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Positional Distinctiveness and the Ratio Rule in Free Recall

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The ratio rule relates the recency effect in free recall to the ratio of the duration of the interitem presentation interval (IPI) and the retention interval (RI). Three experiments examined this ratio rule in an immediate memory setting. An approximately linear relationship was discovered to hold over ratios ranging from 1:12 to 12:1 (Experiment 1), and also for constant ratios ranging from 1:1 to 12:12 (Experiments 2 and 3). However, in contrast to a ''true'' ratio rule, recency systematically decreased with increases in absolute duration, despite a constant IPI to RI ratio. A new distinctiveness model is proposed that accurately predicts the reported empirical relationships. The model incorporates a precise definition of stimulus distinctiveness, based on the dimensional distinctiveness model, and includes a specific mechanism to account for how the distinctiveness of each item arises, based on the perturbation model.

The concept of stimulus distinctiveness has a long and troubled history in experimental psychology, particularly among researchers interested in the study of remembering. Distinctive items are thought to be remembered well (e.g., Koffka, 1935; von Restorff, 1933) but, outside of intuition, there is little agreement about the boundary conditions that create or underlie distinctiveness (Neath, 1993a,b; for reviews, see Schmidt, 1991, or Wallace, 1965). Part of the problem is that items can be distinctive in many ways. For example, the word ''apple'' is distinctive semantically if it appears in a list composed primarily of animals; it acquires spatial distinctiveness if it appears in its own unique spatial position during presentation; and, it would be considered temporally distinctive if it appeared widely separated in time from the other items in the list. Unfortunately, there is no straightforward way to capture all of these different meanings of the term ''distinctive'' in a single definition.

In this article, we offer a rigorous definition of stimulus distinctiveness, but our discussion will be limited to cases in which items vary systematically along only a single temporal, or positional, dimension. This means that we will be focusing on those instances in which an item can be said to be distinctive relative to the occurrence of other presented items in time. Temporal, or positional, distinctiveness turns out to be an important determinant of performance in memory tasks, especially in free recall. When items are temporally distinct, especially items near the end of a list, they tend to be remembered well. One way to think about this conceptually is to assume that the farther apart two items reside in one's episodic ''memory space''—in our case along the memory dimension of temporal position—the easier it is to discriminate among those

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items and recognize that each occurred individually in the experiment.

To formalize these ideas, we follow Murdock (1960) and propose that the positional distinctiveness of an item, and its accompanying mnemonic value, is a function of its summed distance from other items in the presentation group (see also Neath, 1993a). What makes our approach unique, however, is that we offer a specific mechanism for the production and calculation of mnemonic distances, and we specify exactly how those distances can be expected to change with time. We will be focusing our attention empirically on the recency effect in free recall, primarily because recency has played a pivotal role in the development of notions about positional distinctiveness over the years. When the recency effect is defined as the slope of the best fitting regression line covering recall of the last several list serial positions, it can be shown to vary systematically as a function of the ratio of the inter-item presentation interval (IPI), which is the time separating the presentation of successive items, to the retention interval (RI), or period separating the end of the list from the beginning of recall. Glenberg and his associates (Glenberg, Bradley, Kraus, & Renzaglia, 1983) have shown that recency varies in a roughly logarithmic fashion with the ratio of the IPI to RI. This regular relationship, or ratio rule, provides the empirical grist for our formal model of positional distinctiveness.

THE POSITIONAL DISTINCTIVENESS MODEL

We begin by assuming that people represent information about each item's occurrence in the presentation sequence in memory. Rather than a temporal tag, however, we propose that information is represented about the serial position of each item in a list (e.g., Estes, 1972; Lee & Estes, 1977; Murdock, 1960; Nairne, 1991). Recall of a particular item is then assumed to be proportional to its distinctiveness, defined as the summed distance of its remembered position from the remembered positions of all other items on the list (Murdock, 1960). (As we will discuss shortly, an item's final ''remembered'' position does not necessarily correspond to its initially encoded (or nominal) serial position in the list.)

To illustrate, assume that subjects are presented with a 12-item ''list'' containing 5 to-be-remembered letters interspersed among 7 additional distractor digits. If the letters occur initially at positions 2, 4, 6, 8, and 10, and we assume no forgetting of position, then the last presented letter would be 2, 4, 6, and 8 units from the remaining letters for a total summed distance of 20. The probability of recalling the item would then be proportional to this summed distance value (see Neath, 1993a). Similar distance values could be calculated for the remaining to-be-remembered letters, thereby forming individual distinctiveness values for each of the items on the list. More specifically, the distinctiveness value, D_i, for any given item would be calculated as follows:

$$D_i = \sum_{j=1}^{n} |X_j - X_i|. \quad (1)$$

The main difference between Murdock's (1960) original formulation and the recent extension by Neath (1993a) is that in the latter, the durations of the IPI and RI are seen as critical in determining where the item sits along the position dimension, and thereby its distinctiveness. Thus, depending on the IPI and RI durations in the lists, two items that appear in the same nominal list position in two otherwise identical lists could end up occupying two quite different values along the position dimension. By taking such temporal variables into account, Neath (1993a) was able to account for primacy and recency effects observed in both recognition and recall, and Neath and Knoedler (1994) accounted for primacy- and recency-like effects in sentence processing.

However, neither Murdock's (1960) original model nor Neath's (1993a) revised dimensional distinctiveness model specify a mechanism for determining how the remembered positions of items actually change with the passage of time. We think an attractive solution to this problem lies in an immediate memory model—the perturbation model—proposed originally by Estes (1972; Lee & Estes, 1977), but recently extended to a wider range of data and far longer durations by Nairne (1990, 1991, 1992; Nairne & Dutta, 1992). Perturbation theory assumes that subjects form position memories during presentation, but that these memories become fuzzy and uncertain with the passage of time. More precisely, memory for position diffuses along a dimension of temporal position, in accordance with a perturbation process, such that the probability that a particular item will be remembered as having occurred in interior position i at time $n + 1$ is

$$X_{i,n+1} = (1 - \theta)X_{i,n} + \frac{\theta}{2} X_{i-1,n} + \frac{\theta}{2} X_{i+1,n}. \quad (2)$$

The parameter theta is the probability that a subject's position memory will diffuse at time $n + 1$ and adopt a neighboring position value. Thus, the likelihood that an item will be remembered as occupying, say, the third position in the list at time $n + 1$ will be equal to the probability that it was remembered in position 3 at time n and no perturbation occurred $(1 - \theta)$, plus the probability that it was remembered in either position 2 or position 4 at time n and a perturbation did occur ($\theta/2$ assumes that movement is equally likely in either direction).

The probability that subjects will remember an item as having occurred in an endpoint of the position dimension (first and last in the list) is slightly different in the model because when the item sits at an endpoint position the diffusion process can operate in only one direction (inward). For the first item in a sequence, for example, the equation becomes

$$X_{1,n+1} = \left(1 - \frac{\theta}{2}\right)X_{1,n} + \frac{\theta}{2} X_{2,n}. \quad (3)$$

In this case, the item's probability of leaving the endpoint position is only $\theta/2$ because it is possible to perturb in only one direction.

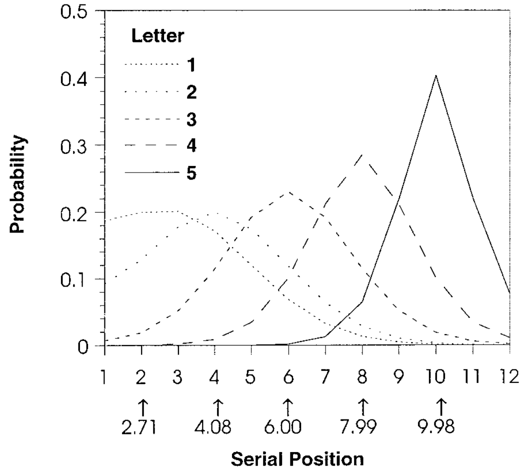

FIG. 1. Hypothetical positional uncertainty gradients for items originally presented at positions 2, 4, 6, 8, and 10, in a 12-item list.

Figure 1 presents a visual illustration of how the distributions of position memories might look for our example memory list at the point of test. Each distribution, or positional uncertainty curve, shows the probabilities that an item presented at a given nominal serial position will be remembered as having occurred in each of the possible positions. Notice that as a result of the perturbation process, an item's remembered serial position might well be different from its absolute position in the presentation sequence. Note as well that there is more uncertainty about the earlier items in the list than there is for the later items. This is because early items, which have occurred farther back in time, have had more opportunities for perturbations to occur.

To predict recall in the positional distinctiveness model, we simply take the expected values of each of the positional uncertainty distributions and sum the relevant distances from the target item to the other to-be-remembered items (in accordance with Eq. (1)). Equations (2) and (3) are used to compute the expected perturbations for each position and the expected values of the resulting positional uncertainty distributions (rather than the abso-

TABLE 1

SAMPLE DISTINCTIVENESS CALCULATIONS

Nominal position	Remembered position	Distinctiveness
2	2.71	$\lvert 2.71 - 4.08\rvert + \lvert 2.71 - 6.00\rvert + \lvert 2.71 - 7.99\rvert + \lvert 2.71 - 9.98\rvert = 17.21$
4	4.08	$\lvert 4.08 - 2.71\rvert + \lvert 4.08 - 6.00\rvert + \lvert 4.08 - 7.99\rvert + \lvert 4.08 - 9.98\rvert = 13.10$
6	6.00	$\lvert 6.00 - 2.71\rvert + \lvert 6.00 - 4.08\rvert + \lvert 6.00 - 7.99\rvert + \lvert 6.00 - 9.98\rvert = 11.18$
8	7.99	$\lvert 7.99 - 2.71\rvert + \lvert 7.99 - 4.08\rvert + \lvert 7.99 - 6.00\rvert + \lvert 7.99 - 9.98\rvert = 13.17$
10	9.98	$\lvert 9.98 - 2.71\rvert + \lvert 9.98 - 4.08\rvert + \lvert 9.98 - 6.00\rvert + \lvert 9.98 - 7.99\rvert = 19.14$

Note. Remembered positions are calculated as the expected values for the positional uncertainty distributions at the point of test.

lute position values) are used to compute distinctiveness according to Eq. (1). In our example list, the expected values for items 2, 4, 6, 8, and 10 are 2.71, 4.08, 6.00, 7.99, and 9.98, respectively. As shown in Table 1, this results in summed distances of 17.21, 13.10, 11.18, 13.17, and 19.14. As can be easily seen, the general characteristics of the prototypical serial position function—notably primacy and recency—are present in the relative magnitude of these distances.

In our three reported experiments, we show that this positional distinctiveness model provides a reasonable qualitative fit of data relevant to recency recall in general and to the ratio rule in particular. In Experiment 1, we report the results of an experiment in which a wide variety of IPI to RI ratios are manipulated in a recall task modeled after the one employed by Neath and Crowder (1990). In Experiments 2 and 3, we extend the distinctiveness logic to cover temporal constancy, in which the overall IPI to RI ratio remains the same but the absolute IPI and RI values increase systematically. These last two experiments are noteworthy because they represent the first time that a wide range of constant IPI to RI ratios has been employed systematically in the same experiment. The resulting empirical data are fit to our simple positional distinctiveness model with little, if any, change in the model parameters across experiments.

EXPERIMENT 1

The majority of studies investigating the ratio rule for recency have been conducted using traditional long-term memory paradigms. However, as Neath and Crowder (1990) have shown, it is possible to use an immediate memory paradigm, modeled after the presentation techniques of Conrad (1964) and Healy (1975), to produce recency effects that are consistent with the ratio rule. Immediate memory paradigms have several advantages: For example, the short presentation schedules allow an experimenter to present lots of trials in a session, thereby enhancing statistical power. Demonstration of the ratio rule in an immediate memory setting also expands the generality of the phenomenon. It might prove possible to demonstrate, for instance, that the ratio rule is yet another case where short- and long-term memory phenomena appear to follow similar rules (e.g., Crowder & Neath, 1991; Greene, 1986; Nairne, 1992; Neath & Crowder, 1996). In Experiment 1, subjects received 135 six-item memory lists. Each list contained six letters, presented at a rapid rate, interspersed with the rapid presentation of digits. The digits occurred between the presentation of each to-be-remembered letter (forming the IPI) and for a period following the presentation of the final list item (forming the RI). In this way we were able to tightly control the IPI and the RI durations, as well as to prevent selective rehearsal. The critical independent variable was the IPI to RI ratio—how many digits separated each list item compared to the number of digits that followed the last list item. Our intent was to expand the number of IPI to RI ratios that are typically used in studies examining the ratio rule. For example, whereas Neath and Crowder (1990) used only four IPI to RI ratios in their Experiment 1, we used a total of nine and covered a much broader range. Subjects were told to shadow both the letters and digits aloud as each item was presented. At the conclusion of the last digit, subjects were asked to recall the six letters in any order.

Method

Subjects and apparatus. Fifty-two Purdue University undergraduates participated in this experiment for credit in introductory psychology courses.

Materials and design. All stimulus events were presented and controlled by an IBM-compatible computer. Subjects received 135 six-item memory lists, presented in three blocks of 45, in a six (serial position) by nine (IPI to RI ratio) within-subjects design. Each list contained six different lower case consonants drawn randomly from a set of 17 letters (l, v, w, y, and the vowels excluded). Interspersed among the letters, forming the IPI, and during the period prior to recall, forming the RI, digits appeared that were randomly chosen from the set 1–9. Both the stimulus letters and the distractor digits were presented for 500 ms apiece, in the center of the computer screen.

A given list was associated with one of nine IPI to RI ratios. Across the lists, these ratios were set at 1:1, 1:2, 1:4, 1:8, 1:12, 2:1, 4:1, 8:1, and 12:1. For a list with a 1:1 ratio, 2 distractor digits were presented between each list item and an additional 2 were presented at the end of the list prior to recall. Because each digit was presented for 500 ms, this meant that there was 1 s of distractor activity between each item and 1 s between the last list item and test. A list with an 8:1 ratio would have 16 digits presented between each letter, but only 2 digits would appear during the interval between list and test, and so on. Each of the ratios was sampled randomly across the experimental session and equally often. On a given trial there was no way for a subject to predict how many digits would appear during the IPI and RI.

Procedure. A trial began with the word ‘‘Ready’’ presented in the center of the screen, accompanied by a short beep. Subjects were instructed to attend to the screen after hearing and seeing this signal in preparation for list presentation. Subjects were asked to read the individual events of a trial aloud (letters and digits) as each appeared in the center of the screen. Following the last digit of the RI, subjects were asked to type in the letters that they had just seen in any order that they wished. It was necessary to enter six letters, and subjects were not allowed to correct their responses. Two seconds after the sixth digit had been typed into the computer, the next trial was initiated.

There were two rest periods in the session, one after trial 45 and another after trial 90. The rest period could last up to 6 min, during which time the subject was encouraged to relax, stretch, and/or walk around a bit. Pressing the space bar allowed the subject to move into the next block of trials. In addition, there were four practice trials, selected randomly from the nine IPI to RI ratios, presented just prior to the actual experimental trials.

Results and Discussion

Because we were primarily interested in the relationship between the recency portion of the curve and the ratio of IPI to RI, two analyses were performed on subsets of the data. When the IPI was held constant at 1 and the RI varied from 1 to 12 (Fig. 2, top) a 5 ratios by 6 serial positions ANOVA revealed reliable effects of the ratio ($F(4,204) = 69.20$, $MSe = 0.028$, $p < .01$) and of the serial position ($F(5,255) = 56.26$, $MSe = 0.062$, $p < .01$). There was also a reliable interaction ($F(20,1020) = 9.71$, $MSe = 0.031$, $p < .01$). Thus, as the ratio decreased from 1:1 to 1:12, the proportion of items correctly recalled at the final position decreased from 0.95 to 0.63. This was the expected pattern—increasing the interval separating presentation and testing affects the serial position curve primarily in the recency portion of the list (e.g., Postman & Phillips, 1965).

When the RI was held constant at 1 and the IPI varied from 1 to 12 (Fig. 2, bottom), a 5 ratios by 6 serial positions ANOVA once again revealed reliable effects of the ratio ($F(4,204) = 14.90$, $MSe = 0.035$, $p < .01$) and of the serial position ($F(5,255) = 147.38$, $MSe = 0.091$, $p < .01$). There was also a reliable interaction ($F(20,1020) = 5.72$, $MSe = 0.029$, $p < .01$). Thus, when the ratio increased from 1:1 to 12:1, the slope became steeper.

The empirical results of main interest are displayed in Fig. 3. The term ''recency slope'' refers to the slope of the best fitting least-squares regression line covering recall of the last three serial positions. Each data point (the filled circles) represents the recency slope as a function of a particular IPI to RI ratio. Recency slope is actually plotted as a function of the natural logarithm of the IPI to RI ratio—this is typically done because according to the ratio rule, the slope covering the last three serial positions is predicted to vary logarithmically with the IPI to RI ratio. When plotted against natural logarithms, recency slope should appear to increase linearly with increasing ratio (see Glenberg et al., 1983).

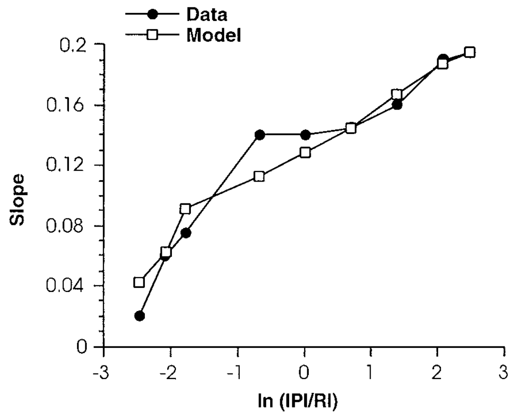

FIG. 3. The slope of the best-fitting line for the last three positions as a function of the log ratio of the duration of the interpresentation interval (IPI) and retention interval (RI).

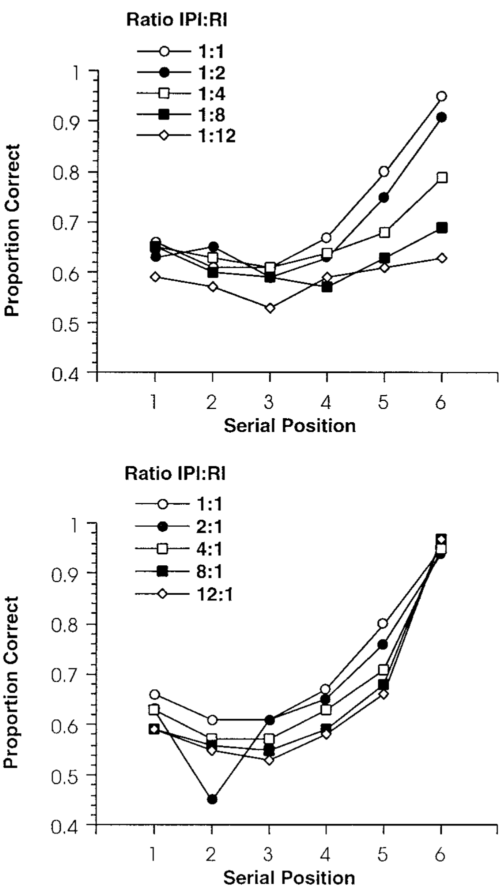

FIG. 2. Proportion of items recalled as a function of ratio and serial position. Note that the data from condition 1:1 are replotted in both panels.

The data clearly indicate a pattern that approximates the ratio rule, even with the large increase in the number of ratios tested and the use of an immediate rather than a long-term memory task. The equation of the best fitting straight line to the data was $y = 0.126 + 0.031x$, $r = 0.956$. From a purely empirical standpoint, then, the results of this experiment replicate previous experiments but greatly extend their generality. With small IPI to RI ratios (that is, when RI is large relative to IPI), recency is virtually absent; as IPI increases relative to a fixed RI, the slope of the last three serial positions increases dramatically. We now turn our attention to the positional distinctiveness model to see how well it can handle this basic data pattern.

APPLICATION OF THE MODEL

At encoding, items are assumed to be represented in their true position. During acquisition of the remaining items, and during the RI, the perturbation process allows for items to migrate away from their starting position. The end results are hypothetical positional uncertainty gradients of the type illustrated in Fig. 1. The expected values of these uncertainty distributions at the end of the perturbation process are then used as the basis for determining the distinctiveness of each item relative to the other items in the ensemble. The distinctiveness values are scaled appropriately, and the result is the expected level of recall. The model, then, specifies how the distinctiveness of each item relative to the other items varies over time.

The model has two experimentally defined parameters, which correspond to the duration of each IPI and the duration of the RI (in seconds), and two scaling parameters, S_I and S_R. The former is applied to the duration of all the IPIs and the latter is applied to the duration of the RI. In the example that is illustrated in Fig. 1, the IPI was 1 s (the duration of two digits) and the RI was 2 s (the duration of four digits). The two scaling parameters affect the number of possible perturbations; we have found that a value for S_I that is approximately twice as large as a value for S_R produces a satisfactory number of opportunities to perturb. In the example, these parameters were 10 and 5, respectively. The value of theta, the probability that an item will undergo a perturbation at that interval—technically a free parameter—was held constant for all simulations at .05 based on experience in previous work.

After the results of the perturbation process are determined (according to Eqs. (2) and (3)), the relative temporal distinctiveness of each of the to-be-remembered items is calculated (according to Eq. 1) and the results scaled by the final parameter, *K*. For the above example, *K* was simply set to 1. This parameter is used so that comparisons across different list-lengths and different list durations will be meaningful.

For the data from Experiment 1, there was no formal attempt to obtain the best of all possible fits; rather, a selective examination of the parameter space revealed a satisfactory fit with the following parameters: The values of IPI and RI were determined by the experimental condition; S_I and S_R were set at 17 and 7, respectively, and *K* was set at 22. The values of the last three parameters, once set, were used for all conditions. When applied in this way, the model enabled us to calculate serial position functions for each condition. We then simply calculated the recency slope for each condition, and these values are shown as the open squares in Fig. 3. The model is quite accurate, accounting for nearly 95% of the variance (RMSD = 0.0046). Thus, when one combines the perturbation model to describe how positional uncertainty unfolds over time (Nairne, 1991) with the dimensional distinctiveness model (Neath, 1993a), the resulting model can predict the ratio rule in free recall. Not only does this model specify exactly what distinctiveness is and how it is calculated, it also specifies a mechanism, perturbation, through which changes in distinctiveness arise.

Still, it is one thing to fit a model to a data set, but quite a different thing to make accurate predictions with the model. In our next experiment, we sought to use the parameter values established in Experiment 1 to generate predictions about what should happen when the ratios stay constant but the absolute durations of the IPI and RI vary from 1 to 12 s. Experiment 2 tested the accuracy of these predictions.

EXPERIMENT 2

In Experiment 1, the duration of the IPI and RI varied from 1 to 12 s and performance consistent with the ratio rule was observed. Experiment 2 was designed to test the effect of ratios that were identical mathematically, but were very different in terms of absolute duration. Although there are some hints in the literature that the magnitude of the recency slope may change little with increases in absolute duration (i.e., Glenberg et al., 1983), the issue has yet to be explored systematically in an experiment. In Experiment 2, we employed six IPI to RI intervals, 1:1, 2:2, 4:4, 6:6, 8:8, and 12:12, which varied in absolute duration but which all formed a constant ratio of 1.0. The positional distinctiveness model, using the parameters established in Experiment 1, predicts a slightly decreasing trend in the magnitude of the recency slope as the absolute duration increases. This is because the longer the absolute duration, the more opportunities there are for an item to perturb or diffuse along the position dimension.

An alternate prediction, made on the basis of distinctiveness alone, is that there should be no difference in performance because the ratios are constant. According to a ''true'' ratio rule, manipulations of absolute duration such as these should not affect performance because most distinctiveness theories use the *relative* distinctiveness of an item as a determiner of recall (see Neath & Crowder, 1990). These relative values do not change with an increase in absolute duration so long as the ratios remain constant.

Method

Subjects and apparatus. Forty-nine different Purdue University undergraduates participated in exchange for credit in introductory psychology courses.

Materials and design. All stimulus events were presented and controlled by an IBM-compatible computer. The materials and design were the same as in Experiment 1, except that the ratios of IPI to RI were held constant at 1. Thus, the ratios were 1:1, 2:2, 4:4, 6:6, 8:8, and 12:12. Each subject received 90 lists, 15 in each condition, in random order. As in Experiment 1, subjects had as much time as necessary to enter their six responses, they recalled the items in any order they wished, and they were given two breaks during the session.

Results and Discussion

Figure 4 shows the proportion of items recalled as a function of the ratio and serial position. As the duration of both the IPI and the RI increased, recall at the recency positions became systematically lower, although there was little effect apparent for the early items.

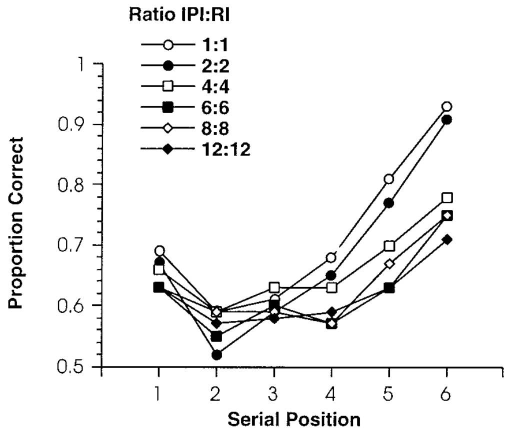

FIG. 4. Proportion of items recalled as a function of the absolute duration of the IPI and RI and serial position in Experiment 2.

A six ratios by six serial positions ANOVA revealed reliable effects of ratio ($F(5,240) = 16.49$, $MSe = 0.038$, $p < .01$), serial position ($F(5,240) = 42.00$, $MSe = 0.049$, $p < .01$), and a reliable interaction ($F(25,1200) = 2.43$, $MSe = 0.031$, $p < .01$), confirming the above observations. An analysis of the simple effect of ratio at the six different serial positions found no reliable effect for the first two positions, but reliable effects at the last four positions.

The empirical results of main interest are displayed in Fig. 5. Each data point (the filled circles) represents recency slope, again defined as the best fitting regression line covering recall of the last three serial positions, as a function of the absolute duration of the IPI and RI. If a ''true'' ratio rule holds, one should find a slope of zero when the best fitting regression line is fit to these data points; as Fig. 5 shows, this clearly was not the case. The magnitude of the recency slope appeared to decline with increasing absolute duration and certainly did not remain flat. Thus, absolute time matters in this setting, and in a way that appears to be consistent with the predictions of our positional distinctiveness model.

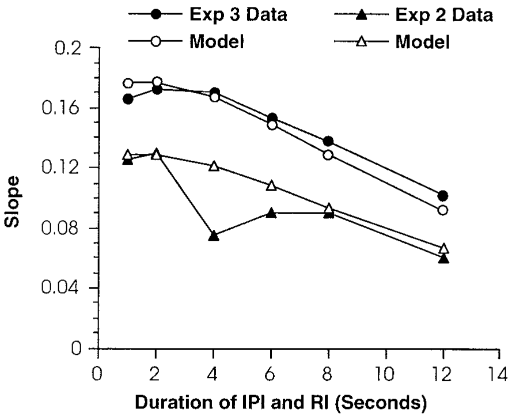

FIG. 5. The slope of the best-fitting line for the last three positions as a function of the duration of the interpresentation interval (IPI) and retention interval (RI). The triangles show the data and fit for Experiment 2 and the circles show the data and fit for Experiment 3.

The model, without changing any of the parameters used for the fit in Experiment 1, accounted for nearly 60% of the variance (RMSD = 0.0084). Moreover, when the anomalous-looking data point for the 4:4 condition is eliminated from the analysis, the fit of the model is dramatically improved. For comparison, we also examined the best fitting line with a zero slope: $y = 0.09495 + 0x$. It did not fare well ($r = 0.00$). This finding is significant because any view of memory proposing that only relative time is important cannot explain the data: Regardless of where one draws a line with slope of 0, it will not fit the data as well as a model, such as our positional distinctiveness model, which also takes into account absolute time.

EXPERIMENT 3

Using the parameters established in Experiment 1, the positional distinctiveness model accurately predicted the nature of the recency effect observed in Experiment 2 when the ratios were held constant but the absolute durations increased. We have no explanation for the anomalous point for the 4:4 ratio condition; we assume it to be due to random causes, but a replication will determine whether this deviation from the predicted performance level is theoretically important. Experiment 3 was designed to provide such a replication. The only change between Experiment 2 and Experiment 3 was in the way that subjects responded. In the current experiment, rather than typing in their responses, subjects used a mouse to click on appropriately labeled buttons.

Method

Subjects and apparatus. Fifty Purdue University undergraduates participated in exchange for credit in introductory psychology courses.

Materials and design. All stimulus events were presented and controlled by an Apple Macintosh 6100 computer. The materials and design were the same as in Experiment 2, with the following exceptions. Each subject received 72 lists, 12 in each condition, in random order. The six-item lists were drawn from a pool of 16 uppercase consonants (B, C, D, F, G, H, J, K, M, N, P, R, S, T, X, and Z); in Experiment 2, Q was used as a stimulus but in Experiment 3 it was not. In Experiment 2, subjects recalled by typing in the letters in any preferred order. In Experiment 3, the computer presented all 16 consonants on the screen in alphabetical order. The subjects were asked to click, using a mouse, on the six items that had been presented in the most recent list. It was emphasized that they could click on the buttons in any order, and they were allowed 12 s to make their six responses. No subject reported difficulty with this method of responding. Subjects were given five short rest breaks evenly spaced during the experiment.

Results and Discussion

Figure 6 shows the proportion of items recalled as a function of the ratio and serial position, and the results generally replicate the findings of Experiment 2. As the duration of both the IPI and the RI increased, recall at the recency positions became systematically lower. A six ratios by six serial positions ANOVA revealed reliable effects of ratio ($F(5,245) = 48.14$, $MSe = 0.020$, $p < .01$), serial position ($F(5,245) = 186.29$, $MSe =$

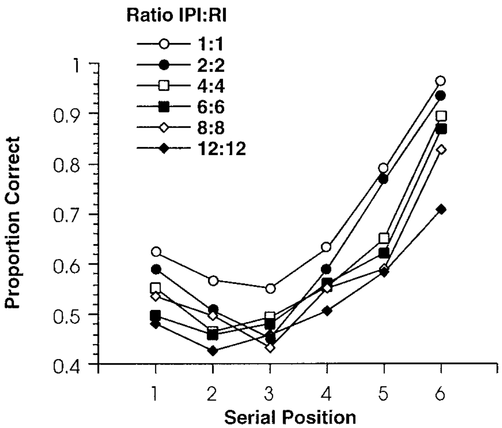

FIG. 6. Proportion of items recalled as a function of the absolute duration of the IPI and RI and serial position in Experiment 3.

0.035, $p < .01$), and a reliable interaction ($F(25,1225) = 3.06$, $MSe = 0.021$, $p < .01$).

The empirical results of main interest are shown in Fig. 5, along with the results from Experiment 2. The slopes of the lines that best fit the last three serial positions were steeper in Experiment 3 than in Experiment 2, presumably because of the new response procedure that required the subject merely to click on the appropriate responses. Notice as well that the anomalous point found previously for the 4:4 ratio condition is no longer present. However, in all other respects, the pattern of results across experiments is quite similar. To compensate for the overall change in level we adjusted the constant *K*, but otherwise we used the same model parameter values that we used to fit the data from Experiments 1 and 2. The model accounted for nearly 97% of the variance (RMSD = 0.0031). When the ratio of IPI to RI is held constant, there is apparently a decrease in the slope as the absolute numbers increase. As we will discuss shortly, this finding has important implications for memory theory.

GENERAL DISCUSSION

The results of these three experiments replicate and extend our empirical knowledge about how recency effects in free recall vary as a function of the temporal schedule of presentation. In Experiment 1, we greatly expanded the number of IPI to RI ratios used in previous investigations of the ratio rule and confirmed that recency slope varies in a roughly logarithmic fashion with the IPI to RI ratio. Experiments 2 and 3 tested an important prediction of the ratio rule, namely, that the magnitude of the recency slope depends on the ratio of the IPI to RI but not on the absolute durations involved. Contrary to the predictions of a ''true'' ratio rule, we discovered that there is a decrease in recency slope as the absolute durations increase. To explain and help frame these data, we offered a new model of positional distinctiveness.

To have an adequate model of positional distinctiveness, one must not only specify how distinctiveness should be calculated, but one should also be able to specify exactly how the distinctiveness of each item arises. By combining a mechanism based on Estes' perturbation model (Nairne, 1991) with a rigorous definition of distinctiveness based on a suggestion by Murdock (Neath, 1993a), we have been able to do just that. The positional distinctiveness model produced acceptable fits of data when the IPI to RI ratio varied from −2.5 to +2.5 on a log scale. Using the same parameters, it also fit data when the ratio remained constant but the absolute magnitude varied from 1 to 12 s between each IPI and the RI. Notice that once again we are predicting the ratio rule by first predicting the general shape of the serial position function and then determining the recency slope.

For the simulations presented here, no further perturbations were permitted once the recall period was initiated. We did, however, test a version of the model that allowed for perturbations to occur for each item throughout the recall period until the item was successfully recalled. This entailed an additional assumption about output order. In free recall, the final items are generally recalled first, followed by the early items (e.g., Murdock, 1974). This alternate model assumed that the number of additional perturbations for any given item was a function of how much time elapsed before recall. The only substantive change in the predictions of the model was a reduction in overall performance of prerecency items, resulting in serial position curves even more similar to those observed in the data. The quantitative fits of the slope of the last three items were essentially unchanged, increasing only marginally for Experiment 1, and a similarly small increase was found for Experiments 2 and 3. Because the experiments were not designed to measure output order, however, the particulars of the alternate version are not presented in detail.

It is worth noting that the perturbation component of the model has been shown elsewhere to predict error gradients and overall memory performance for lists lasting a few seconds to lists lasting a day or so (Nairne, 1992). Moreover, the distinctiveness component has been shown to predict not only recency but also primacy effects observable in free recall and recognition (Neath, 1993a,b). Thus, the individual components of the combined model have received solid empirical support in several contexts outside of the present paradigm. However, there is one important problem that arises when both the perturbation and distinctiveness components are combined. Neath and Crowder (1990) reported an experiment in which the total duration of a list was unrelated to the relative presentation time of items within that list. They reported the extended ratio rule, which relates performance on item *n* to the ratio of the IPI immediately prior to item *n* to the total time until item *n* is recalled. They found that performance was better when this ratio was higher than when it was lower, regardless of the absolute duration of the list. For example, one list had 56 s of distractor activity but a median ratio of 1; a second had 66 s of distractor activity but a median ratio of 0.75; and a third had only 36 s of distractor activity but a median ratio of 0.53. The probability of recall depended on the ratio, not on the absolute duration. Neath and Crowder argued that this finding ruled out explanations that involved absolute time.

The perturbation model, as it currently stands, does rely on absolute time, and thus it is not clear how it can account for such data. The perturbation model would appear to predict better recall for a shorter-lasting list than for a longer-lasting list, other things being equal. Of course, both Estes (1972; Lee & Estes, 1977) and Nairne (1991, 1992) have remained largely silent on the issue of what causes a perturbation—one might argue that it is not time *per se* that leads to item perturbations, but rather events that happen in time that produce forgetting (e.g., McGeoch, 1932). At the same time, a pure distinctiveness component, such as the one proposed by Neath and Crowder (1990), is unable to account for the slightly decreasing function observed for constant ratios in our current Experiments 2 and 3. Much has been said lately concerning the roles of relative versus absolute time in forgetting, with some arguing for solely relative time (e.g., Neath & Crowder, 1990, 1996) and some for solely absolute time (e.g., Cowan, Winkler, Teder, & Näätänen, 1993). The data from these experiments suggest that both views have some merit.

By combining two well-specified models, one that emphasizes the role of absolute time in forgetting and one that emphasizes the role of relative time in forgetting, we have been able to fit the ratio-rule observed in free recall, and also to predict the appropriate function when the ratios are constant but absolute time increases. Each model, by itself, is unable to account for some part of the data, but together, they provide a successful account of the empirical patterns.

Returning to the general issue of distinctiveness in memory, is there any way that the current positional distinctiveness model can be applied to other forms of mnemonic distinctiveness? As we discussed earlier, there seems to be no simple way of capturing all of the potential meanings of the term ‘‘distinctive’’ in a single definition. We have chosen to follow Murdock (1960) and others in treating distinctiveness as the summed ‘‘distance’’ of a target item from other items in a memory space. In the case of temporal position, there is a clear dimension along which such a distance measure can be calculated, and data exist showing how item memory changes along the position dimension over time (e.g., Lee & Estes, 1977).

It seems likely that a positional distinctiveness model such as the one we have proposed here could be applied to other well-defined mnemonic dimensions, such as spatial position (Nairne & Dutta, 1992). It is less clear how the model can be applied to any kind of meaning-based dimension. However, distance in semantic space could be defined through multidimensional scaling or through other assumptions common to categorization models. In such a scheme, distances and expected movements would follow from the assumptions made about the characteristics of the dimension. Thus, in principle, the positional distinctiveness model could apply to many different kinds of mnemonic distinctiveness.

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