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Positional discriminability in linear orderings

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Subjects were taught two eight-term linear orders of the form "A taller than B taller than C...". They were then asked to choose the "taller" term in all possible pairwise combinations within each series, and reaction time was measured for each pair. In addition, subjects performed a further task in which they judged whether or not two terms were adjacent in the ordering. In subsequent sessions, subjects were told that the "shortest" term on one list was taller than the "tallest" term on the other, so that the two lists were merged into a single 16-term series. They were then required to choose the "taller" term for both within-groups and between-groups pairs. Subjects did not appear to use the initial groupings in performing this task, even when given training on differential categorical codes ("tall" vs. "short") for the two subsets. Rather, subjects in all tasks appeared to represent the terms as ordered positions along an internal array, so that comparison times depended largely on the differential discriminability of the item positions. In each task decisions were made more quickly if the terms being compared were near the ends of the ordering, rather than near the middle.

The problem of how information about serial order is stored in memory has concerned psychologists from Ebbinghaus (1885/1964) to the present (e.g., an excellent historical review, see Crowder, 1976, Chapter 12). This classic problem has recently been investigated in a relatively new reaction time paradigm, in which subjects answer questions about an arbitrary ordering of stimuli along a dimension. A typical procedure is to first train the subjects on adjacent pairs of stimuli (e.g., Henry taller than Pete, Pete taller than Bill, Bill taller than Steve, etc., and then ask questions about all possible pairs (e.g., Pete taller than Steve)). This paradigm began with the study of "three-term series problems" (Burt, 1919; Clark, 1969; DeSoto, London, & Handel, 1965; Huttenlocher, 1968). More recent investigators have used larger series and emphasized different experimental phenomena; however, the primary emphasis of the earlier work, the process by which people make transitive inferences, remains a major concern (Trabasso, 1975).

A major finding in the recent work on linear orderings is that during the testing phase, subjects can compare nonadjacent pairs more quickly than they can compare adjacent pairs (Potts, 1972, 1974, Trabasso & Riley, 1975; Trabasso, Riley, & Wilson, 1973). The advantage of the nonadjacent or "remote" pairs is particularly interesting in that these pairs are not presented during training. Subjects are actually faster to compare items never previously paired (e.g., B > D) than to compare items that were explicitly learned together (e.g., B > C). It seems that subjects do not simply store the adjacent pairs during training and then use them to draw transitive inferences at the time of testing (as an "associative chaining" model might suggest). Rather, people appear to form a unified representation of the entire ordering during learning, so that comparison times depend on emergent properties of the entire ordering rather than on the particular pairs from which the ordering was induced.

These linear order studies depart from the traditional serial order memory paradigm, the serial anticipation method, in several ways. The main dependent measure in the linear order work is usually reaction time (RT), rather than percent correct or trials to criterion. The task involves evaluating the relation between two stimuli, rather than using one stimulus as a cue to recall the next. However, there is also evidence that suggests the linear ordering paradigm taps some of the same mental processes as are involved in serial learning tasks. In particular, studies of linear order judgments
DISCRIMINABILITY IN LINEAR ORDERS

The subjects were eight Stanford University undergraduates who were paid to participate in a series of experimental sessions, spaced 1 week apart and each lasting approximately 1 hour.

Materials consisted of two eight-letter ordered lists. Each experimental session consisted of eight sessions, with each session containing 16 trials. The order of the trials was randomized for each subject, and each subject participated in a different order than any other subject.

The tone duration for all trials was constant at 1.5 seconds, and the intertrial interval was 5 seconds. The LD and RF stimuli were presented via headphones, and the subjects were seated approximately 2 feet from a loudspeaker.

Presentation of the stimuli began with a fixation point located in the center of the display. The fixation point was red, and the background was black. Upon the subject's response, the fixation point was replaced by a tone, which was a pure sine wave at a frequency of 1000 Hz. The tone duration was 1.5 seconds, and it was presented through headphones. The intertrial interval was 5 seconds.

The main event of each trial was the presentation of a stimulus pair, consisting of two letters. The subject was required to indicate whether the stimulus pair was old or new by pressing one of two buttons. If the stimulus pair was old, the subject pressed the left button, and if it was new, the subject pressed the right button. The buttons were labeled with the words "old" and "new." The correct response was rewarded with a 50 ms tone at 1000 Hz.

The experimental session consisted of 16 trials, with each trial containing a stimulus pair. The session was divided into four blocks of four trials each. The order of the stimulus pairs was randomized for each block, and the order of the blocks was randomized across subjects.

The experiment was conducted in a double-blind manner, with the experimenter not knowing the hypothesis being tested. The experimenter was blind to the experimental groups and did not communicate with the subjects during the course of the experiment.

The results of the experiment showed that the subjects were able to discriminate between the stimulus pairs with greater than chance accuracy. This finding is consistent with previous research demonstrating that humans are capable of discriminating between linear orders.

In conclusion, the results of this study provide evidence that humans are capable of discriminating between linear orders, even when the orders are not presented in a fully specified form. This finding has important implications for the study of human cognition and the development of artificial intelligence systems.
RESULTS AND DISCUSSION

Eight-Term Orders

The error rate for comparisons based on the eight-term orders was very low (1.49%). Reaction times greater than 3,000 msec were truncated to that value, and all analyses were performed on correct RTs only. Table 1 presents mean RTs broken down by ordinal distance between the two terms (step size) and number of end anchors in the pair (one, two, or four). These means are averaged over the two lists and pairs order (left-right vs. right-left). As in previous studies, RT decreased as the distance between the terms increased from Step Size 1 to Step Size 3 [F(2, 50) = 9.24, p < .001], by a linear trend. This distance effect is clearly present even when only the terms without end anchors are considered [F(4, 99) = 2.82, p < .05].

Table 1 also reveals that RT decreased as the number of end anchors in the pair increased from zero to two [F(2, 50) = 23.3, p < .001]. A linear distance effect was obtained for pairs containing an end anchor [F(1, 75) = 3.24, p < .05]. Reaction time was faster for pairs containing the "taller" anchor (98.57) rather than the "shorter" anchor (125.52), presumably reflecting the relative bias in favor of the end anchors in the comparison task. The ordinal distance between adjacent terms increases, the curves begin to flatten and become increasingly linear, at the lower portion of the bow-shaped curve, the distance effect is clearly present even when the pairs including end terms are ignored, reaction times between pairs of different step sizes often overlap. For example, response latencies were faster to pairs B, D, and G than to pairs D, F, and E, even though the former are adjacent pairs and the latter are not. These results are quite consistent with those of previous investigations (McKinley, 1973; Trabasso & Riley, 1975) and indicate that serial position effects are not due to anchors alone, but are more continuous. Both the distance and serial position effects obtained here are consistent with the positional discriminability hypothesis (1).

Sixteen-Term Order

The overall mean RT was much longer for the first half of testing on the 16-term list (1,935 msec) than for the separate 8-term lists tested previously (1,137 msec). The mean rate on the 16-term list was still quite high (3.63), however, and was virtually identical for between-groups and within-groups comparisons.

Mean correct RTs for the various conditions are presented in Table 2. The most important finding is that, contrary to the expectation of a grouping model, pairs containing items from different halves of the list were evaluated more slowly than pairs containing items from the same half. This trend was maintained even when within-groups comparisons containing end anchors were excluded, although the difference was not significant [F(1, 21) = 1.11, p < .10]. In addition to this major result, strong end anchor effects were obtained (when only the A and P terms were considered end anchors). Reaction times to pairs involving either the first or last item of the 16-term ordering were consistently faster than those involving no end terms [F(1, 21) = 13.13, p < .001]. As with the eight-term orders, this effect was mainly due to pairs including the "taller" term (mean RT = 1,194 msec), whereas the "shorter" term (mean RT = 1,369 msec) was not significantly C. Two-way ANOVA with increasing distance was also obtained, although this trend was just barely significant [F(1, 21) = 4.39, p < .05]. However, overall distance was confounded with the relative number of between-groups and within-groups comparisons. The farther apart two items are, the more likely they are to fall in different halves of the ordering. When between-groups and within-groups comparisons are examined separately, Table 2 reveals that the effect of distance was obtained for both types of comparisons. Figure 1 plots the mean RTs for each pair as a function of step size and the larger term of the pair. This graphical display of the data clearly shows that serial position effects occurred within any given distance. For Step Size 1 (the adjacent pairs), the serial position effect was not significant, as the data points for the adjacent pairs are almost perfectly aligned. For Step Size 2, the serial position effect was significant, with the reaction times for the adjacent pairs being significantly faster than the reaction times for the non-adjacent pairs. This trend was maintained even when the pairs were not adjacent, as the data points for the non-adjacent pairs are still significantly faster than the reaction times for the adjacent pairs. This indicates that serial position effects are not due to anchors alone, but are more continuous. Both the distance and serial position effects obtained here are consistent with the positional discriminability hypothesis (1).
as step size increases. The results are again consistent with the view that RT is primarily determined by the positional discriminability of items within the entire 16-term ordering.

This conclusion derives further support from the results of multiple-regression analyses performed (separately for the two sessions) on the mean RTs for the 16-term ordering. In each case four "distance from end anchor" variables accounted for most of the systematic variance (about 45% of the total variance). These were the minimal distance from an end term (A or P) and the distance from the "tallest" term (A); both of these variables were significant for both the "taller" and the "shorter" pair members. These variables are essentially the same as those that predicted RTs for the eight-term orders. The distance between the two terms in a pair accounted for a small but significant amount of residual variance. However, the factor of within-groups vs. between-groups comparisons was not significant after the variance due to distance and end anchor variables was removed. For the test items used in the present study, the items in between-groups pairs were relatively far apart in the ordering, but also relatively far from an end anchor (A or P). Since the latter variable had a greater influence on RT, decisions about between-groups pairs tended to be relatively slow. However, the multiple-regression results indicate that list position factors were the critical determinants of RT, and the between-groups vs. within-groups factor had no direct influence on the results.

Adjacency Judgments

The error rate on the adjacency task (which followed the eight-term series judgments on Session 1) was 5.89. Mean RTs over 4,000 were truncated to that value. Figure 4 displays mean RT to respond "true" for each adjacent pair, ordered from "tallest" to "shortest." The curves are plotted separately for both presentation orders (e.g., A-B vs. B-A), as well as collapsing across order: the data for the two lists are combined. The asymmetrical bow-shaped curve emerges once again in this new type of judgment. In fact, the serial position effects obtained for adjacency judgments are remarkably similar to the pattern obtained for "taller" judgments about the same pairs (Figure 1). This pattern is consistent with the hypothesis that subjects used an internal array to perform this task as well, and that differences in RT again reflect differences in the discriminability of item positions along the array.

Figure 4 also reveals that RT was faster overall when pairs were presented with the "taller" term on the left ("correct" order) rather than on the right ("reverse" order) \( F(1,56) = 418.8, p < .01 \). However, the advantage of the correct order disappeared for pairs near the "shorter" end of the list (F-F, F-C, G-H) \( F(7,56) = 9.1, p < .01 \). These order effects suggest that something more than positional discriminability (which should not vary with order) affects RT in this task.

Furthermore, it seems plausible that such a scan may have a directional bias. Since the list was to be learned in the order "tallest" to "shortest," the scan would generally move from the "taller" items toward the center of the list; however, the "shortest" items may have tended to be acquired "from the end in" (Trabasso et al., 1975), rendering them relatively neutral with respect to direction of scan. Such directional biases may have produced the obtained interaction between presentation order and serial position. A scanning model of the above sort might generally account for the bow-shaped serial position curves found in linear order studies, and thus provide a mechanism to explain the directional availability of positions in an array. Wooncher (1976) has formulated a mathematical version of an end-inward search model and applied it successfully to the data from 8-term and 16-term orderings.

The mean RTs to respond "false" to the nonadjacent pairs are presented in Table 4. These also show an asymmetrical bow-shaped serial position function, although it is less pronounced than that obtained with the adjacent pairs. Since all but one of the pairs had a step size of two between the items, no strong conclusion can be reached about the effect of the distance between the items on time to decide a pair is not adjacent. Nevertheless, the fact that the one pair with Step Size 3, C-F, tended to be evaluated relatively quickly is at least suggestive. If speed to reject a pair as nonadjacent in fact increases with the distance between the items, this would provide further evidence that discriminability along an internal array also influences adjacency judgments.

GENERAL DISCUSSION

The results of the present study are consistent with the hypothesis that serial order information is coded in memory as an internalized array. The ease of retrieving information from the array is largely governed by the relative discriminability of the relevant item positions, with end positions being more discriminable than central ones. This conclusion appears to hold not only for decisions about which of two items is taller, but also for decisions about whether the two items are adjacent in the array. The latter result illustrates the general uselessness of examining different but related judgment processes in order to find converging evidence for a single underlying knowledge structure. Our results provide a broader empirical base for models of serial order that incorporate the positional discriminability hypothesis (Bover, 1971; Murdoch, 1969, Trabasso & Riley, 1975).

Perhaps the most surprising result of the present study is the failure to find any clear evidence that experimentally imposed groupings affect the time to retrieve information from a linear ordering. When two 8-term series were combined in a single 16-term list, the existence of a clear break in the ordering did not facilitate comparisons of items that straddled the division. Rather, subjects appeared to treat the new list as a unified linear array, so that RTs were largely

Table 3

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean Reaction Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Size</td>
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<tr>
<td>No Anchors (overall)</td>
<td>1656</td>
</tr>
<tr>
<td>One Anchor (overall)</td>
<td>1529</td>
</tr>
<tr>
<td>Within Groups (all pairs)</td>
<td>1644</td>
</tr>
<tr>
<td>Within Groups (no anchors)</td>
<td>1681</td>
</tr>
<tr>
<td>Between Groups</td>
<td>1606</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean Reaction Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Size 2</td>
<td>A-C</td>
</tr>
<tr>
<td>Correct Order</td>
<td>1557</td>
</tr>
<tr>
<td>Reverse Order</td>
<td>2115</td>
</tr>
<tr>
<td>Mean</td>
<td>1836</td>
</tr>
</tbody>
</table>
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NOTES

1. The data were also submitted to multiple-regression analyses, which essentially confirmed the pattern apparent in Figure 1. The major variables predicting RT were the minimal distance from the item in a pair to one of the two-end anchors, and in particular, the distance of the item from the "tail-end." (Received for publication October 11, 1977; revision accepted October 26, 1977.)

REFERENCES


