Coding Position in Short-term Memory

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Many formal models of short-term memory have recently been proposed (e.g. Anderson & Matessa, 1997; Brown, Preece, & Hulme, in press; Burgess & Hitch, 1992; Henson, 1998; Lee & Estes, 1981; Lewandowsky & Murdock, 1989; Murdock, 1995; Nairne, Neath, Serra, & Byun, 1997; Neath, 1993; Page & Norris, 1998). An important issue addressed by these models is the problem of serial order: that is, how people store and retrieve a novel sequence of items in the appropriate order. A popular solution to this problem is to assume that each item is coded for its position within a sequence. The present article discusses three different means of coding position. It is argued that the pattern of errors people make when they misrecall a sequence supports the hypothesis that position is coded relative to the start and the end of a sequence. Other evidence, however, suggests that positional coding is also sensitive to temporal factors. A new model is described that reconciles these two strands of evidence.

Plusieurs modèles formels de mémoire à court terme ont été récemment proposés (Anderson & Matessa, 1997; Brown, Preece, & Hulme, sous presse; Burgess & Hitch, 1992; Henson, 1998; Lee & Estes, 1981; Lewandowsky & Murdock, 1989; Murdock, 1995; Nairne, Neath, Serra, & Byun, 1997; Neath, 1993; Page & Norris, 1998). Une question importante abordée par ces modèles est le problème de l'ordre sériel, c'est-à-dire comment les gens emmagasinent et récupèrent une nouvelle séquence d'items dans l'ordre approprié. Une solution populaire à ce problème est de supposer que chaque item est codé selon sa position dans une séquence. Cet article discute de trois façons différentes de coder la position. Il est proposé que le patron d'erreurs, lorsqu'une séquence n'est pas rappelée correctement, appuie l'hypothèse d'un codage de la position en rapport avec le début et la fin d'une séquence. D'autres données suggèrent que le codage de la position est aussi sensible à des facteurs temporels. Un nouveau modèle est décrit qui incorpore ces deux ensembles de résultats.

Models of serial order in short-term memory can be classified as *chaining*, *ordinal*, or *positional* models (Henson, 1998). Chaining models, such as TODAM (Lewandowsky & Murdock, 1989; Murdock, 1995), store order via associations between successive items. The order of items can be reconstructed by chaining along these associations, such that each item becomes the cue for retrieval of its successor. However, though a long-standing and recurring idea (e.g. Ebbinghaus, 1964; Jordan, 1986), there is in fact little evidence to support chaining models of short-term memory (Henson, 1996; Henson, Norris, Page, & Baddeley, 1996). Ordinal models, such as the Primacy Model (Page & Norris, in press) store order via the relative strengths of item representations in memory. These models escape many of the criticisms of chaining models. However, because order is stored relationally, ordinal models cannot account for positional errors in serial recall (see following). These errors demand some approximate coding of item positions in a sequence, as assumed in positional models, such as the List Memory Model (Anderson & Matessa, 1997), the Articulatory Loop Model (Burgess & Hitch, 1992, 1998), the OSCAR Model (Brown et al., in press), the Start-End Model (Henson, 1998), the Perturbation Model (Lee & Estes, 1981), and the Positional Distinctiveness Model (Nairne et al., 1997; Neath, 1993).

THREE CODINGS OF POSITION

The positions of items within a sequence can be defined in *temporal*, *absolute*, or *relative* terms. A coding of temporal position assumes that each item is associated with its time of occurrence (Yntema & Trask, 1963), perhaps relative to the start (Brown et al., in press) or end (Glenberg & Swanson, 1986; Neath, 1993) of a sequence. In the OSCAR model of Brown et al. (in press), for example, items are associated with the states of temporal oscillators of different frequencies (e.g. the hour and minute hands of a clock, Fig. 1a). By resetting the oscillators (rewinding the clock), the order of items can be recalled.

A coding of absolute position assumes that items are associated with their ordinal position (*first*, *second*, *third*, etc.), regardless of their time of occurrence (Anderson & Matessa, 1997; Burgess & Hitch, 1992). In the connectionist model of Burgess and Hitch, for example, items are associated with a context signal, implemented as a window of activity that moves across an array of nodes

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This work was supported by a BBSRC grant awarded to Neil Burgess and Graham Hitch.

from left to right (Fig. 1b). In one version of this model (Burgess & Hitch, 1992), the context signal is event-driven, in that the window only moves 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 list.

A coding of relative position assumes that items are coded with respect to both the start and the end of a sequence (Henson, in press; Houghton, 1990). The Start-End Model (SEM) of Henson (1998) for example, assumes 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 (Fig. 1c). The relative strengths of the start and end markers therefore provide an approximate two-dimensional code for each position within the sequence. Associating items with these marker strengths codes their position relative to the end as well as the start of a sequence.

A temporal coding of position is sensitive to presentation rate, such that items further apart in time are associated with more distinctive positional codes (cf. a line of telegraph poles receding into the distance, Neath & Crowder, 1990). An absolute coding of position, however, 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 (relative to the start of a sequence) 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. A relative coding of position, however, is sensitive to sequence length, in that 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 at the end of the sequence, whereas the latter item is coded in the middle of the sequence.

EVIDENCE FROM ERROR PATTERNS IN SERIAL RECALL

Positional models of serial order derive support from two main types of error. The first occurs when a sequence is grouped into subsequences by, for example, inserting a pause every third item (e.g. Ryan 1969; Wickelgren, 1967). Though the total number of errors is reduced by grouping, one class of error actually increases (Lee & Estes, 1981; Nairne, 1991). These *interpositions* (Henson, 1996) are transpositions between groups that maintain their position within groups, such as the swapping of middle-group items illustrated in Fig. 2a. The relatively high incidence of isolated interpositions (Henson, 1996) indicates that items are somehow coded for their position within groups.

The second type of positional error occurs between recall of successive sequences. In a typical serial recall

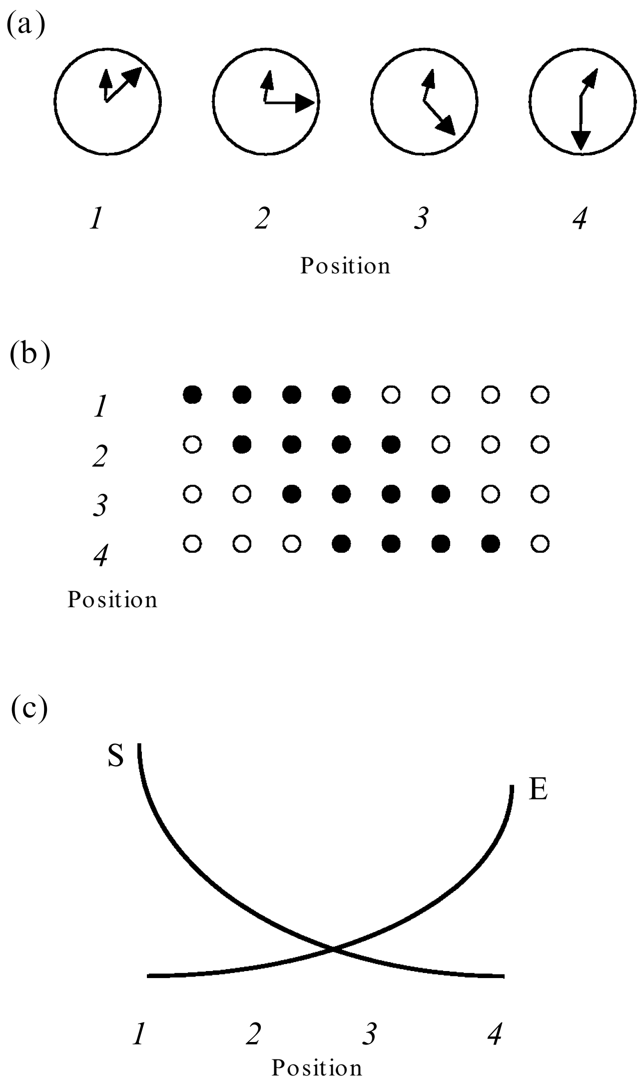

FIG. 1. Illustrations of positional coding in (a) the temporal terms of Brown et al. (in press), (b) the absolute terms of Burgess and Hitch (1992), and (c) the relative terms of Henson (1998).

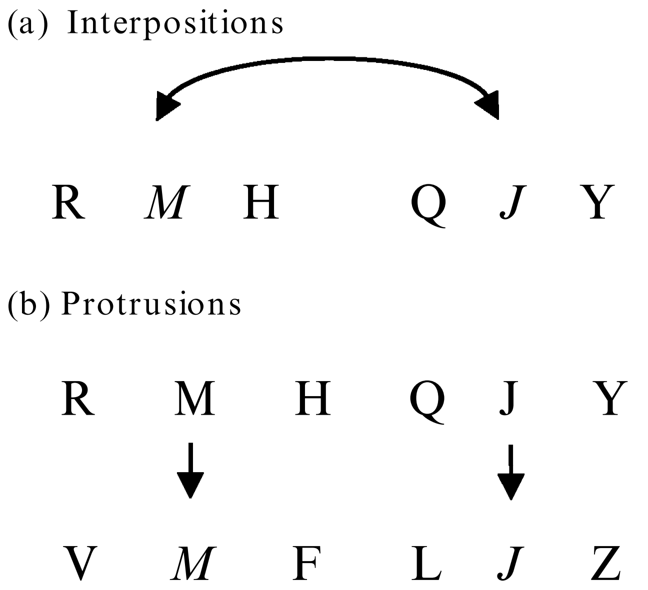

FIG. 2. Positional errors in serial recall: (a) interpositions between groups, and (b) protrusions between trials.

experiment, participants attempt multiple trials of presentation and recall. Detailed analyses of the errors in such experiments reveal that erroneous items are more likely than chance to occur at the same position in the previous trial (Conrad, 1960; Estes, 1991). Henson (1996) called such errors *protrusions* (Fig. 2b). Such proactive interference of positional information indicates that items are somehow coded for their position within trials.

Both interpositions and protrusions are examples of a general tendency for substitutions between sequences to maintain their position within a sequence. However, most previous demonstrations of such positional errors have used sequences of equal length presented at a constant rate, for which the definitions of temporal, absolute, and relative position are confounded. Only recently have these errors been used to investigate the nature of positional codes in short-term memory.

Temporal vs. Absolute Position

To test whether position within groups is coded in temporal or absolute terms, Ng (1996) examined the pattern of interpositions between groups presented at different rates. In one condition, the middle group in three groups of three items was presented twice as slowly as the first and last group. Considering only the first two groups for simplicity (Fig. 3a), the question was whether the third item in the first group was more likely to transpose with the third item of the second group (as predicted by an absolute coding of position from the start), or with the second item of the second group (as predicted by a temporal coding of position from the start, 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. This result held with both visual and auditory presentation of the stimuli (Ng & Maybery, 1999).

One problem with Ng's experiments is that participants may have rehearsed the items at rates that differed from the objective presentation rates. Indeed, it is possible that they rehearsed the groups at the same rate (e.g. their maximum rate of subvocal articulation), in which case the predictions of a temporal coding of position no longer differ from those of an absolute coding. One solution to this problem is to repeat the experiments with concurrent articulatory suppression, which should minimise any rehearsal (Baddeley, 1986). The results of such an experiment are currently being analysed (Ng & Maybery, 1999).

Absolute vs. Relative Position

Absolute and relative codings of position cannot be distinguished by Ng's experiments. To test whether position within groups is coded in absolute or relative terms, Henson (in press) examined the pattern of interpositions between groups of different sizes. In one condition

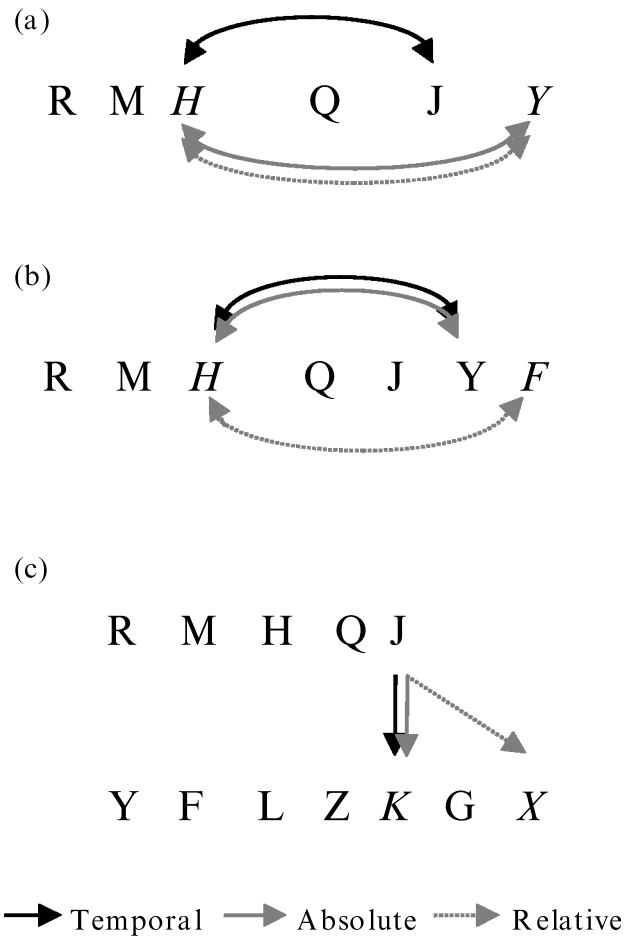

FIG. 3. Positional errors respecting temporal, absolute or relative position with (a) groups presented at different rates, (b) groups of different size, and (c) trials of different length. (Note: temporal and absolute position are defined relative to the start of a sequence in these examples.)

(Fig. 3b), a group of three items was followed by a group of four. The question was whether the third item in the first group was more likely to transpose with the third item of the second group (as predicted by an absolute coding of position from the start), or with the fourth item of the second group (as predicted by a relative coding of position, given that these items occurred at the end of a group). The latter errors proved more common, favouring a relative coding of position. In a second experiment, Henson examined the pattern of protrusions between trials of different length (Fig. 3c). A relative coding of position was again supported by the finding that items at the end of one report were more likely to have occurred at the end of the previous report than at the same absolute position in the previous report.

These results are difficult to explain in terms of different rehearsal rates, because there is no obvious reason for participants to rehearse longer sequences faster than shorter ones, such that the total rehearsal time for the different sequence lengths is equated. Furthermore, though the finding of end-to-end errors is not incompatible with a temporal or absolute coding of position defined relative to the end (rather than start) of a sequence, further analysis also revealed that start-to-start errors were more common than errors between items at the same temporal or absolute position relative to the ends of sequences. These data therefore suggest that position is coded relative to both the start and the end of a sequence.

One might object that there is some property unique to the final item in a sequence that explains why end-to-end substitutions were so common. A more general test of a relative coding of position needs to examine the pattern of errors between the middle positions of sequences. For example, a general coding of relative position predicts that the second item in a group of three is most likely to substitute with the third item in a group of five. Indeed, a more comprehensive test of temporal, absolute, and relative position might involve sequences like those depicted in Fig. 4a, in which a sequence of three items is followed by a sequence of five items presented three times as fast. Consider the second item in the first sequence: A temporal coding of position relative to the start of a sequence predicts that this item is most likely to substitute for the fourth item of the second sequence. Alternatively, a temporal coding of position relative to the end of a sequence predicts that this item is most likely to substitute for the second item of the second sequence. An absolute coding of position relative to the start of a sequence predicts that this item is most likely to substitute for the second item of the second sequence. Alternatively, an absolute coding of position relative to the end of a sequence predicts that this item is most likely to substitute for the fourth item of the second sequence. Only a relative coding of position predicts that the second item in the first sequence is most likely to substitute for the third item of the second sequence.

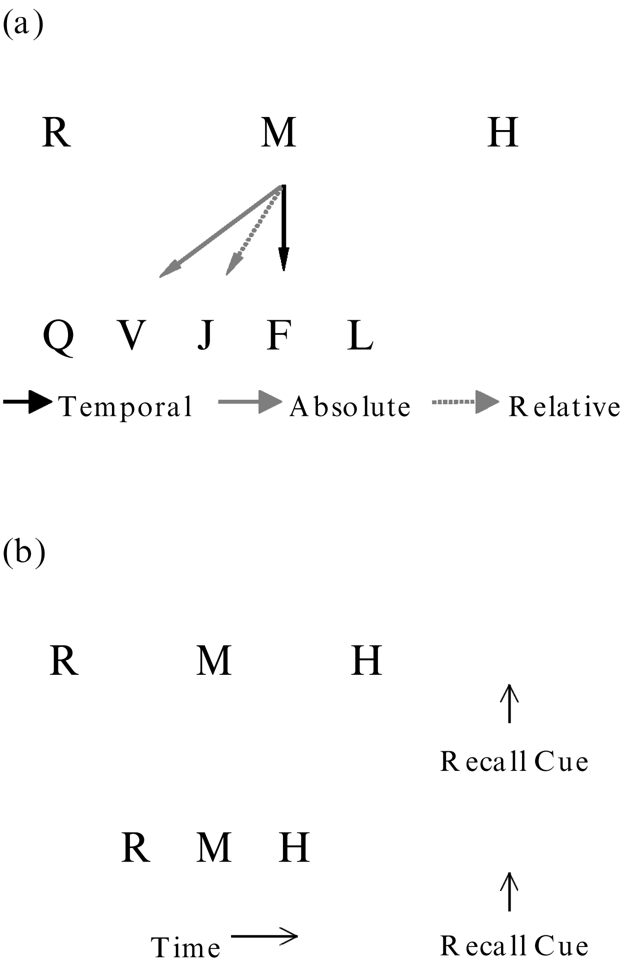

FIG. 4. Predictions for future experiments: (a) combined test of temporal, absolute and relative positional coding of nonterminal items (note: temporal and absolute position are defined relative to the start of a sequence in these examples), and (b) test for the effects of temporal spacing on serial recall performance.

THE START-END MODEL

Of the three positional models outlined in Fig. 1, the results given favour the SEM (Henson, 1998). However, the data also raise questions regarding the nature of the end marker assumed by this model. First, there is the question of how the end marker grows in strength towards the end of a sequence, when that end has not yet occurred in time. One possibility is that the strength of the end marker corresponds to the degree of expectation for the end of the sequence (Henson, 1998). This is a plausible assumption when the sequence lengths are known in advance (such as the groups in Experiment 1 of Henson, in press). However, the length of the sequences used in Henson's Experiment 2 varied from trial to trial in an unpredictable manner. In other words, participants did not know the length of a sequence in advance, making an expectancy interpretation of the end marker strength less plausible. Another possible solution is described next.

OSCILLATOR-CODING OF RELATIVE POSITION

A model developed by Henson and Burgess (1997) demonstrates how a relative positional coding can be implemented with temporal oscillators. This model assumes that people possess a number of internal oscillators with a range of different frequencies. However, rather than combining the states of these oscillators to form a single timing signal, as in OSCAR (Brown et al., in press), Henson and Burgess assumed that each oscillator competes separately to best represent a sequence. The "best oscillators" are those with a half-period closest to the temporal duration of the sequence (see Fig. 5a). Thus sequences of different temporal durations are represented by different oscillators. Importantly, however, the positional codes associated with items are defined by the phase of the oscillators at the point in time when each item was presented. The use of phase information automatically defines position relative to both the start and the end of a sequence: The phase of an oscillator that is associated with an item at the end of a short sequence, for example, will be identical to the phase of a slower oscillator that is associated with an

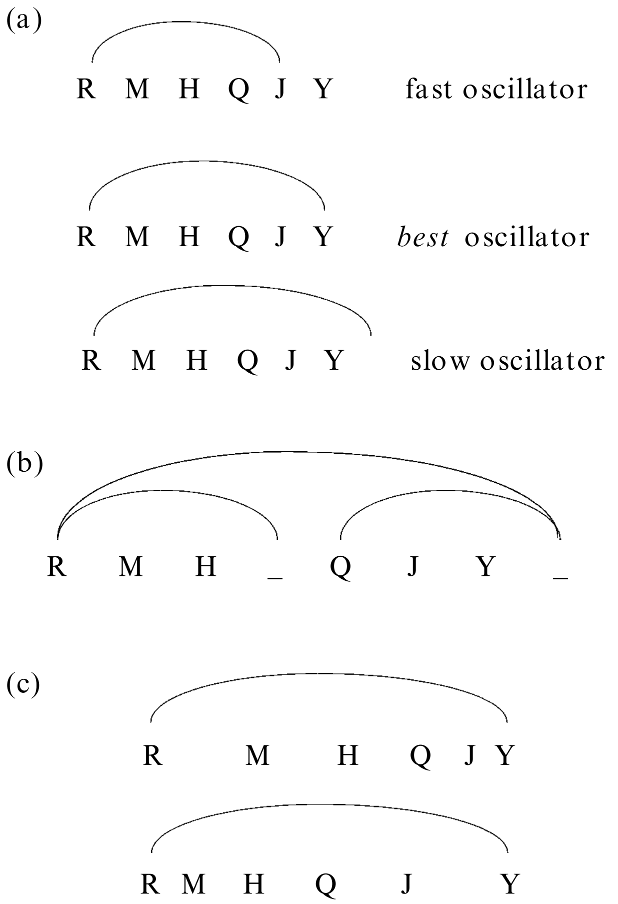

FIG. 5. Illustrations of (a) competition between oscillators to best represent a sequence (Henson & Burgess, 1997), (b) rhythmic parsing of grouped sequences, and (c) oscillator representations of increasing and decreasing schedules of Neath and Crowder (1996).

item at the end of a long sequence. Positional codes are therefore independent of both the number of items in a sequence and the rate of presentation of those items.

More precisely, the model assumes that items are associated with the phase of all oscillators as they are presented. When the sequence ends (as defined later), the oscillators with a frequency that means they are closest to completing a half-period (i.e. closest to their state at the start of the sequence) are selected to represent the sequence. An important advantage of this model over the SEM (Henson, 1998) therefore is that it does not need to know the length or duration of a sequence in advance. Because multiple oscillators compete during presentation, many possible "parsings" of a sequence are maintained in parallel, and only when a sequence ends is the correct "parsing" selected. At recall, oscillators of any frequency can be chosen in order to recall the items serially (depending on the desired speed of recall). The strength with which items are cued at each time point during recall is determined by the similarity in the phases of the recall oscillators and the oscillators that won the competition to represent the sequence. (For a more detailed mathematical formalization of this model, and demonstrations that it can reproduce appropriate similarity gradients, see Henson & Burgess, 1997.)

In order to detect the end of a sequence, Henson and Burgess assumed additional input from a rhythmic tracker. This tracker flags the end of a sequence whenever an item fails to occur in time with the beat defined by the previous items. Thus the pause after the third item in Fig. 5b will signal the end of the first group. (Surprisingly, the precise temporal characteristics that determine grouping in short-term memory do not appear to have been studied.) For such grouped sequences, oscillators compete to represent both the position of each item within a group, and the position of each group within the sequence. Structured sequences are therefore represented by oscillators of several different frequencies; fast ones coding item positions in groups, slower ones coding group positions in groups of groups, etc. In other words, the model is extendible to hierarchies of positional codes (Lee & Estes, 1981; though see Henson & Burgess, 1997, for the problems with synchronizing oscillators at each level of a hierarchy).

EVIDENCE FROM TEMPORAL PRESENTATION SCHEDULES

An alternative test of positional coding involves comparing serial recall performance as a function of different temporal presentation schedules. Several studies have shown that measures of the recency effect are sensitive to the ratio of inter-item interval to retention interval (e.g. Bjork & Whitten, 1974; Glenberg & Swanson, 1986; Neath & Crowder, 1990), consistent with the distinctiveness models of Neath (1993) and Nairne et al. (1997). However, these studies have used either free recall or recognition, for which the use of positional information is not strictly necessary. Moreover, the recency effect is not necessarily the best index of positional coding in short-term memory. The regression slope over the last few serial positions, for example, (Nairne et al., 1997) is likely to depend on several factors, including overall performance level. This is particularly relevant to serial recall, where other factors affecting recency include, for example, the suppression of previous responses (see Henson, 1998). These studies do not therefore provide direct evidence for temporal effects on positional coding in short-term memory for serial order.

One clear prediction of a temporal coding of position is that, all else being equal, items more widely separated in time will be coded more distinctively. This suggests that slower presentation rates should produce superior serial recall performance. However, one problem with this prediction is that rehearsal rates are again likely to differ from objective presentation rates. When rehearsal was prevented by articulatory suppression, Baddeley and Lewis (1984) found that serial recall was worse with slow presentation rates, contrary to what might be expected from a temporal coding of position. (Neath & Crowder, 1996, showed that slower presentation rates did aid performance when mean presentation rates were as fast as five items per second, but the danger with such rapid presentation rates is that they do not allow such effective encoding of items.)

A second problem with varying presentation rates is that other factors that affect serial recall may also be a function of time. For example, phonological information is often assumed to be rapidly forgotten from short-term memory (Tehan & Humphreys, 1995). The greater lag between presentation and recall of each item that is entailed by the slower presentation rates of Baddeley and Lewis (1984) might impair serial recall despite more distinctive positional codes. What is required is a comparison of serial recall performance when the temporal spacing between items is varied but the mean time between presentation and recall of items is kept constant. In Fig. 4b, for example, temporal distinctiveness theory predicts superior performance for the slower presentation rate. Assuming a linear relationship between lag and the recall probability of each item (and that rehearsal is prevented by articulatory suppression), the oscillator model of Henson and Burgess (1997), however, predicts no difference between the two presentation schedules, because the positional codes are equivalent in both cases.

A study by Neath and Crowder (1996) suggests that the timing of presentation can affect positional coding in other situations. They compared serial recall under two presentation schedules: an increasing schedule in which the interitem interval increased with serial position, and a decreasing schedule in which the interitem interval decreased with serial position (Fig. 5c). Performance with the increasing schedule was superior to that with the decreasing schedule. Because the total presentation time and mean lag between presentation and recall was equal in both schedules, this difference is difficult to attribute to encoding or rehearsal differences, or to decay of item information. The temporal distinctiveness explanation offered by Neath and Crowder was that participants adopted a forward perspective (from the start of the sequences), from which it is more beneficial for later items to be widely spaced in time than it is for early items (cf. the telegraph pole analogy).

This sensitivity to increasing and decreasing presentation schedules is not necessarily problematic for the oscillator model of Henson and Burgess (1997), however. Assuming that the rhythmic tracker does not identify any rhythm or grouping in either schedule, sequences will be coded by the same oscillators in both cases (Fig. 5c). Inter-item intervals that increase towards the end of a sequence will therefore be associated with increasing phase differences, whereas inter-item intervals that decrease towards the end of a sequence will be associated with decreasing phase differences. Larger phase differences between successive positions result in more distinctive coding of those positions, just as in temporal distinctiveness theory. Thus the model can appeal to the same explanation of a forward perspective that was proposed by Neath and Crowder (though one might also consider other consequences of changing the distinctiveness of successive positions, such as the effects of recalling early items on the probability of recalling subsequent items; cumulative effects that are characteristic of serial recall, Henson, 1996).

The oscillator model of Henson and Burgess (1997) only models the coding of position: It is not a complete process model of serial recall. As mentioned earlier, the probability of recalling each item correctly during serial recall depends on other factors such as response competition, response suppression, available item information, and the retention interval. The competition between items for recall at each position (normally via a variant of the Luce choice rule) is assumed by almost every model of serial recall. This competition explains why it is the coding of position relative to the coding of surrounding positions that is important in determining the probability of correct recall of items. Response suppression, the process that reduces the probability of an item being recalled more than once, is also assumed by nearly every model of serial recall. This will affect the oscillator model's predictions for overall performance level and serial position curves. Finally, the model needs to address the issue of retention interval before it can be compared with the temporal distinctiveness theory of Neath and Crowder (1990). Indeed, recent evidence from free recall (Nairne et al., 1997) suggests that the absolute duration of a retention interval exerts an effect despite a constant ratio of inter-item interval to retention interval, which is not predicted by temporal distinctiveness theory. One possibility is that the forgetting during a retention interval reflects the decay of the associations between items and the oscillators representing the sequence (cf. Burgess & Hitch, 1998). In this case, the effects of the retention interval are different from those of the inter-item interval: That is, there are effects of time on short-term memory for serial order that are distinct from its effects on positional coding.

CONCLUSION

A review of recent data suggests that models of short-term memory for serial order must include some form of positional information associated with the items in a sequence, and that this information should be defined relative to both the start and the end of that sequence. A new model was outlined that codes positions in such relative terms via the phases of oscillators. This model not only overcomes the problems associated with predicting the end of a sequence, but also allows some influence of temporal factors on positional coding, particularly when no rhythmic grouping is identified within a sequence. The challenge for future developments of this model is to specify more precisely how the timing of items effects their grouping and to address the issue of retention interval in order to compare the model to theories of temporal or positional distinctiveness.

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