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The Development of Memory for Serial Order: A Temporal-contextual Distinctiveness Model

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A model of adult human memory, OSCAR, is applied to the development of memory for serial order. In the model, development of serial order memory is assumed to result from age-related changes in a dynamic learning-context signal that underpins memory for serial order. Developmental improvement in this dynamic learning-context signal leads to more temporally distinctive representations in memory, and this leads in turn to a reduction in order errors. It is shown that the model correctly predicts developmental changes in the movement error gradients in children's serially ordered recall, as well as developmental changes in the number of movement errors obtained. The model is also applied to repetition errors across development.

Un modèle de mémoire humaine adulte, OSCAR, est appliqué à l'étude du développement de la mémoire de l'ordre sériel. Dans ce modèle, le développement de la mémoire sérielle est le produit de changement liés à l'âge au niveau d'un contexte dynamique d'apprentissage qui soutient la mémoire sérielle. Des améliorations lors du développement, dans ce contexte dynamique d'apprentissage, mènent à des représentations en mémoire qui sont plus distinctes au plan temporel, entraînant un diminution des erreurs d'ordre. Lors d'un rappel sériel, le modèle prédit adéquatement les changements liés au développement dans les gradients d'erreurs ainsi que dans le nombre d'erreurs observé chez les enfants. Le modèle est aussi appliqué aux erreurs de répétition observées en fonction de l'âge.

The aim of this paper is to develop and test a computationally explicit account of the development of short-term memory for serial order, as no such account is available at present. According to the model, the development of serial order memory results in part from improvements in a dynamic internal learning-context signal that is involved in representing information about serial order. This implements the idea that the serial order of items can be represented in terms of their location along a temporal dimension, and that younger children have less temporally distinctive representations available to them.

Existing Models

Recent models of children's memory for serial order have largely been developed to account for data collected using specific experimental paradigms. Here we focus on data from the most widely used paradigm: serially ordered recall (SOR).

The concept of *subvocal rehearsal* has been accorded a central role in recent accounts of SOR development. Initial accounts emphasized the role of developmentally increasing use of subvocal rehearsal in maintaining information in short-term memory. Consistent with the importance of rehearsal in SOR development, memory span for verbal materials is linearly related to the rate at which the to-be-remembered items can be rehearsed (Baddeley, Thomson, & Buchanan, 1975), with developmental increases in articulation rate being closely and linearly related to parallel developmental increases in memory span (Hulme, Thomson, Muir, & Lawrence, 1984; Hulme & Tordoff, 1989; Nicolson, 1981). The presence of word length effects (assumed to reflect the use of rehearsal) in the different age groups suggested that children as young as 4 years of age rehearse when verbal stimuli are presented auditorily (Hulme et al., 1984). When nameable pictures are used, however, effects of picture-name length on recall are not observed until later in development, suggesting that SOR for pictorial stimuli does not involve spontaneous use of rehearsal strategies in younger children (Hitch & Halliday, 1983; although cf. Hulme, Silvester, Smith, & Muir, 1986). Consistent with this account, Halliday, Hitch, Lennon, and Pettipher

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(1990) found that articulatory suppression (to prevent rehearsal) disrupted SOR of pictures in older but not younger children. Furthermore, Johnston, Rugg, and Scott (1987) found that rehearsal training led to improved SOR for pictures in children as young as 5 years of age, consistent with the suggestion that high-level executive or strategic function may be important in determining whether a rehearsal strategy is used spontaneously by young children.

Despite the considerable support for rehearsal-based accounts of SOR development, several difficulties have recently emerged for any simple rehearsal-based model. First, the development of computational models of short-term SOR in adults has demonstrated that item length effects may be explained more parsimoniously without the assumption of subvocal rehearsal (Brown & Hulme, 1995; Neath & Nairne, 1995; see also Gathercole & Hitch, 1993), and these theoretical developments undermine the inference from word length effects to rehearsal strategies in children. Second, the rehearsal-preventing manipulation of articulatory suppression does not severely disrupt SOR for auditorily presented verbal material in young children even though children of the same age are sensitive to word length (Henry, 1991). Third, it is clear that short-term SOR is sensitive to variables other than the rate of articulation of the material to be remembered, such as word frequency and lexicality, both in adults (e.g. Brown & Hulme, 1992; Hulme, Maughan, & Brown, 1991) and children (Henry & Millar, 1991; Hitch, Halliday, & Littler, 1989, 1993; Roodenrys, Hulme, & Brown, 1993), and this has been taken as evidence that phonological representations in long-term memory are important in determining SOR performance (Brown & Hulme, 1992, 1995; Hulme et al., 1991; Hulme, Roodenrys, Brown, & Mercer, 1995; Hulme et al., 1997; Schweickert, 1993). Finally, no computationally explicit version of the rehearsal-development account of children's SOR has been forthcoming.

In summary, there are inadequacies with specific rehearsal-based models of the development of memory for serial order, although rehearsal rate does correlate with some unique variance in memory span (see, e.g., Cowan et al., 1998; Kail & Park, 1994). Other accounts of SOR development have focused on processes occurring during output (Cowan et al., 1992, 1994; Henry, 1991). Thus both individual differences in span within an age group, and differences across age groups, are correlated with the length of pauses between successive item recalls (Cowan et al., 1992, 1994, 1998), consistent with the idea that memory search for each successive item during serial recall is an important factor contributing to individual differences. However, there are as yet no computationally explicit models of SOR that have incorporated such results into a complete developmental account.

A final possibility is that developmental differences in inhibition may be related to memory development (e.g. Harnishfeger, 1995; McCormack, Brown, Vousden, & Henson, 1999). McCormack et al. examined the specific hypothesis that SOR development might be related to developmental changes in the process of *post-output response inhibition* that plays a major role in many recent models of adult SOR (Brown, Preece, & Hulme, in press; Hartley & Houghton, 1996; Henson, 1998a; Houghton, 1990; Lewandowsky, this issue; Vousden & Brown, 1998), but a detailed analysis of errors found evidence against the claim that this particular type of inhibition is important in SOR development.

In summary, there remains a lack of well-specified (e.g. implemented) models of rehearsal-based SOR. Implemented models of short-term serial recall that do exist focus almost exclusively on the performance of skilled adults (e.g. Brown et al., in press; Burgess & Hitch, 1992, 1996; Estes, 1972; Henson, 1998b; Houghton, 1990; Johnson, 1991; Lewandowsky & Murdock, 1989; Nairne, 1990; Page & Norris, 1998) and it is unclear that such models could easily be extended to account for developmental phenomena (see Brown, Hulme, & Dalloz, 1996; Brown, Preece, & Hulme, 1995). In short, we are aware of no computationally explicit account of the development of short-term memory for serial order. Therefore, we develop such an account in the present paper. The developmental model is an extension of a dynamic computational model that addresses adult data from both immediate serial recall and recency memory paradigms (Brown et al., in press). The model is called OSCAR (for OSCillator-based Associative Recall). The core assumption of OSCAR is that items in a list become associated to states of a time-varying learning-context signal, and that retrieved states of this learning-context signal are used as probes to recall successive list items. When applied to the development of serial recall, the central assumption is that less accurate (less temporally distinctive) retrieval cues are available to younger children. This leads to order errors, because less distinctive cues are available to distinguish between the temporal positions of adjacent list items, and can also lead to slower output (increased inter-item pauses) to the extent that retrieval is slower when less discriminative retrieval cues are available.

The OSCAR Model

The model is similar to several other recent accounts in which successive items in a sequence become associated to successive states of a time-varying control or learning-context signal (Brown et al., in press; Brown & Vousden, 1998; Burgess, 1995; Burgess & Hitch, 1992, 1996; Glasspool, 1995; Gupta, 1996; Hartley & Houghton, 1996; Henson, 1998b; Hitch, Burgess, Towse, & Culpin, 1996; Houghton, 1990, 1994). In other words, a series of item-to-context associations is learned. OSCAR uses an array of oscillators, of different frequencies, to provide the dynamic learning-context signal to which successive items in a sequence become associated. Retrieval of the sequence involves reinstatement of the dynamic learning-context, allowing the item-to-context associations to be probed one after the other. The full implementation is described in Brown et al. (in press); here we attempt to give an intuitive flavour of the general principles of operation of the model. A motivation for the general approach is given in Brown and Vousden (1998).

Successive states of the dynamic learning-context signal can be seen as analogous to successive states of a clock face. Each one of the rotating hands on the clock face (the hour hand, the minute hand, and the second hand) is analogous to one of the larger number of oscillators that combine to make up the learning context as a whole in the implemented model. The representation of a sequence is analogous to a set of associations between successively presented list items and successive states of the clock face. This process is illustrated in Fig. 1(a). Here, the state of a clock face at 2 o'clock represents the learning-context at the start of list learning. An association between the first list item and the state of the clock face at 2 o'clock is formed, creating the first item-to-context association. By the time the second list item is presented, the oscillators (the hands on the clock) will have moved on, to (say) 2.05. The second item-to-context association can then be formed, linking the second list item to the state of the clock face at 2.05. For a six-item list presented at a constant rate, further item-to-context associations will be formed between the representations of 2.10 and item 3; 2.15 and item 4; 2.20 and item 5; and 2.25 and item 6.

The set of learned item-to-context associations is the stored representation of the sequence, and if the dynamic learning-context can be reinstated then the item-to-context associations can be used to reconstruct the sequence. This is analogous to rewinding the clock to its state at the start of list learning. After this initial state (2.00) has been specified, successive states (2.05, 2.10, etc.) are obtained "for free" as the clock runs forward under its own intrinsic dynamics. Thus there is no need to maintain an explicit memory of the dynamic contexts associated with each list position. Each state of the learning-context signal can be used as a probe to recall each successive list item. This process is illustrated in Fig. 1(b). So, for example, the state of the clock face corresponding to 2.05 can be used as a probe to recall the second list item, and 2.10 for the third list item. Other list items will become activated to the extent that they were associated with clock face states similar to the one used as a recall cue.

The basic model architecture of the implemented OSCAR model (Brown et al., in press) is shown in Fig. 2. Items (e.g. words or letters in a list to be learned), and also states of the learning-context, are represented as vectors. As in the clock face analogy, individual items in an incoming sequence (such as words in a serial list) become associated with a dynamic representation of the internal cognitive context at the time of learning. In OSCAR, this dynamic representation is made up from the output of an array of sine-wave oscillators (illustrated at the bottom of the figure). Some of these oscillators are low in frequency (i.e. they change their output by only a small amount in each unit of time); others are higher in frequency. The outputs of these oscillators combine to make up the learning-context signal as illustrated in the figure. The state of this learning-context vector changes over time, as the output of the oscillators changes over time. Successive items in a to-be-learned sequence are associated (via simple Hebbian association) to successive states of this time-varying learning-context signal. Thus the resulting memory contains a set of item-to-context associations. Recall involves reinstatement of the dynamic context of learning—successive states of the time-varying learning-context signal are used as probes to the multiple item-to-context associations. The reconstructed states of the learning-context signal are subject to noise, and so may lead to the retrieval of an item that was originally associated to a cue similar to the original learning-context signal rather than to retrieval of the correct item. Because there are both slow and fast oscillators contributing to the dynamic learning-context vector, the vector has both slow-moving and fast-moving underlying components. This can be seen as an approximate instantiation of the clock face analogy.

Furthermore, as with the clock face example earlier, states of the signal that are near to each other in time are more similar than are states separated in time; and consequently states of the signal never repeat themselves over arbitrary time periods provided the lowest-frequency oscillator is sufficiently slow (analogous to including an arbitrarily slow hand on the clock face). This leads to a

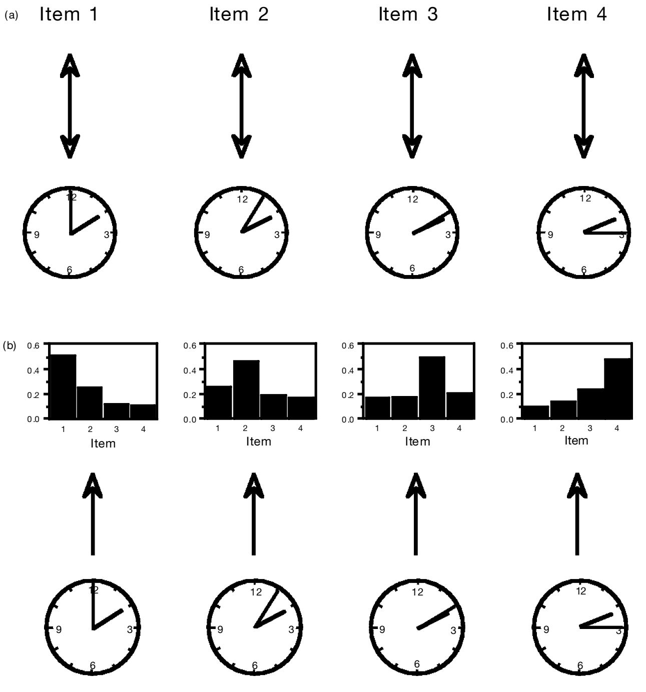

FIG. 1. (a) The association between four successive list items and four successive states of a learning-context signal, illustrated using the clock face analogy. (b) The retrieval of four successive list items from four successive states of a learning-context signal, illustrated using the clock face analogy.

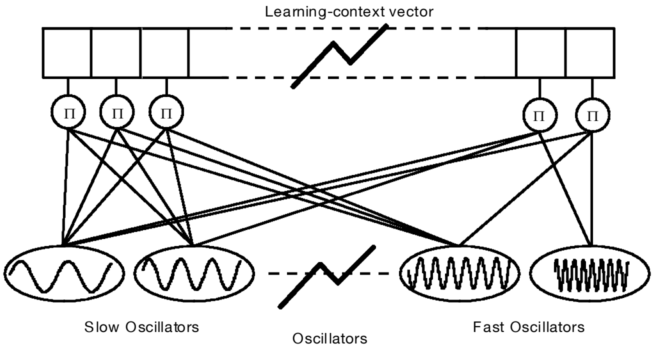

Fig. 2. The basic architecture of the OSCAR model, as described in the text.

dynamic system with many of the necessary properties to account for serial list learning. Brown et al. (in press) apply the model to a range of serial order phenomena obtained from the study of adults; here we focus on the model's ability to account for *movement errors* in immediate serial recall, for these will underpin testing of the model as applied to the development of memory.

Movement Errors in the Model

In the immediate serial recall of short lists of items such as letters, many of the errors (often the majority) are order errors, where the correct items are recalled in the incorrect order. For example, the list A B C D E may be recalled as A C B D E or A D C B E. It has been widely observed in studies with adults (e.g. Healy, 1974; Henson, Norris, Page, & Baddeley, 1996) that most movement errors occur across relatively short distances within the list—so, for example, the second list item is more likely to be incorrectly recalled in output position three than in output position four or five. Thus there are orderly "movement gradients" such that around 60% of all movement errors involve a movement of just one position, whereas only a small percentage of errors involves movements of four or more positions (see Fig. 3a).

In the OSCAR model, movement errors arise because learning-context states that are near to each other in time are similar to one another, and hence tend to lead to the erroneous recall of items that were adjacent in the sequence. Thus, as in the human data, there are many movement errors, and these are most likely to occur between neighbouring list items. In terms of the clock face analogy, a list item that was associated (during list learning) with 2.10 would be more likely to be incorrectly recalled in response to the 2.05 or 2.15 cues than in response to the 2.00 or 2.20 cues. A typical movement gradient produced by the model in recalling six-item lists is shown in Fig. 3b, where it can be seen that a movement gradient similar to that observed in the empirical data is obtained.

The OSCAR Model, Temporal Distinctiveness, and Order Memory Development

Several models have suggested that items in memory are represented in terms of their absolute or relative temporal position within a list, such that the discriminability of items in memory will be determined by their proximity to other items and their temporal distance from the point of recall (see, e.g., Baddeley, 1976; Bjork & Whitten, 1974; Crowder, 1976; Crowder & Neath, 1991; Neath, 1993a, b; Neath & Crowder, 1990). The OSCAR model can be interpreted as a mechanism-level implementation of the same basic idea: In OSCAR the serial order of items in a list is represented in terms of the items' relative positions along a temporal dimen-

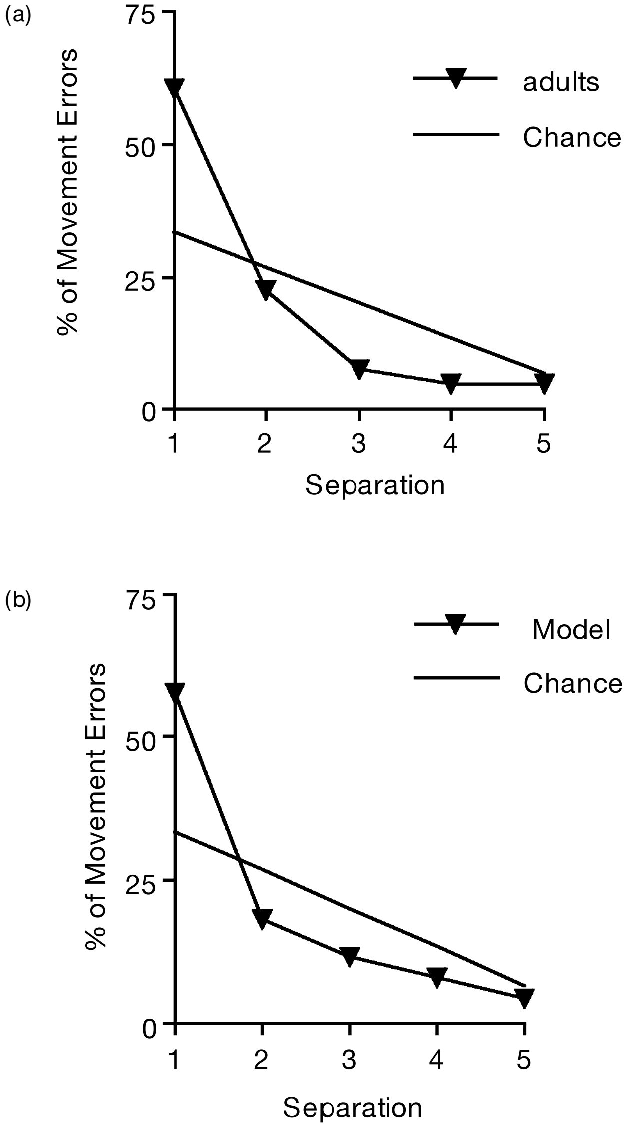

FIG. 3. The proportion of movement errors that occur over different distances in a short-term serial recall task. (a) Unpublished representative data from the authors' own laboratory. (b) Model. The error movement gradient that would be expected if errors were randomly distributed is also shown.

sion. Neighbouring items within a list will have memorial representations that are less temporally distinctive from one another, and therefore items close to one another in the list are more likely to be recalled in the wrong relative order, as illustrated by the error movement gradients described earlier. The examination of memory development within the OSCAR framework, as described later, can therefore alternatively be interpreted as an assessment of the idea that order memory develops as a result of the availability of memory representations of increasing temporal distinctiveness.

Sources of Possible Developmental Improvement in the OSCAR Model

Within the framework of the OSCAR model there are several possible sources of developmental improvement in the model (see Maylor, Vousden, & Brown, in press, for a discussion in relation to SOR in elderly adults). The availability of the implemented model allows us to examine the predictions of the model for developmental changes in overall performance and error movement gradients in terms of each hypothesized source of developmental improvement. Broadly speaking, sources of development in the model could be located within the learning-context signal (temporal distinctiveness of encoding); the accuracy of the reconstructed learning-context signal used as a retrieval cue (temporal distinctiveness of retrieval cue); the forgetting of the item-to-context associations, or the learning process itself (relative strength of initial encoding). We consider each source in turn in the model below.

EVALUATION OF THE MODEL

In order to evaluate these hypotheses, we applied the model to a subset of data from an experimental investigation of error movement gradients in the serial recall of six-item lists in three groups of children (of different ages) and adults (McCormack et al., 1999). Although some researchers have published detailed serial recall error data from children of different ages (e.g. Pickering, Gathercole, & Peaker, 1998; see also Healy, Cunningham, Gesi, Till, & Bourne, 1991), reports of error types and error movement gradients have not generally been reported in sufficient detail to be directly compared with the behaviour of the OSCAR model.

One of the experiments in the McCormack et al. (1999) study examined serial recall of six-item lists of confusable letters. (In order to compare error movement gradients across different age groups, it is necessary to use the same list length for all groups. This is because the movement gradient that would be expected by chance alone varies considerably with list length, and so it is difficult to compare movement gradients in a meaningful way across different list lengths. Fixing list lengths in this way has the consequence that overall levels of performance will not be equated in the different groups, but such performance level matching is in any case inappropriate in the present context as the developmental changes in overall performance form an important part of the data that the model seeks to explain.) The study, which employed visual presentation and written recall, examined error types and error movement gradients produced by adults and by three groups of children. The youngest group of children had verbal ages < 9 years; the middle group verbal ages between 9 and 11 years, and the oldest group > 11 years. The data of interest for present purposes involve error type proportions and movement error gradients, and we focus on these results while paying less attention to serial position effects. Comprehensive description and analyses of the data are reported by McCormack et al. (1999).

Errors were classified as follows. We illustrate with examples of recalls following a presented sequence of A B C D E F. *Omission errors* were recorded when a recall box was left blank (e.g. recall as A B – D E F involves one omission error). This therefore refers to the number of response boxes in which no item was recalled, rather than the number of presented list items that were not recalled (see McCormack et al., 1999, for separate examination of "input omissions" and "output omissions"). *Movement errors* were recorded when list items were recalled in incorrect positions, and the distance of the movement was also noted. For example, recall as A D C B E F involves two movement errors, each of distance 2. *Intrusion errors* were recorded whenever an extra-list item was recalled (e.g. recall as A B X D E F).

Repeat errors were also examined. The three error categories just given can be exhaustive and mutually exclusive, but it is also useful to examine separately errors where an item is erroneously recalled in two separate output positions (see Vousden & Brown, 1998, for detailed discussion of repeat errors in SOR and speech production). Recall as A C B C E F would qualify as a repeat error, as would recall as A B B D E F; this analysis took no account of whether or not one of the repeated items was recalled in the correct position. Repeat errors were not also classified as movement errors in the McCormack et al. (1999) study. We refer to these as repeat errors to distinguish them from "repetition errors"—failure to recall both occurrences of an item that occurred twice in the presented list (Henson, 1998a).

Figure 4 summarizes the error data from the McCormack et al. (1999) experiment. It is evident that percentage correct performance increases with age, that movement errors reduce very substantially with age, and that intrusion and omission errors also reduce with age although they are always at a much lower level then movement errors. Thus it is clear that a major part of the reduced performance of younger children in this serial order memory task is due to inability to remember the target items in the right order, in addition to inability to remember the items themselves. It is this deficit in order memory that the present model emphasizes.

Detailed information on movement errors is available from the McCormack et al. (1999) study, but some summary data are given here. Figure 5 shows the error

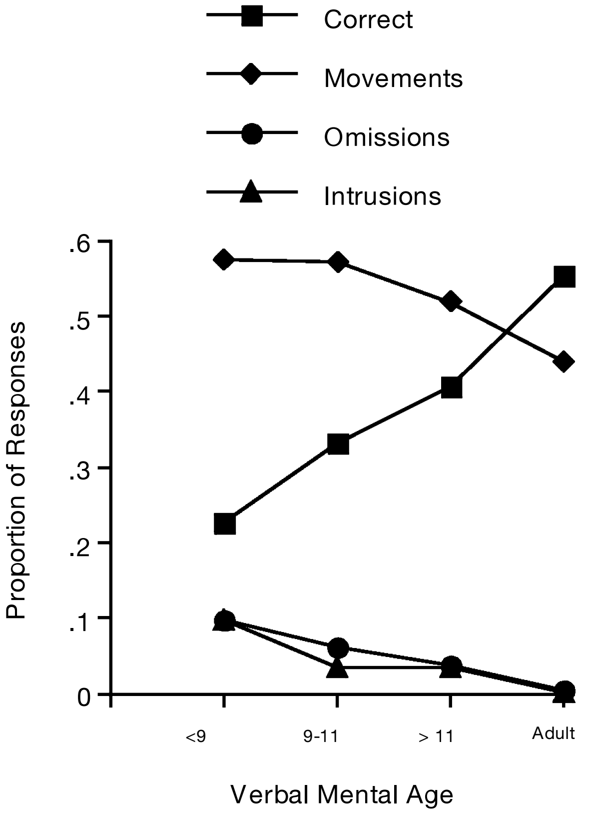

FIG. 4. Proportion of responses of different ages produced by different age groups (calculated from data reported by McCormack et al., 1999).

gradients for movement errors and repetition errors. The movement gradients express the proportion of all movement errors that occurred over each separation. Not only do older participants produce fewer movement errors overall (as indicated by Fig. 4); a much higher proportion of the movement errors that they do produce involve short movements (about 55% of the adults' movement errors involve a movement of just one position, compared with about 35% for the youngest children)[1].

The repetition error gradients show that most repetition errors occur over intermediate separations. This is assumed to be due to the time course of post-output response suppression (Houghton, 1994; McCormack et al., 1999; Vousden & Brown, 1998). If the representation of an item is suppressed or inhibited when that item has been output, as most current models of serial memory assume, then it is unlikely that an item will be recalled a second time very soon after it has been recalled once. The post-output response suppression must wear off over time, however, or it would not be possible ever to recall the same item twice. This would lead to an increasing proportion of repeat errors over larger separations. Offset against this, however, is the fact that long-distance repeat errors are unlikely for the same reason that long-distance movement errors are rare; i.e., there is little similarity between the contextual retrieval cues for temporally distal items. The combination of these two tendencies leads to the observed pattern, with relatively few repeat errors over either small or large within-list separations. McCormack et al. interpret these data as evidence that the time-course of inhibitory processes in serial recall is developmentally invariant.

In summary: McCormack et al. (1999) found a clear developmental increase in overall performance on the SOR task, with systematic developmental changes in the observed error movement gradients observed, while repeat errors occurred over intermediate separations for all age groups. In intuitive terms, the results seem likely to be consistent with a version of the OSCAR model in which developmental improvement is due to improvement in the quality of the oscillator-based dynamic learning-context signal used to underpin memory for serial order. If older children have available to them a better dynamic learning-context signal, they will be able to assign more temporally distinctive representations to each list item, and better order memory will result. We now examine the ability of the model to account for the detailed pattern of results obtained.

SIMULATION

In order to assess the predictions of the different possible developmental accounts within the OSCAR framework, we implemented a simple form of each hypothesis outlined earlier. In each case, we varied the relevant parameter (e.g. the parameter that determines context quality, or the parameter that determines relative encoding strength) over a range sufficient to cause overall level of performance (number of items recalled in their correct serial positions) to vary in accordance with that seen in the data. We then examined the error types and movement gradients produced by the model, with all other parameters being held constant.

The complete version of the OSCAR model (Brown et al., in press) has many parameters and is applied to a wide variety of different experimental paradigms, including studies of relative recency judgements, item and list grouping effects, list length effects, differential memory for item and order information, and probed serial recall. In the present extension of the model most of these parameters are absent or remained fixed in all simulations, as the demonstrations are concerned only with serial recall and we wished to use a simple version of the model. A full description of the operation and effects of all parameters is given in the Brown et al. paper; parameter values used in the present simulations are given in Table 1. One parameter of particular relevance to the present simulations, however, is the *output threshold,* which enables the possibility of omission errors. An omission error is recorded in the model whenever no potentially recallable vocabulary item exceeds the activation of its nearest competitor by more than a fixed amount; the output threshold parameter specifies this quantity. This parameter was held constant in all

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[1] Although the steepness of movement error gradients will tend to correlate with overall level of performance, these can dissociate due to the possibility of other error types.

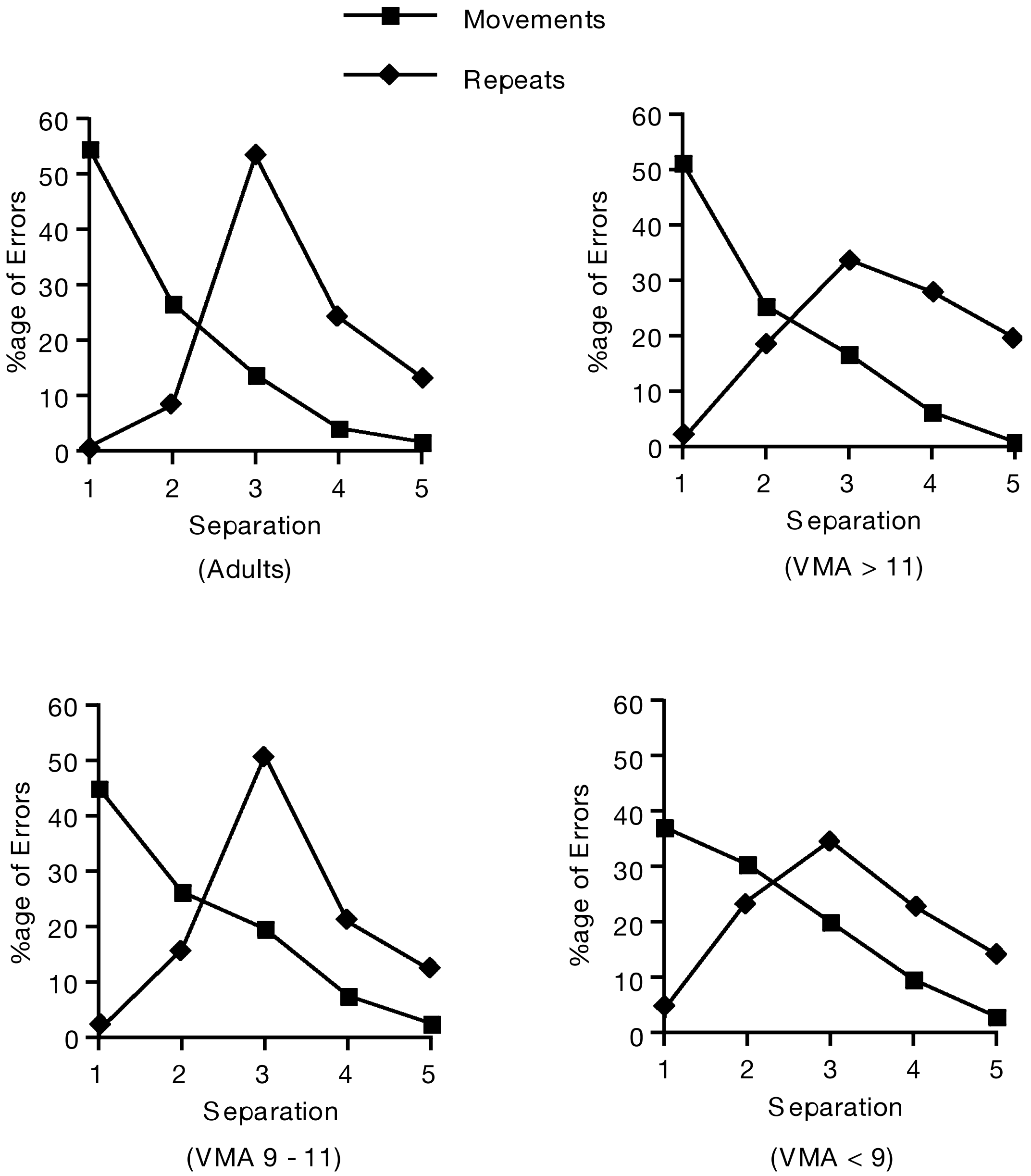

FIG. 5. Separation gradients for movement errors and repeat errors, for different age groups (calculated from data reported by McCormack et al., 1999).

TABLE 1
Values of Parameters Used in Demonstrations

Parameter	*Value*
D (distinctiveness of context)	Variable (4; 2; 1.2; 0.1)
Output threshold	.0007
Inhibition: I_0 , *d*, I_b	−.8, .97, −.035
Retrieval cue noise parameter	Variable (0.65; 1.1; 1.5; 5.3)
Learning rate reduction	Variable (.8; .45; .25; .05)
No. of item vector elements similar	12
Weight Decay	Variable (.95; .6; .5; .3)

demonstrations here, as the aim was to gain a computational-level understanding of the effects of different manipulations, rather than the most impressive possible fit to the data by varying many parameters simultaneously. One change in the present version of the model, compared with the version reported in Brown et al. (in press), concerns the storage of associations. In the original OSCAR model, all item-to-context associations were stored in a single weight matrix. In the present version, each item-to-context association was stored separately, with the result that associations did not interfere with one another during encoding. This change makes no qualitative difference to the model's performance in most cases, including the serial ordered recall examined here, but enables the model to provide a better account of the recall of repeated items than did the original version[2]. A further change concerned the time-course of post-output response suppression. The original implementation made the simplifying assumption that during a recall of a given list an item's representation would be completely inhibited. This has the consequence that repeat error separation gradients cannot be examined, because repeat errors can never occur. Post-output response suppression is implemented in the current model as follows. When an item has been recalled, it is assumed to be less likely to be recalled in subsequent positions because its activation is inhibited. The amount of inhibition after *s* items have elapsed since the item was last output is given by:

$$I_s = I_0 * (1-d)^s + I_b$$

where I_s is the amount of inhibition after *s* items have passed, I_0 is the amount of inhibition applied initially (i.e. during recall of the item immediately following first recall of the item, when $s = 0$), I_b is a constant, and *d* is a decay rate parameter ($d \leqslant 1$). The amount of inhibition is simply subtracted from the level of activation that the previously output item would have had if no response suppression took place (see Vousden & Brown, 1998, for detailed exploration). In all other respects the implementation was identical to that reported in Brown et al. (in press); space does not permit duplication of all implementational details here.

Obtaining a Fit to the Adult Data

The first step was to choose a set of parameter values that would give a satisfactory fit to the adults' data. Figure 6a shows the serial position curves for correct performance and for each error type reported by McCormack et al. (1999), and Figure 6b shows the fit of the model. It can be seen that a reasonable fit to most aspects of the data was obtained, with an appropriate serial position curve and a predominance of movement errors at all serial positions. The next step was to take the parameter settings chosen to obtain the fit to the adult data, and vary one parameter at a time to examine the effects on error types and error separation gradients.

Temporal-contextual Distinctiveness

One possible source of developmental change located within the learning-context concerns the temporal distinctiveness of successive states of the signal. This distinctiveness is determined by the speed with which the learning-context vector evolves over time—the greater the rate of change, the less similar are states of the learning-context signal that become associated with successive items (assuming a constant rate of presentation). Use of a learning-context signal whose successive states are not very distinct leads to a system prone to making order errors. This is because if the cues for temporally adjacent items in a sequence are too similar, performance will decrease because list items adjacent to a target will be cued almost as highly at retrieval as the target item itself. In terms of the clock face analogy, it is like trying to recall the correct sequence of events when each was associated to a state of the clock face separated by only 30 seconds (rather than, say, 5 minutes). In young children, successive states of the learning-context signal might be less distinctive than in adults. Adults, whose learning-context signals are better able to distinguish between successive states, would on this account perform better than children. Variable context distinctiveness is modelled in OSCAR by using vectors made from low-frequency (slowly-changing) oscillators to provide a learning-context with poor discrimination between successive states, and context signals made from higher-frequency oscillators to provide a learning-context with better discrimination. Thus the developmental change is controlled by a parameter that determines the frequencies of the oscillators in the learning-context.

The results of varying this parameter to achieve the correct levels of overall performance are shown in column (a) of Fig. 7. The top panel shows the errors produced by versions of the model at the different "developmental stages," and the remaining three panels show the separation gradients for movement errors and repeat errors. Comparison with the experimental data (Figs. 4 and 5) reveals that the main features of the data were reproduced by the model. The error movement gradients became progressively shallower in the "younger" versions of the model, and the reduction in memory performance arose primarily due to a large increase in the number of movement errors. Furthermore, the separation gradients for the repeat errors remained largely unchanged. The main deviation from the data concerned the lack of developmental change in the number of omission and intrusion errors in the model as compared with the data. Although a better fit could easily be obtained by altering other parameters (e.g. by changing the output threshold parameter to produce more omissions), it was felt that introducing changes in several parameters simultaneously, although possibly plausible psychologically, would not add to the understanding of the model's behaviour.

Accuracy of Retrieval Cue

A second manipulation concerns the accuracy of the learning-context vector that is used as a retrieval cue for each item. The default assumption in the model is that retrieval cues are generated accurately, analogously to regenerating states of the clock face by allowing it to run forwards. However a parameter can be used to specify an amount of noise to be added to each element of each learning-context vector prior to its use as a retrieval cue; each learning-context vector element has added to it

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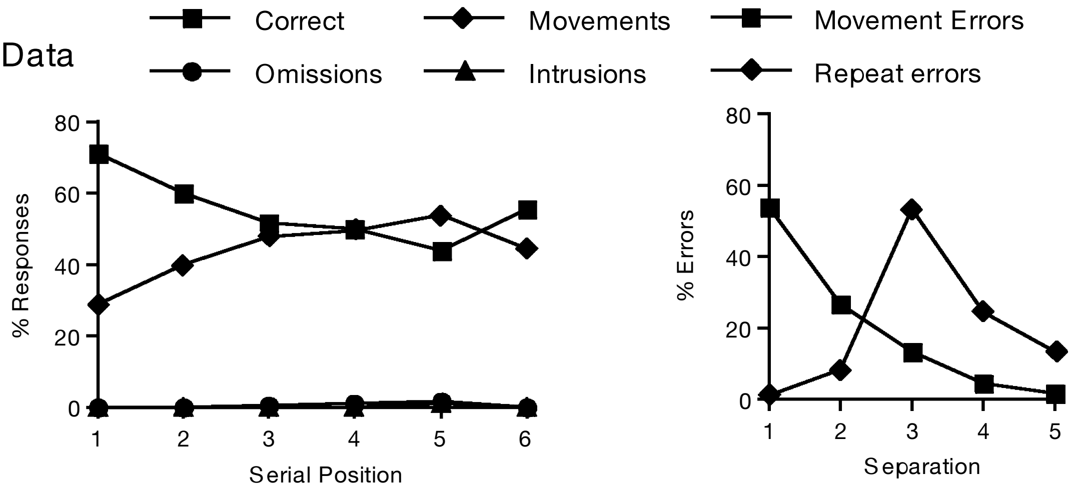
[2] The original model, like several other similar models, sometimes has a tendency to recall repeated items too early due to the summation of associative strengths within a single weight matrix. This is obviated by the use of noninterfering associations.

(a) Data



(b) Model

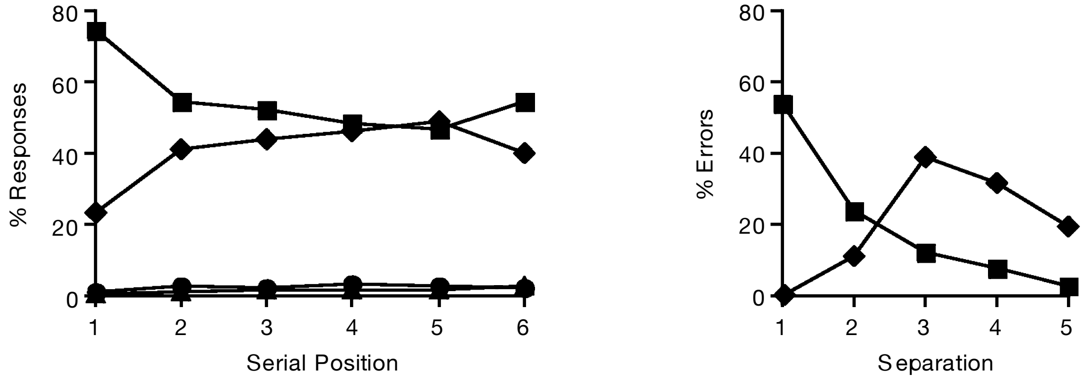


FIG. 6. (a) Serial position curves produced by adult participants in the McCormack et al. (1999) experiment. (b) Fit of the model.

a random number, drawn from a normal distribution with $SD = 1$ and $M = 0$, and multiplied by the parameter value. In psychological terms, this is equivalent to reducing the temporal-contextual specificity of the memory retrieval cues.

The results of this manipulation can be seen in the second column of Fig. 7, where it can be seen that the results are generally similar to those obtained in the previous demonstration. Detailed consideration is postponed to the General Discussion.

Forgetting Parameter

The standard version of the OSCAR model incorporates a weight decay parameter, which causes each item-to-context association to become weaker during encoding of each subsequent item-to-context association. Despite the name, this parameter could equally be thought of as representing the effects of interference; the result of its operation is that the learning of each new item reduces the quality of the representation of previously learned items. Each association is multiplied by a constant when each new association is learned, and the relevant parameter is simply the value of the constant.

The results of varying this parameter, such that greater trace degradation occurs in younger children, is shown in the third column of Fig. 7. This shows that variation in this parameter has effects that are rather different than those of the two context-distinctiveness manipulations described earlier. The error patterns are not too different from the data, with the main reduction in overall correct performance being due to increased movement errors and a rise in omissions (the latter of which could trivially be reduced by changing the output threshold parameter). However it is evident that the separation gradients for repeat errors are very different from those observed in the data; there are many more long-distance repeat errors in the model than in the data, especially at lower levels of performance. This is because the representations of early-presented items become so weak, compared with the representations of late-list items, that there are many anticipations of late-presented items into early recall positions, thus increasing the level of long-distance repeat errors to a level not seen in the data. It seems reasonable to conclude that any computational manipulation that has this effect on the errors can be ruled out as a plausible account of developmental change.

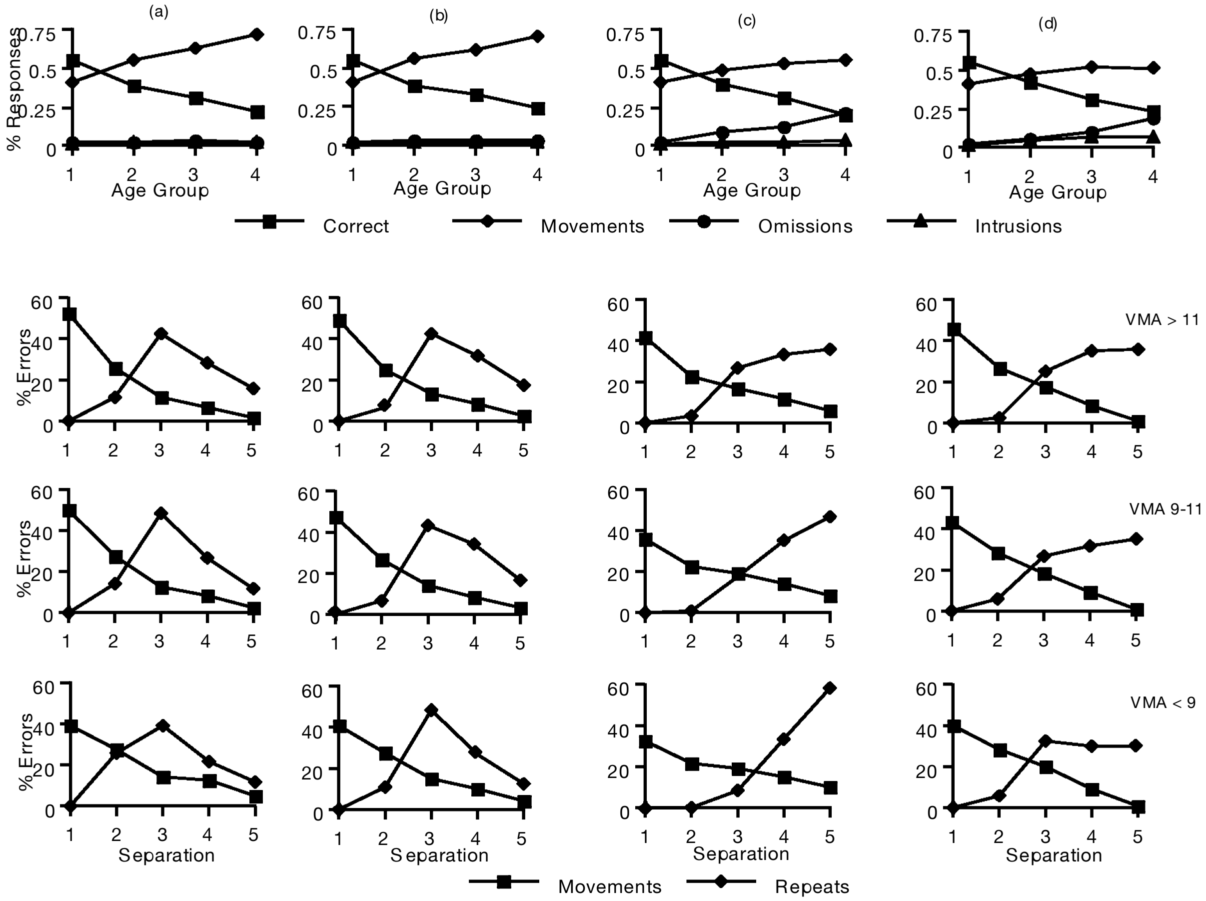


FIG. 7. Movement error and repeat error separation functions produced by the model.

Encoding Differences

Finally, we consider the process of encoding the item-to-context associations as a possible source of developmental improvement. In the OSCAR model, items in a serially ordered list are remembered by forming associations between the items and successive states of the learning-context. In common with other models (e.g. Lewandowsky & Murdock, 1989), OSCAR makes use of an attentional parameter that reduces the strength of encoding of item-to-context associations progressively through the list. If the value of this parameter is 0.9, for example, then the second item will be encoded with a strength of 0.9 times the strength of the first item; the third item with a strength of 0.9^2, and so on.

A reduction in this parameter to model development can be seen as an implementation of the idea that children pay less attention at encoding, particularly to items towards the end of the list. The results of this manipulation are shown in the rightmost column (d) of Fig. 7. Here it can be seen that a similar pattern was obtained to the one seen when the weight decay parameter was manipulated, with the separation gradients for repeat errors being very different from those seen in the data. However the reason is a different one: When attentional encoding reduces quickly throughout the list, as in the model of the youngest children's memory performance, the early-list items are very strongly encoded relative to the late-list items. This results in a relatively high number of long-distance perseverations compared to that seen in the data.

It seems, therefore, that manipulations that simulate reduced encoding of late-list items are unlikely to capture the relevant developmental data.

GENERAL DISCUSSION

In summary, the OSCAR model provides the best fit to developmental error patterns in serial recall tasks if it is assumed that developmental improvement is underpinned by changes in the effectiveness of a dynamic learning-context signal that is used to maintain information about serial order. Although changes in single parameters unsurprisingly failed to capture all aspects of the data, the only features of the data that were not duplicated by the two contextual distinctiveness manipulations (small developmental increases in the number of intrusions and omissions) seem less related than do movement and repeat errors to our central concern of the development of memory for serial order. It is in any case not difficult to capture these additional features of the data by incorporating additional parameter changes (e.g. increasing the similarity of item vector representations increases the number of intrusions; changing the output threshold increases the number of omission errors). We note that it is necessary to examine the developmental error data in considerable detail (e.g. the repeat error separation gradients) if models are to be constrained adequately.

The model can be seen as an implemented instantiation of the hypothesis that the development of memory for serial order is due to developmental increases in the temporal distinctiveness of items' representations in memory. However, further work will be needed to examine the relative merits of encoding-stage vs. retrieval-stage accounts; similar effects in the model were seen whether the temporal-contextual distinctiveness of cues was reduced at learning and retrieval, or just at retrieval.

Relationship to Other Accounts of the Development of Serial Memory

How does the OSCAR model of SOR development relate to the psychological accounts that we outlined in the introduction? The OSCAR model can be seen as a mechanism-level instantiation of a type of temporal distinctiveness model, for items that are assigned more temporally distinctive memorial representations will be more easily and accurately retrieved. Although a variety of temporal distinctiveness models have been applied to adult human memory (e.g. Crowder, 1976; Glenberg, 1987; Glenberg & Swanson, 1986; Neath, 1993a, b; Neath & Crowder, 1990, 1996), such models have not been used to account for the development of memory. Thus the claim embodied in the present developmental model, that the development of memory for serial order results at least in part from developmental increases in the temporal distinctiveness of retrieval cues, is a novel one. The OSCAR account of SOR development contrasts with rehearsal-based accounts, for no rehearsal process is included in the model. However we note the possibility that one function of rehearsal may be to increase the temporal distinctiveness of items' representations in memory. This is because recently encoded items will have more temporally distinctive representations (Crowder, 1976), and so the re-encoding of items enabled by rehearsal may serve to increase the temporal-contextual distinctiveness and diversity of the memory representations of rehearsed items. In the present paper we have focused on purely temporal distinctiveness, as this provides the main constraint on serial recall of unrelated items in the short term. However, contextual and other non-temporal cues also vary with the passage of time, and over longer time periods other aspects of temporal-contextual distinctiveness will assume greater importance in determining recall probability.

The OSCAR approach to SOR development can also be related to developmental accounts based on inter-item pauses (e.g. Cowan et al., 1992, 1998). Items with less distinctive cues will take longer to retrieve in any plausible associative-network memory system involving winner-take-all competition for response selection, and this is also true in the OSCAR model, although such simulations are not reported here. In terms of OSCAR, therefore, the longer inter-item pauses associated with reduced serial recall (Cowan et al., 1998) can be interpreted as the longer retrieval times for each item that will result when less temporally distinctive retrieval cues are available at recall. Our account therefore contrasts with that given by Cowan and his colleagues, for in a model such as OSCAR there is no separate "memory scanning" process occurring during the inter-item pauses other than the competitive winner-take-all process of selecting an item for output. This process will be faster (and hence the inter-item gaps will be shorter and span itself will be increased) just to the extent that the memory representation of the target item is distinctive. Thus there is no central executive involvement (Cowan et al., 1998) other than that involved in attention to the retrieval process itself; span and pause duration will both simply be affected directly by temporal-contextual distinctiveness.

The present version of OSCAR is limited in its ability to account for cross-list proactive interference effects, although later versions of the model accord a central role to such interference. Although proactive interference plays an important part in contributing to phenomena such as word length effects and phonemic similarity effects that are traditionally attributed to a short-term memory system (e.g. Nairne, Neath, & Serra, 1997), explanations of developmental increases in SOR have not generally focused on effects of proactive interference. In the context of a model such as OSCAR, however, proactive interference and temporal-contextual distinctiveness are closely related—proactive interference from temporally distal items in memory occurs just when insufficiently distinctive retrieval cues are available for target items. For example, proactive interference from items in previous lists will occur just to the extent that there is inadequate temporal-contextual distinctiveness at the level of lists.

How does the OSCAR account relate to that of other computational models of serial recall? Other models have not generally been applied to developmental data, although there is no reason in principle why they could not be extended to do so. Indeed, OSCAR is just one member of a family of recent computational models according to which the recall of items in correct serial position will be determined by the positional, temporal, or contextual distinctiveness of the item's representations in memory (e.g. Burgess & Hitch, 1992, 1996; Henson, 1998b; Houghton, 1990; Lewandowsky & Murdock, 1989; Neath, 1993a, b). Although these models differ from one another in a number of respects, in most cases the models could probably be modified to encompass a developmental distinctiveness account of some type.

Relation to Neurobiology

We have made no theoretical commitments regarding the neurobiological substrate of the developmental improvements in SOR. However, tentative relations between the development of frontal function and the availability of highly distinctive temporal-contextual memory representations can be outlined. Patients with frontal lobe lesions are known to have deficits in memory for serial order, at least as assessed by their ability to perform some temporal memory tasks (e.g. Milner, Corsi, & Leonard, 1991; Shimamura, Janowsky, & Squire, 1990; although cf. Hunkin & Parkin, 1993; Parkin, Leng, & Hunkin, 1990); imaging studies have related frontal activity to order memory (e.g. Cabeza et al., 1997), and frontal functioning generally is widely assumed to develop throughout childhood (e.g. Diamond, 1991). Furthermore, the context-providing role of the dynamic learning-context signal in OSCAR is highly similar to the role of maintaining representations of task-related contextual information assigned to pre-frontal cortex in several computational models of pre-frontal function (see, e.g., Cohen & Servan-Schreiber, 1992; Cooper & Shallice, 1997; Dehaene & Changeux, 1989; Levine & Prueitt, 1989). It is therefore possible that the developmental changes in OSCAR's learning-context signal assumed in the present account to underpin SOR development can be related to concomitant development in frontal lobe function. A similar interpretation of OSCAR has been given by Maylor et al. (in press) in applying the model to changes in memory for serial order in elderly adults. Such an account remains speculative at the present time, however.

Contrast with Connectionist Approaches to Cognitive Development

The mechanism that we have proposed contrasts strongly with the types of computational mechanisms that have been used to model developmental change within a more traditional connectionist framework. Although connectionist models have provided useful accounts of the development of low-level psychological processes such as verb-tense learning (Rumelhart & McClelland, 1986) or reading (Seidenberg & McClelland, 1989), the availability of gradient-descent learning algorithms has not led to adequate models of memory development. We have argued (e.g. Brown et al., 1996) that this is because of the types of learning algorithm that are available within connectionism. There are many extant associative mechanisms for forming associations within a single learning trial (e.g. standard Hebbian association) and also several variants of backpropagation and other gradient-descent learning procedures. But there has until recently been no exploration of how gradual development of the ability to perform one-shot learning could take place. OSCAR provides such an account, in terms of the development of the internal cognitive dynamics that can be used to represent structure in the world (Brown & Chater, 1999), rather than in terms of the increasing exposure to the learning task as is emphasized in many current connectionist accounts (e.g. Elman et al., 1996).

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