

Serial order in short-term memory

HOW do we maintain a novel sequence of items in the correct order? For example, how do we remember an unfamiliar telephone number during the few seconds between putting down the telephone directory and picking up the telephone? This immediate serial recall or ‘memory-span’ task has fascinated psychologists for decades; it remained the dominant empirical tool behind contemporary theories of short-term memory, such as Alan Baddeley’s working-memory theory (Baddeley, 1986). However, like many questions in cognitive psychology, the apparent ease with which we perform such a simple task (providing the telephone number is not too long!) masks a rich and complex host of issues.

Three theories of serial order

The above question is just one example of a more general problem that Karl Lashley called the ‘problem of serial order’ (Lashley, 1951). He saw this problem as pervading many aspects of our behaviour, from the order of finger movements in a skilled pianist, to the order of words in a sentence. At least three different solutions to this problem have been proposed over the years, all of which have been reincarnated in recent computer models of short-term memory. I have called these ‘chaining’, ‘positional’ and ‘ordinal’ theories (Henson, 1998a).

Chaining theory assumes that order is



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stored by a ‘chain’ of associations between successive items (Figure 1:A). This idea can be traced back to stimulus–response theory, whereby each response becomes the cue for its successor (Ebbinghaus, 1964). Simple chaining models assume only pairwise associations between successive items.

There are several immediate objections to chaining models. For example, how do they cope with repeated items, where two different responses will share the same cue? The chaining model also has difficulty handling erroneous responses, after which the cue for subsequent items will be incorrect, leading to a cascade of further errors – after all, a ‘chain is only as strong as its weakest link’? More sophisticated models can overcome these problems by including remote associations between items, an approach exemplified by recent neural network models (Elman, 1990). In these models, the cue becomes a ‘compound’ of previous responses. This ‘recent history’ allows repeated items to be disambiguated by their preceding context; the effect of a single error is thereby less devastating because the preceding responses can keep recall ‘on track’.

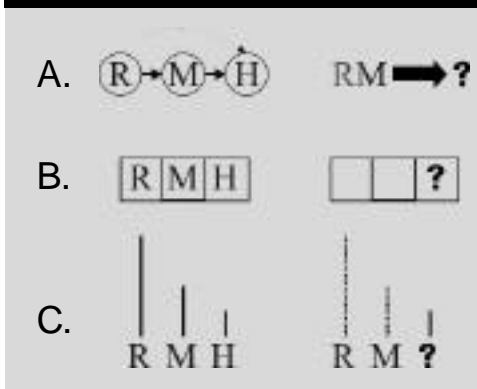
Positional theory, on the other hand, assumes that each item is coded for its position in the sequence. Conrad (1965), for example, assumed that each item is stored in a separate ‘box’ in memory, and their order is retrieved by stepping through the boxes in a predetermined routine (Figure 1:B). This idea is analogous to the memory of conventional von Neumann computers, where information is stored in separate ‘addresses’.

Positional models do not have problems with repeated items (because they are stored in different boxes), nor with erroneous responses (because recall can

proceed to the next box, even if the contents of the current box are not retrieved correctly). However, the model also raises questions. How many boxes do people have in short-term memory: six, seven, eight? More importantly, the ‘perfect’ coding of position in this model does not explain the most common error people make in serial recall, which is to swap, or transpose, nearby items. One response is to assume that the positional codes are not perfect, but ‘overlap’ with each other. In the computational model of Burgess and Hitch (1992), for example, positions are cued by a sliding window (see ahead to Figure 3:B). The overlap between cues for nearby positions provides a rationale for the misordering of nearby items. One problem faced by such models, however, is to specify precisely what these positional codes represent (both psychologically and in the brain).

The third type of theory, ordinal theory, assumes that order is represented by the relative values of some continuous property of the items. For example, Grossberg (1978) assumed that order is represented by the strength of items in memory, with the first item ‘strongest’ and the last item ‘weakest’. The order of items can be retrieved by an iterative process of selecting the strongest item and then temporarily suppressing it so as to recall the next strongest item, and so on (Figure 1:C). If some random noise is added to each item’s strength, this selection process can reproduce the dominant pattern of order errors in immediate serial recall, as demonstrated by the primacy model (Page & Norris, 1998). The simplicity of such models is appealing: no explicit coding of position is required, for example. However, as argued below, the evidence suggests that people do somehow code position.

FIGURE 1 Chaining (A), positional (B) and ordinal (C) models of serial order



Evidence from errors in immediate serial recall

One way to distinguish between these three theories is to examine the errors people make when they misrecall a sequence. For example, most chaining models (even those with 'compound' cues) predict a higher probability of an error when the cue for one item is similar to the cues for other items. Following an idea from Baddeley (1968), we tested this prediction by examining the errors made when people recalled sequences of alternating phonologically confusable (e.g. B and P) and phonologically non-confusable items (Henson *et al.*, 1996). Given that items in short-term memory are assumed to be represented in phonological terms (Baddeley, 1986), chaining models predict increased errors on the items following the phonologically confusable items (Figure 2:A). However, we found no evidence for an increased probability of errors following confusable items compared with control trials with no confusable items: contrary to chaining theory.

The extreme case of similarity is the repetition of an item. Most chaining models thus predict an increased probability of errors following repeated items (Figure 2:B). Wickelgren (1966) originally reported evidence in support of this prediction. However, the mere presence of repeated items in a sequence has several important effects on recall of that sequence (Henson, 1998a). When these other effects are taken into account, the evidence for a direct effect of repetition on recall of subsequent items is far from compelling (Henson, 1997). Our failure to find any effect of phonological similarity or repetition on recall of subsequent items calls into doubt the role of chaining in immediate serial recall.

In contrast with the absence of clear evidence for chaining theory, there is abundant evidence in support of positional theory. One example is the pattern of errors that arises when sequences are temporally grouped (by inserting a pause every three items, for example). Though such grouping improves overall recall (which is why it is a common strategy for remembering sequences such as telephone numbers), one type of error actually increases. This is the swapping of items between groups that maintain their position within a group (Ryan, 1969). The middle item of one group is likely to swap with the middle item of another group (Figure 2:C). Such 'long-distance' swaps are uncommon in ungrouped sequences,

and can only be explained by assuming that the items are somehow coded for their position within a group. These errors are not predicted by ordinal theory, according to which the middle item of a group can only be recalled after having already recalled the first (or last) item.

Another example of such 'positional' errors occurs between trials. In typical short-term memory experiments, participants attempt multiple trials of serial recall. On closer inspection, one finds that the errors on one trial are more likely than chance to have occurred in the same position on the previous trial (Conrad, 1960; see Figure 2:D). Such 'proactive interference' of positional information can only arise if items are somehow coded for their position within trials.

Both these examples – the positional errors between groups and between trials – reflect a general tendency for errors between sequences to maintain their position within a sequence. They cannot be explained by chaining or ordinal theories alone. However, the question remains as to exactly how position is coded.

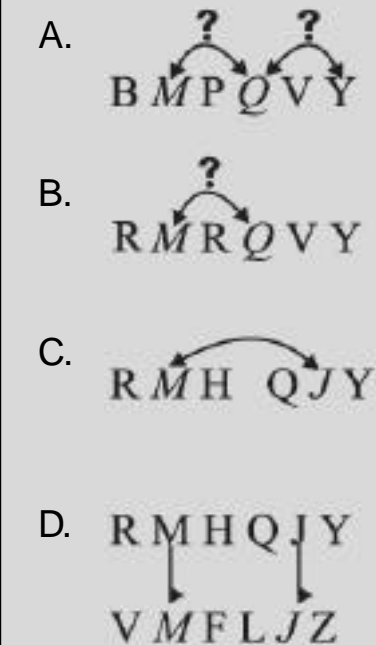
Three theories of positional coding

At least three different types of positional codes are possible. I have called these 'temporal', 'absolute' and 'relative' codes (Henson, 1999). A temporal coding of position assumes that each item is associated with its time of occurrence, perhaps relative to the start of the sequence. In the OSCAR model of Brown *et al.* (2000), for example, items are associated with the states of temporal oscillators of different frequencies (e.g. the hour and minute hands of a clock, Figure 3:A). By resetting the oscillators (rewinding the clock), the order of items can be recalled.

An absolute coding of position assumes that items are associated with their ordinal position (first, second, third, etc.), regardless of their time of occurrence. In the aforementioned model of Burgess and Hitch (1992), for example, the window of activity (Figure 3:B) changes only when a new item is presented, regardless of the delay between successive items. In other words, items are associated with their absolute position from the start of the sequence.

A relative coding of position assumes that items are coded with respect to both the start and the end of a sequence. In the start-end model (Henson, 1998a) I

FIGURE 2 Predicted chaining errors following phonologically confusable items (A) and repeated items (B); positional errors between groups (C) and trials (D)



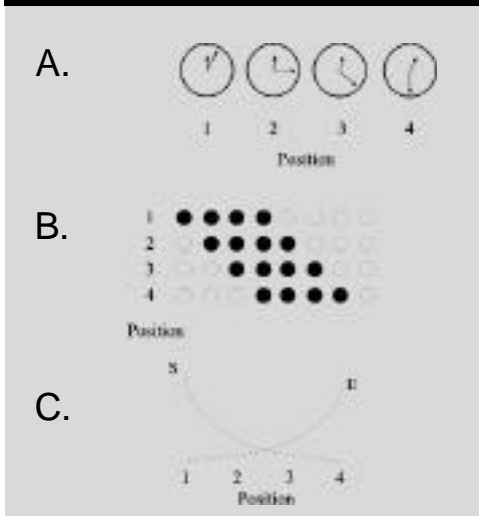
followed the ideas of Houghton (1990) by assuming a start marker, which is strongest at the start of a sequence and decreases in strength towards the end, and an end marker, which is weakest at the start of a sequence and increases in strength towards the end. These markers function like 'anchors', the relative strengths of which provide an approximate two-dimensional code for each position within a sequence (Figure 3:C).

A temporal coding of position is sensitive to presentation rate, so items further apart in time are associated with more distinctive positional codes. However, an absolute coding of position is insensitive to presentation rate, in that the code for the second item in a sequence presented rapidly is identical to the code for the second item in a sequence presented slowly. An absolute coding of position is also insensitive to the length of a sequence, in that the code for the third item in a sequence of three is identical to the code for the third item in a sequence of five. But a relative coding of position is

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FIGURE 3 Temporal (A), absolute (B) and relative (C) codings of position



sensitive to sequence length: the code for the third item in a sequence of three is different from the code for the third item in a sequence of five. The former item is coded for the end of the sequence, whereas the latter item is coded for the middle of the sequence.

Evidence from errors in immediate serial recall To test whether position within groups is coded in temporal or absolute terms, Ng (1996) examined the pattern of errors between groups presented at different rates. Consider two groups, for example, with the second presented twice as slowly as the first (Figure 4:A). The question was whether the third item in the first group was more likely to swap with the third item of the second group (as predicted by an absolute coding of position), or with the second item of the

second group (as predicted by a temporal coding of position, given that these items occurred at the same time relative to the start of a group). The former errors proved more common, favouring an absolute coding of position. Nonetheless, the same pattern is also predicted by a relative coding of position.

To test whether position within groups is coded in absolute or relative terms, I examined the pattern of errors between groups of different sizes (Henson, 1999). Consider, for example, a group of three items followed by a group of four (Figure 4:B). The question was whether the third item in the first group was more likely to swap with the third item of the second group (as predicted by an absolute coding of position), or with the fourth item of the second group (as predicted by a relative coding of position, given that both items occurred at the end of a group). The latter errors proved more common, favouring a relative coding of position. In a second experiment I found the same pattern of errors between trials of different lengths, again favouring a coding of position relative to both the start and the end of sequences.

A new model of relative position

These data were consistent with the start–end model (Henson, 1998a). However, they also raised a problem with this model. In my second experiment (Henson, 1999) the length of a given trial was not known in advance by participants. Yet the errors at the end of one trial were still most likely to have occurred at the end of the previous trial. How could an end marker grow in strength towards the end of

FIGURE 4 Predicted temporal, absolute and relative positional errors between groups presented at different rates (A) and groups of different sizes (B)

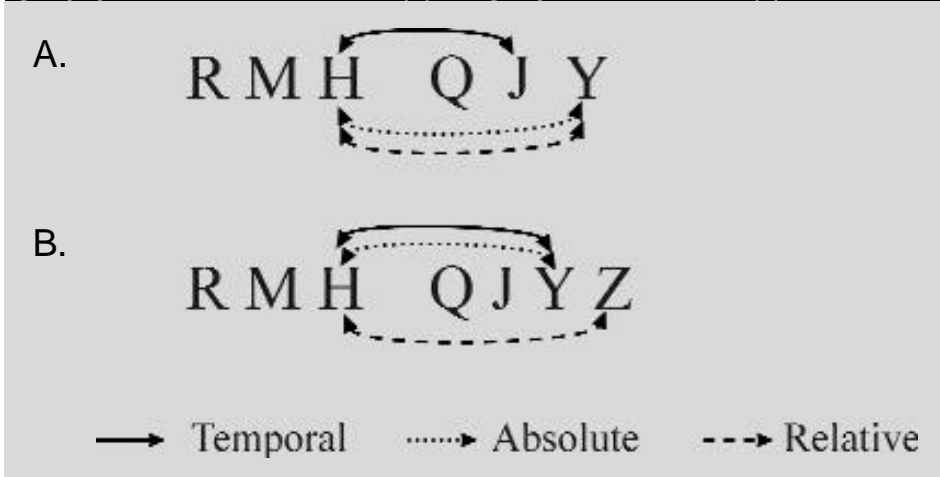
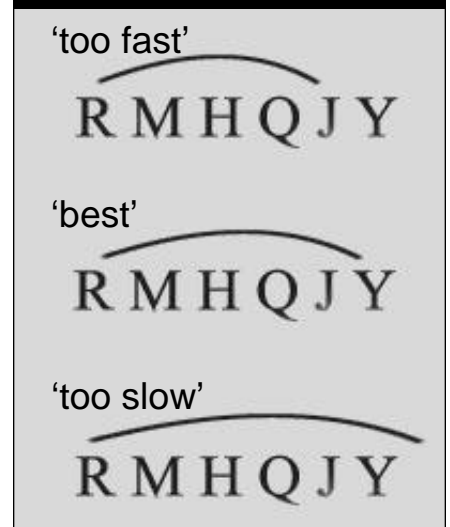


FIGURE 5 Relative positional coding via multiple competing oscillators



a sequence even though the end of that sequence was unpredictable?

To overcome this problem we turned to an alternative means of coding relative position. Following the ideas of Tom Hartley, we proposed that position is coded by a number of temporal oscillators that compete to ‘best’ represent the sequence (Henson & Burgess, 1997). The oscillator that ‘wins’ this competition is the one whose (half) period best matches the temporal duration of the sequence (Figure 5). We also assumed that the position of items in the sequence is coded by the ‘phase’ of the winning oscillator (i.e. the proportion of that oscillator’s period that had been completed by the time each item is presented). This is automatically a relative coding of position; though different length sequences will be coded by different oscillators, the similarity between ‘phase’ codes is always relative to the period of each oscillator, and therefore always relative to the start and end of that sequence. Most importantly, however, because multiple oscillators compete in parallel to represent a sequence, the length of that sequence does not have to be known in advance. This can explain why relative errors occur between the ends of sequences even when those ends are not predictable.

The use of oscillators is appealing, given the overwhelming evidence for periodic oscillations in the brain, and the natural emergence of oscillations from simple dynamic models of neural interactions. Moreover, there are other interesting properties of the model described above. For example, not only does it predict the appropriate pattern of

errors within and between sequences, it also provides a rationale for the limited capacity of people's memory spans. As the number of items coded by an oscillator increases, the similarity between the phase codings of each position also increases. Ultimately, those codes may be so similar that the order of items cannot be determined (and this limit may be 7 ± 2 items (Miller, 1956/1994)). In other words, the limited range of phases automatically restricts the precision with which we can code position in short-term memory.

Future directions

Though an appealing idea, a more detailed model using competing oscillators has yet to be developed. In particular, the details of how these oscillators generalise to hierarchical sequences of sub-sequences, and possibly longer-term learning of temporal sequences, remain to be established (Henson & Burgess, 1997). In the meantime, we have been attempting to interfere experimentally with these

hypothetical oscillators by the use of concurrent temporal distraction tasks (but with only limited success to date).

We have also used brain-imaging techniques to look for a neuroanatomical locus for these oscillators. By comparing covert serial recall of temporally grouped and ungrouped sequences, we identified a plausible candidate in left dorsal premotor cortex (Henson *et al.*, 2000). We are optimistic that this iterative combination of computational modelling and detailed empirical investigation, possibly together with contributions from neuroimaging and neuropsychology, will continue to shed new light on a long-standing problem in cognitive psychology.

■ *Dr Richard Henson is at the Institute of Cognitive Neuroscience, University College London, 17 Queen Square, London, WC1N 3AR. Tel: 020 7833 7483; e-mail: r.henson@ucl.ac.uk.*

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