Journal of Experimental Psychology:
Human Perception and Performance
1981, Vol. 7, No. 6, 1283-1302

0096-1523/81/0706-1283$00.75

A Positional Discriminability Model of Linear-Order Judgments

Keith J. Holyoak
Human Performance Center
University of Michigan

K. Keith Patterson
Bell Northern Research

The process of judging the relative order of stimuli in a visual array was investigated in three experiments. In the basic paradigm, a linear array of six colored lines was presented briefly, and subjects decided which of two target lines was the leftmost or rightmost (Experiment 1). The target lines appeared in all possible combinations of serial positions and reaction time (RT) was measured. Distance and semantic congruity effects were obtained, as well as a bowed serial position function. The RT pattern resembled that observed in comparable studies with memorized linear orderings. The serial position function was flattened when the background lines were homogeneously dissimilar to the target lines (Experiment 2). Both a distance effect and bowed serial position functions were obtained when subjects judged which of two target lines was below a black bar cue (Experiment 3). The results favored an analog positional discriminability model over a serial ends-inward scanning model. The positional discriminability model was proposed as a "core model" for the processes involved in judging relative order or magnitude in the domains of memory and perception.

Are there important commonalities between the cognitive processes involved in memory and in perception? This general question has influenced hypothesis formation in several research areas (Shepard & Podgorny, 1978). One such area is the investigation of relative judgment, and in particular, judgments of order in a linear array. In the memory version of this paradigm, the subject is first taught an arbitrary ordering of items along some dimension, usually by studying the adjacent pairs (e.g., "Tom is taller than Harry, Harry is taller than Bill, Bill is taller than Pete"). During the subsequent testing phase the subject is asked to make relative judgments for all possible pairs (Griggs & Shea, 1977; Potts, 1972, 1974). Reaction time (RT) is typically the primary dependent measure.

Three robust empirical phenomena are observed in such studies. First, an apparent *distance effect* is obtained. That is, during the testing phase subjects can compare pairs of remote items more quickly than they can compare adjacent pairs. This basic finding has been obtained with lists containing from 4 (Potts, 1972) to 16 items (Woocher, Glass, & Holyoak, 1978). The distance effect is particularly interesting because it implies that subjects are actually faster to compare items never previously paired (e.g., B > D) than to compare items that were explicitly learned together (B > C). Second, RT is faster when the form of the comparative matches the positions of the target items in the ordering. For example, it is easier to choose the taller of two items near the "tall" end of an ordered list, whereas it is easier to choose the shorter of two items near the "short" end of the list (Trabasso, Riley, & Wilson, 1975). This is termed the *semantic congruity effect.* Third, collapsing over the two possible comparatives, comparisons tend

---

Authors' names are listed alphabetically.

This research was supported by National Institution of Mental Health Grant 5-R01-MH33278-02 to Keith J. Holyoak.

Herbert Clark generously provided us with the use of his laboratory. We thank Ira Appelman for programming the tachistoscope and advising us on appropriate stimulus parameters, as well as for helpful discussions of conceptual matters. The article also benefited from discussions with John Jonides and J. E. Keith Smith. Bill Banks and two anonymous reviewers provided valuable criticisms of an earlier draft.

Requests for reprints should be sent to Keith J. Holyoak, University of Michigan, Human Performance Center, 330 Packard Road, Ann Arbor, Michigan 48104.

to be made more quickly for pairs near the ends of a linear ordering than for pairs near the center. The result is a bow-shaped serial position curve when RT is plotted as a function of pair position. This bow-shaped serial position function is similar to that obtained in studies of serial recall. Items from the center of a list, which are compared most slowly in the RT paradigm, also produce the most errors in a serial recall task (see Crowder, 1976, chap. 12, for a review).

Our primary concern in the present article is with the first and third phenomena—distance effects and bowed serial position curves. These patterns suggest that people form a unified representation of the entire ordering so that comparison latencies depend on emergent properties of the linear array rather than on the particular pairs from which the ordering was induced. Furthermore, a number of theorists have proposed that the representation of linear orderings in memory is closely related to the representation of perceived spatial arrays (DeSoto, London, & Handel, 1965; Huttenlocher, 1968; Trabasso & Riley, 1975).

Given the theoretical importance of the claim that linear orderings are processed much like spatial arrays, surprisingly little experimental evidence directly substantiates it. The first step toward providing such evidence would be to demonstrate that judgments of order in a visual array produce the phenomena that characterize order judgments based on memory—distance effects, congruity effects, and a bow-shaped serial position curve. However, only Trabasso et al. (1975) have investigated perceptual order judgments using the choice RT paradigm. Furthermore, methodological problems leave the interpretation of their results open to question. In one of their experiments, subjects were shown an array of six differently colored sticks (see Trabasso et al., 1975, pp. 223-226, "distance condition"). The sticks were ordered from left to right, 1 in. (2.5 cm) apart. All were equal in size (8 in. or 20 cm), but subjects were told to imagine the leftmost stick as shortest and the rightmost as longest (or vice versa). This linear array was continuously in view beside a test apparatus in which a pair of colored sticks was presented on each trial. Subjects were timed as they chose the stick that was supposedly longer or shorter, with the correct answer being determined by the position of the relevant sticks in the displayed array. All possible pairs of sticks were tested. Trabasso et al. found that the obtained RT pattern was essentially identical to that observed with a memorized linear ordering. A distance effect was obtained; decisions were relatively slow for pairs drawn from the middle of the array; and decisions were especially fast for pairs from the end of the array congruent with the comparative (longer or shorter). Trabasso et al. therefore concluded that linear-order judgments may involve a scan of an "internal display."

However, the above experiment provides little evidence for this view. First, subjects certainly had to make eye movements in scanning the large perceptual display. Because eye movements were not recorded, we do not know what role they played in producing the obtained results. More important, we do not know whether similar results would be found for arrays that can be processed in a single fixation. Since presumably an "internal scan" need not involve a process analogous to eye movements, the latter type of perceptual display would seem to provide a more appropriate comparison condition.

Second, the Trabasso et al. (1975) "perceptual" condition probably involved a large and uncontrolled memory component. The same physical array was visible throughout all comparison trials. As a result, subjects could have memorized the perceptual array, either completely or in part, during the early trials. On later trials, they could then respond without scanning the presented display at all. This problem is compounded in view of the training results obtained by Trabasso et al. (1975) in other experiments, which demonstrate that subjects learn orderings from the ends in, first memorizing the end sticks and proceeding into the middle. As a result, the subjects would have needed to consult the array least often for pairs including an end item and most often for pairs of middle items. The nominally "perceptual" order judgments may therefore have been largely based on a remembered linear ordering, with systematic differential learning of the item positions. If so, it is no surprise that the experiment produced results similar to other studies of order judgments based on remembered linear orderings.

No other study has investigated visual order judgments using a comparative judgment paradigm. However, there is a large body of literature on the perception of items, usually letters, that are presented in a linear array. In these studies, the array is presented tachistoscopically and the main dependent measure is error probability (rather than RT), measured using either full or partial report techniques (Harcum, 1967; Townsend, Taylor, & Brown, 1971; Wagner, 1918). In addition to effects of absolute retinal position (accuracy decreases with greater distance from the fixation point), effects of relative serial position are also obtained. When the fixation point is to the left or right of the display, detection accuracy is greater for items at the ends of the arrays than for central items (Estes, Allmeyer, & Reder, 1976). Estes et al. demonstrated that this bow-shaped serial position function is obtained even when the array is viewed (without eye movements) for as long as 2,400 msec. In addition, Estes et al. showed that this serial position function characterized not only the availability of individual items but also information about relative order (as indexed by the prevalence in subjects' reports of inversions of adjacent letters). Such results provide some evidence that order information may be processed similarly in memorized and perceived linear arrays.

Ends-Inward Scanning and Positional Discriminability Models

Although numerous models have been proposed to account for order judgments with memorized lists, not all are readily extendable to perceptual paradigms. However, given the similarities of the serial position functions associated with the processing of memorized and perceived arrays, it is not surprising that some similar models have been developed independently in the two research areas. Here we consider two models that can be applied to both domains—ends-inward scanning and positional discriminability models. We consider various other proposals specific to the memory domain in the General Discussion section. The ends-inward scanning model explains both distance and serial position effects on the basis of differences in the time required to access item locations by a serial search process. In contrast, the positional discriminability model assumes that serial position effects arise as a result of interitem interactions that affect the time required to identify the locations of individual items, whereas the distance effect is the product of a subsequent comparison process.

Ends-inward scanning. Although various types of scanning models have been proposed in the comparative judgment literature, only the "ends-inward" scanning model (Woocher, 1977; described in Woocher et al., 1978) can account for all of the major results obtained in studies using memorized orderings. This model assumes that on each trial the subject performs serial searches from the two ends of the list in toward the middle, comparing each list item in turn to an item in the presented pair. Because the subject is assumed to know from which end each search process was initiated, a correct response can be made as soon as either pair member is encountered. Bow-shaped serial position effects will arise because middle items will be accessed most slowly. The distance effect is explained on the basis of the fact that pairs of highly separated items tend to include at least one item near an end. To account for the congruity effect, the model assumes that the search from the congruent end of the list is relatively rapid.

The ends-inward scanning model has the advantage of corresponding to proposed models of how linear orders are initially learned (Feigenbaum & Simon, 1962; Trabasso et al., 1975). Trabasso et al. found that the serial position curve for number of errors prior to criterion, obtained for the adjacent pairs during training, corresponded closely to the serial position curves obtained for RT in the comparison phase of their study. That is, pairs of adjacent middle items are learned most slowly. Trabasso et al. assumed that subjects construct a mental linear array by fixing first the "end anchors," then the two most extreme interior items, and so on toward the middle of the array, placing the most central items last. The ends-inward search model extends this same basic mechanism to the process of order judgment.

A similar ends-inward scanning model has been proposed to account for the bow-shaped serial position curves obtained in studies that use report procedures to investigate processing of letter arrays (Merikle & Coltheart, 1972). In the context of visual processing, the model assumes that processing of items at the center of a letter array is delayed relative to the processing of items near the ends. However, this hypothesis does not adequately explain why the serial position function is essentially unchanged even when the exposure duration of the array is greatly increased (Estes et al., 1976).

Positional discriminability. A major theoretical construct incorporated in positional discriminability models is *positional uncertainty,* which has been introduced in models of visual-array processing (Estes et al., 1976; Wolford, 1975). The notion is that the subjective location of an item in an array can be represented as a distribution around the true location. These distributions will tend to overlap to a greater extent for central than for peripheral items. As a result, it will be relatively difficult to locate the positions of central items due to competing information from surrounding items.

Positional uncertainty is closely related to measures of relative distinctiveness (Murdock, 1960) and stimulus generalization (Bower, 1971), both of which predict maximal uncertainty for the central items in a series. Trabasso and Riley (1975) have shown that each of these measures can be used to derive accurate ordinal predictions of mean RTs across pairs. A related positional discriminability model was sketched by Woocher et al. (1978) and is elaborated here as a more explicit process model.

We assume that judgments of relative position are made on the basis of an iterative two-step procedure: (a) locating each pair member and generating a code for its position, and (b) comparing the resulting position codes for the two items. Positional uncertainty will affect the time required to complete Step a. If the position distributions of neighboring items overlap that of a target item (i.e., a pair member), it will be relatively difficult to discriminate the target item from the surrounding alternatives so that a position code can be generated. This difficulty will be accentuated if the neighboring items are similar to the target along the relevant dimensions of encoding. The precise mechanism by which the targets are located in Step a is not specified here, but we assume the array positions will be processed at least partially in parallel to locate the targets.

The two models differ most clearly with respect to Step b, since the ends-inward scanning model does not postulate a comparable comparison of position codes. The positional discriminability model assumes that the output of Step a is a position code for each target. The position code for any item will be a random variable with an expected value linearly related to the item's relative position in the array. If the items are equally spaced (as in all the present experiments and most previous studies), the position codes will be equivalent to ordinal positions. However, if the items are unequally spaced (Griggs & Shea, 1977), the codes will reflect the interval-scale distances. In Step b the position codes for the two targets will be the input to a comparison process that determines the difference between them. This comparison process will involve a sequential sampling mechanism (Buckley & Gillman, 1974; Holyoak, 1978), such as a random walk or diffusion process (e.g., Link, 1975; Ratcliff, 1978). Consider a random-walk formulation. In Step b the subject will assess the difference between the position codes for the two targets, T1 and T2. This (positive or negative) difference will be added to an accumulator, which will be initialized at zero (if the subject is not biased in favor of a particular response). The two-step procedure will then be iterated until the value of the accumulator reaches a positive or a negative criterion, triggering a response. For example, suppose the subject is viewing a linear array. The position codes increase from left to right, and the subject is asked whether T1 or T2 is rightmost. The subject will iteratively assess the difference (e.g., code for T1 minus code for T2). If the positive criterion is reached, the subject will respond that T1 is rightmost; if the negative criterion is reached, the selected response will correspond to T2.

This positional discriminability model attributes the slower comparison RTs observed for pairs of central items to Step a (time to identify the positions of the two target items), because position distributions will maximally overlap for central items. Both Step a and Step b will contribute to the distance effect. Pairs of widely separated items will tend to include items near the ends, for which position codes will be generated relatively quickly in Step a. In addition, the expected value of the difference between the position codes, calculated in Step b, will increase with distance; as a result, a decision criterion will tend to be reached with relatively few iterations of the random-walk process.

The positional discriminability model must be augmented by additional assumptions to account for the congruity effect. A number of alternative assumptions seem plausible and are mentioned in the General Discussion section.

Additional predictions can be derived from the positional discriminability model. First, the serial position function for comparison RT should become less bowed as the distance between pair members increases. The extra difficulty of identifying the locations of central items will increment RT to compare central pairs, relative to end pairs, each time Step a is iterated. Because the number of required iterations will be negatively correlated with the distance between the items, the serial position function will be maximally bowed for pairs with the least separation between them (i.e., adjacent pairs). This pattern in fact characterizes the serial position functions obtained in studies of order judgments with memorized lists (e.g., Trabasso et al., 1975; Woocher et al., 1978), but comparable tests have not been made with visual arrays.

A second prediction is that order judgments will be sensitive to the similarity of the array items. Recall that Step a of the iterative process involves discriminating each of the two target items from neighboring alternatives to generate position codes for the targets. The difficulty of this discrimination process will decrease if interitem similarity is decreased, because even if the location distribution of a target item overlaps that of an alternative item, a decision mechanism can select the target relatively easily if the neighboring alternative is dissimilar. Reduced similarity should therefore produce faster RTs, particularly for the central items, which are most affected by overlap among the apparent locations of items. This prediction distinguishes the present model from the related proposal of Trabasso and Riley (1975), which does not address the effect of interitem similarity.

The relevant dimensions of similarity will presumably differ between perceived and memorized arrays—visual in the former case, primarily acoustic and semantic in the latter. The effect of similarity has not been investigated within a choice RT paradigm in either domain. However, visual similarity is known to interfere with subjects' performance in reporting letters in a visual array (Estes, 1975). In addition, it has been demonstrated that acoustic similarity impedes processing of order information in a serial recall task (Watkins, Watkins, & Crowder, 1974). The similarity prediction of the positional discriminability model therefore has at least indirect support.

Formalization of positional discriminability model. It may be helpful to summarize the assumptions of the model in a quantitative form. The predictions tested in the present article require only that the major functional relationships among parameters be monotonic. We first define $I_{T1,T2}$, the expected number of iterations of the two-step procedure required to reach a decision for the targets T1 and T2:

$$I_{T1,T2} = f_{mon}(d_{T1,T2}); \qquad (1)$$

where f_{mon} is a decreasing function of the intertarget distance (i.e., the absolute value of the difference between the expected values of the position codes for the two targets). Equation 1 is consistent with any of the various sequential sampling mechanisms mentioned above.

We assume that the time to locate a target and generate a position code for it is proportional to an index of confusability, C_T:

$$C_T = \sum_{i=1}^{n} s_{T,i} g_{mon}(d_{T,i}), \qquad (2)$$

where n is the number of items in the array, $s_{T,i}$ is an index of the similarity of the target to an item, and g_{mon} is a decreasing function of target-to-item distance. It is convenient for the values of $s_{T,i}$ and $g_{mon}(d_{T,i})$ to be normalized between zero and one. A plausible form for g_{mon} is a negative exponential (Shepard, 1958). When $s_{T,i}$ is a constant, the confusability measures proposed by Murdock (1960) and Bower (1971) are both special cases of Equation 2.

We assume that decision latency will be proportional to the product of the expected number of iterations and the expected time to complete each iteration. Target confusability will affect iteration time; specifically, if the targets are located sequentially in Step a, then

$$RT_{T1,T2} = h_{mon}[I_{T1,T2}(aC_{T1} + aC_{T2} + K)], \qquad (3)$$

where h_{mon} is an increasing function, a is a positive proportionality constant, and K is a positive constant equal to the minimal time required to complete an iteration.[1]

The following predictions relevant to the present study can be derived from Equations 1–3:

1. Reaction time will decrease with intertarget distance (from Equations 1 and 3).
2. Holding distance constant, RT will increase from end pairs to central pairs (from Equations 2 and 3, because C_T will be higher for central targets).
3. The serial position curves will flatten as distance increases (from the interaction implied by Equation 3).
4. Serial position curves will also flatten if interitem similarity is decreased (from Equations 2 and 3, because the values of C_T across serial positions will tend toward equality as $s_{T,i}$ approaches zero).
5. The distance effect will also be reduced as $s_{T,i}$ decreases (from Equations 2 and 3, because the value of C_T will decrease for all serial positions).
6. A residual distance effect will be obtained even if all values of C_T approach a constant (from Equation 3). In other words, a distance effect can be obtained even in the absence of detectable serial position effects.

Article Overview

The three experiments reported below all involve judgments of order in a visual array. These experiments address two questions directly: (a) Can the phenomena obtained in studies of memorized orderings (distance, congruity, and bow-shaped serial position effects) also be obtained using perceptual arrays? (b) Is it possible to distinguish ends-inward scanning and positional discriminability models in the context of a visual order-judgment paradigm? The evidence obtained in these experiments is also used to address two further questions more indirectly: (c) Can similar process models account for order judgments based on memory and on perception? (d) What is the relationship between models of order judgments and models proposed for other similar types of relative judgments?

The paradigm used in the experiments to be reported was modeled after the "perceptual" condition of Trabasso et al. (1975); however, it uses a tachistoscopic presentation procedure that eliminates the methodological problems associated with that earlier study. The basic stimulus displays used were horizontal arrays of six differently colored lines, equal in length, presented briefly to either the left or the right of a fixation point. Each array included two critical lines (e.g., red and green), and the subject was asked to decide as quickly as possible which of these was further to the left (or right) in the display. Over trials the two critical lines appeared in each possible combination of positions (thus eliminating any influence of memory for the positions of target items) and with each of the two forms of the question. This paradigm therefore made it possible to examine the effects of all the variables that are known to influence comparisons

---

[1] If it was assumed that the two targets are located in parallel, then Equation 3 could be modified by substituting $a[\max(C_{T1}, C_{T2})]$ for $aC_{T1} + aC_{T2}$. The predictions tested in the present study would not be altered by such a modification.

based on memorized linear orderings—distance between the positions of the two critical items, their serial positions, and the relation between item positions and the form of the question.

Experiment 1

Method

Subjects judged the relative order of two colored lines presented tachistoscopically within an array of six lines, and RT was recorded.

Subjects. Eight Stanford University undergraduates served as paid subjects. All had normal color vision as determined by prescreening vision tests.

Materials. Each linear array was drawn with colored pencils (Eagle Primacolors and Verithins) on a separate white card. All of the vertical lines were 2 mm wide and 17.5 mm high; a 2-mm horizontal space separated each line. Each array contained a yellow and a green line designated as the target items to be compared; the additional background lines in the array were brown, pink, purple, and gray. Across different cards, the yellow and green lines were placed in all possible combinations of ordinal positions; the positions of the background lines were randomized for each card. Thirty different arrays were constructed in this fashion.

Procedure. Subjects judged which of the two target lines was further left or further right and responded by pressing a left or right key. Trials were blocked by the form of the question, with the order of the two question blocks counterbalanced across subjects.

Each trial began with the subject viewing a fixation dot on a white field in an Iconix three-field tachistoscope. As soon as the subject was ready, he or she pressed a button to initiate the presentation. After a 500-msec delay the fixation dot was replaced by the array of colored lines located either to its left or its right. The lateral display locations were used to control the influence of retinal factors that produce greater visual acuity for positions at the fixation point (e.g., Winnick & Bruder, 1968). The horizontal width of the bar array was approximately 1.30° of visual angle, either ending (for left visual-field displays) or beginning (for right visual-field displays) at the position previously occupied by the fixation point. Because the display was presented to each visual field with equal frequency, the average distances from the six bar positions to the fixation point were equated (collapsing across the visual-field variable).

The array was displayed for 200 msec, after which it was replaced by an empty "stare" field of medium brightness, which remained in view until the subject responded. The absence of a postmask allowed a poststimulus icon. Pilot work indicated that subjects could respond with sufficient accuracy under these conditions so that RT could be used as a reliable dependent measure. A 200-msec exposure duration is slightly longer than the mean time required to respond with an eye movement to a simple selective attention cue (Colegate, Hoffman, & Eriksen, 1973). However, subjects were instructed to avoid making eye movements, and previous research indicates that subjects can refrain from making an eye movement for at least 2 sec (Estes et al., 1976). It is therefore extremely unlikely that our subjects made eye movements during stimulus presentations.

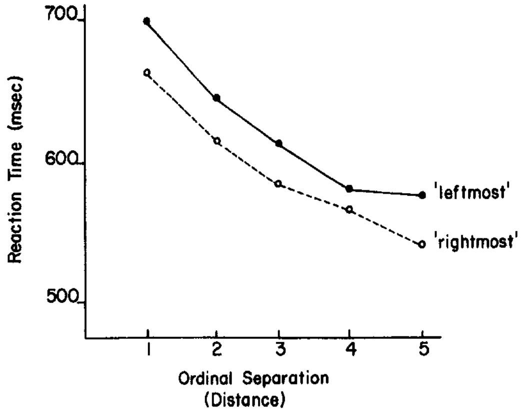

Figure 1. Reaction time as a function of the distance between the two target lines (Experiment 1).

Subjects were informed when they made errors, and items that produced errors were retested later in the trial block. Presentations to the two visual fields were randomly intermixed within each block of trials. Each subject went through the 120 test items twice in a single experimental session. These test trials were preceded by 60 randomly selected practice trials, presented as a block of 30 trials for each question.

Results and Discussion

Several analyses of variance (ANOVAS) were performed on the RT data. One analysis included distance as a factor (collapsing across serial positions); the others included serial position as a factor, with a separate analysis for each distance (from one to four steps of ordinal separation). The resulting mean square errors (MS_e) were used to perform trend tests. The field of presentation had no significant influence on the RT pattern. The results reported below therefore collapse across this variable, as well as the left/right order of the yellow and green lines and the counterbalancing conditions.

All of the three phenomena of interest—distance, congruity, and bowed serial position effects—were observed. Figure 1 illustrates the decline in RT that accompanied increasing ordinal separation of the critical lines, plotted separately for the two forms of the question. This 125-msec distance effect was significant by a linear trend test, $t(28) = 14.7, p < .001, MS_e = 1{,}382$. Sub-

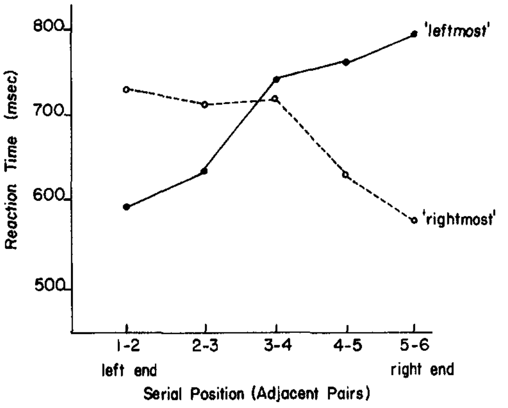

Figure 2. Reaction time as a function of the instructions and serial position of the target lines in adjacent pairs (Experiment 1).

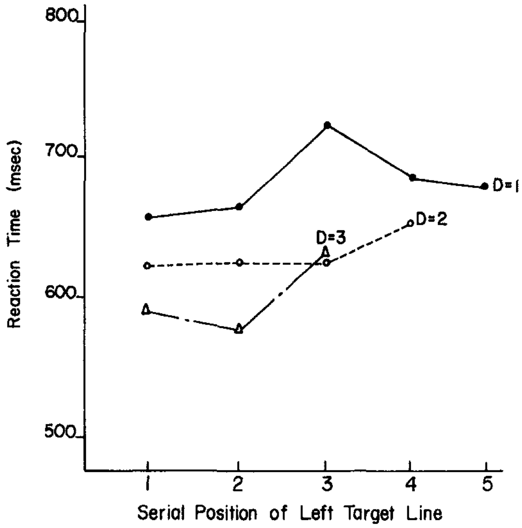

Figure 3. Reaction time as a function of serial position for pairs at different distances, collapsing over the two forms of the instructions (Experiment 1). (D = distance.)

jects responded more quickly overall when making "rightmost" rather than left-most" judgments, $F(1, 7) = 14.9$, $p < .01$, $MS_e = 2{,}480$, in the distance analysis. Previous studies of question answering with the terms *right* and *left* have sometimes found an advantage for *right* even after subjects have had time to encode the question, as was the case in the present experiment (Just & Carpenter, 1975).

Figure 2 plots RT for the five pairs of adjacent lines as a function of the instructions, "choose leftmost" or "choose rightmost." A 176-msec "crossover" congruity effect was obtained for these pairs, $t(28) = 10.6$, $p < .001$, $MS_e = 5{,}945$, by a bilinear trend test. Subjects were faster in choosing the leftmost line for pairs near the left end of the array, whereas they were faster in choosing the rightmost line for pairs near the right end of the array. A smaller but still significant interaction was also obtained for pairs two steps apart; congruity effects were not obtained for more widely separated pairs.

The congruity effect depicted in Figure 2 is sufficiently large that it obscures any tendency toward overall slower RTs for pairs of central lines. However, any bowing of the serial position function, which both ends-inward scanning and positional discriminability models predict, should become apparent when mean RTs are collapsed across the two forms of the question. Figure 3 presents the overall mean RTs for each serial position, plotted separately for pairs with an ordinal separation of one, two, and three steps. For the pairs of items one step apart (i.e., adjacent pairs), RTs increased from the end pairs to the middle pair, $t(28) = 3.46$, $p < .002$, $MS_e = 4{,}695$, by a quadratic trend test. Any extra difficulty of central pairs was not detectable for ordinal separations of two or three; rather, RTs tended to be longest for the rightmost pairs. Recall that the positional discriminability model predicts that the serial position function will flatten with increased intertarget distance.[2]

As noted earlier, the visual field in which the array was presented had little influence on the RT pattern. In particular, there was no evidence of any "visual-field congruity effect" (i.e., faster "leftmost" judgments for displays in the left visual field, faster "rightmost" judgments for displays in the right). However, a gradient of retinal acuity was detectable in Experiment 1. Collapsing over all other factors, RT to adjacent pairs tended to increase with increasing distance from the fixation point, $t(28) = 4.45$, $p < .001$,

---

[2] Virtually identical results were obtained in a further experiment in which, following the procedure of Trabasso et al. (1975), subjects were told to imagine that the lines in the array were ordered in size, and *leftmost* and *rightmost* were mapped onto the terms *larger* and *smaller* (or vice versa).

$MS_e = 5{,}553$, by a linear trend test. The mean RTs for the five pair positions, ordered from closest to furthest, were 637, 637, 723, 716, and 699 msec. The overall error rate in Experiment 1 was 3.6%.

Experiment 2

The results of Experiment 1 indicate that the three basic phenomena obtained in studies of order judgments with memorized lists—a decline in RT with increased interitem distance, reduced RT when the question is congruent with the item positions, and relatively fast RTs for pairs of items near the ends of the ordering—can all be obtained when order judgments are based on a linear visual array. These results correspond to Predictions 1-3 derived from the positional discriminability model. We discuss the import of these parallels between the results obtained with memorial and perceptual paradigms in the General Discussion section. However, it is first desirable to clarify the mechanisms underlying performance in the present perceptual task. As we pointed out in the introduction, both ends-inward scanning and positional discriminability models can account for the general pattern of RTs associated with order judgments. Both models are therefore consistent with the results of Experiment 1. The remaining two experiments were designed to discriminate between these two types of process models.

As noted earlier, the positional discriminability model predicts that position codes for target items will be derived relatively quickly in Step a of the two-step comparison procedure if the targets are easily discriminated from the background items (i.e., the values of $s_{T,i}$ are low). Furthermore, any variable that makes item discrimination easier will particularly benefit centrally located targets, thus flattening the bowed serial position function for comparison RTs. Studies of letter identification indicate that targets are detected more readily if the background items are either visually dissimilar (Estes, 1975) or homogeneous (Estes, 1974; McIntyre, Fox, & Neale, 1970). In Experiment 2, the four background lines were uniformly black, rather than drawn in four different colors as in the earlier experiment. Under these conditions the positional discriminability model predicts that the extra difficulty of comparing pairs of central items will be attenuated or eliminated (Prediction 4).

The ends-inward scanning model also predicts a flattening of the serial position function if the similarity of the targets and background is reduced, because then the hypothetical serial scanning process could presumably proceed more rapidly. However, the two models differ in their predictions regarding the distance effect. The scanning model assumes that the distance effect arises solely from the natural confounding of distance with serial position (i.e., pairs of widely separated items tend to contain items near at least one end of the array). Accordingly, the model predicts that the distance effect will be linked to the shape of the serial position function. In particular, if the scanning rate is greatly increased, so that the extra difficulty of central pairs is essentially eliminated, then the distance effect should be eliminated as well. In contrast, the positional discriminability model ascribes the distance effect to both steps in the comparison process (i.e., generating position codes and then comparing them). Under this view, even if item discrimination were made so easy that RT differences between central and end pairs were no longer detectable, a distance effect would still arise in Step b (because the greater expected difference between the position codes of widely separated items would produce a decision after relatively few iterations). In other words, the model predicts that greater ease of item discrimination will attenuate the distance effect (Prediction 5), but not eliminate it (Prediction 6). Experiment 2 was performed to test these alternative predictions.

Method

Subjects and procedure. Sixteen Stanford undergraduates served as paid subjects. Each subject went through the 120 test trials once. The stimulus arrays were the same size as those used in Experiment 1, but the four background lines were black. For half the subjects the target lines were blue and green; for the other half they were red and green. In all other respects the design and procedure were identical to those of Experiment 1.

Results and Discussion

The ANOVAs were performed on the RT data in the same manner as in Experiment

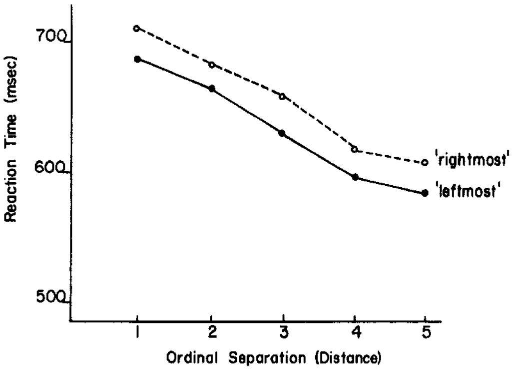

Figure 4. Reaction time as a function of the distance between the two target lines (Experiment 2).

1. The 103-msec distance effect depicted in Figure 4 was highly reliable, $t(56) = 7.93$, $p < .001$, $MS_e = 7{,}632$, by a linear trend test. Highly significant congruity effects were also obtained. Figure 5 presents the mean RTs for the five adjacent pairs as a function of the question, leftmost versus rightmost. The 178-msec congruity effect was highly significant, $t(56) = 7.16, p < .001$, $MS = 22{,}026$, by a bilinear trend test. Smaller but still significant congruity effects were also observed at distances of two and three steps. Unlike Experiment 1, there was no significant overall RT difference between the two forms of the question.

The distance and congruity effects obtained in Experiment 2 were quite similar to those observed in Experiment 1. However, subjects in Experiment 2, unlike those in the previous experiment, did not produce consistently longer latencies for adjacent pairs of central items than for pairs of end items. Figure 6, which presents mean RTs as a function of serial position for pairs with one to three steps of ordinal separation, can be compared with the corresponding Figure 3 for the first experiment. Whereas in the earlier experiment the curves for the adjacent pairs were bowed upwards from the end pairs to the central one, the curves in Figure 6 are statistically flat at all distances, $F(4, 56) = 1.89, p > .05$, $MS_e = 13{,}716$, for the adjacent pairs. In particular, the quadratic trend was not significant for the adjacent pairs, $t(56) = .83$. The only apparent trend, which was not statistically reliable, was a dip in RT for the rightmost adjacent pair.

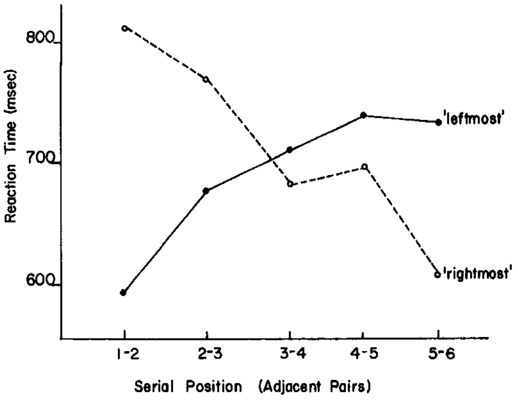

Figure 5. Reaction time as a function of the instructions and serial position of the target lines in adjacent pairs (Experiment 2).

As we pointed out earlier, both ends-inward scanning and positional discriminability models predicted that the serial position function would flatten when item discrimination was made easier. The use of homogeneous black background lines in Experiment 2 in fact eliminated the extra difficulty of comparing central pairs. However, the scanning model predicts that if bowed serial position curves are eliminated, the distance effect will necessarily be eliminated as well. The results of Experiment 2 contradict this prediction, because a robust distance effect was obtained in the absence of any bowed serial position functions. In contrast, the positional discriminability model predicted that

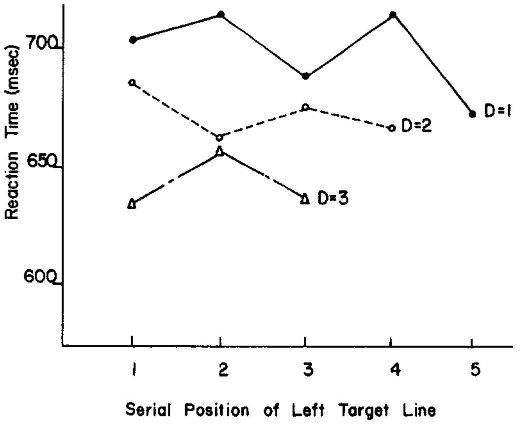

Figure 6. Reaction time as a function of serial position for pairs at different distances, collapsing over the two forms of the instructions (Experiment 2). (D = distance.)

an attenuated distance effect would be obtained even when item discrimination was made easy. Although comparisons across experiments must be interpreted cautiously, the 103-msec distance effects obtained in Experiment 2 is slightly smaller than the comparable 125-msec effect observed in Experiment 1. The results of Experiment 2 thus favor the positional discriminability model over the ends-inward scanning model, providing support for Predictions 4–6 derived from the former.[3]

The particular colors used as targets (blue and green vs. red and green) did not significantly affect overall decision time, nor did they alter the basic RT pattern described above. As in the previous experiments, overall RT did not differ for the two visual fields. However, collapsing across all other factors, RT tended to increase with distance from the fixation point in a fashion similar to that observed in Experiment 1. Mean RTs for the adjacent pairs, in increasing order of distance from the fixation point, were 668, 692, 693, 737, and 703 msec. This increase, which reflects the gradient of retinal acuity, was significant by a linear trend test, $t(56) = 2.43$, $p < .02$, $MS_e = 12063$. The overall error rate in Experiment 2 was 2.4%.

Experiment 3

Experiment 3 was disigned to provide additional evidence that might discriminate between ends-inward scanning and positional discriminability models. The basic idea was to modify the order-judgment task so that the need for an extended scanning process would be eliminated. To accomplish this, an array of six colored lines was presented underneath a black reference bar. The subjects' task was to choose which of two target lines was directly below the reference bar. Subjects could therefore perform this task simply by attending to the black bar and identifying the color of the line located directly beneath it. Because the bar was a distinctive visual cue that afforded direct acess to the position of the correct target, it seems extremely implausible to suppose that subjects would nonetheless scan the array from its ends inward. Numerous studies have shown that similar bar markers can influence stimulus processing even in the absence of eye movements (Eriksen & Colegate, 1971; Eriksen & Hoffman, 1973), and the scanning interpretation has been that the cue directs the order of search (Hoffman, 1975). In fact, there is evidence that subjects cannot avoid shifting attention to a peripheral cue, even if it is uninformative (Jonides, in press). In the present task, the location of the bar relative to the target lines actually determines the correct response, making it essential for subjects to attend to it. Accordingly, the scanning model should predict that both serial position and distance effects will be eliminated when a reference bar is introduced.

The predictions of the positional discriminability model are dramatically different. Because the model assumes that item locations are characterized by a gradient of uncertainty, an iterative comparison process should still be required to select the target beneath a reference bar. A task analysis suggests that each cycle of the comparison process will require three steps: (a) generating position codes for the bar and target, (b) estimating the distances from each target to the bar, and (c) comparing the two resulting distances. Note that Step b distinguishes the bar task from the order-judgment task used in the previous experiments. However, the basic judgment process is assumed to be similar. In particular, the greater overlap of location distributions should make Step a relatively difficult for central items, producing bow-shaped serial position functions in the bar task. In addition, distance effects should arise in the subsequent comparison process. In short, the discriminability model predicts that the RT pattern observed in the bar task will be similar to that previously obtained with leftmost and rightmost judgments (except that no congruity effect can arise in the bar task, because only one question is used:

---

[3] A further experiment carried the manipulation of ease of item discrimination to its logical extreme—the background lines were simply omitted, and subjects judged the relative order of pairs of isolated target lines. Both serial position and congruity effects were entirely eliminated, and the distance effect was very small and nonmonotonic. These results raise the possibility that subjects use qualitatively different strategies to process isolated lines versus linear arrays.

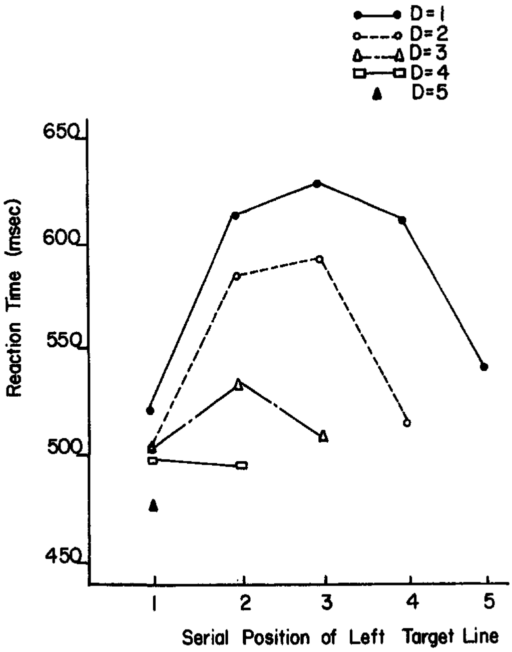

Figure 7. Reaction time as a function of serial position for pairs at difference distances (Experiment 3). (D = distance).

"Which line is beneath the bar?"). Experiment 3 was performed to test these competing predictions of the scanning and discriminability models.

Method

Subjects and procedure. Four Stanford undergraduates served as paid subjects. Each subject participated in two sessions on consecutive days, and on each session completed four blocks of the 60 test trials. Thirty practice trials were administered at the beginning of each session.

The arrays of colored lines were identical to those used in Experiment 1. The subject initiated each trial by pressing a button while viewing a fixation dot. After a 500-msec delay two sets of black bars were presented, which consisted of two arrays of six black bars presented to the left and the right of the fixation dot. Each array included one large cue bar, 2 mm thick and 12.5 mm high, and five smaller bars, .5 mm thick and 6 mm high. The bases of all the black bars were aligned immediately above the locations in which the colored lines might later appear. The bars were presented in both visual fields so that subjects would not be motivated to move their eyes toward one or the other visual field, since the bar locations did not reveal the visual field in which the array of colored lines was to be presented. Pilot work indicated that the smaller bars helped subjects to identify the serial position cued by the critical large bar, while the size disparity made it easy for them to discriminate the critical cue bar from its smaller neighbors.

After the cue bars had been exposed for 250 msec, the fixation dot was removed, and the array of colored lines appeared randomly in either the left or right visual field, as in previous experiments. The black bars remained in view, and one of the two target lines was always located directly below the critical large bar in the relevant visual field. The line array and cue bars remained in view for another 200 msec, after which the display was replaced by an empty "stare" field. Subjects were asked to decide which of the two targets was located beneath the reference bar and to press one of two decision keys as quickly as possible. As in the previous experiments, assignment of target colors to response keys was counterbalanced across subjects.

Results and Discussion

As in the previous experiments, the overall RT pattern did not vary in any important ways with practice or presentation field. Accordingly, the reported analyses collapse across these variables, as well as left/right order of the two target lines. Figure 7 presents the mean RTs for all pairs at each of the five levels of ordinal separation between the correct and incorrect targets as a function of the serial position of the left target. The ends-inward scanning model predicted that providing a bar as a visual cue to the location of the correct (i.e., closer) target would eliminate distance and serial position effects, because neither the position of the correct target nor its relative distance from the incorrect target should influence RT if the need for a serial search is eliminated.

However, the RT pattern displayed in Figure 7 clearly disconfirms these predictions. In fact, robust distance and serial position effects were observed in Experiment 3, much like the comparable effects obtained with leftmost and rightmost judgments in Experiment 1. RT declined monotonically by a total of 109 msec with increasing separation between the critical lines, $t(12) = 12.5, p < .001, MS_e = 370$, by a linear trend test. For pairs of adjacent items (the top line in Figure 7), RT increased substantially from the end pairs to the middle pair, $t(12) = 7.24$, $p < .001$, $MS_e = 1243$, by a quadratic trend test. The bowing of the serial position functions was actually more pronounced in Experiment 3 than in Experiment 1, extending to more widely separated pairs. The quadratic trend was also significant for pairs with an ordinal separation of two steps, $t(9) = 5.86$, $p < .001$, $MS_e =$

1565, and three steps, $t(6) = 2.48$, $p < .05$, $MS_e = 680$.

The above results are consistent with the predictions of the positional discriminability model. This model assumes that the present task is not as simple as "reading off" the line located beneath the reference bar because the perceived locations of all lines correspond to distributions. As a result, judging which target is beneath the bar will require essentially the same basic comparison process as does judging which target is leftmost or rightmost. The obtained distance and serial position effects are entirely in accord with the predictions of the discriminability model. The greater bowing of the serial position functions in the bar task is attributable to an extra advantage that pairs containing an end item would have, due to differential positional uncertainty. When the cue was centrally located, the targets might momentarily appear to straddle it. But when the cue and the correct target were at the same end of their respective arrays, such a misperception would be effectively blocked, since subjects knew that the cue and target arrays were vertically aligned.

The presence of a clear distance effect is sufficient to demonstrate that the decision process was influenced by the location of the *incorrect* target, as well as by the location of the correct target. A closer examination of the RT pattern supports the same conclusion. For any fixed serial position of the correct target, it is possible to compare RTs for pairs in which the incorrect target is on the exterior versus interior side of the correct target (e.g., Pairs 1-2 versus 2-3, where in each case the correct target is at Position 2 of the array). If the decision process requires localization of *both* target lines, RT should be faster in such cases when the incorrect target is nearer an end rather than the center of the array. There are six sets of matched pairs for which the above comparison can be made (four at ordinal distance one and two at distance two). These sets produced a 40-msec trend for RT to be faster when the incorrect target was on the exterior side. This predicted trend was obtained for five of the six comparisons and for all four of our subjects, $F(1, 3) = 6.52$, $p < .10$, $MS_e = 2{,}946$. In general, then, decision time was influenced both by the distance from the correct to the incorrect target and by the serial position of each of the two targets. These results clearly support the use of a comparison process of the sort postulated by the positional discriminability model.

A small trend toward a retinal acuity gradient was observed, as overall RT was 35 msec faster for the adjacent pair closest to the fixation point than for the pair furthest away, $t(12) = 2.06$, $p < .10$, $MS_e = 1{,}427$. The overall error rate in Experiment 3 was 2.1%.

General Discussion

The present experiments provide evidence directly relevant to two issues. First, the results demonstrate that the major aspects of the RT pattern typically observed in studies of order judgments with memorized lists (distance effects, congruity effects, and bowed serial position functions) can also be obtained when subjects judge the order of items in a visual array. Furthermore, the above pattern was obtained in a paradigm that eliminated the influence of memory for the positions of target items (unlike the study of Trabasso et al., 1975). These results thus lend credence to the hypothesis that similar mental processes link order judgments based on memory and on perception. We examine the plausibility of this hypothesis in more detail below.

Second, within the domain of perceptual order judgments, the present study generated evidence that favors the positional discriminability model over an ends-inward scanning model. In particular, Experiment 2 produced a robust distance effect even when item discrimination was made relatively easy, so that any extra difficulty of central pairs was no longer detectable. In addition, the results of Experiment 3 indicated that a visual cue affording direct access to the position of the correct target does not eliminate either the distance effect or bowed serial position functions. These results, which were predicted by the positional discriminability model, are consistent with related evidence indicating that items in a multielement array are processed in a parallel or overlapping fashion, rather than sequentially (Eriksen & Schultz, 1979; Jonides, 1980). In contrast, our results are difficult to reconcile with an ends-inward scanning process. Of course, the fact that the present study argues against the scanning model in the domain of perceptual judgments does not directly affect the plausibility of an analogous model in the domain of memory judgments. However, our results suggest that the positional discriminability model is the more promising candidate for an integrative process model linking order judgments in the two domains.

As we noted in the introduction, the positional discriminability model must be augmented by some additional assumption in order to account for semantic congruity effects, such as those obtained in the present study. As described earlier, the model does not specify how the time to discriminate between two items positions could depend on the relationship between the question and the positions of the items in the array. There are two general approaches, both consistent with the basic discriminability model, that could be used to account for congruity effects. The first is to assume that the question actually influences the relative discriminability of item pairs (e.g., by increasing allocation of attention to the congruent end of the array), and hence influences the time to complete the two-step judgment process. The second is to assume that the question does not affect the basic decision process but affects a later response-execution stage. Because the present results do not discriminate between alternative potential sources of the congruity effect, we do not dwell upon the issue here. (For more detailed discussions of alternative accounts, see Patterson, 1979; Holyoak & Mah, in press).

Comparison With the Semantic Coding Model

One potential explanation of the congruity effect deserved further mention, however, since it emerges from a model that presents an alternative to the positional discriminability model as a general framework for the process of relative judgment. This is the "semantic coding model" proposed by Banks, Fujii, and Kayra-Stuart (1976). The model was introduced to account for magnitude comparisons (e.g., selecting the larger or smaller of two digits). It assumes that on each trial a magnitude criterion is set, and that any item less than that criterion will be coded *small* and any item greater than that criterion will be coded *large*. If codes for the two presented items mismatch, the correct item can be selected immediately. The probability of obtaining such an immediate mismatch will increase with the magnitude difference between the items, producing a distance effect. If the two codes initially match, a second stage is required in which one of the items is recoded. The extra time required for such recoding and conversion processes is assumed to be the source of the congruity effect. The semantic coding model thus postulates that the codes used in the comparison process are nominal, binary category labels, rather than analog values with interval-scale properties.

Banks (1977) has suggested that the semantic coding model can be extended to account for order judgments, so it is reasonable to assess the overall model in the light of the present results obtained with visual arrays, as well as previous findings obtained with memorized orderings. The basic problem for the model is that it requires additional assumptions to explain the relative difficulty of central pairs (i.e., bowed serial position functions). One possibility is to assume that central items are subjectively spaced closer together than end items. This assumption can be criticized as ad hoc; furthermore, the assumption of central compression fails to explain why the extra difficulty of central pairs depends on the ease of discriminating targets from background items (Experiment 2). In addition, the assumption is difficult to reconcile with the Woocher et al. (1978) finding that central pairs also produce relatively long RTs when the task is to decide whether or not two items are adjacent in a memorized ordering. In the context of the coding model, it would seem that if two items receive the same initial code, this should constitute evidence that they are in fact adjacent. But this reasoning leads to the prediction that subjects should be faster, rather than slower, in deciding that a "close" central pair is adjacent, as opposed to a more "widely-separated" end pair. In contrast, the positional discriminability model assumes that because the location distributions of more items will overlap at the center of an ordering, it will be relatively likely that an extraneous item will be momentarily perceived as lying between two items that are in fact adjacent. The result will be longer decision latencies for central pairs than for pairs near the ends of the ordering.

An alternative suggestion made by Banks (1977) is that end items are compared relatively quickly because subjects use special processing strategies for pairs with end terms. For example, subjects may learn that a certain item is "larger" than any other, and therefore respond immediately as soon as they identify the end term in a test pair (Potts, 1972). However, such an "end anchor" strategy is inapplicable in the present perceptual paradigm, because the assignment of targets to array positions varied from trial to trial (e.g., it was never the case that the green target was always the leftmost in the arrays). The end-anchor hypothesis also fails to explain the Woocher et al. (1978) results for adjacency judgments with a memorized ordering, because end items are obviously not adjacent to all other items. It appears, then, that the semantic coding model cannot adequately explain a variety of findings obtained in order-judgment tasks using both perceived and memorized orderings (also see Holyoak, 1978; Holyoak & Mah, in press).

Order Judgments Based on Perception and Memory

As we pointed out in the introduction, many theorists have suggested that memorized linear orderings are represented and processed in a manner similar to spatial arrays. The present results lend support to this possibility by demonstrating that perceptual order judgments produce RT patterns similar to those obtained in previous studies using memorized orderings. However, we have yet to scrutinize carefully the claim that a link exists between order judgments based on memory and on perception. To say simply that similar processes operate in memory and perception is to say little, without specifying what those processes are and how they are similar. One could certainly argue that the parallels we have noted between the perceptual and memorial order-judgment paradigms are fortuitous and superficial. After all, the memory task involves information retrieved from long-term memory, whereas the perceptual task involves information picked up from an external display or a quickly fading icon. The extra difficulty of central items in the visual task falls under the general rubric of "lateral interference" (Estes et al., 1976) and may be produced at a relatively peripheral level, whereas the comparable phenomenon obtained in memory studies must surely depend on more central cognitive processes. In what sense is it reasonable to suppose that a unitary model could link such diverse domains?

It seems to us that the positional discriminability model is a plausible candidate for such a unifying model, in the following sense. Order judgments based on memory and on perception may share a set of common (or more precisely, analogous) processes, as well as having additional processes unique to each domain. As an example of the latter, perceptual judgments are sensitive to the gradient of retinal acuity, which has no obvious parallel in the memory system; and, as is suggested below, memory judgments may involve additional strategies not available in the perceptual paradigm. However, the positional discriminability model may be taken as a kind of "core model" for those processes shared by the two domains. That is, a basic strategy for order judgments may be to perform an iterative comparison process, in which position codes are first generated for the target items and then compared. This core model implicitly defines two sets of theoretical elements, one for each domain, which can be brought into analogical correspondence (Gick & Holyoak, 1980). For example, *the mental representation of* a linear ordering must be analogous to the representation of a spatial array. This requirement need not imply that the memory representation for an ordering is a visual image in a "pictorial" sense; however, it implies that the memorized items are represented by location distributions along a continuum. Just as the items in a spatial array are processed at least partially in parallel, the items in a memorized ordering may be retrieved and examined partially in parallel. In each domain some mechanism must isolate the targets and assign them position codes; furthermore, this mechanism must be sensitive to lateral interference between items with overlapping location distributions. It also seems reasonable to suppose that in both domains a mechanism exists to shift attention to a particular portion of the ordering. Finally, the core model implies that in each domain the decision process integrates successive samples of information about relative order by means of a sequential sampling procedure. The positional discriminability model thus constitutes a general schema that highlights the analogical correspondences between process models of order judgments in the domains of perception and memory.

Additional Factors in the Memory Paradigm

How adequate is the above core model as an account of order judgments with memorized lists? The memory study most comparable to the present perceptual paradigm (Experiment 1) is that of Trabasso et al. (1975), particularly their "linguistic" condition with adult subjects (see their Table 4, p. 214). Indeed, their study essentially provides a "memory control" that can be compared with our Experiment 1. As we have already noted, the positional discriminability model is consistent with the general pattern of results obtained in that and similar studies (Potts, 1974). However, two possible discrepancies are worthy of scrutiny. First, the serial position functions obtained in memory studies are typically more bowed than those obtained here; furthermore, the central pairs are relatively difficult not only for adjacent items, as was found in the present study, but for more widely separated items as well. In addition, order asymmetries are sometimes found in memory studies. When subjects make true-false decisions about sentences, RT for pairs containing an end item (particularly a noncongruent end item) is faster when the end item appears in the left rather than the right position of the sentence (Potts, 1972, 1974; McKinley, 1975). (This sentence-verification paradigm has not been used with perceived orderings.) Such order effects are not obtained when subjects choose the greater or lesser item in a pair (Polich & Potts, 1977).

Several factors may account for these departures from the RT pattern observed in the present perceptual paradigm. Some of these factors suggest additional processing strategies unique to the memory domain; however, we argue that none of these can entirely supplant the processes specified by the positional discriminability model.

1. Perhaps the simplest explanation of the greater relative difficulty of central pairs in memory studies is that the location distributions of items in a memorized ordering typically have greater variances than do those of items in a visual array of the sort used in the present study. Increasing the extent to which location distributions overlap will have the greatest detrimental effect on central pairs, which include items flanked by the most neighbors. Increasing locational variance, or more generally, increasing the difficulty of discriminating targets from background items, will also make it more likely that central pairs will be detectably more difficult even for nonadjacent items. In terms of Equation 2, the function g_{mon} will decrease less steeply with distance. Conversely, if the variances of location distributions were sufficiently reduced that the distributions associated with adjacent items did not overlap, the model would predict that the resulting serial position functions should be flat.

2. As noted in the introduction, there is considerable evidence that subjects memorize linear orderings from the ends in (Trabasso et al., 1975). As a result, the locations of central items may be less well learned than the locations of end items at the time the choice RT task is performed. In the context of the positional discriminability model, poorer initial learning will be reflected in greater variance of location distributions. If these variances increased from the end to the central items, the result would be an accentuated bowing of serial position functions. However, Banks, White, and Mermelstein (1980) have shown that a new item added to either the end or the middle of a well-

practiced four-term ordering behaves almost immediately like the end or central term, respectively, of a well-practiced five-term ordering. Since such serial position effects can not be attributed to differential learning, it is clear that the bowed serial position functions obtained with memorized orderings are not entirely attributable to differential acquisition of item locations.

3. As mentioned in our previous discussion of the semantic coding model, subjects may adopt special end anchor strategies (Potts, 1972, 1974). These will naturally accentuate the advantage of end over central items, and may also produce the order asymmetries mentioned above (Potts, 1974). However, as noted previously, end anchor strategies cannot explain the Woocher et al. (1978) results for adjacency judgments. In addition, the bowing of serial position functions typically is not restricted solely to the two end terms; rather, it is more continuous. Thus, although end anchor strategies probably play a role in order judgments based on memory, they do not provide a satisfactory alternative to the positional discriminability model.

4. When all possible pairs formed from a linear ordering are tested, the relative frequencies of the two responses will vary systematically with item position. For example, in a five-term ordering (smallest to largest), the first item will be the smallest in all of the four possible pairs of which it is a member, the third item will be smallest in two and largest in two, and the fifth item will be largest in all four. In general, frequencies of the two possible responses will be relatively equal for central items; this increased uncertainty may produce slower decisions (Humphreys, 1975). Indeed, Patterson (Note 1) has shown that when only a subset of the possible pairs is tested, so that a consistent response is made to central items, RTs for central pairs are selectively facilitated. However, it is unlikely that differential response frequencies are the sole factor responsible for the serial position effects obtained with memorized orderings. The adjacency task of Woocher et al. (1978) again provides clear counterevidence. When all possible pairs are tested, the end items enter into only one adjacent pair, whereas all internal items enter into two. Nevertheless, adjacency judgments are made more quickly for end than for central pairs (see also Potts, 1977).

It seems, then, that the positional discriminability model affords a plausible core model for order judgments based on memory. This core model may be supplemented but not supplanted by additional memory-specific processing strategies. The positional discriminability model provides a relatively explicit statement of the relationship between order judgments based on memory and on perception; in addition, it generates predictions (e.g., regarding manipulations of item discriminability) that are yet to be tested in the memory domain.

Order and Magnitude Comparisons

So far we have restricted our discussion to tasks in which subjects judge the relative order of items embedded in a perceived or memorized linear array. In a closely related paradigm, subjects judge the relative magnitude of items that are *not* necessarily learned in the context of an ordered series. The stimulus magnitudes may be available to perception (e.g., line lengths) or only in memory (e.g., names of objects that vary in size). Distance and congruity effects have been obtained in tasks involving the comparison of either perceived or remembered stimuli (e.g., Audley & Wallis, 1964; Holyoak & Walker, 1976; Jamieson & Petrusic, 1975; Moyer, 1973; Moyer & Landauer, 1967; Welford, 1960). However, tasks that do not involve an explicit ordered series (which may be termed *magnitude comparisons*) typically do not yield the bowed serial position functions that characterize order comparisons of the sort we have so far been considering.

What is the theoretical relationship between order and magnitude comparisons? The ends-inward scanning model cannot be extended to account for magnitude comparisons, because it is implausible to suppose that concepts in memory are stored in multiple linear arrays corresponding to all dimensions of continuous variation (e.g., size, weight, speed, etc.). In contrast, the positional discriminability model may clarify the relationship between the mental processes involved in these two types of relative judgments and explain the absence of bowed serial positions functions in magnitude comparisons. We assume that comparisons based on magnitudes, like those based on order, involve an iterative two-step procedure of generating analog values for each item and assessing their difference. That is, item magnitudes may be represented by distributions of values along various continuous dimensions (e.g., size, ferocity, and intelligence). These distributions will be processed in a manner analogous to the location distributions associated with items in a linear ordering.

The essential difference between the two paradigms is simply that in the case of order comparisons, presentation of a test pair will necessarily trigger processing of the entire array (or at least of those portions of it surrounding the target items); whereas in the case of magnitude comparisons, presentation of the test pair will in general trigger processing of those two items alone. For example, people typically learn the approximate size of object concepts individually, rather than as an explicit ordering. As a result, if a person is asked to decide whether a goat is larger than a cat, the probe is unlikely to bring to mind an entire array of objects ordered in size. Rather, the person will simply sample and compare the size values associated in memory with the two target concepts. This process will be unaffected by the density of concepts with similar size values (wolves, rabbits, etc.), because these values will generally not be activated by presentation of the pair. Accordingly, people will have no particular difficulty in assessing the size values of average-sized objects, as opposed to those with relatively extreme size values.

In contrast, items learned in the context of a linear ordering will serve as recall cues for all or part of the ordering. The ease with which the location of an item along the continuum can be determined will therefore depend on the ease with which it can be discriminated from its neighbors. The natural result will be the bowed serial position functions characteristic of order comparisons. According to this view, magnitude comparisons are much like order judgments for which the difficulty of discriminating the targets from background items has been made maximally easy by simply eliminating processing of any background items. In terms of Equation 2, the values of C_T will not vary systematically with the magnitudes of the targets.

It is likely that additional processing strategies play a role in magnitude comparisons (Holyoak, Dumais, & Moyer, 1979; Kosslyn, Murphy, Bemesderfer, & Feinstein, 1977; Pliske & Smith, 1979), as they do in order comparisons. Nevertheless, the kind of analog comparison process embodied in the positional discriminability model may provide a core model for judgments of order and magnitude in the domains of both perception and memory. Whether this tentative integration will prove successful remains to be seen.

Reference Note

1. Patterson, K. K. *Analysis of comparative judgment processes in semantic and episodic memory.* Unpublished manuscript, Stanford University, 1978.

References

Audley, R. J., & Wallis, C. P. Response instructions and the speed of relative judgments. I. Some experiments on brightness discrimination. *British Journal of Psychology*, 1964, *55*, 59-73.

Banks, W. P. Encoding and processing of symbolic information in comparative judgments. In G. H. Bower (Ed.), *The Psychology of learning and motivation* (Vol. 11). New York: Academic Press, 1977.

Banks, W. P., Fujii, M., & Kayra-Stuart, F. Semantic congruity effects in comparative judgments of magnitudes of digits. *Journal of Experimental Psychology: Human Perception and Performance*, 1976, *2*, 435-447.

Banks, W. P., White, H., & Mermelstein, R. Position effects in comparative judgments of serial order: List structure vs. differential strength. *Memory & Cognition*, 1980, *8*, 623-630.

Bower, G. H. Adaptation-level coding of stimuli and serial position effects. In M. H. Appley (Ed.), *Adaptation-level theory.* New York: Academic Press, 1971.

Buckley, P. B., & Gillman, C. B. Comparisons of digits and dot patterns. *Journal of Experimental Psychology*, 1974, *103*, 1131-1136.

Colegate, R. L., Hoffman, J. E., & Eriksen, C. W. Selective encoding from multi-element displays. *Perception & Psychophysics*, 1973, *14*, 217-224.

Crowder, R. G. *Principles of learning and memory.* Hillsdale, N.J.: Erlbaum, 1976.

DeSoto, C. B., London, M., & Handel, S. Social reasoning and spatial paralogic. *Journal of Personality and Social Psychology*, 1965, *2*, 513-521.

Eriksen, C. W., & Colegate, R. L. Selective attention and serial processing in briefly presented visual displays. *Perception & Psychophysics*, 1971, *10*, 321-326.

Eriksen, C. W., & Hoffman, J. E. The extent of processing of noise elements during selective encoding from visual displays. *Perception & Psychophysics*, 1973, *14*, 155-160.

Eriksen, C. W., & Schultz, D. W. Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics*, 1979, *25*, 249-263.

Estes, W. K. Redundancy of noise elements and signals in visual detection of letters. *Perception & Psychophysics*, 1974, *16*, 53-60.

Estes, W. K. Memory, perception, and decision in letter identification. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola Symposium*. Hillsdale, N.J.: Erlbaum, 1975.

Estes, W. K., Allmeyer, D. J., & Reder, S. M. Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics*, 1976, *19*, 1-15.

Feigenbaum, E. A., & Simon, H. A. A theory of the serial position effect. *British Journal of Psychology*, 1962, *53*, 307-320.

Gick, M. L., & Holyoak, K. J. Analogical problem solving. *Cognitive Psychology*, 1980, *12*, 306-355.

Griggs, R. A., & Shea, S. L. Integrating verbal quantitative information in linear orderings. *Memory & Cognition*, 1977, *5*, 287-291.

Harcum, E. R. Parallel functions of serial learning and tachistoscopic pattern recognition. *Psychological Review*, 1967, *74*, 51-62.

Hoffman, J. E. Hierarchical stages in the processing of visual information. *Perception & Psychophysics*, 1975, *18*, 348-354.

Holyoak, K. J. Comparative judgments with numerical reference points. *Cognitive Psychology*, 1978, *10*, 203-243.

Holyoak, K. J., Dumais, S. T., & Moyer, R. S. Semantic association effects in a mental comparison task. *Memory & Cognition*, 1979, *7*, 303-313.

Holyoak, K. J., & Mah, W. A. Cognitive reference points in judgments of symbolic magnitude. *Cognitive Psychology*, in press.

Holyoak, K. J., & Walker, J. H. Subjective magnitude information in semantic orderings. *Journal of Verbal Learning and Verbal Behavior* 1976, *15*, 287-299.

Humphreys, M. S. The derivation of endpoint and distance effects in linear orderings from frequency information. *Journal of Verbal Learning and Verbal Behavior*, 1975, *14*, 496-505.

Huttenlocher, J. Constructing spatial images: A strategy in reasoning. *Psychological Review*, 1968, *75*, 550-560.

Jamieson, D. G., & Petrusic, W. M. Relational judgments with remembered stimuli. *Perception & Psychophysics*, 1975, *18*, 373-378.

Jonides, J. Toward a model of the mind's eye's movement. *Canadian Journal of Psychology*, 1980, *34*, 103-112.

Jonides, J. Voluntary versus automatic control over the mind's eye's movements. In A. Baddeley & J. Long (Eds.), *Attention and Performance* (Vol. 9). New York: Academic Press, in press.

Just, M. A., & Carpenter, P. A. The semantics of locative information in pictures and mental images. *British Journal of Psychology*, 1975, *66*, 427-441.

Kosslyn, S. M., Murphy, G. L., Bemesderfer, M. E., & Feinstein, K. J. Category and continuum in mental comparisons. *Journal of Experimental Psychology: General*, 1977, *106*, 341-375.

Link, S. W. The relative judgment theory of choice reaction time. *Journal of Mathematical Psychology*, 1975, *12*, 114-135.

McIntyre, C., Fox, R., & Neale, J. Effects of noise similarity and redundancy on the information processed from brief stimulus displays. *Perception & Psychophysics*, 1970, *7*, 328-332.

McKinley, J. E. *Utilizing comparative information from memory: The symbolic distance effect.* Unpublished master's thesis, University of Massachusetts, 1975.

Merikle, P. M., & Coltheart, M. Selective forward masking. *Canadian Journal of Psychology*, 1972, *26*, 296-303.

Moyer, R. S. Comparing objects in memory: Evidence suggesting an internal psychophysics. *Perception & Psychophysics*, 1973, *13*, 180-184.

Moyer, R. S., & Landauer, T. K. Time required for judgments of numerical inequality. *Nature*, 1967, *215*, 1519-1520.

Murdock, B. B., Jr. The distinctiveness of stimuli. *Psychological Review*, 1960, *67*, 16-31.

Patterson, K. K. Mental processes in magnitude comparisons (Doctoral dissertation, Stanford University, 1979). *Dissertation Abstracts International*, 1979, *40*, 957B. (University Microfilms No. 79-17,270).

Pliske, R. M., & Smith, K. H. Semantic categorization in a linear order problem. *Memory & Cognition*, 1979, *7*, 297-302.

Polich, J. M., & Potts, G. R. Retrieval strategies for linearly ordered information. *Journal of Experimental Psychology: Human Learning and Memory*, 1977, *3*, 10-17.

Potts, G. R. Information processing strategies used in the encoding of linear orderings. *Journal of Verbal Learning and Verbal Behavior*, 1972, *11*, 727-740.

Potts, G. R. Storing and retrieving information about ordered relationships. *Journal of Experimental Psychology*, 1974, *103*, 431-439.

Potts, G. R. Frequency information and distance effects: A reply to Humphreys. *Journal of Verbal Learning and Verbal Behavior*, 1977, *16*, 479-487.

Ratcliff, R. A theory of memory retrieval. *Psychological Review*, 1978, *85*, 59-108.

Shepard, R. N. Stimulus and response generalization: Deduction of the generalization gradient from a trace model. *Psychological Review*, 1958, *65*, 242-256.

Shepard, R. N., & Podgorny, P. Cognitive processes that resemble perceptual processes. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (Vol. 5). Hillsdale, N.J.: Erlbaum, 1978.

Townsend, J. T., Taylor, S. G., & Brown, D. R. Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics*, 1971, *10*, 375-378.

Trabasso, T., & Riley, C. A. On the construction and use of representations involving linear order. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola Symposium*. Hillsdale, N.J.: Erlbaum, 1975.

Trabasso, T., Riley, C. A., & Wilson, E. G. The representation of linear order and spatial strategies in reasoning: A developmental study. In R. Falmagne (Ed.), *Psychological studies of logic and development*. Hillsdale, N.J.: Erlbaum, 1975.

Wagner, J. Experimentelle Beitrage zur Psychologie des Lesens. *Zeitschrift fur Psychologie*, 1918, *80*, 1-75.

Watkins, M. J., Watkins, O. C., & Crowder, R. G. The modality effect in free and serial recall as a function of phonological similarity. *Journal of Verbal Learning and Verbal Behavior*, 1974, *13*, 430-447.

Welford, A. T. The measurement of sensory-motor performance: Survey and reappraisal of twelve years progress. *Ergonomics*, 1960, *3*, 189-203.

Winnick, W. A., & Bruder, G. E. Signal detection approach to the study of retinal locus in tachistoscopic recognition. *Journal of Experimental Psychology*, 1968, *78*, 528-531.

Wolford, G. Perturbation model for letter identification. *Psychological Review*, 1975, *82*, 184-199.

Woocher, F. D. Storage and retrieval of information from artificial linear orderings (Doctoral dissertation, Stanford University, 1977). *Dissertation Abstracts International*, 1977, *38*, 2918B. (University Microfilms No. 77-25,747).

Woocher, F. D., Glass, A. L., & Holyoak, K. J. Positional discriminability in linear orderings. *Memory & Cognition*, 1978, *6*, 165-173.

Received July 25, 1980 ■

Instructions to Authors

For further information on content, authors should refer to the editorial in the August 1978 issue of the Journal (Vol. 5, No. 3, pp. 355-356). Authors should prepare manuscripts according to the *Publication Manual of the American Psychological Association* (2nd ed.). Instructions on tables, figures, references, metrics, and typing (all copy must be double-spaced) appear in the Manual. Manuscripts should include an abstract of 100-175 words. Authors are requested to refer to the "Guidelines for Nonsexist Language in APA Journals" (Publication Manual Change Sheet 2, *American Psychologist*, June 1977, pp. 487-494) before submitting manuscripts to this journal.

Authors should submit manuscripts in quadruplicate, and all copies should be clear, readable, and on paper of good quality. Authors should keep a copy of their manuscript to guard against loss. Mail manuscripts to Editor-elect William Epstein, Department of Psychology, University of Wisconsin, W. J. Brogden Psychology Building, 1202 West Johnson Street, Madison, Wisconsin 53706.

Addresses for the editors of the other JEP journals are as follows: *Journal of Experimental Psychology: General*, Gregory A. Kimble, Department of Psychology, Duke University, Durham, North Carolina 27706 (submit 4 copies of the manuscript); *Journal of Experimental Psychology: Learning, Memory, and Cognition*, Richard M. Shiffrin, Department of Psychology, Indiana University, Bloomington, Indiana 47405 (submit 4 copies of the manuscript); and *Journal of Experimental Psychology: Animal Behavior Processes*, Donald S. Blough, Department of Psychology, Brown University, Providence, Rhode Island 02912 (submit 3 copies of the manuscript).

The editors have agreed to use blind review when it is requested by the author. Authors requesting blind review should prepare manuscripts to conceal their identity.