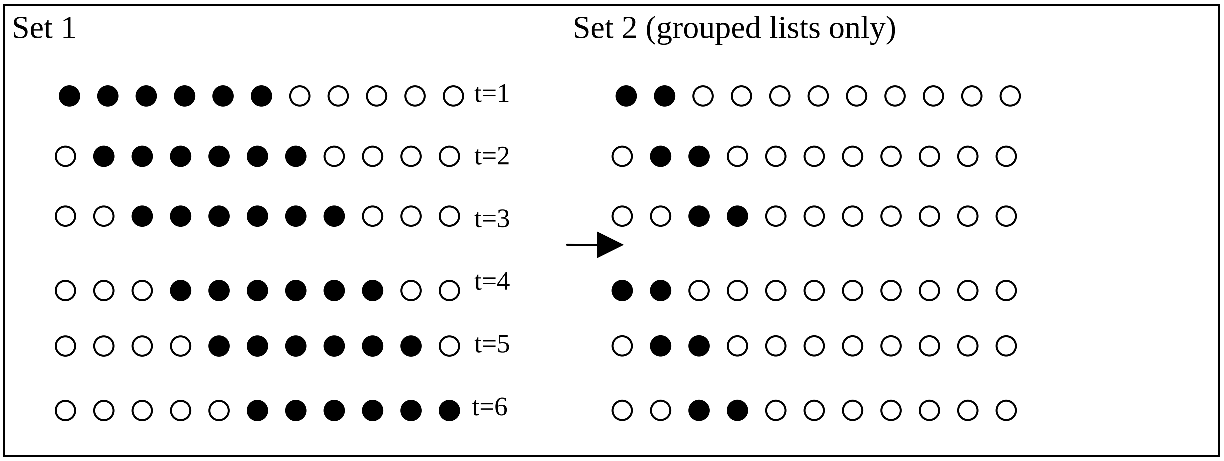

Figure 1. The “context timing” signal of the PL model (taken from Hitch et al., 1996, Figure 13). Activation of temporal oscillators is represented using filled circles. For ungrouped lists, a single set of oscillators (Set 1) is activated at the start of list presentation and re-activated at the start of recall. The second set of oscillators (Set 2) is activated at the start of list presentation and reactivated following each pause (indicated by the arrow). Reprinted by permission of The Experimental Psychology Society.

Phonological Loop (PL) model. The PL model assumes that associations are formed between items, phonemes and a context signal at list presentation. The context signal is derived from a recurrent timing signal presumed to arise from sets of temporal oscillators, each set varying around a modal frequency. For ungrouped lists, as list presentation occurs, a wave of activation passes across the set of oscillators (see Figure 1). The contextual information encoded overlaps, but is distinguishably different, for adjacent items. This allows for order information to be encoded by the context signal. For grouped lists, “a second set of oscillators become entrained such that they are reset after every pause” (Hitch et al., 1996, p. 134). Thus the PL model explains grouping phenomena by assuming that there are two sets of temporal oscillators, one set encoding within-list position and the other set (entrained to the inter-group frequency) encoding within-group position (see Figure 1). During recall or rehearsal, the two sets of oscillators are reset and their unfolding activation is used to cue item retrieval. This means that the timing of recall should reflect directly the timing of items at presentation. The separation of items within and between groups should be preserved in recall (Table 1). Across-group transposition errors should also depend on the timing of items at input. The oscillators that encode within-group context operate in cycle with the onsets of the groups. Any two items in different groups will therefore share context (and be likely to be exchanged in error) if they are presented with similar delays after the onsets of their respective groups.

OSCillator-based Associative Recall (OSCAR) model. The OSCAR model of Brown et al. (2000) is similar to the PL model in assuming that the context signal, which is supported by temporal oscillators, is associated with items at encoding and reinstated during recall. The context signal comprises a number of vectors representing the output of oscillators of different frequencies. Like the PL model, the state of the context vectors at the start of list presentation is retained and used to reset the context at recall, so that list-wise temporal positions of items are encoded. For grouped lists, the OSCAR model like the PL model, adopts a second context signal. Two context signals are described with reference to a clock analogy (see Brown et al., 2000, p. 162). Some of the oscillators (the “hour hand”) encode list-wise position and never repeat their output throughout list presentation. However, other oscillators (the “minute hand”) repeat their cycles of output in phase with the groups and encode within-group position. Context encoded from these oscillators explains across-group transposition errors. Finally, a general feature of the OSCAR model is that the rate of evolution of the temporal oscillators is assumed to be under strategic control, both at encoding and at recall (Brown et al., 2000). This means that, unlike the PL model, the OSCAR model is not constrained to predicting that recall latencies should directly reflect absolute intervals in the timing of presentation. This is because the oscillators can be replayed at recall using a rate of evolution different from the rate used at encoding. However, even if a different rate is used, the ratios of presentation intervals, both within and across groups should be preserved in recall (Table 1).

The extended or Oscillator-Revised Start-End (ORSE) model. The ORSE model (Henson & Burgess, 1997)—an extension of the SE model—was developed to overcome the anticipatory nature of end markers. The ORSE model adopts the idea that position markers are encoded using sets of temporal oscillators. It differs from the PL and OSCAR models by assuming that the temporal oscillators are organized in frequency-matched pairs. More significantly, different oscillator pairs have different frequencies and these compete to best represent positional information for each list and for each group within a list. The winning oscillator pair for the list is the one with a half-cycle closest to the duration of the list. For grouped lists, the winning oscillator pair for each group has a half-cycle closest to the duration of the group. These oscillators are assigned at the end of each group and at the end of the list. The selection of oscillators that have a half-cycle matching the duration of the list or group means that the oscillators do not code absolute timing; rather they code the proportionate timing of items at presentation. Another feature of the model is that oscillators of different frequencies to those selected at encoding can be used to cue recall. This freedom is available both in choosing oscillators for reinstating list-wise information (onsets of the groups) and in choosing oscillators for reinstating group-wise information (onsets of individual items within groups). This means that the ratios of within-group intervals to between-group intervals at list presentation need not be preserved at recall. Nevertheless the ORSE model remains sensitive to within-group variation in timing. For instance, for a group of three items, if the interval between the 1st and 2nd items is double the interval between the 2nd and 3rd items, the recall latencies should reflect this 2:1 ratio in timing. The ratio of timing of items within a group should be preserved from encoding to recall.

The ORSE model therefore completes a transition in the relaxation of constraints on the timing of recall in moving from the PL and OSCAR models. The PL model predicts that recall intervals should preserve the absolute intervals that separate items at presentation; the OSCAR model predicts that only the ratios of these intervals, both within and across groups, should be preserved; finally, the ORSE model predicts that only the ratios of the within-group intervals should be preserved in recall (Table 1).

Oscillator or non-oscillator models?

Is time and hence temporal oscillators essential to the understanding of grouping phenomena? The issue of time having a direct impact on grouping effects has been investigated from different perspectives. One way has been to investigate if the duration of the pause between groups has a direct effect on performance (Ryan, 1969b). It appears not to be important over the range tested: Compared to control lists matched for total list duration, lists with pauses of 900 ms and 3400 ms had indistinguishable effects in elevating accuracy (Ryan, 1969b). Ng and Maybery (2002) conducted a more direct test of the importance of time. They examined whether absolute time is encoded during the presentation of grouped lists. Three experiments were set up to test this idea. The presentation rate was varied from one group to another in the groups comprising individual lists. The items within each group were presented with SOAs of either 500 or 1000 ms. Based on the descriptions of the PL and OSCAR models, transposition errors should depend on the time of occurrence of items from the start of the group rather than their serial positions. Consider a nine-item list split by extended pauses into three groups of three, but where the stimulus onset asynchrony (SOA) is 500 ms for the items in the first group, 1000 ms for items in the second group and 500 ms for items in the third group. According to the PL and OSCAR models, this should result in transposition errors such as item 2 of the second group swapping with item 3 of either the first or third group. This is because these items take the same temporal positions within their respective groups—each commences 1000 ms after the start of its group. However, these types of error were infrequent in each of the three experiments. Transposition errors respected within-group serial position rather than temporal position (Ng & Maybery, 2002). The PL and OSCAR models were not supported.

However, it would be premature to dismiss the role of time in the serial recall of temporally grouped lists. The ORSE model, which codes proportionate rather than absolute time, predicts the pattern of transposition errors observed by Ng and Maybery (2002) for their grouped lists. In each type of group used by Ng and Maybery, the three items were spaced regularly relative to each other. Irrespective of whether the item-to-item SOA was 500 ms or 1000 ms, the three items always occurred at the same relative points (i.e., at the start, midpoint, and end of the interval occupied by the group). It is this relative temporal position that the ORSE model assumes is encoded, so the prediction for the Ng and Maybery (2002) lists is that transposition errors should respect within-group serial position. The ORSE model makes this prediction because oscillators are chosen for each group so that their half-cycle matches the duration of the group. If the PL and OSCAR models adopted a similar assumption they also could predict the predominant form of transposition errors observed by Ng and Maybery.

Some preliminary evidence from the timing of recall also favours the ORSE model over the other two oscillator models (Maybery et al., in press). In their first experiment they showed that the latencies separating the recall of successive items were sensitive to temporal grouping at presentation. In particular, there was an extended recall latency for the between-group transition compared to the within-group transitions. Furthermore, the profile of latencies over serial position resembled the profile of SOAs (short within-group and long between-group) that had driven presentation of the grouped lists. These data supported the three oscillator models, but data from a second experiment clearly favoured the ORSE model. The ratio of within-group SOA to between-group SOA was varied from 1:5 (a “tight-bunched” condition) to 1:2 (a “loose-bunched” condition). The sensitivity of recall to the timing of item presentation was not maintained. These two conditions yielded almost identical latency profiles as a function of serial position. The insensitivity to timing in this second experiment is not consistent with the PL and OSCAR models, which minimally require that the ratio of within- to between-group intervals is preserved from presentation to recall (Table 1). The ORSE model can accommodate these latency data with some post hoc assumptions (see Maybery et al., in press). However, these data do not exclusively support the ORSE model: The central feature of their data for grouped lists—the peak in latency at the onset of each group—can be accommodated by the ACT-R model (which, as explained above, does not incorporate oscillators).

One way to differentiate the ORSE and ACT-R models is to vary the timing of items within individual groups. This approach was taken in the experiment reported below. In two critical types of grouped list, the SOAs separating the three items in individual groups were 500 ms and 1000 ms. The ORSE model, and the other two oscillator models, minimally predict that latencies of recall should retain this 1:2 ratio of the within-group presentation intervals. The non-oscillator based ACT-R model does not predict preservation of this ratio: It does not attribute any influence to the within-group timing of items (provided any variation in timing does not alter the hierarchical grouping structure applied to the lists). These predictions are developed in more detail below.

Whereas investigations of serial recall typically have relied on analyses of accuracy and patterns of errors, analyses of latencies of recall can provide important additional evidence (see Maybery et al., in press). In the present study, latencies of recall were compared for lists that varied the timing of items at presentation. We used a touch-sensitive screen to record the intervals separating successive responses as participants recalled sequences by pressing letters displayed in a visual array.

Method

<u>Design and Predictions</u>

Each participant was tested for recall of six-item lists of consonants while engaging in articulatory suppression to limit sub-vocal rehearsal. Ungrouped lists (with a consistent SOA for the items in the list) and grouped lists (with an extended SOA for the transition from the 3rd to the 4th item) were used. There were also four grouped lists differentiated with reference to the four within-group SOAs (i.e. for the 1st to 2nd, 2nd to 3rd, 4th to 5th and 5th to 6th items). These SOAs were either 500 ms (S = short) or 1000 ms (L = long), and the within-group SOAs for the four types of grouped lists were LL-LL, SS-SS, LS-LS, and SL-SL.

The last two lists are critical in evaluating the oscillator models (and the ORSE model in particular)—these models predict that the 1:2 ratio of within-group SOAs in the LS-LS and SL-SL lists should be preserved in latencies of recall. The PL and OSCAR models also predict an extended peak in latency between the 3rd and 4th items (i.e. for the transition from one group to the next) given that the ratio of within- to between-group intervals should be preserved from list presentation. These models also predict a more pronounced peak for the SS-SS lists (with a 1:6 ratio of within- to between-group SOAs) compared to the LL-LL lists (with a 1:2 ratio; Maybery et al., in press). The ACT-R model also predicts this peak in latency, but predicts uniform latencies within groups.

All of the positional models, whether oscillator-based or not, predict that a frequent type of transposition error for grouped lists is where items exchange groups but so as to preserve within-group serial position. (For the oscillator models this is because the two groups in any list have identical within-group SOAs.) This type of error for grouped lists should contrast with a less frequent error consisting of the swapping of items across the group boundary (item 3 taking the position of item 4, or vice versa). With ungrouped lists, by contrast, the relative frequencies of these two types of errors should be reversed.

Participants

The 46 participants (20 women) were undergraduates at the University of Western Australia aged between 18 and 27 years.

Apparatus

The apparatus consisted of a Pentium IBM-compatible personal computer and keyboard with a 36 cm Hitachi touch-screen monitor, a Sound Blaster AWE 32 sound card, and Arista FS 300 fully enclosed headphones.

Stimuli

Auditory sequences were formed using the 20 consonants excluding W (which comprises three syllables). The consonants were spoken by an Australian woman in English, her first language, and recorded using Goldwave audio software. Each consonant was recorded in 16-bit wave format and fitted to a 450 ms envelope.

Sequences were formed using 80 lists, each comprising six different consonants. Each list was generated randomly except that any obvious patterns were excluded (i.e. there were no alphabetically adjacent pairs, such as BC, and no words, such as TRY). For each participant, 64 of the 80 lists were randomly selected and then assigned at random to the trials for the different sequence types.

There were two ungrouped and four grouped sequence types. For all types, the time from onset of the first consonant to onset of the response display was 7000 ms. Both types of ungrouped sequence used a constant stimulus onset asynchrony (SOA) across the six consonants; for one type it was 500 ms and for the other, 1000 ms. The four types of grouped sequence are illustrated in Figure 2. In each case, the interval separating the 3rd and 4th items was larger than the other inter-item intervals to encourage encoding of the six items as two groups of three. Across the four types of grouped list, the interval from onset of the first group to onset of the second was always 4000 ms. The two types critical to evaluating the models used different SOAs (500 ms & 1000 ms) within each group. These are labeled short (S) and long (L), respectively. For the LS-LS type, SOAs for successive consonants were 1000 ms, 500 ms, 2500 ms, 1000 ms and 500 ms, whereas for the SL-SL type, the SOAs were 500 ms, 1000 ms, 2500 ms, 500 ms and 1000 ms. That is, the LS-LS and SL-SL types differed simply in the order of the two within-group SOAs, with one SOA double the other. The two remaining types of grouped sequence were less critical to evaluating the models in that each used a constant within-group SOA. For the SS-SS type, SOAs were 500 ms, 500 ms, 3000 ms, 500 ms and 500 ms, and for the LL-LL type, they were 1000 ms, 1000 ms, 2000 ms, 1000 ms and 1000 ms (see Figure 2).

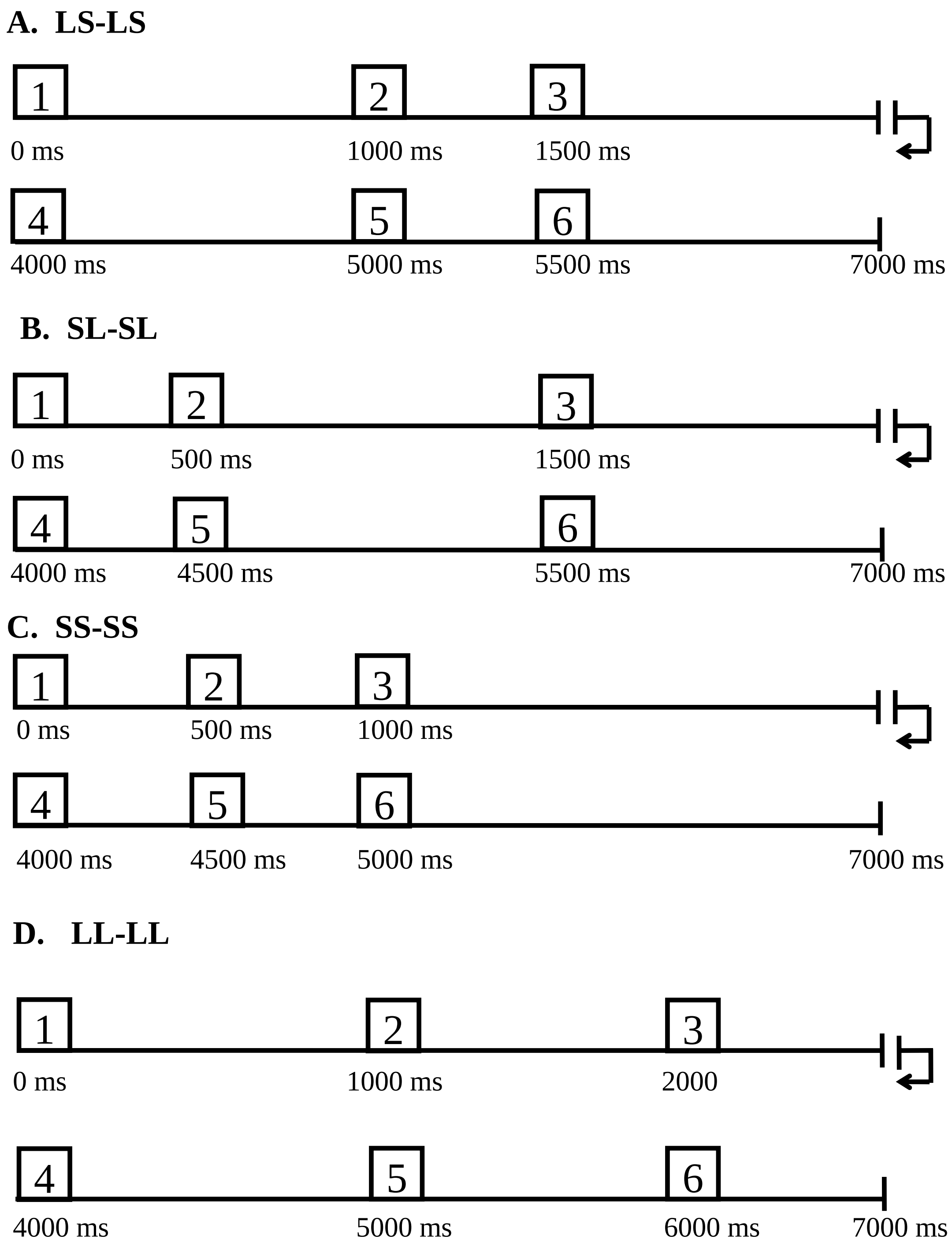

Figure 2. The timing of stimulus sequences for the different grouped lists.

Numbers represent within-group serial position.

Procedure

Participants were tested individually in a small room. Each received 64 trials comprising, in order of presentation, 4 practice ungrouped sequences, 10 test ungrouped sequences, 40 test grouped sequences, and 10 test ungrouped sequences. In each set of ungrouped sequences, each participant received equal numbers of sequences with 500 ms and 1000 ms SOAs presented in random order. For the trials with grouped sequences, each set of 4 successive trials used the LS-LS, SL-SL, SS-SS, and LL-LL types once each, in random order. The 64 trials were presented in one continuous block.

The procedure for each trial was as follows. An instruction asking the participant to start saying “the, the, the” was shown in the centre of the screen for 1500 ms. This was followed by presentation of one of the consonant sequences through the headphones. Recall was initiated by the appearance of a letter board, which consisted of a 5x4 matrix of the consonants arranged alphabetically. Each consonant was printed inside a 37 mm square. A row of 6 empty boxes was printed below. The participant was asked to touch out the letters in the order they had been presented, responding as quickly as possible, but avoiding errors. As the participant responded, the row of boxes was filled from left to right with the selected consonants. After all 6 boxes were filled (which was necessary to proceed), an instruction appeared asking the participant to stop saying “the, the, the”. To proceed to the next list, the participant touched a screen icon labeled “Ready”. Presentation of the next trial began 1500 ms later.

Participants were instructed that sequences of letters would be heard over the headphones and they would be required to recall the items in order of presentation. The method of recording responses using the touch screen was explained, with participants instructed to rest their dominant finger on a dot at the bottom centre of the screen. The experimenter monitored conformity to the instruction to engage in articulatory suppression.

Error analysis

We refer to particular order errors with an input position→output position convention (e.g. 3→4 refers to recalling the 3rd item in the 4th serial position). Sometimes it is convenient to collapse pairs of symmetrical errors (e.g. 3→4 & 4→3 might be collapsed and symbolized as 3-4). In analyses of these errors, we use procedures described in Ng and Maybery (2002). Raw counts of the different types of error are not ideal, since there are more opportunities to make some types of errors than others. The measure we adopt to correct for differential opportunity is the ratio of the actual number of errors of a particular type divided by the number of errors expected of that type if the total errors had been distributed equally. More precisely, if there are n cases forming a type (e.g. there are 2 cases of adjacent inter-group errors, 3→4 & 4→3) and Σe errors observed for that type, then using N to refer to the total number of cases (e.g. 30 possible transposition errors for 6-item sequences) and ΣE to refer to the total number of errors observed, the ratio would be:

$$R = \frac{\sum e}{n \sum E / N}$$

Equivalently, the ratio is the mean error rate for a particular type (Σe/n) divided by the overall mean rate (ΣE/N). So a ratio greater than one implies that the error type occurred with above-average frequency, whereas a ratio less than one implies that it occurred with below-average frequency. The error ratio has the advantage that it is independent of both the total numbers of errors made (ΣE) and the opportunities available for each type of error (n).

Results

The results are presented in four sections. The first two sections report analyses of accuracy and transposition errors to establish that grouping has been achieved. The next section reports analyses of inter-response interval (IRI) recall latencies restricted to the grouped lists. These analyses are targeted at evaluating the oscillator and non-oscillator models. The last section reports a broader analysis of IRIs.

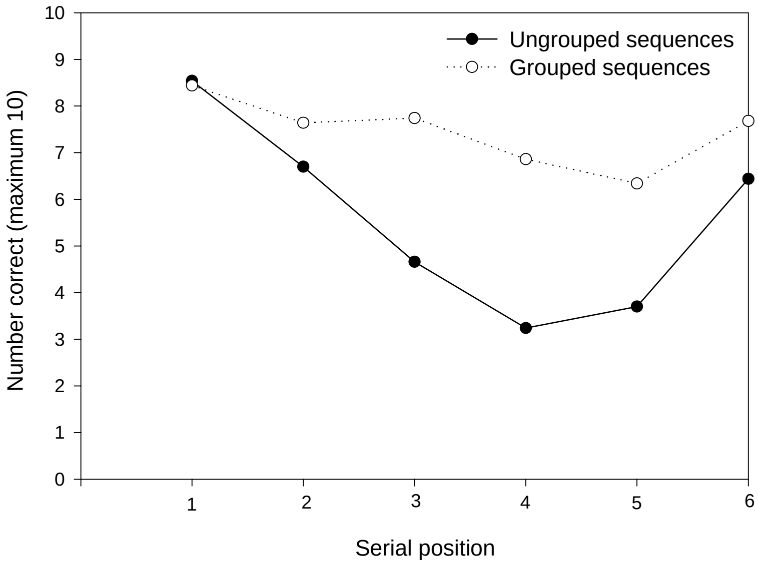

Figure 3. Mean number correct at each serial position as a function of list type.

Accuracy for grouped versus ungrouped sequences

The mean number correct at each serial position (maximum 10) was consolidated for grouped and ungrouped sequences. A 2 (sequence type—grouped vs. ungrouped) x 6 (serial position) repeated measures ANOVA was conducted. All effects were significant with $F(1, 42) = 170.32$, $MSE = 2.61$, $p < 0.001$, for the main effect of sequence type, $F(5, 210) = 99.28$, $MSE = 1.65$, $p < 0.001$, for the main effect of serial position and $F(5, 210) = 55.70$, $MSE = 0.79$, $p < 0.001$, for the interaction. Overall, performance was better for grouped than for ungrouped sequences, with both types displaying strong primacy and weaker recency. The grouped sequences also demonstrated a multiple bowed serial position curve (see Figure 3). These observations were supported when a quadratic trend over serial position was calculated (Ferguson, 1976). This trend was significant overall, $F(1, 210) = 496.53$, $MSE = 0.81$, $p < .001$, and also interacted with sequence type, $F(1, 210) = 195.92$, $MSE = 0.81$, $p < .001$. The quadratic trend was more pronounced for the ungrouped sequences compared to the grouped sequences, as there was more scalloping in the function for the grouped sequences. An appendix presents more detailed analyses of accuracy for the four types of grouped lists and for the ungrouped lists presented in the first and third phases.

Transposition errors for grouped versus ungrouped sequences

As indicated earlier, previous studies (e.g., Henson, 1996; Maybery et al., in press; Ng & Maybery, 2002; Ryan, 1969a, 1969b) have reported that temporal grouping modifies the pattern of order errors: Typically, adjacent inter-group errors (in this experiment, 3→4 and 4→3) are less frequent and same serial position inter-group errors (e.g. 2→5 and 6→3) are more frequent for grouped sequences compared to the corresponding errors for ungrouped sequences. Thus to examine whether our temporal manipulations induced grouping, a 2 (sequence type—grouped vs. ungrouped) x 2 (error type—adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted. Both main effects were significant, with F(1,42) = 15.82, MSE = 0.91, $p < 0.001$, for sequence type and F(1,42) = 33.16, MSE = 0.94, $p < 0.001$, for error type. The interaction was significant also, with F(1, 42) = 63.31, MSE = 0.11, $p < 0.001$. Examining the interaction further, the simple effect of sequence type was significant for both the adjacent inter-group errors, t (42)= 6.48, $p < 0.001$, and the same serial position inter-group errors, t (42) = 10.82, $p < 0.001$. For adjacent inter-group errors, the mean error ratio was higher for ungrouped sequences than for grouped sequences. This pattern was reversed for same serial position inter-group errors (see Figure 4). Thus, as expected from all models, temporal grouping led to a reduction in errors that involve items 3 and 4 displacing each other across the group boundary, and an increase in errors where items swap to the same serial position in a different group.

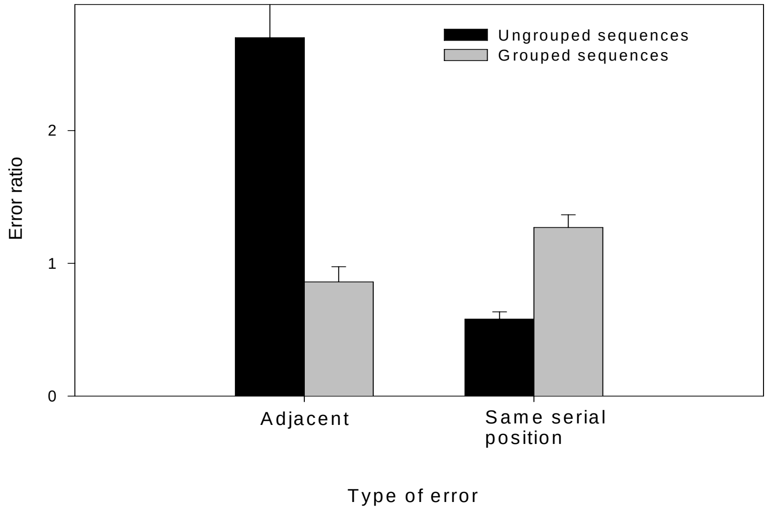

Figure 4. Error ratio for two types of error as a function of list type.

IRIs for grouped sequences: Evaluation of the oscillator and non-oscillator models

The oscillator models predict that the IRIs for the two mixed-timing sequences, LS-LS and SL-SL, should show a contrasting pattern. For LS-LS sequences, the SOAs for the item-to-item transitions 1-2 and 4-5 are double the SOAs for the transitions 2-3 and 5-6, so IRIs are expected to be longer for the former compared to the latter. The reversal of these SOAs for the SL-SL sequences means that here IRIs should be shorter for 1-2 and 4-5 compared to 2-3 and 4-6. A further prediction from the PL and OSCAR models is that SS-SS lists should show a more pronounced peak in IRI from one group to the next (item 3 to item 4) compared to the LL-LL list. For each participant, median IRIs were calculated for correct responses. Then, to compare the different types of grouped lists, a 4 (sequence type: LS-LS vs. SL-SL vs. SS-SS vs. LL-LL) x 5 (interval position: 1-2 vs. 2-3 vs. 3-4 vs. 4-5 vs. 5-6) repeated measures ANOVA was conducted. Both main effects were significant, with $F(3, 126) = 3.35$, $MSE = 67627.49$, $p < 0.05$, for sequence type, and $F(4, 168) = 44.01$, $MSE = 254348.96$, $p < 0.001$, for interval position. However, the interaction between sequence type and interval position was not significant, $F(12, 504) = 1.42$, $MSE = 83721.63$ (see Figure 5, Parts A & B). Thus there appear to be no systematic differences in the profiles of IRIs attributable to the variations in within-group SOAs in the four grouped lists. Returning to the main effect of sequence type, the means for the four types were 1115.67 ($SE = 50.54$) for LL-LL sequences, 1099.07 ($SE = 42.05$) for LS-LS sequences, 1063.92 ($SE =42.95$) for SS-SS sequences and 1044.14, $SE =42.38$ for SL-SL sequences. Post hoc t tests showed that the mean for the SL-SL sequences was significantly lower than the means for the LL-LL and LS-LS sequences, but no other differences were significant. These differences do not appear to demonstrate any systematic trend. The main effect of interval position primarily reflects the peak in the IRIs for the transition from the first to the second group (Figure 5, Parts A & B). This feature of the response latencies for the grouped sequences is examined in more detail in an analysis reported below, which includes the IRIs for ungrouped sequences.

In including all grouped conditions and all intervals, the above analysis may however have been insensitive to critical differences specific to intra-group intervals for the SL-SL and LS-LS lists. Therefore, the analysis reported next collapsed the intra-group IRIs for the SL-LS and LS-SL sequences into two categories. These categories were dependent on the presentation SOAs. One category was for the long (1000 ms) SOAs, and comprised IRIs of 1-2 and 4-5 for the LS-LS sequences and IRIs of 2-3 and 5-6 for the SL-SL sequences. The second category was for the short (500 ms) SOAs, and comprised IRIs of 2-3 and 5-6 for the LS-LS sequences and IRIs of 1-2 and 4-5 for the SL-SL sequences. The median IRIs for these two categories (correct responses only) were then entered into a one-way ANOVA with SOA (500 ms vs. 1000 ms) as the factor. This effect yielded $\underline{F}(42) = 3.42$, $\underline{MSE} = 20764.87$, $p < 0.1$. The mean of the median IRIs for the short SOA was 930.22 ($\underline{SE} = 33.86$), whereas it was 987.71 ($\underline{SE} = 35.11$) for the long SOA. Thus there is a non-significant trend towards shorter IRIs for the short SOA compared to the long SOA.

Focussing instead on the LL-LL and SS-SS lists, it is obvious from Figure 5 (Part A) that an additional prediction of the PL and OSCAR models is not supported. The trend is for the LL-LL lists to actually have a more pronounced peak in IRIs at the onset of the second group compared to the SS-SS lists. Thus there is no sign that recall latencies reflect the substantial difference for these lists in the ratios for within- to between-group SOAs (1:2 for LL-LL; 1:6 for SS-SS).

IRIs for grouped versus ungrouped lists

A further analysis was conducted to compare the IRIs for the ungrouped sequences (Figure 6, Part C) with those for the grouped sequences (Figure 5, Parts A & B). Again the median IRI for correct responses was calculated for each interval. A 2 (sequence type: grouped vs. ungrouped) x 5 (interval position) repeated measures ANOVA was conducted.[1] All effects were significant with $F(1, 41) = 39.33$, $MSE = 84876.83$, $p < 0.001$, for sequence type, $F(4, 164) = 36.69$, $MSE = 137016.54$, $p < 0.001$, for interval position, and $F(4, 164) = 10.02$, $MSE = 96463.55$, $p < 0.001$, for the interaction. In follow-up analyses, the simple effect of sequence type was significant for interval 2-3, $t\ (42) = 5.50$, $p < 0.001$, and also for interval 4-5, $t\ (41) = 5.44$, $p < .001$. In addition, a contrast (with weights 1, 1, -4, 1, 1 for the five intervals) was conducted to examine if there was a spike in IRI for the transition to the second group. This trend was significant overall, $F(1, 164) = 4.47$, $MSE = 96463.55$, $p < .05$, and also interacted with sequence type, $F(1, 164) =153.89$, $MSE = 96463.55$, $p < 0.001$. As can be seen in Figure 5, the spike in IRI was more pronounced in grouped compared to ungrouped sequences.

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[1] One participant’s data were excluded because an IRI could not be calculated for one interval position because all responses were incorrect.

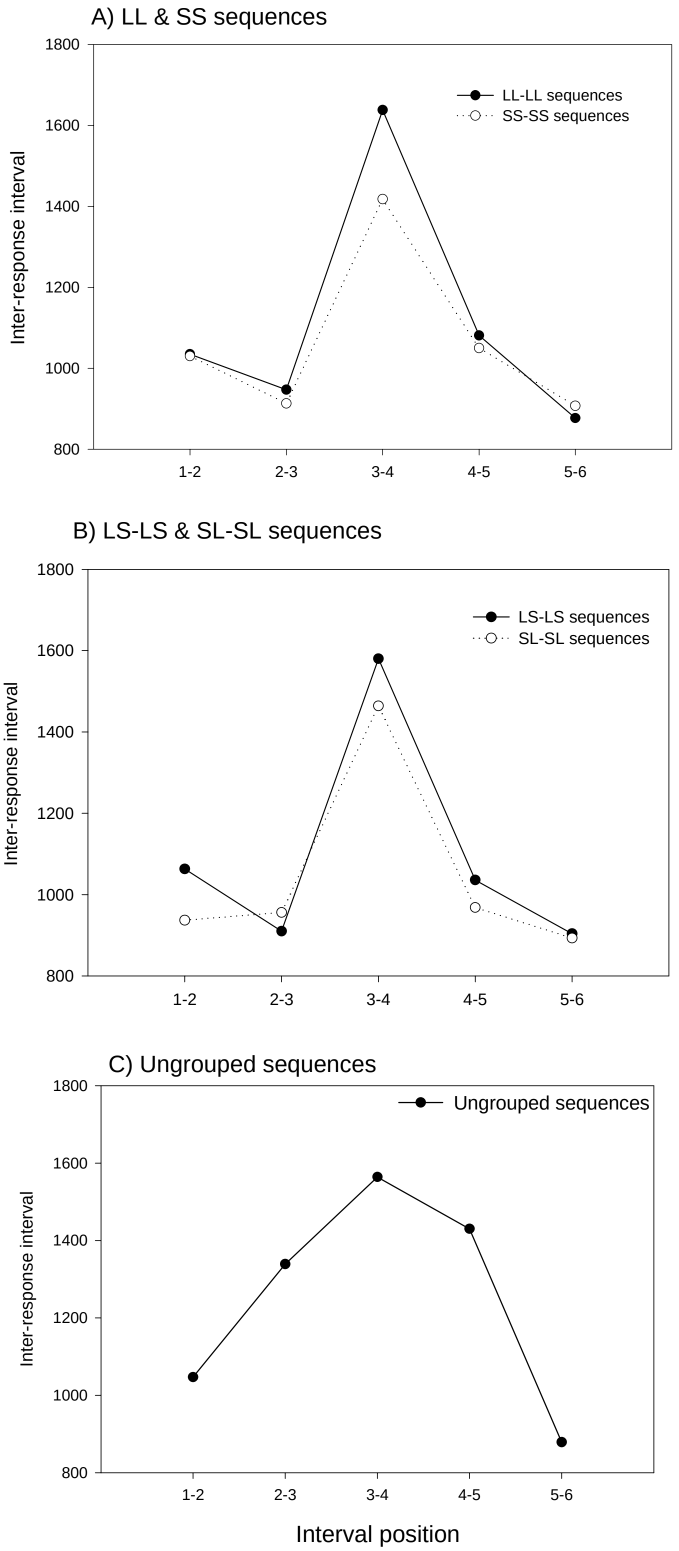

Figure 5. Latency of recall for the five IRIs as a function of list type.

Discussion

Are oscillator or non-oscillator models better able to explain performance in the serial recall of temporally grouped sequences? The timing of presentation of the grouped sequences was manipulated and latencies of recall were recorded to investigate this issue. According to all the oscillator models, the latency of recall should demonstrate sensitivity to within-group differences in the timing of presentation. On the contrary, non-oscillator models do not predict sensitivity in latency of recall to the timing of presentation. In analyzing the data, there were no significant differences in recall latencies when comparing the four different types of grouped sequences. However, a further step was taken to compare the IRIs for short and long within-group SOAs from the LS-LS and SL-SL sequences. The mean IRI for the 500 ms SOA transitions was slightly shorter the mean IRI for the 1000 ms SOA transitions, but the difference was not statistically significant. Therefore there was no strong evidence supporting the common prediction of the oscillator models that the ratio of within-group intervals at presentation should be preserved in the timing of recall.

These findings were observed under conditions in which articulatory suppression was employed during list presentation and recall. Continuous articulation was used to minimize sub-vocal rehearsal, which could perhaps be used to regularize the intervals separating items. However perhaps this feature of the method was unnecessary because existing oscillator models do not contain mechanisms for regularizing within-group intervals via rehearsal. The OSCAR and ORSE models allow for changing the overall rate at which a group of items is cued for recall or rehearsal, but this would not allow for a change in the ratio of within-group intervals.

The present experiment also provided a further test of the PL and OSCAR models through a comparison of the SS-SS and LL-LL lists. These models predict that the ratio of within- to between-group SOAs should be preserved in the IRIs at recall. However, the SS-SS lists (within-group SOA = 500 ms; between-group SOA = 3000 ms) did not show a more pronounced peak in IRIs at the transition from the first to the second group compared to the LL-LL lists (within-group SOA = 1000 ms; between-group SOA = 2000 ms). In fact the trend in latencies was the reverse of the prediction made by the PL and OSCAR models (Figure 5, Part A).

All of the grouped lists show a pronounced peak in recall latencies for the transition from the first to the second group compared to the four within-group transitions, which show similar latencies (see Figure 5, Panels A & B). According to the ACT-R model, the latency for onset of the second group should be extended because all the items of a group have to be retrieved before the first item can be reported. However, one unexpected feature of the IRI data is the inverted U-shaped pattern observed for the ungrouped lists (Figure 5, Part C). Maybery et al. (in press) suggested that this pattern may reflect spontaneous grouping of the ungrouped sequences, with some participants grouping the six memory items in threes and others grouping in twos. According to ACT-R theory, a single peak in IRIs would be expected for grouping in threes (at the transition from item 3 to item 4) whereas two peaks would be expected for grouping in twos (at the transitions from item 2 to item 3 and item 4 to item 5). Amalgamation of IRIs across participants using these two grouping strategies could explain the inverted U-shaped pattern for ungrouped lists.

Collectively the grouped sequences yielded more accurate recall compared to the ungrouped lists. There was also multiple bowing of the serial position curve for the grouped lists. In addition, there was a higher level of transposition errors that preserved within-group serial position (such as 2↔5) for the grouped lists compared to the ungrouped lists. The direction of this difference was reversed when adjacent inter-group errors (3↔4) were compared. As detailed by Henson (1998; Henson & Burgess, 1997) this pattern of shift in order errors with temporal grouping is difficult to explain under chaining and ordinal models and provides support for positional models such as the SE, ACT-R, PL, OSCAR and ORSE models.

In sum, the present study replicates evidence from order errors in serial recall that supports positional models over chaining and ordinal models. It also confirms findings of Maybery et al. (in press) in showing that the ratio of within- to between-group SOAs is not preserved in recall latencies, contrary to the PL and OSCAR models. All of the oscillator models (i.e. including the ORSE model) predict that when SOAs are varied within groups, the ratio of these SOAs should be represented in the corresponding IRIs. There was no convincing support for this prediction in the present experiment. The non oscillator-based ACT-R model appears to provide the best account of the latency data we report.

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Appendix

Accuracy for different phases for the ungrouped lists

Recall that half the ungrouped lists were presented in the first and half in the third phase of testing (with grouped lists presented in the second phase). Performance on ungrouped lists before and after grouped list presentation was compared with a 2 (phase—1st vs. 3rd) x 6 (serial position) repeated measures ANOVA. Only the main effects of phase and serial position were significant with F (1, 43) = 17.32, MSE = 3.51, $p < 0.001$, and F (5, 210) = 114.99, MSE = 3.16, $p < 0.001$, respectively. There was no evidence that participants imposed grouping on the lists in the third phase after experiencing the grouped lists in the second phase.

Accuracy for different types of grouped lists

Whether variation in timing of item presentation within groups changed the pattern of recall performance was examined in a 4 (list type—LS-LS vs. SL-SL vs. LL-LL vs. SS-SS) x 6 (serial position) repeated measure ANOVA conducted on the accuracy scores. Only the main effect of serial position was significant with F (5, 210) = 30.36, MSE = 3.45, $p < 0.001$. There were no differences between the different types of grouped lists when accuracy was compared.

Authors' Notes

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Chapter 4

Grouping in verbal short-term memory:

Do oscillators code the positions of items?

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Grouping in Short-Term Memory: Do Oscillators Code the Positions of Items?

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According to several current models of short-term memory, items are retained in order by associating them with positional codes. The models differ as to whether temporal oscillators provide those codes. The authors examined errors in recall of sequences comprising 2 groups of 4 consonants. A critical manipulation was the precise timing of items within the groups, whereby temporal position (time from group onset) and ordinal position (number of items from group onset) were partially unconfounded. Errors that involve items migrating across groups should preserve within-group temporal position according to oscillator models, but should preserve within-group ordinal position according to nonoscillator models. Results from the intergroup errors strongly favored preservation of ordinal rather than temporal position.

Critical to many areas of human activity is the representation, retention, and reproduction of information in sequence. For instance, the accurate comprehension and production of language depends on the errorless processing of word order. It is not surprising, then, that a persisting theme in research on short-term memory (STM) has been the search for mechanisms responsible for retaining items in order (Brown, Preece, & Hulme, 2000). Recently, several substantial computational models of STM have been developed, each based around core mechanisms for the retention of serial order. These models fall into three major categories (Henson, 1998). In *chaining* models, one retains serial order using interitem associations (Murdock, 1995). With *ordinal* models, order is based on a single dimension, such as the relative strength with which items are encoded (Page & Norris, 1998). Alternatively, in *positional* models, items are associated with extralist information to code position in the sequence (Henson, 1998).

The effectiveness of these models in explaining memory for order has been evaluated recently with reference to temporal grouping, which consists of using one or more extended pauses to break a list of items into sublists. Immediate recall of verbal items is facilitated by temporal grouping for both auditory and visual presentation (Ng & Maybery, 2002b). The improved performance on grouped lists is due largely to the better recall of midlist items, particularly items on the ends of sublists—the serial position function assumes a scalloped form (Hitch, Burgess, Towse, & Culpin, 1996). Order errors also change with temporal grouping. For ungrouped lists, items tend to migrate to nearby serial positions. With temporal grouping, there is a reduction in these errors if they cross a group boundary (e.g., recalling *Q* in place of *B* in *SNRQ—BLXH*), but an increase in intergroup migrations that preserve an item's within-group serial position (e.g., N taking the place of L; Henson, 1998).

These grouping phenomena, especially the patterns of errors, are difficult to explain under chaining and ordinal models (Henson, 1998). Currently, positional models are best able to handle temporal grouping effects and several other phenomena (Brown et al., 2000). In an early positional model, the perturbation model (Lee & Estes, 1977, 1981), ideas that are central to contemporary positional models were introduced—the association of list items to positional codes and temporally based reactivation of these associations. However, in the perturbation model, how the associations are reactivated in correct positional order is not explained (Brown et al., 2000; Henson, 1998). In accordance, we focus on more recent positional models, which specify encoding and retrieval mechanisms in more detail.

These recent positional models can be segregated into whether temporal oscillators provide the extralist information that codes position. The start–end (SE) model (Henson, 1998) and the adaptive character of thought-rational (ACT–R) model (Anderson & Matessa, 1997) do not incorporate temporal oscillators, whereas oscillators are central to the phonological loop (PL) model (Burgess & Hitch, 1992, 1996, 1999), the OSCillator-based Associative Recall (OSCAR) model (Brown et al., 2000), and a model we label the oscillator–revised start–end (ORSE) model (Henson & Burgess, 1997).

Temporal oscillators are cell assemblies that fire in simple rhythms. They have been used in theories developed for diverse areas of cognition, including the perception of rhythm in music and speech (Large & Kolen, 1995), time estimation (Treisman, Cook, Naish, & MacCrone, 1994), tempo discrimination (McAuley, 1994), and feature binding in visual perception (Hummel & Biederman, 1992). Given their broad application elsewhere, it is op-

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portune to evaluate the use of oscillators in models of STM. In the next two sections, we describe and contrast the different models relying on temporal oscillators or, alternatively, on nonoscillator positional codes. In the current study, we evaluate the predictions of these two classes of positional model and provide critical information on the extent to which the temporal footprint of a sequence of events is preserved in STM.

Models Relying on Positional Codes Not Derived From Temporal Oscillators

According to the *SE model* (Henson, 1998), items are retained in order through their associations with output from start and end markers. Output from the start marker is strongest for the first list item and weakest for the last, whereas the reverse occurs for the end marker. For grouped lists, two sets of markers apply—one set codes within-list position, and the other set codes within-group position. Output of the latter set of markers is reset at the start of each group. At recall, output from the two sets of markers cues item retrieval. The markers that code position within a group provide similar output for items with similar within-group positions. This explains the higher intergroup transposition errors for these items. The timing of item presentation is inconsequential to this model (except inasmuch as an extended gap demarcates groups) because changes in the coding provided by the markers are event-driven. Predictions concerning transposition errors simply depend on within-group ordinal position.

Under the *ACT–R model* (Anderson, Bothell, Lebiere, & Matessa, 1998; Anderson & Matessa, 1997), the representation of serial order in grouped lists relies on a hierarchy of position codes provided by semantic memory. Like the SE model, items are coded for position in their groups, but for ACT–R, the codes are in essence labels like *first* and *second*. Positional labeling also applies at a superordinate level in the hierarchy where the positions of groups in the list are coded. Intergroup order errors are influenced by the within-group positional codes; for example, if the third item of one group were to swap to another group, it would most likely be recalled as the third item of that group. Positional coding and, consequently, intergroup errors are independent of the within-group timing of items at list presentation.

Temporal Oscillator Models

In contrast, the models incorporating temporal oscillators predict that intergroup order errors should depend on within-group timing. According to the *PL model* (Burgess & Hitch, 1999), information encoded from list items is associated with contextual information derived from temporal oscillators. Sets of oscillators provide a repeatable timing signal. Each oscillator is activated periodically, and by operating out of phase with one another, the oscillators in a set provide a window of activation that repeatedly sweeps across the ensemble. For ungrouped lists, a single set of oscillators encodes within-list position. A second set of oscillators is employed for grouped lists. This set becomes entrained to the intergroup frequency (i.e., its cycle of activation is in step with group onset). These oscillators then encode within-group position. During recall or rehearsal, the two sets of oscillators are reset, and their unfolding activation cues item retrieval. This means that the timing of recall should reflect the timing of items at presentation. More important for this investigation, intergroup order errors should also depend on the within-group timing of items at input. The oscillators that encode within-group context operate in cycle with the onsets of the groups, so two items in different groups will share context and be confusable in recall, if they occur with the same delay after the onsets of their respective groups. In the Oscillator or Nonoscillator Models? section, we show that it is possible to match the temporal positions of two items in their different groups, even though the items occupy different within-group ordinal positions. A critical test of the PL model will be the intergroup order errors committed in this circumstance.

In the *OSCAR model* (Brown et al., 2000), it is also assumed that a context signal derived from temporal oscillators is associated with items at encoding and reinstated at recall to enable reproduction of items in list order. For grouped lists, this model, like the PL model, adopts a second context signal that operates in phase with the groups to encode within-group position. Recall is more flexible for the OSCAR model in that the overall rate of evolution of the oscillators can be different than the rate used at encoding, so recall can proceed at a faster or slower rate overall compared with the presentation rate. However, transposition errors must depend on whether items in different groups occupied, at presentation, the same or different temporal positions relative to the onsets of their respective groups, and it is on this basis that predictions common to the oscillator models can be differentiated from predictions of the nonoscillator models.

The *ORSE model* (Henson & Burgess, 1997) is an extension of the SE model that overcomes a problem in the original model concerning the anticipatory nature of end markers: How could an end marker provide consistent coding for the last list item if lists were to vary unpredictably in length? The ORSE model adopts the idea that position markers are encoded using temporal oscillators. It differs from the PL and OSCAR models in the assumption that oscillator pairs with different frequencies compete to best represent positional information for each list and for each group within a list. The winning oscillator pair for the list is the one with a half cycle closest to the duration of the list, and the winning pair for each group has a half cycle closest to the duration of the group. These oscillators are assigned at the end of each group and at the end of the list. The adaptive selection of oscillators means that they code proportionate timing of items at presentation rather than absolute time. Therefore, items should transpose to the extent that they occupy the same proportional temporal positions in their groups. For instance, two items presented halfway through their respective groups should have very similar within-group positional codes and be likely to exchange positions, even if their groups' durations differ. This means that in some circumstances, predictions of the ORSE model can be differentiated from predictions of the PL and OSCAR models (Henson, 1999; Ng & Maybery, 2002a,b). It is important to note that in the present experiment, we designed the critical manipulations of timing so that all the oscillator models share a common set of predictions based on timing.

Oscillator or Nonoscillator Models?

To evaluate the two classes of positional models, we used two critical types of grouped lists. Each involved eight consonants presented in two groups of four. What varied for the two types was the stimulus onset asynchrony (SOA) separating the items within groups (Figure 1). We label the first type of sequence LSS–SSL, reflecting the within-group SOAs, which were 800 ms (L), 400 ms (S), and 400 ms (S) for the first group and 400 ms (S), 400 ms (S), and 800 ms (L) for the second group (Figure 1A). This pattern of SOAs means that Items 2 and 7 occupy the same temporal positions (whether relative or absolute) in their groups, despite occupying different ordinal positions. Therefore, according to the oscillator models, these items should be more likely to transpose than should Item 2 with Item 6 or Item 3 with Item 7 (i.e., pairs with matching ordinal positions). The second critical type of grouped sequence is labeled SSL–LSS (Figure 1B). Here Items 3 and 6 occupy the same temporal positions in their groups and so should be likely to transpose despite their different within-group ordinal positions. These predictions of the oscillator models (solid arrows in Figure 1) contrast with predictions of the nonoscillator models (broken arrows). Recall that the latter models (SE and ACT–R) use position codes that depend on the ordinal positions of items in their groups. Thus they predict that, for all grouped sequences, Items 2 and 6 and Items 3 and 7 should transpose more frequently than Items 2 and 7 and Items 3 and 6. To provide a condition comparable with other studies of temporal grouping, we also included a third grouped sequence (MMM–MMM; Figure 1C) in which items were evenly spaced within the two groups. In this case, all models predict that Items 2 and 6 and Items 3 and 7 should transpose more frequently than the other across-groups pairings of these items.

In summary, five models of STM address the critical issue of how items are retained in order by proposing that items are associated with contextual–positional codes. For three models (PL, OSCAR, and ORSE), temporal oscillators provide the positional codes, and items should transpose across groups in a manner that preserves within-group temporal position. For the other two models (SE and ACT–R), contextual–positional codes change as a function of item order, and so items should transpose across groups in a manner that preserves within-group ordinal position. By partially unconfounding temporal and ordinal within-group positions, the LSS–SSL and SSL–LSS sequences test the competing predictions from the two classes of model.

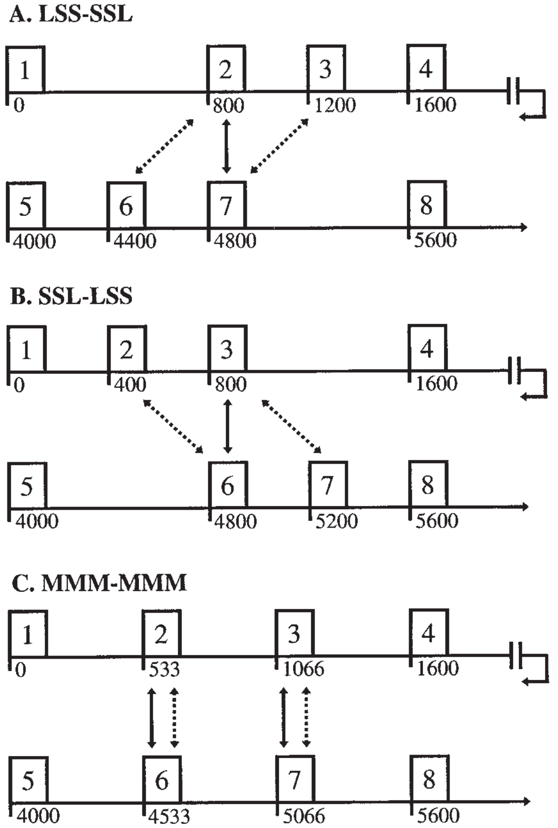

Figure 1. The timing of stimulus sequences for the different grouped sequences. Numbers in boxes represent the serial positions of items. Numbers below the boxes represent time (in milliseconds) from list onset. Solid arrows depict errors predicted by oscillator (phonological loop, OSCillator-based associative recall, and oscillator–revised start–end) models. Broken arrows depict errors predicted by the nonoscillator (adaptive character of thought-rational and start–end) models The LSS–SSL, SSL–LSS, and MMM–MMM labels for the sequences refer to the within-group stimulus onset asynchronies, which were 400 ms (S), 800 ms (L), or 533 ms (M).

Method

Participants

The 37 University of Western Australia, Crawley, West Australia, Australia undergraduates (ages 17–33 years) were recruited and tested in accordance with University of Western Australia ethical procedures.

Apparatus

Equipment included a Pentium computer, Hitachi touchscreen monitor, and Arista FS300 headphones.

Procedure

Each participant received, in order, 5 practice ungrouped sequences, then 10 test ungrouped sequences, 30 test grouped sequences (10 each of SSL–LSS, LSS–SSL, and MMM–MMM, in random order), and, finally, 10 additional test ungrouped sequences. Each sequence comprised 8 randomly selected consonants, excluding the trisyllabic *W*.

We presented the sequences auditorily using 350-ms recordings of the consonants. We used an item-to-item SOA of 800 ms for the ungrouped sequences. The three types of grouped sequence had a common SOA of 2,400 ms for the transition from the fourth to the fifth item but differed in the SOAs used within each sequence half, as described in the Oscillator or Nonoscillator Models? section (see Figure 1). Total duration (5,950 ms) was equated for all sequence types.

Each trial began with a visual instruction to start saying *the* repeatedly.[1] Next, a sequence was presented through the headphones. Recall was initiated by the appearance of a 5 × 4 letter array. A row of eight empty boxes appeared below the letter array. As the participant touched letters on the array, those letters were entered in the boxes. A cursor moved along the boxes, and moving the cursor to any box permitted correction. Instructions emphasized reporting letters in correct serial position, with guessing permitted in filling list positions when uncertain. After the participant completed recall using the touch screen, an instruction to stop saying *the* appeared.

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[1] We used articulatory suppression to limit subvocal rehearsal and force participants to rely more heavily on representations established at encoding. See Ng and Maybery (2002b) for a discussion of subvocal rehearsal in relation to predictions from models.

Order Errors

None of the current models make different predictions for symmetrical errors (e.g., recalling the second presented item in the sixth position [2→6] vs. recalling the sixth presented item in the second position [6→2]), so frequencies for symmetrical errors are combined and labeled without the arrowhead (e.g., 2−6). In analyses of these errors, we use a procedure described in Ng and Maybery (2002b). Raw counts of the different types of error are not ideal, because there are more opportunities to make some types of error than others. The measure adopted to correct for differential opportunity is the ratio of the actual number of errors of a particular type divided by the number of errors expected of that type if the total number of order errors had been distributed uniformly. That is, if there are n cases forming a type (e.g., there are 2 cases of the 2–6 type, viz. 2→6 and 6→2) and Σe errors observed for that type, then using N to refer to the total number of cases (e.g., 56 possible transpositions for an 8-item sequence) and ΣE to refer to the total number of order errors observed, the ratio would be:

$$R = \frac{\Sigma e}{n\Sigma E/N} \qquad (1)$$

Equivalently, the ratio is the mean error rate for a particular type ($\Sigma e/n$) divided by the overall mean rate ($\Sigma E/N$). So a ratio greater than one implies that the error type occurred with above-average frequency, whereas a ratio less than one implies that it occurred with below-average frequency. The error ratio has the advantage that it is independent of both the total numbers of errors made (ΣE) and the opportunities available for each type of error (n). However, because the ratio is novel, we also report nonparametric analyses to confirm some of the critical outcomes from the analyses of ratios.

Results

Intergroup order errors are of central interest, but we first examine recall accuracy.

Accuracy

Figure 2 shows the mean number correct at each serial position (maximum 10) for the three types of grouped sequence and the ungrouped sequences. The functions for the three types of grouped sequence show very similar trends, an observation confirmed by a 3 (sequence type: LSS–SSL vs. SSL–LSS vs. MMM–MMM) × 8 (serial position) analysis of variance (ANOVA).[2] Only the main effect of serial position was significant, $F(7, 252) = 81.72$, $MSE = 4.02$, $p < .01$ (with the interaction yielding $F < 1$).

Recall was better for grouped compared with ungrouped sequences, and whereas we observed a typical bowed serial position function for the ungrouped sequences, the grouped sequences yielded a scalloped function consistent with grouping in fours (Figure 2). We confirmed these characteristics when we averaged the data for the three types of grouped sequence and conducted a 2 (sequence type: grouped vs. ungrouped) × 8 (serial position) ANOVA. All effects were significant, with $F(1, 36) = 63.01$, $MSE = 2.08$, $p < .01$, for sequence type; $F(7, 252) = 118.38$, $MSE = 2.24$, $p < .01$, for serial position; and $F(7, 252) = 21.20$, $MSE = 0.84$, $p < .01$, for their interaction. A quadratic trend calculated over serial position was significant overall, $F(1, 252) = 1313.56$, $MSE = 0.84$, $p < .01$, and also interacted with sequence type, $F(1, 252) = 110.25$, $MSE = 0.84$, $p < .01$. This trend was less pronounced for grouped sequences because of the scalloping in the serial position function, which elevated accuracy for intermediate serial positions, especially Positions 4 and 5 (Figure 2).

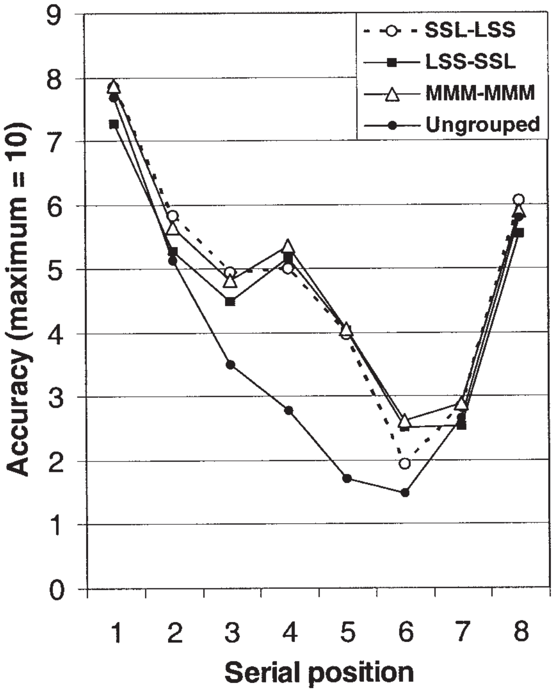

Figure 2. Mean number of correct responses at each serial position for the ungrouped sequences and the three types of grouped sequences (SSL–LSS, LSS–SSL, and MMM–MMM). Note that S, L, and M refer to within-group stimulus onset asynchronies of 400 ms, 800 ms, and 533 ms, respectively.

Next we report analyses of order errors, which for ungrouped lists constituted 28% (1,710) of all responses (or 45% of errors) and for grouped lists constituted 25% (2,256) of all responses (48% of errors). Transposition matrices for the grouped and ungrouped sequences are presented in the Appendix.

Intergroup Order Errors for Grouped Sequences: Evaluation of Oscillator and Nonoscillator Model Predictions

Recall that oscillator models predict for LSS–SSL lists that Items 2 and 7 (with equivalent temporal positions within their groups) should be more likely to transpose than should Items 2 and 6 and Items 3 and 7 (with equivalent ordinal positions). Similarly, for SSL–LSS lists the oscillator models predict that Items 3 and 6 should be more likely to transpose than should Items 2 and 6 and Items 3 and 7. On the other hand, the nonoscillator models predict the reverse for each of these list types (see Figure 1). To evaluate the contrasting error predictions for oscillator and nonoscillator models, we conducted a 3 (sequence type: LSS–SSL vs. SSL–LSS vs. MMM–MMM) × 3 (error type: 2–7 vs. 3–6 vs. 2–6/3–7)

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[2] None of the outcomes of the reported ANOVA changed in any substantial way when we applied the Geisser–Greenhouse correction for nonsphericity of error terms.

ANOVA on the error ratios. Only the main effect of error type was significant, $F(2, 72) = 9.30$, $MSE = 2.23$, $p < .01$. (The interaction yielded $F < 1$.) The error ratio was higher for 2–6 and 3–7 errors than for the other two error categories (Figure 3). Therefore, regardless of type of grouped sequence, there were consistently high levels of same ordinal position intergroup errors. The timing of item onset within groups did not influence the pattern of intergroup order errors.

The error ratios showed some evidence of bimodality for the infrequently occurring 2–7 and 3–6 error types, with approximately half the sample having zero scores for each of these types for each grouped sequence (numbers of participants with zero ratios ranged from 18 to 23). Given this bimodality, we also conducted a simpler nonparametric analysis of the intergroup errors. Recall that for LSS–SSL lists, oscillator models predict that 2–7 errors should occur more frequently than 2–6 and 3–7 errors. The reverse prediction applies for nonoscillator models. When we compared the mean numbers of errors for these two categories, only 7 participants showed the trend predicted by the oscillator models, whereas 23 participants showed a difference in the reverse direction, as predicted by the nonoscillator models, $\chi^2(1, N = 30) = 8.53$, $p < .01$. For SSL–LSS lists, the critical prediction for oscillator models is that 3–6 errors should occur more frequently than 2–6 and 3–7 errors. However, only 8 participants showed a difference in mean error rates in this direction, whereas 25 participants showed the contrary ordering of means, as predicted by the nonoscillator models; $\chi^2(1, N = 33) = 8.76$, $p < .01$. So for both sequence types, predictions of nonoscillator models (based on ordinal position) were supported over predictions of oscillator models (based on temporal position).

Errors for Grouped Versus Ungrouped Sequences

The dominant errors in the preceding analysis (2–6 and 3–7) are same ordinal position intergroup errors, and other errors in this category include 1–5 and 4–8. For grouped sequences, these errors typically occur more frequently than adjacent intergroup errors (4–5), whereas corresponding errors for ungrouped sequences show the reverse pattern (Ng & Maybery, 2002b). To assess whether this interaction occurs here, we conducted a 2 (sequence type: grouped vs. ungrouped) × 2 (error type: adjacent intergroup vs. same ordinal position intergroup) ANOVA on error ratios. Only the interaction was significant, $F(1, 36) = 13.03$, $MSE = 0.89$, $p < .01$. For same ordinal position intergroup errors, the error ratio was higher for grouped compared with ungrouped sequences, $t(36) = 4.95$, $p < .01$, whereas for adjacent intergroup errors, the trend was in the reverse direction, $t(36) = 1.79$, $p = .09$ (Figure 4). Thus there is a general tendency for grouping to result in migrations that preserve within-group ordinal position.

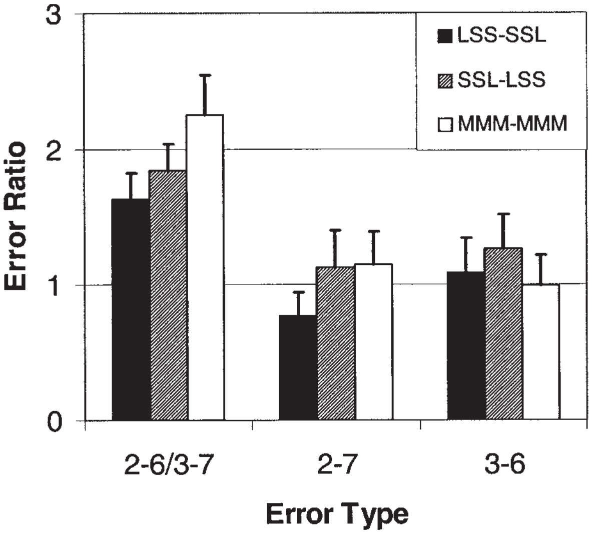

Figure 3. Mean error ratios for three types of intergroup order error as a function of type of grouped sequence (SSL–LSS, LSS–SSL, and MMM–MMM). Note that S, L, and M refer to within-group stimulus onset asynchronies of 400 ms, 800 ms, and 533 ms, respectively.

Discussion

Verbal communication and most other areas of complex behavior depend on the ability to track events and order them correctly. Recent attempts to identify mechanisms that code serial order in STM have resulted in sophisticated models such as the SE, ACT–R, PL, OSCAR, and ORSE models. These models share the assumption that extralist contextual information is associated with list items and is critical to retaining them in order. However, the models divide on whether this extralist information is provided by temporal oscillators or consists of more abstract codes.

To evaluate the models with reference to this central distinction, we used grouped presentation of sequences and teased apart the temporal and ordinal positions of items within their groups. Models incorporating oscillators predict intergroup order errors that maintain within-group temporal position, whereas models incorporating other forms of positional coding predict errors that maintain within-group ordinal position. Results showed that when items migrated across groups, it was ordinal rather than temporal position that dictated recall. Therefore, the nonoscillator models were supported, rather than the oscillator models.

Our investigation of transposition errors is complemented by another investigation in which we also manipulated SOAs within individual groups but examined recall latencies (Ng & Maybery, 2002a). In this study of recall latencies, we used six-item lists and a 3–3 grouping structure. Two grouped lists, SL–SL and LS–LS, were of critical interest because the three oscillator models predict that the ratios of the within-group SOAs (1:2 and 2:1 for the two lists, respectively) should be reflected in the latencies separating the recall of successive items. This prediction was not supported. Instead, the within-group interresponse latencies did not differ as a function of SOA, consistent with predictions of the ACT–R model. (See Maybery, Parmentier, & Jones, 2002, for additional timing-of-recall data favoring the ACT–R model over the PL and OSCAR models.)

Returning to the present study, perhaps particular methodological features favored the nonoscillator models. For instance, perhaps articulatory suppression (see Footnote 1) introduced additional events to the episodic stream, which reduced the salience of timing cues and thereby limited the support observed for predictions of the oscillator-based models. This particular suggestion is implausible for several reasons. First, temporal grouping and articulatory suppression affect recall independently (Hitch et al., 1996). It is more significant to note that other work completed

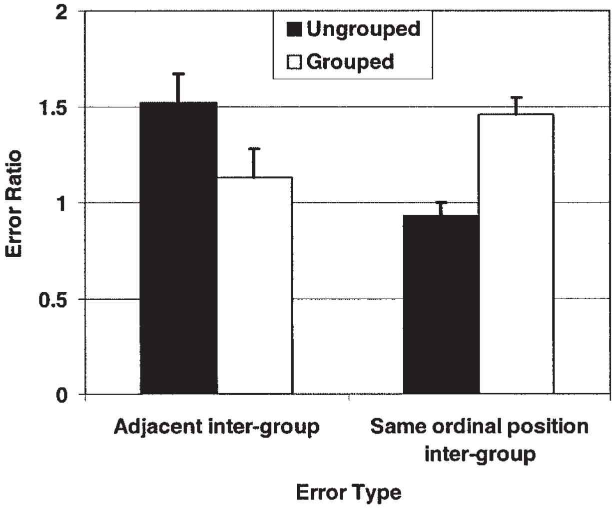

Figure 4. Mean error ratios for two types of intergroup errors (adjacent and same ordinal position) for the grouped and ungrouped sequences.

recently in our laboratory consistently supports predictions of the nonoscillator models over predictions of the oscillator models. This work shows that support for ordinal rather than temporal coding of within-group position is robust in relation to (a) whether articulatory suppression is imposed (Ng & Maybery, 2002b), (b) whether the mode of presentation is visual or auditory (Ng & Maybery, 2002b), (c) whether temporal separation is manipulated using unfilled intervals or irrelevant items (Ng & Maybery, 2004), and (d) whether the critical outcomes concern transposition errors or recall latencies (Maybery et al., 2002; Ng & Maybery, 2002a).

Although our results are consistent with an absence of coding of temporal information, there is evidence from Neath and Crowder (1996) that manipulating the temporal separation of sequence items affects the shape of the serial position function (see also Neath & Crowder, 1990). Neath and Crowder (1996) found that systematically increasing the interitem intervals across a sequence benefited the recall of items late in the sequence, whereas systematically decreasing the intervals benefited the recall of items early in the sequence. These results are consistent with temporal distinctiveness improving recall accuracy. However, as Lewandowsky and Brown (in press) argue, it is also possible that lengthening the interval following an item allows for more elaborate encoding or rehearsal of that item. To evaluate these temporal-distinctiveness and encoding explanations, Lewandowsky and Brown independently manipulated the intervals preceding and following each item. Recall accuracy was influenced only by the duration of the interval that followed an item, an effect abolished with the application of articulatory suppression. Thus the encoding explanation was favored, suggesting that Neath and Crowder's (1996) results should not be interpreted as evidence for the coding of temporal information.

Perhaps advocates of oscillator models could argue that temporal as well as ordinal within-group position is encoded, but that the latter dominates the former. However, because all of the available evidence can be understood in terms of ordinal coding, it would not be parsimonious to adopt this invisible temporal footprint position. Nevertheless, although evidence from the current study and the other studies reviewed is consistent with a limited role for temporal information in coding the positions of items in STM, it is possible that temporal information is implicated in other ways. For instance, temporal gaps are extremely effective in promoting grouping (Frankish, 1995; Parmentier, Maybery, & Jones, in press), so it is possible that oscillators play a critical role in the perceptual parsing of sequences of events.

Although we grouped the SE and ACT–R models together in contrasting them with the temporal-oscillator models, there are clear differences between the two, and available evidence suggests that each is in need of development. First, Henson (1999) has shown that when sequences are composed of different-sized groups (3–4 or 4–3 sequences), intergroup order errors respect position relative to the end of the group as well as position relative to the front of the group (e.g., the last item of a three-item group will tend to be recalled in place of the last, rather than the third, item of a four-item group). Accommodating these results would require some extension of the current ACT–R model, for which item position is marked with reference to the start of the group. On the other hand, ACT–R provides a detailed account of response latencies for grouped sequences, whereas the SE model would need to be extended to model these recent data (Maybery et al., 2002; Ng & Maybery, 2002a).

In summary, considerable evidence accumulated in our laboratory supports the conclusion that the coding of positions within groups in serial STM is based on ordinal rather than temporal information. However, models based on ordinal coding will need to be extended to accommodate other recently collected data for grouped sequences, and further empirical research is needed to decide whether temporal oscillators are implicated in the initial parsing of temporally grouped sequences.

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Appendix

Frequencies of Order Errors Accumulated Over the 37 Participants for Grouped (Upper Right) and Ungrouped (Lower Left) Sequences

Serial position	1	2	3	4	5	6	7	8
1		70	38	21	107	41	31	13
2	33		203	53	52	120	65	30
3	44	134		142	53	73	128	34
4	25	81	100		87	73	70	98
5	51	42	76	95		122	91	40
6	21	76	60	74	81		194	80
7	21	36	61	61	87	136		127
8	17	20	26	54	42	66	90	

Note. Each participant received 30 trials of grouped sequences and 20 trials of ungrouped sequences.

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Appendix

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Abstract

The Phonological Loop (PL) model of verbal short-term memory, whilst presented as a time-based model, can be interpreted to be an event-based model. It is, however, ambiguous as to whether critical events are any attended-to events or only phonologically encoded events (Burgess & Hitch, 1999; Hitch, Towse, & Culpin, 1996). A previous series of experiments failed to support the time-based version of the model (Ng & Maybery, 2002). This experiment evaluated the phonological and non-phonological event-based interpretations of the model. Presentation of visual lists of 9 consonants grouped into 3 groups of 3 using extended temporal gaps was employed. The critical manipulation was the inclusion of a to-be-ignored item (an asterisk) between the first and second consonants in some groups. The predicted patterns of inter-group interposition errors enabled testing of the 2 different event-based interpretations of the PL model. According to the phonological interpretation of the PL model, because the to-be-ignored asterisk should not be encoded phonologically, intergroup transposition errors should depend on the within-group serial positions of the to-be-remembered items: For instance, if the second consonant of one group migrates to a different group, it should take the place of the second consonant in that group. On the other hand, a non-phonological event-based interpretation of the PL model should predict encoding of the asterisk as an event, and the transposition of items across groups should depend on the within-group serial positions of all events (inclusive of the asterisk's occurrence). The results from this experiment support a phonological event-based interpretation of the PL model.

Recently the nature of the coding of serial order in short-term memory has been examined and debated from the perspective of whether temporal information is implicated (Lewandowsky, Duncan & Brown, 2004; Lewandowsky, Brown, Wright & Nimmo, 2006; Ng & Maybery 2002, 2005). Some recent models have included temporal information as an essential feature in coding serial order (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1997). However, other models have taken a non-temporal stand, with the encoding of order depending simply on the succession of events (Anderson & Matessa, 1997; Farrell & Lewandowsky, 2002; Henson, 1998). However, there is a model, which, although described as time-based, could be interpreted as event-based. This model also invites discussion of what constitutes an event for visually presented verbal items.

The Phonological Loop (PL) model (Burgess & Hitch, 1992, 1996, 1999; Hitch, Burgess, Towse & Tulpin 1996) is essentially an extension of the verbal subsystem of Baddeley's (1990) theory of working memory. The PL model has three layers of nodes coding different types of information, namely, item, phonological and contextual information. The latter information is provided by output from sets of temporal oscillators. According to the PL model, visually presented to-be-remembered verbal items (e.g. printed letters) are converted to phonological codes, which are then associated with item information. The item information is then associated with contextual information. The beginning of list presentation starts a wave of activation in a set of oscillators. This activation passes across the oscillators as the list is presented sequentially, and the association of oscillator output with item information allows for order to be encoded. When items are grouped (e.g. by using extended pauses to segment a list), a second set of oscillators repeats a cycle of activation in step with the start of each group. In effect, this set of oscillators codes within-group position, whereas the first set codes within-list position. During recall or rehearsal, the waves of activation of the two sets of temporal oscillators are reinitiated and used to cue the retrieval of successive items. For the second set of oscillators used with grouped lists, similar patterns of activation occur for items that occupy the same temporal position within different groups because the activation is restarted with the onset of each new group. Thus, in relation to transposition (order) errors, the PL model predicts the frequent exchange of items in the same serial position in different groups because the contextual information is similar for these items (provided timing is held constant for the groups – see Ng & Maybery, 2002, 2005).

The PL model's reliance on time was implemented indirectly when simulating the model (Burgess & Hitch, 1992, 1996, 1999; Hitch et al., 1996). It was assumed that "each time step has a duration equal to time taken to present or recall an item" (p. 560, Burgess & Hitch, 1999). To implement the time component, "index T increases by 1 per time step" (p. 560, Burgess & Hitch, 1999) where index T corresponds to time. Therefore, although the context signal was interpreted as time-dependent, with reference made to temporal oscillators, the PL model could be modified to be event-dependent, with an increment of 1 in the context signal with each event, such as the presentation of an item.

A further complication is the representation of events in terms of what constitutes a substantive change in contextual information. Is an event any attended-to event (e.g. a visual stimulus), or it is an event marked by encoding of new information at a phonological (or other non-perceptual) level? The latter possibility could be entertained with reference to the PL model, which assumes that visual information is represented phonologically, and it is an item's phonological representation that is associated with contextual information via the item representation. However, Parmentier, Maybery and Jones (2004) have recently reported grouping effects for auditory-spatial information, in which the stimuli were bursts of white noise presented from loudspeakers distributed in space. Therefore, if contextual codes are important in retaining serial order, then it seems likely that these codes can be associated with representations that are non-phonological in form.

Therefore, there can be three interpretations of the PL model: (1) a time-based version in which the context signal is provided by temporal oscillators, as proposed by the architects of the model (Burgess & Hitch, 1999); (2) a phonological event-based version, in which the context signal is advanced whenever an event is coded phonologically; and (3) a version in which any attended-to event, whether it is encoded phonologically or not, advances the context signal (we refer to this version as the non-phonological event-based PL model).

A previous test directed at the original time-based PL model was conducted by Ng and Maybery (2002). They ran a series of experiments that presented lists of 6-9 items in groups of three for immediate recall. They manipulated the timing of events while holding the number of items constant. According to a time-dependent PL model, the pattern of inter-group transposition errors should depend on the timing of the items with reference to the onsets of their respective groups. The critical list types varied the item presentation rate from one group to another. For instance for one type of list, the item-to-item SOA was 500 ms for the first group, 1000 ms for the second group, and 500 ms for the third group. The interval from start of one group to start of the next was kept at 4 s. According to the prediction of the PL model following a time-dependent interpretation, these mixed presentation rate lists should mean that any across-group transposition of items should depend on the time of occurrence at presentation. That is, item 2 of a 1000 ms SOA group should transpose with item 3 of a 500 ms SOA group because both items occur 1000 ms after group onset. This correspondence in timing should mean that the two items are associated with very similar contextual information from the temporal oscillators that code within-group position. Inter-group transposition errors should depend on the timing of items rather than their ordinal positions within their groups. This was not found. Instead, the transposition of items tended to respect ordinal position rather than temporal position.

Since outcomes of the Ng and Maybery (2002) research challenge the time-based version of the PL model (and a similar model described by Brown et al, 2000), this experiment examines the two alternative versions of the PL model. If changes in context are event-based, do the changes depend on the phonological coding of events, or do any attended-to events result in changes in context?

To examine this issue, irrelevant items were included in some lists. For all lists, there were nine to-be-remembered consonants, and for grouped lists, these were formed into three groups of three items. The critical list types had an irrelevant visual stimulus (an asterisk) presented between the 1st and 2nd to-be-recalled item in one, two or three of the groups. An SOA of 500 ms was used for all the stimuli (TBR and irrelevant) in a group, and 4 s was the fixed interval from onset of one group to onset of the next. Groups containing the irrelevant asterisk between the 1st and 2nd consonants were labeled [4] and those without the asterisk were labeled [3]. The two critical list types were designated [3][4][3] (i.e. an asterisk was included in only the second group; see Figure 1A) and [4][3][4] (i.e. an asterisk was inserted in both the 1st and the 3rd groups; see Figure 1B). For two other grouped lists, there was either no asterisks ([3][3][3]; Figure 1C) or an asterisk in each of the three groups ([4][4][4]; Figure 4D).

For the non-phonological event-based interpretation of the PL model, the asterisk should be encoded as a visual event because its occurrence is unpredictable, with the four types of grouped list presented in a pseudo-random order. This version of the PL model should predict that a [4][3][4] list would present a different pattern of inter-group transposition errors to a [3][4][3] list (see Figure 1, Parts A & B). A [3][4][3] list should result in a high frequency of exchanging the items in serial position 3 of the 1st and 3rd groups with the item in serial position 2 of the 2nd group (collectively we refer to these errors as 3-2-3 errors; see Figure 1A). In contrast, a [4][3][4] list should result in a high frequency of exchanging items from serial position 2 of the 1st and 3rd group with the item from serial position 3 of the 2nd group (labeled 2-3-2 errors; see Figure 1B). The 3-2-3 errors for [3][4][3] lists and 2-3-2 errors for [4][3][4] lists should occur with higher frequencies than errors 2-2-2 and 3-3-3 (in which items in the 2nd serial position exchange with each other or items in the 3rd serial position do so) for either type of list. The reverse prediction holds for a phonological event-based interpretation of the PL model. For this model, the asterisk should not be encoded phonologically, so errors 2-2-2 and 3-3-3 should predominate. Finally, both the phonological and non-phonological versions of the PL model predict predominately 2-2-2 and 3-3-3 errors for the [3][3][3] and [4][4][4] lists.

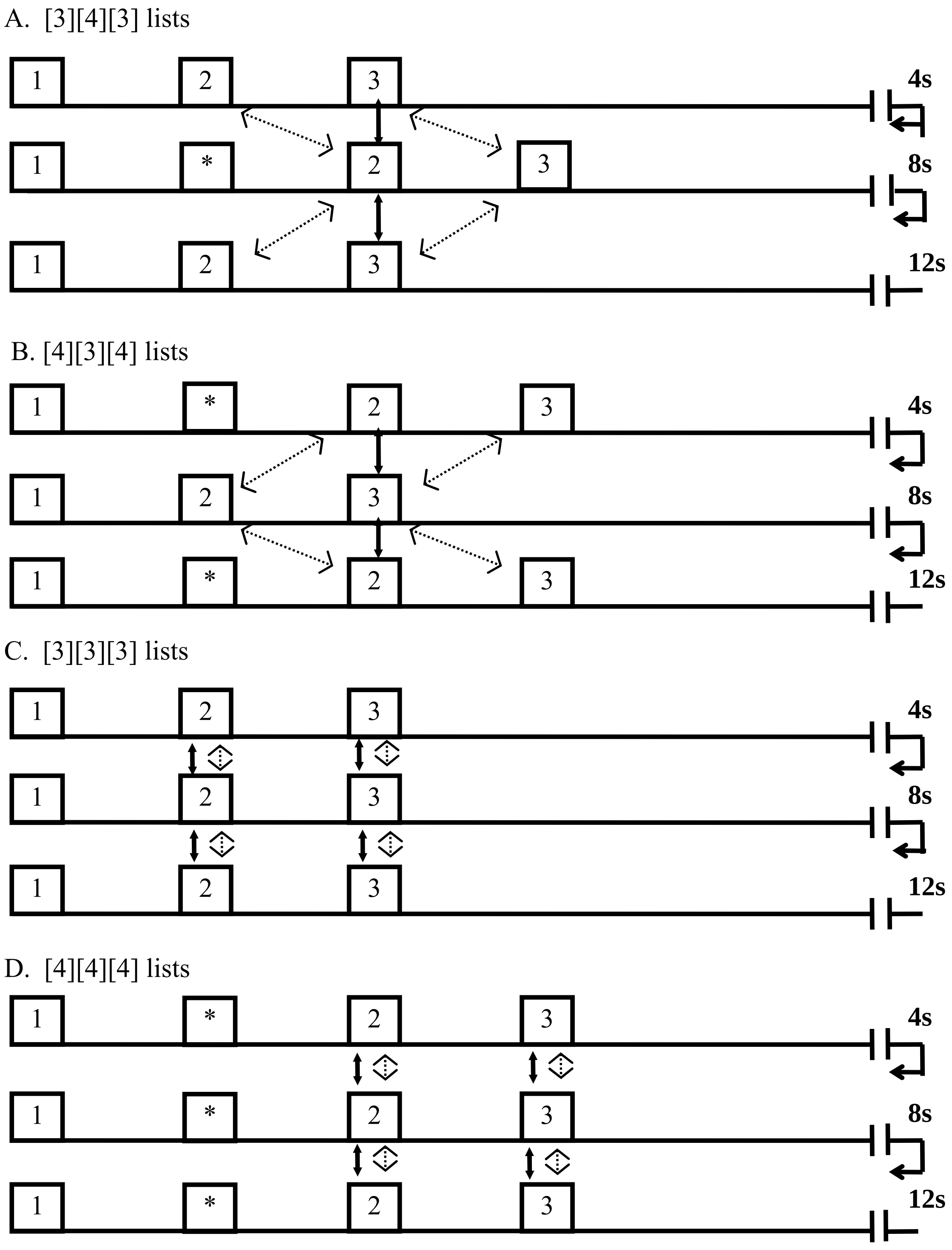
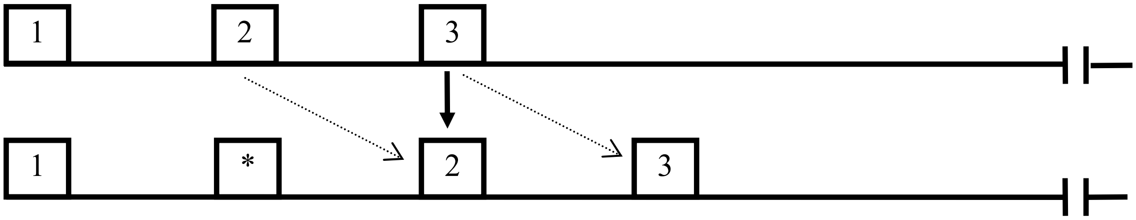


Figure 1. The timing of stimulus sequences for the different grouped lists. Numbers represent within-group serial position. Solid arrows depict errors predicted by the non-phonological event-based PL model. Broken arrows depict errors predicted by the phonological event-based PL model.

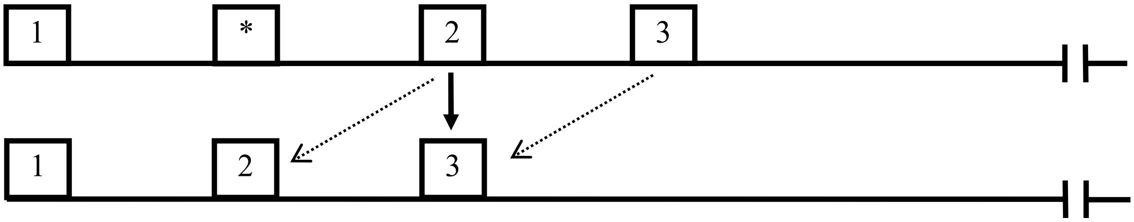
A protrusion (or intrusion) error occurs when an item from previous list intrudes on recall of the current list (Henson, 1998; Ng & Maybery, 2000). (Note that this error can be identified only when the protruding item does not appear in the current to-be-remembered list.) These errors can also be used to evaluate the different versions of the PL model. According to a non-phonological event-based interpretation, a protrusion from a [3] group (i.e. no asterisk) in the previous list to a [4] group (with asterisk) in the current list should result in a higher frequency of the item in serial position 3 of the group from the previous list protruding on serial position 2 rather than serial position 3 of the group from the current list (we label these two errors 3→2 and 3→3 respectively; see Figure 2A). Also, a protrusion from a [4] group to a [3] group should result in a higher frequency of the item from serial position 2 of the group from the previous list protruding on serial position 3 (i.e. a 2→3 error) instead of serial position 2 (2→2) of the group from the current list (see Figure 2B). The protrusion errors predicted for the phonological interpretation of the PL model should be 2→2 and 3→3 regardless of whether the "donor" and "recipient" groups are [3] or [4], that is, regardless of whether an asterisk appears in either of the groups (see Figure 2, broken arrows).

Although the present experiment was designed to evaluate the phonological and non-phonological event-based versions of the PL model, it should be noted that predictions of the original time-based PL model are aligned with those of the non-phonological event-based version of the model. This is because the time-based PL model predicts interposition and protrusion errors that depend on the timing of items with reference to group onset, and this timing depends on the number of visual events (i.e. letters with or without the asterisk) that are presented in each group. The experiment therefore provides further evidence on the viability of the time-based PL model.

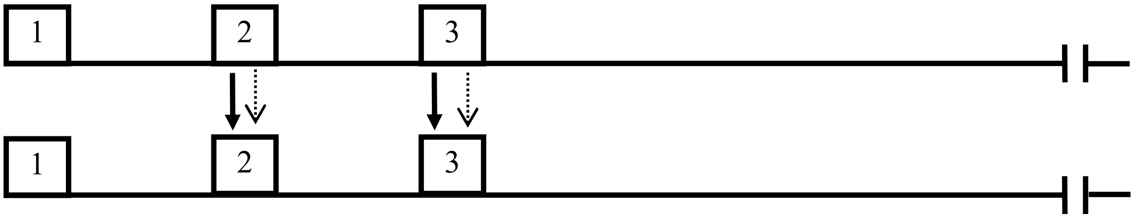
A. [3] to [4] protrusion



B. [4] to [3] protrusion



C. [3] to [3] protrusion



D. [4] to [4] protrusion

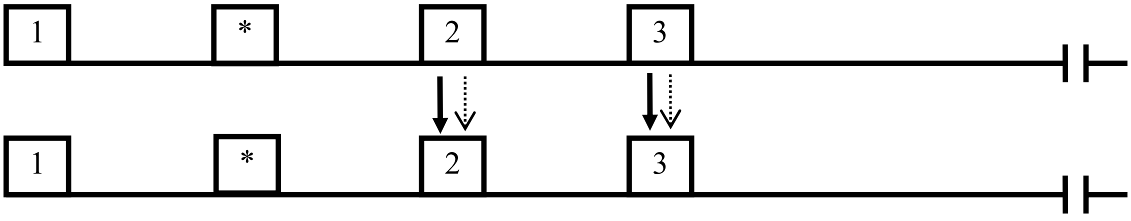


Figure 2. Protrusion errors predicted by non-phonological (solid arrows) and phonological (broken arrows) event-based interpretations of the PL model for four combinations of donor group (previous list) and recipient group (current list).

Method

Participants

Thirty-two undergraduates (19 women) at the University of Western Australia participated. They were aged between 18 and 56[1] years and were recruited and tested in accordance with University of Western Australia ethical procedures.

Apparatus

An IBM compatible computer with a QWERT keyboard and a 36 cm colour monitor were used to present the stimulus sequences and record answers.

Stimuli

Eighty 9-item lists of consonants (excluding *w* which comprises 3 syllables) were generated randomly, but so that consonants were not repeated within a list, consecutive items in a list were not alphabetic neighbours (e.g. BC) and words (e.g. SLY) were avoided. For each participant, 68 of the 80 lists were selected at random and used to form 4 practice and 10 test trials with ungrouped lists, then 4 practice and 40 test trials with grouped lists, followed by a further 10 test trials with ungrouped lists.

An item-to-item SOA of 500 ms was used for all ungrouped lists. For grouped lists, the interval from the start of one group to start of the next was fixed at 4 s. Groups consisted of either the three consonants alone (a "3" group), or the three consonants with an asterisk inserted between the first and second consonants (a "4" group). The 3 or 4 stimuli within a group were presented with an SOA of 500 ms (see Figure 1).

There were 1 practice and 10 test trials for each type of grouped list—[4][4][4], [4][3][4], [3][4][3] and [3][3][3]. These lists differed as to whether an asterisk was inserted

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[1] The accuracy of recall for the oldest (56 years old) participant was comfortably within the range of accuracy for the other participants, the oldest of whom was 33.

between the first and second letters for (a) each group ([4][4][4]), (b) only the first and last groups ([4][3][4]), (c) only the second group ([3][4][3]), or (d) none of the groups ([3][3][3]; see Figure 1).

Procedure

Participants were tested individually. As indicated earlier, each participant received 4 practice and 10 test ungrouped lists, then 4 practice followed by 40 test grouped lists (with order of the 4 types randomised for each set of 4 trials), and finally a further 10 test ungrouped lists, in one continuous block.

The procedure for each trial was as follows. A warning signal (a brief tone and a cross centred on the screen) preceded each sequence by 1,500 ms. Each letter or asterisk was presented in Times New Roman font, size 36, in the centre of the screen for 250 ms. The SOAs depended on the list type, as described earlier (and see Figure 1). Recall was initiated by the appearance of 9 boxes across the bottom of the screen. These boxes appeared 4 s after the onset of the last group for the grouped lists, and 500 ms after the onset of the last item for the ungrouped lists. A marker was shown under the left-most box. This box signified the first serial position, and when the participant typed a letter on the keyboard, that letter was printed in the box. The marker then moved to a position under the next box to the right. Thus the boxes were filled from left to right as the letters were typed. The mouse enabled movement across the boxes. After filling all 9 boxes (which was necessary to proceed), the participant pressed the down-arrow key to signal the end of the response. To proceed to the next list, the participant pressed any key when ready.

Participants were instructed that sequences of letters would be presented on the screen and they would be required to recall the items in correct order at the end of each sequence. It was emphasized that each letter had to be said aloud as it was presented. Participants also were instructed to ignore any asterisks that appeared in the lists and concentrate on the nine letters. Instructions stressed recalling the letters in correct serial position, with guessing permitted when items could not be recalled.

Analytic methods for transposition and protrusion errors

Analyses of transposition and protrusion errors used an error-ratio measure introduced by Ng and Maybery (2002) to correct for differential opportunity for the various types of errors (e.g. compare the possible transposition errors of the two types illustrated for the [4][3][4] and [3][4][3] lists in Figure 1). This measure was calculated using the ratio of the actual number of errors of a particular type divided by the number of errors expected of that type if the total number of observed errors (e.g. the total number of transposition errors) had been distributed equally across all the possible errors (e.g. across all 72 possible transpositions). Therefore, a ratio greater than one suggests that the error type occurred with above-average frequency, whereas a ratio less than one implies that it occurred with below-average frequency. The error ratio is therefore independent of both the total numbers of errors made and the opportunities available for each type of error (see Ng & Maybery, 2002, for more details). We also reported nonparametric analyses to confirm some of the critical outcomes from the analyses of ratios.

Results

The analyses are presented in five sections. We first compare accuracy of recall for grouped versus ungrouped lists. This is followed by analyses examining the transposition and protrusion errors for grouped lists that are critical to evaluating the phonological and non-phonological event-based interpretations of the PL model. Finally two broader analyses of transposition and protrusion errors for grouped and ungrouped lists are reported.

Accuracy for group versus ungrouped lists

The serial position curves for the grouped and ungrouped lists (Figure 3) are similar to those reported elsewhere (Hitch et al., 1996). In particular, accuracy is higher for grouped compared to ungrouped lists. Primacy and recency trends are present for both types of list but are somewhat less pronounced for the grouped lists, where there is evidence of multiple bowing, with elevated recall for intermediate list items. These observations were confirmed by a 2 (list type: grouped vs. ungrouped) x 9 (serial position) repeated-measures ANOVA.

The main effects of list type and serial position were significant, with F (1, 31) =102.33, MSE = 3.54, p < .01, and F (8, 248) = 47.39, MSE = 3.49, p < .01, respectively. The interaction between list type and serial position was also significant, F (8, 248) = 13.37, MSE = 0.88, p < .01. The quadratic trend was significant overall, F (1, 248) = 28.55, MSE = 3.49, p < .01, and interacted with list type, F (1, 248) = 78.86, MSE = 3.49, p < .01. This trend is less pronounced for the grouped lists as a result of the stronger recency and primacy effects within each group.

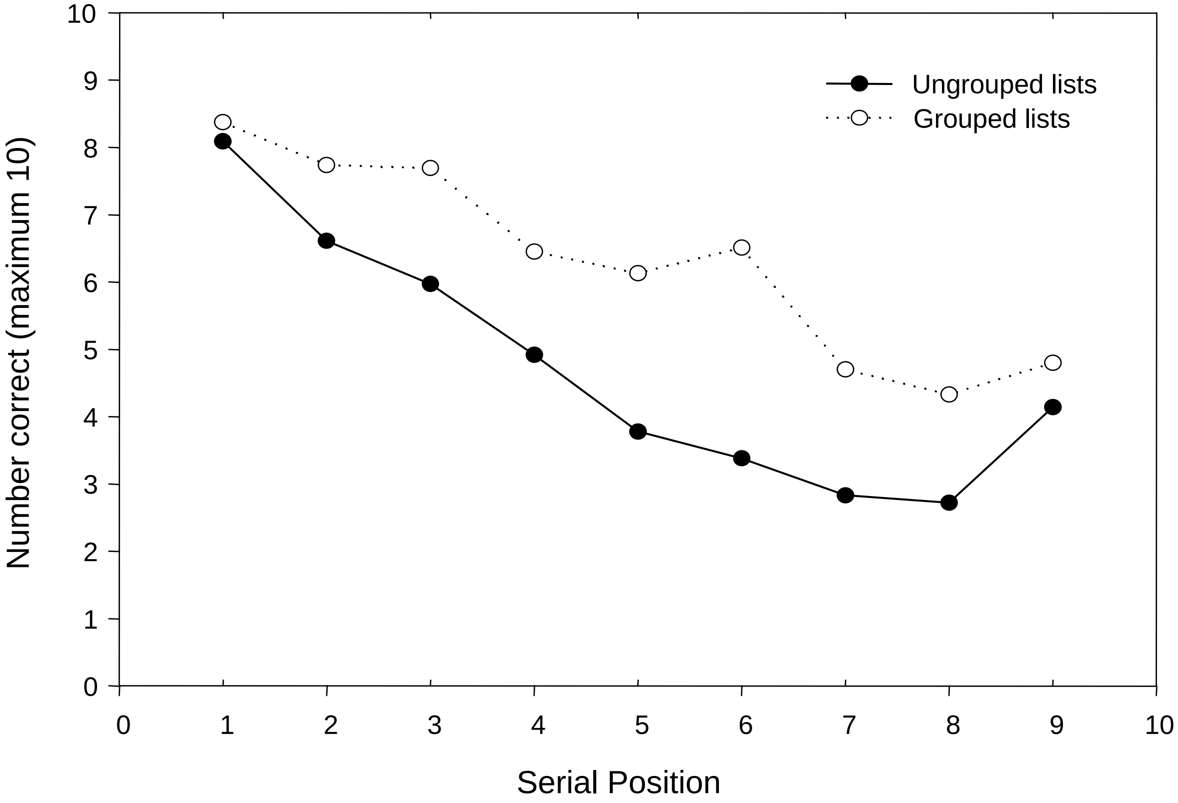


Figure 3. Mean number of correct responses at each serial position as a function of list type.

Transposition errors for grouped lists: Evaluating different versions of the PL model

To recapitulate, a non-phonological event-based PL model predicts: (i) a higher 3-2-3 error rate for [3][4][3] lists compared to other lists; and (ii) a higher 2-3-2 error rate for [4][3][4] lists compared to other lists. (The time-based PL model makes the same predictions.) Alternatively, all list types should show a predominance of 2-2-2/3-3-3 errors according to the phonological event-based version of the PL model. A 4 (type of grouped list: [3][3][3] vs. [4][4][4] vs. [4][3][4] vs. [3][4][3]) x 3 (error type: 3-2-3 vs. 2-3-2 vs. 2-2-2/3-3-3) repeated measures ANOVA was conducted on the error ratios. The only significant effect was the main effect of error type, $\underline{F}$ (2, 62) = 29.92, $\underline{MSE}$ = 1.33, $\underline{p} < .01$. Post hoc t tests with a Bonferroni adjustment to the alpha level showed that error ratios were higher for the 2-2-2/3-3-3 error type ($\underline{M}$ = 1.65, $\underline{SE}$ = 0.07) than for either the 3-2-3 ($\underline{M}$ = 0.55, $\underline{SE}$ = 0.07) or the 2-3-2 ($\underline{M}$ = 0.96, $\underline{SE}$ = 0.11) error type, smaller $\underline{t}$ (31) = 4.69, $\underline{p} < .01$. The latter two means provided a non-significant post hoc t test. Therefore, the dominant error type preserved the within-group positions of the to-be-remembered items, irrespective of whether or not irrelevant events (asterisks) were interpolated between them.

As a check on the validity of the results reported from the analyses of the error ratio, a simpler alternative analysis was conducted on the transposition errors. This analysis focused on the predictions of the phonological and non-phonological event-based versions of the PL model for the [3][4][3], and [4][3][4] grouped lists. We started with the number of errors each participant made in each cell of the matrix of possible order errors. Then, for each of the three critical categories of error (2-3-2, 3-2-3, 2-2-2/3-3-3), we calculated the mean number of errors for the cells included in that category. Finally, we compared these means for individual participants. Recall that for the [3][4][3] lists the prediction for the non-phonological event-based version of the PL model is that 3-2-3 transpositions should occur more frequently than 2-2-2/3-3-3 transpositions. However when the mean number of errors was compared for these two categories of error, only 1 participant showed a difference in the predicted direction, whereas 29 participants showed the contrary ordering of means; $\chi^2(1)$ = 26.12, $\underline{p} < .01$, for the comparison of these frequencies. For the [4][3][4] lists the critical prediction for the non-phonological interpretation is that 2-3-2 transpositions should occur more frequently than 2-2-2/3-3-3 transpositions. However only 3 participants showed a difference in the predicted direction, whereas 24 participants showed the contrary ordering of means; $\chi^2(1) = 16.33$, $p < .01$. Therefore, for both list types there was a preponderance of 2-2-2/3-3-3 errors, consistent with the phonological rather than the non-phonological event-based model.

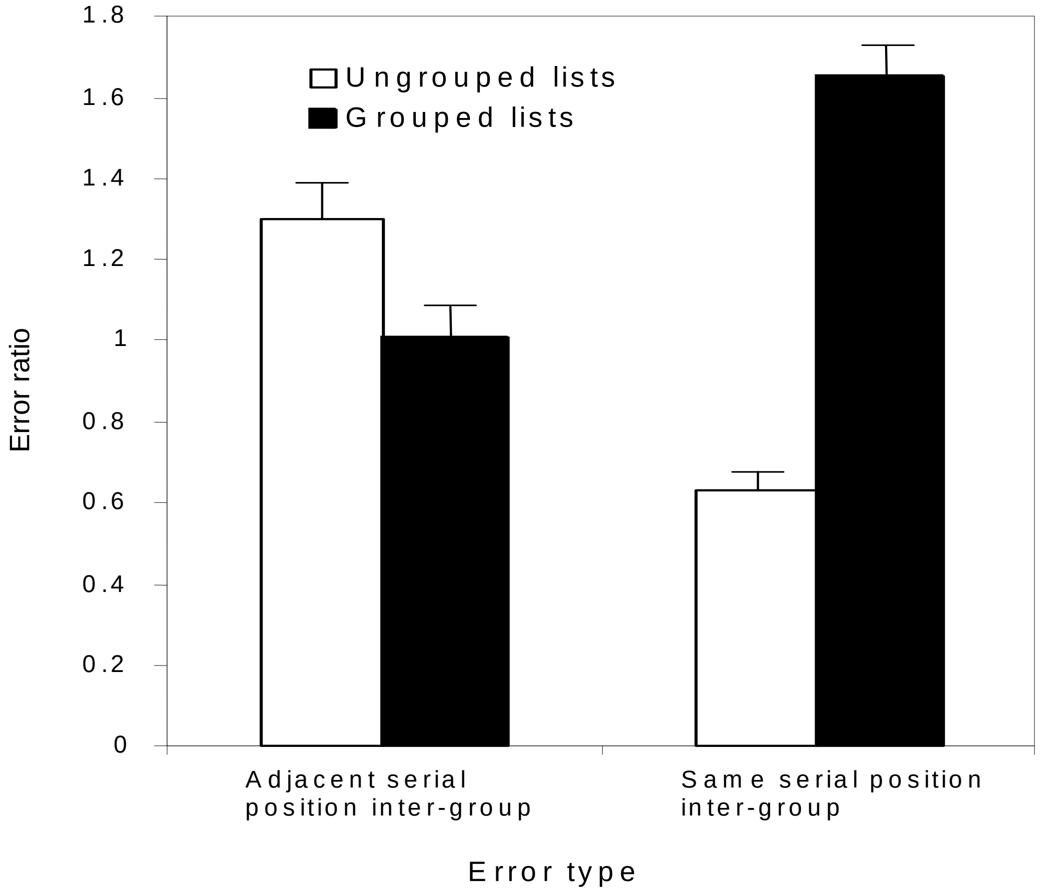
Protrusion errors: Evaluating different versions of the PL model

Recall that the phonological and non-phonological event-based interpretations of the PL model predict certain protrusion errors. The critical cases are when the donor and recipient groups contain different numbers of items because one but not the other contains the asterisk. Two errors predicted by the non-phonological event-based version of the model to occur at higher frequency are 2→3 for a [4]→[3] group transfer, and 3→2 for a [3]→[4] group transfer (see Figure 2). Also errors labeled 2→2,3→3, are predicted when the protrusions are from and to groups that are matched in terms of the presence or absence of an asterisk (i.e. [3]→[3] or [4]→[4]). On the other hand, the phonological event-based interpretation of the PL model predicts a higher incidence of 2→2,3→3 errors for transfers across all group types. Because protrusion errors were infrequent, a single error ratio labeled 2→3,3→2 was calculated for 2→3 protrusions for a [4]→[3] group transfer and 3→2 protrusions for a [3]→[4] group transfer. This ratio was compared to a single ratio calculated for either 2→2 or 3→3 protrusions for either [3]→[4] or [4]→[3] group transfers. In addition, two similar ratios were calculated for [3]→[3] and [4]→[4] group transfers. For one of these ratios, 2→3 and 3→2 protusions were considered for both [3]→[3] and [4]→[4] transfers, and for the other ratio, both 2→2 and 3→3 protrusions were counted for the same transfers. Therefore, there were two types of protrusion (2→3,3→2 and 2→2,3→3) which were calculated for two types of possible group transfer ([3]→[3] or [4]→[4] vs. [3]→[4] or [4]→[3]). The ratios were computed separately for protrusions that came from groups in the same list positions (e.g. middle group to middle group) versus in different list positions (e.g. third group to first group).

To examine these errors, a 2 (group position in list: same vs. different) x 2 (number of items in the "donor" and "recipient" groups: [3]→[3] or [4]→[4] vs. [3]→[4] or [4]→[3]) x 2 (type of error: 2→3,3→2 vs. 2→2,3→3) repeated measures ANOVA was conducted on the error ratios. There was a significant main effect of error type, F(1, 31) = 9.02, MSE = 1.48, p < .01, but no other effects were significant. The error ratio was higher for error type 2→2,3→3 (M =1.25, SE = 0.10) than for error type 2→3,3→2 (M = 0.79, SE = 0.11). There was no indication that variation in the number of items within the donor and recipient groups of the previous and current trials resulted in any differences in errors. The presence of asterisks did not in any way distort the pattern of intrusion errors, which simply reflected the within-group positions of the to-be-remembered items.

Transposition errors for grouped and ungrouped lists

In a more comprehensive analysis of transposition errors, a 2 (list type: grouped vs. ungrouped) x 2 (error type: adjacent inter-group vs. same serial position inter-group) repeated measures ANOVA was conducted on the error ratio measure. Adjacent inter-group order errors are where items cross a group boundary (3-4 or 6-7) whereas same serial



position inter-group errors include 1-4, 4-7, 1-7, 2-5, 5-8, 2-8, 3-6, 6-9 and 3-9. There was a significant main effect of error type, F (1, 31) = 7.75, MSE = 0.54, $p < .01$, which was qualified by a list type by error type interaction, F (1, 31) = 39.90, MSE = 0.34, $p < .01$. The differences in error pattern for the grouped and ungrouped lists apparent in Figure 4 were confirmed by simple-effects analyses. The list-type effect was significant for both the same serial position and adjacent inter-group errors, with values of t (31) = 7.69, $p < .01$, and t (31) = 4.13, $p < .01$, respectively. The error ratio for same serial position inter-group errors was higher for the grouped than for the ungrouped lists, whereas the reverse was the case for the adjacent inter-group errors. Thus, compared to ungrouped lists, grouped lists showed a greater predominance of errors that maintained within-group serial position. The predominance of adjacent inter-group errors for the ungrouped lists is consistent with the transposition gradients typically reported for such lists, in which items transpose more frequently to nearby rather than remote serial positions (Ryan, 1969a, 1969b; Henson, 1998).

Figure 4. Mean error ratio for two types of transposition error as a function of list type.

Protrusions from the previously reported list: grouped versus ungrouped lists

In this section we examine protrusions for ungrouped lists as well as for grouped lists. Our analyses are based on protrusions from the preceding reported list rather than from the preceding presented list, because Ng and Maybery (2002) reported that the two types of protrusions showed similar patterns, although effects tended to be more pronounced for protrusions from the reported lists. A 2 (list type: grouped vs. ungrouped) x 2 (error type: same serial position inter-group vs. adjacent inter-group) repeated-measures ANOVA was conducted on protrusions from the previously reported list. There was a significant interaction between error type and list type, F (1, 31) = 11.43, MSE = 0.55, $p < .01$, however neither main effect was significant. The interaction was examined by calculating the simple effect of list type for each error type. This simple effect was significant for the same serial position inter-group protrusions, t (31) = 3.93, $p < .01$, and for the adjacent inter-group protrusions, t (31) = 2.51, $p < .01$. The error ratio for the same serial position inter-group protrusions was higher for grouped (M = 1.37, SE = 0.09) than for ungrouped lists (M = 1.02, SE = 0.09). In contrast, adjacent inter-group protrusions showed a lower error ratio for the grouped (M = 0.70, SE = 0.14) than for the ungrouped (M = 1.24, SE = 0.16) lists. Thus, protrusions from the previously reported list show a shift in pattern from ungrouped to grouped lists, which reflect a greater influence of an item's serial position within a group.

Discussion

The presence of an irrelevant asterisk within groups was varied to explore whether the coding of positions with temporal grouping in verbal short-term memory is dependent on phonological or non-phonological events, two possibilities that arise from an event-based interpretation of the PL model. The patterns of inter-group transposition errors and protrusion errors were the focus in this study. The non-phonological event-based interpretation of the PL model (i.e. a version of the model in which the visually presented asterisk would be counted as an event) predicts a higher frequency of 2-3-2 errors for [4][3][4] lists and 3-2-3 errors for [3][4][3] lists, relative to 2-2-2/3-3-3 errors in either case. On the other hand, the phonological event-based interpretation of the PL model (in which the asterisk is not registered as an event) would predict a predominance of 2-2-2/3-3-3 errors for all types of grouped list. From the pattern of transposition errors, there was no evidence that 2-3-2 and 3-2-3 errors were higher for [4][3][4] and [3][4][3] lists respectively. Instead, across the different types of lists, 2-2-2 and 3-3-3 errors were consistently higher than 2-3-2 and 3-2-3 errors, suggesting that the mechanism for encoding positions in verbal sequences is dependent on the phonological encoding of items. The protrusion errors also supported a phonological event-based interpretation of the PL model. There was an especially high frequency of 2→2 and 3→3 errors for all donor-recipient cases, including the [4]→[3] and [3]→[4] cases.

The findings of this experiment, although directed at evaluating phonological and non-phonological interpretations of the PL model, can also be interpreted as tests of other models that explain temporal grouping using time-based information to code list positions. For instance, these findings are highly relevant to models like the OSCillator-based Associative Recall (OSCAR, Brown et al., 2000), and the original time-based PL model (Hitch et al., 1966). These models assume that positional information is coded with the passage of time.

Given that the asterisk was presented with the same SOA as the other items, it should have advanced the oscillator-based context signal as much as the presentation of a to-be-remembered item. The expectation would be a higher frequency of 2-3-2 and 3-2-3 errors than 2-2-2/3-3-3 errors for [4][3][4] and [3][4][3] lists respectively. Instead, the results suggest otherwise, and further disconfirm the time-based PL and OSCAR models.

In addition, if it is assumed that the asterisk is not coded, then the findings support the Start-End (SE) model (Henson, 1998), and Adaptive Character of Thought-Revised (ACT-R) model (Anderson & Matessa, 1997) where it is assumed that positional coding is dependent on the passage of events rather than on time.

Perhaps it could be argued that the irrelevant items are encoded as events, but their inclusion disrupts the structure of the temporally grouped lists (by altering the interval from end of one group to start of the next). Alternatively, perhaps the asterisk is not encoded and this then means there is a larger than normal SOA, which presents itself as a break in the presentation of items and results in a change in the group structure (e.g. a [3][4][3] list might be grouped 3-1-2-3). However, these two possibilities are unlikely because effects often associated with temporal grouping, and with a 3-3-3 structure in particular, have been confirmed in the analysis. First, there was significantly higher accuracy of recall of grouped compared to ungrouped lists. Second, the grouped lists also displayed a multiple-bowed serial position curve, showing strong primacy and recency within each group. Third, there was a higher frequency of same serial position inter-group errors for grouped compared to ungrouped lists, whereas adjacent inter-group errors were lower in frequency for grouped lists than for ungrouped lists. Fourth, protrusion errors also were higher in frequency for items that shared the same within-group serial position for the grouped lists compared to comparable errors for the ungrouped lists. Each of these effects is consistent with grouping of the to-be-remembered list items in a 3-3-3 structure. All of the effects have been reported in other studies of temporal grouping where irrelevant items have not been used and where SOA has been constant within a group (see, e.g., Hitch et al., 1996; Ng & Maybery, 2002). Thus it seems that the inclusion of the asterisk did not inhibit grouping and did not lead to any unusual grouping structures.

The present findings appear to rule out a time-based model. They also exclude any model that allows visual to-be-ignored items to be coded as events to the extent that they affect contextual coding of the to-be-remembered verbal items. However, the results are consistent with two possibilities. First, it may be possible that all phonological events, including those that involve an irrelevant item, may influence the contextual position markers. Second, the contextual markers might be influenced only by to-be-remembered events. A method to distinguish these two alternatives would be to replicate this experiment using auditory presentation together with a phonological to-be-ignored event (e.g. the word "skip").

Conclusions

Alternative event-based versions of the PL model were considered. These two versions are where events that advanced the context signal could be any attended-to event or alternatively any phonological event. By varying the number of items visually presented in each group with or without the inclusion of an asterisk (a to-be-ignored event), these phonological and non-phonological interpretations of the PL model were tested. The results favoured a phonological event-based interpretation of the PL model. The findings can also be interpreted as favouring other non time-based models such as the SE and ACT-R models. However, it remains to be determined whether any phonologically encoded event (even a to-be-ignored event) alters the positional coding of to-be-remembered verbal events with which it is grouped.

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