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Visual Gap and Offset Discrimination and Its Relation to Categorical Identification in Brief Line-Element Displays

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Visual processing was investigated in judgments of relative line position. Stimulus continua were generated by bisecting a straight line and displacing the segments. Experiment 1 measured discrimination of pairs of longitudinally displaced segments at equal steps along the continuum. At long (2 s) durations discrimination fell smoothly, but at short (100 ms) durations it was sharp-peaked. In Experiment 2 the short-duration stimuli were labeled with subsets of the labels *no gap, just a gap*, and *more than just a gap*. Theoretical discrimination performances were computed and the one based on *no gap* and *just a gap* closely fitted observed performance. Experiments 3 and 4 were similar to 1 and 2, with lateral replacing longitudinal displacement. Similar "categorical" performance was obtained. It was concluded that there are discrete mechanisms for early detection of relative line position and that 2 labels can be used to characterize performance in each direction.

Judgments about the relative positions of objects and parts of objects play a fundamental role in the analysis of visual scenes and the generation of responses to those scenes. Decisions about the relative positions of edges and lines are particularly important, both in the early stages of visual processing, when they may help to define the boundaries of objects and how they should be separated from each other and their backgrounds, and in the later stages, when they may form the basis of more complex object descriptions.

How well can judgments about relative position be made? The investigation of the limits on this kind of visual sensitivity has a long history (Andrews, Butcher, & Buckley, 1973; Baker & Bryan, 1912; Berry, 1948; Fechner, 1860; Volkmann, 1863; Westheimer & McKee, 1977; Wülfing, 1892). Traditional measurements of performance have been of the vernier-acuity type: A straight line is bisected and the task is to detect the lateral displacement of one of the segments relative to the other (e.g., Baker & Bryan, 1912; Berry, 1948; Sullivan, Oatley, & Sutherland, 1972). Under suitable conditions, displacement thresholds of a few seconds of arc visual angle are usually achieved, an order of magnitude finer than the angular separation of adjacent foveal cones. Performance of this order is not, however, peculiar to judgments of lateral offset, and similarly fine hyperacuity performance (Westheimer, 1975) has been obtained in a variety of judgments of relative position, including, for example, the alignment of three points (Ludvigh, 1953), the separation of two parallel lines (Westheimer & McKee, 1977), and the spacing of three parallel lines (Baker & Bryan, 1912; Klein & Levi, 1985).

Hyperacuity levels of performance are usually achieved with displays of long duration and focused attention. In natural viewing, these conditions may not be obtained: Scenes may be fixated only briefly as the eye pauses between one saccade and the next, and there may be a large number of objects in the scene competing for attention during a fixation. Although there are few data currently available on the effects of reduced exposure duration on judgments of relative position (e.g., Burbeck, 1986), results from experiments on target detection in brief multielement displays suggest that there may be profound changes in the organization of spatial sensitivity during what has been referred to as preattentive vision. Beck and Ambler (1972) measured the discriminability of abutting line segments forming *L* and *T* figures in peripherally presented arrays and showed that when displays were brief, and followed by a poststimulus mask (which controlled the time available to attend selectively to individual figures), subjects became less sensitive to relative line position (i.e., whether a figure was *L* or *T*) than to line orientation (vertical, horizontal, or oblique). A similar result was obtained when subjects had to discriminate texture displays made up of these elements (Beck, 1966, 1982). This result was also obtained in measurements of pattern-specific adaptation effects with similar kinds of displays (Foster & Mason, 1980).

An exception to the finding of reduced sensitivity to line arrangements in preattentive vision was reported by Bergen and Julesz (1983), who demonstrated that although *L* and *T* figures were indeed poorly segregated in texture displays, *L* and intersecting line segments forming plus sign (+) figures were well segregated. Yet carefully controlled search-time measurements by Treisman and Gormican (1988) failed to obtain evidence that the intersection property (and the properties of juncture and convergence or parallelism) was preattentively coded. They suggested (Tresiman & Gormican, 1988) that "no functional feature detectors exist that respond uniquely to properties of line arrangements, at least at the parallel preattentive levels of early vision" (p. 34).

Studies on such early visual processing have traditionally used stimuli drawn from small classes, often comprising just

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two or three members (e.g., the letters *L* and *T*; the letters *O* and *X*; collinear and noncollinear line segments; intersecting and nonintersecting line segments; vertical, horizontal, and 45°-oblique line segments). To reveal some detection mechanisms, however, it may be necessary to sample a stimulus range in more detail (Foster, 1980). Thus, although it would appear from the studies mentioned earlier that relative position receives little or no weight in preattentive vision, it is not clear what kind of spatial information is actually lost, that is, whether it is uniform over various stimulus configurations, reflecting a uniform loss in spatial precision, or nonuniform and representative of an altered allocation of spatial processing resources.

Categorical Effects

This second kind of possible loss has been considered in a different context, in which measurements were made of the discrimination of curved-line stimuli in displays of varying duration (Ferraro & Foster, 1986; Foster, 1983). A continuum of curved lines was generated and parameterized by the amount of "sag" (deviation from linearity). Subjects' capacity to discriminate curved lines differing by a constant amount of sag was determined at successive reference points along the continuum. In displays of 2-s duration, without a poststimulus mask, discrimination performance declined smoothly and monotonically with increasing reference sag value. This performance is similar to that in many hyperacuity tasks in which the measure of interest varied smoothly and continuously with the corresponding spatial parameter (e.g., Andrews et al., 1973; Ludvigh, 1953; Watt, 1984a; Westheimer, 1979, 1981; Westheimer & McKee, 1977), although some exceptions have been reported (e.g., Hirsch & Hylton, 1982, 1985; Klein & Levi, 1985; Watt, 1984b; but see Hirsch, 1985, and Westheimer, 1984, 1985). A different type of performance was obtained when the duration of the display was reduced to 100 ms and a poststimulus mask was introduced: A pronounced peak in curved-line discrimination performance was obtained about halfway along the stimulus range (and a second peak revealed in more fine-grained measurements at smaller curvatures) (Ferraro & Foster, 1986; Foster, 1983). To attempt to relate this "discrete" mode of performance (Ferraro & Foster, 1984) to the characteristics of possible internal descriptors for curvature, independent labeling experiments were also performed with a categorical-identification scale and three uniform categorical-rating scales. From these labeling data, predicted discrimination performances were computed. A categorical-identification scale that used the labels *straight, just curved*, and *more than just curved* was found to fit closely the observed discrimination data (Foster, 1983). One conclusion from these experiments was that early visual processing of curved lines was determined by three curvature-sensitive mechanisms whose spatial characteristics could be identified, in terms of perceptual labels, with these threshold-based descriptors.

There is a useful analogy, albeit perhaps only formal, between such discrete visual performance and the *phoneme-boundary effect* in auditory perception (Liberman, Harris, Hoffman, & Griffith, 1957; Liberman, Harris, Kinney, & Lane, 1961; Wood, 1976). In those studies, as certain speech-like sounds varied along an acoustic continuum, adjacent pairs of stimuli were discriminated better when they fell on different sides of a phoneme boundary than when they fell within the same phoneme category. In the discrimination of curved lines, a possible interpretation of the peaks and troughs in performance with short-duration displays is that they result from a *categorical processing* of the stimuli; that is, in a strict sense, discrimination of the curved lines is achieved only in so far as they can be identified as belonging to separate categories (Studdert-Kennedy, Liberman, Harris, & Cooper, 1970; Watson & Robson, 1981; see General Discussion section).

Categorical processing in vision is not unique to curved-line discrimination. Categorical effects have been demonstrated or suggested in a variety of visual tasks and performance measures, including spatial-frequency and line-separation discrimination (Hirsch, 1985; Hirsch & Hylton, 1982, 1985; Westheimer, 1984, 1985), spatial- and temporal-frequency discrimination (Watson & Robson, 1981), wavelength discrimination (Mullen, in press; Uchikawa & Boynton, 1987), color variation in apparent motion (Kolers & von Grunau, 1975), discrimination of closed curved figures (Cermak, 1977; Shepard & Cermak, 1973), and learning geometric shapes (Rosch, 1973).

Aims of the Investigation

Notwithstanding the findings summarized earlier concerning the role of relative-position information in early vision showed that by suitably sampling a stimulus continuum it is possible to reveal evidence of mechanisms in early vision highly responsive to line arrangement. The present experiments made this assumption prima facie and set out to answer the two basic questions: (a) What is the general form taken by the representation in early vision of relative-position information in determining discrimination performance—discrete or continuous? and (b) If it is effectively discrete, is there a categorical identification scale from which labeling performance can predict discrimination performance and therefore characterize the internal descriptions of relative position?

Experiments were based on two sets of stimuli drawn from orthogonal continua: A straight line was bisected, and the segments were moved progressively away from each other, either (a) longitudinally, so that the stimuli had increasing size of gap, or (b) laterally, so that the stimuli had increasing size of offset. In Experiment 1, the discriminability of adjacent pairs of stimuli was measured along each of these two displacement continua, for short-duration displays and, as a control, for long-duration displays. To attempt to identify possible internal characterizations of the briefly presented pairs of line segments, we also performed experiments in which the stimuli were labeled according to three categorical-identification scales. A general algorithm was used to compute theoretical discrimination performances from each of these sets of labeling data. The congruence of theoretical and observed performances was then used to determine which of the labeling scales was most appropriate. For longitudinally displaced line segments and for laterally displaced line segments, a small set of simple perceptual descriptors was found that corresponded well to the discrimination performances obtained with short-duration displays. This result was consistent with the hypothesis that some information about relative line position is extracted early in vision and is given a discrete representation quite distinct from that used when scrutiny is possible.

Experiment 1: Discrimination of Longitudinally Displaced Line Segments

The discriminability of nonoverlapping, collinear pairs of line segments with different-sized gaps was measured at steps along a continuum of such pairs, a sample of which is shown in the inset of Figure 1. The size of the gap was specified by the parameter s in min arc visual angle. The overall extent of each pair of line segments was fixed at 0.41°. Arrays of three such pairs of line segments with gaps, the lines having common orientation, were presented as illustrated in Figure 1. In each display, two of the pairs of line segments were identical, each with gap $s - ds$ or $s + ds$, and one pair was "odd," with gap $s + ds$ or $s - ds$, respectively. The interval $2ds$, the *discrimination step*, was fixed and independent of s, the *reference value*. The task of the subject was to locate the odd pair of line segments, the position varying pseudorandomly from trial to trial. On the basis of pilot experiments and previous data (Ferraro & Foster, 1986; Foster, 1983), the two durations of the stimulus display were fixed at 100 ms and 2 s. A poststimulus mask to interrupt inspection of the fading visual image of a short-duration display was not necessary (subject MF performed similarly when a 100-ms delayed mask was introduced).

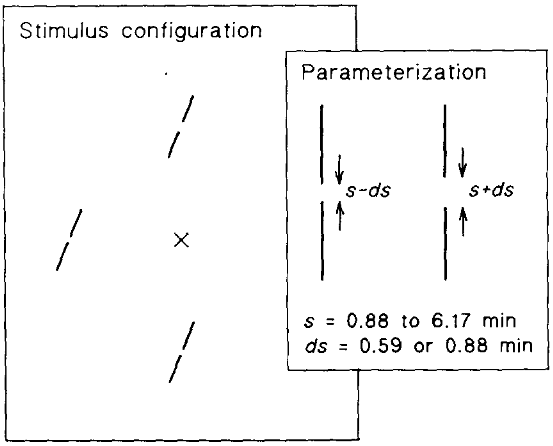

Figure 1. Example of stimulus display (and stimulus parameterization) used in Experiment 1. (The main figure is to scale, except that the line segments are shown 100% larger. The "odd" line-segment pair had gap size $s + ds = 4.41$ min arc, and the two identical line-segment pairs had gap size $s - ds = 2.66$ min arc.)

Method

Subjects. Two subjects with experience of psychophysical procedures participated in the experiment. One subject, SS, an unpaid volunteer, was female and 21 years old; the other subject, MF (coauthor), was male and 36 years old. Each had normal visual acuity (Snellen acuity at least 6/4). SS was unaware of the purpose of the experiment.

Stimuli and apparatus. The continuum of pairs of line segments with gaps was produced by fixing the two terminal members of the range and generating intermediate members by varying the gap size linearly (a trivial case of the general action of a one-parameter group of transformations; Farrell & Shepard, 1981; Foster, 1980, 1983). The overall extent of each pair of line segments was fixed at 25 min arc (0.41°) to eliminate the potentially confounding effects of size cues. The widths of the line segments were approximately 1.0 min arc. The three pairs of line segments in each display were presented at three of the four positions defining the vertices of an imaginary diamond of side 2.0° (as illustrated in Figure 1, in which the line-segment pairs are shown 100% larger than their true scale). (The minimum separation of the pairs was therefore several times their individual extents; see Westheimer & Hauske, 1975). A fixation cross was present at the center of the imaginary diamond. Stimulus eccentricity was thus 1.4°. The assignment of pairs of line segments to vertices varied pseudorandomly from trial to trial. In each display, two of the pairs of line segments had gap $s - ds$ (or $s + ds$), and the third had gap $s + ds$ (or $s - ds$, respectively) with the value of ds fixed at 0.88 min arc for the 100-ms display and at 0.59 min arc for the 2-s display (see inset to Figure 1). These values were chosen on the basis of pilot experiments, the value of 0.59 min arc in particular to avoid ceiling effects in performance with long-duration displays. The reference value of the gap parameter s ranged from 0.88 to 6.17 min arc.

The stimuli were white and appeared superimposed on a uniform white 45° × 33° background field with a luminance of approximately 50 cd/m^2. The intensity of the stimuli was adjusted by each subject at the beginning of each experimental session to be ten times the luminance increment threshold. This setting was achieved by introducing a 1.0-log unit neutral density filter over the stimulus lines and adjusting their intensity to increment threshold on the unattenuated background. Stimuli were therefore adequately suprathreshold, but not so intense as to produce noticeable afterimages (any effects being of duration less than 20–40 ms in control measurements).

Stimuli were produced on the screen of an X-Y display oscilloscope (Hewlett-Packard, Type 1321A) with P4 sulfide phosphor (decay time 60 μs) controlled by a 16-bit minicomputer (CAI Alpha LSI-2) through 12-bit DACs and a vector-graphics (Sigma Electronics System QVEC 2150) true line generator with 10-bit endpoint resolution. Each pair of line segments was drawn within a patch of 1024 × 1024 endpoint resolution and total extent 25 min arc × 25 min arc on the screen. Each patch containing each pair of line segments could be positioned anywhere on the screen to within 4096 × 4096 resolution over the 14° × 10° CRT display. The three pairs of line segments could be displayed on the screen within the 20-ms refresh interval, and displays of varying duration were produced by identically refreshing the display at 50 Hz. The nominal 100-ms display thus comprised 5 refresh cycles, and the 2-s display comprised 100 refresh cycles. This fine temporal structure was not visually apparent. The display screen was viewed binocularly at a distance of 1.7 m through a view tunnel and optical system that produced the uniform background field.

Procedure. The subjects fixated the central fixation target, and when ready initiated a trial by pressing a switch on a push-button box connected to the computer. After a 500-ms delay, the display appeared for either 100 ms or 2 s (constant in any experimental session) and was followed by a blank field. The subjects maintained central fixation during the presentation period, after which they indicated the position of the odd pair of line segments using a pushbutton box connected to the computer. The fixation target reappeared after a delay of approximately 2 s, signaling that the next trial could be started. Subjects were expected to respond as quickly as was consistent with accuracy. (Subjects made no "illegal" responses corresponding to the indication of a location where no pair of line segments appeared. An analysis of correct responses as a function of the location of the odd pair of line segments showed no evidence of significant pattern of bias, $F(3, 24) \leq 0.8$, $p \geq 0.5$.)

Experimental design. Measurements were made in sequences of 28 trials. In each such run sequence, the pairs of line segments in each display occurred with one of seven different reference values of the gap parameters s (from 0.88 to 6.17 min arc), and one of eight different orientations with respect to the vertical (22.5°, 67.5°, 112.5°, 157.5°, with additional orientations obtained by rotating through a further 180°). The sign of the increment ds in s was chosen pseudorandomly. In each session, each subject carried out one block of eight runs, preceded by one practice run. In each block, the display duration and the magnitude of ds were fixed. The sequence of presentations in each run was chosen pseudorandomly but balanced over runs to offset stimulus order and carry-over effects and response bias by subjects. The same run sequences were used in each of the two stimulus-duration conditions (see Westheimer, 1984). Subjects carried out three blocks of eight runs for each of these conditions, but not more than two blocks each day. (Subject SS undertook four blocks in the long-duration, small-ds condition because of reduced level of performance in earlier measurements.) Subjects were not given trial-to-trial feedback on their performances.

Results

Figures 2a and 2b show, for subjects MF and SS respectively, discrimination performance for the two durations of the stimulus display. In each panel of the figure, the percentage of correct responses corresponding to the correct discrimination of the odd pair of line segments (gap parameter $s + ds$ or $s - ds$) from the two identical pairs of line segments (gap parameter $s - ds$ or $s + ds$, respectively) is plotted against the reference value of the gap parameter s. Each data point is based on 96 trials (except for those in the upper part of Figure 2b, for subject SS, which are based on 128 trials). Chance-level performance of 33% based on a 3-AFC task is shown by the horizontal broken line.

Individual performances were broadly similar (although subject SS had lower scores than MF with the 2-s display). For the 2-s display, discrimination declined almost monotonically with s (and the only significant trend was linear, $z \geq 8.74$, $p \ll .001$, for both subjects). For the 100-ms display, there was a pronounced peak around $s = 2.6$ min arc (and there were significant quadratic and cubic trends, $z \geq 2.30$, $p < .02$, for both subjects). These patterns of performance were unaltered when the percentage-correct scores were linearized by being replaced by the corresponding discrimination-index values d' from signal detection theory (Green & Swets, 1966).

Although not used as the principal measure of performance, reaction time (RT) was recorded to provide a general monitor of compliance and to test for time–accuracy trade-off effects. In all conditions, RT for a correct response tended to *decrease* with increase in percentage correct.

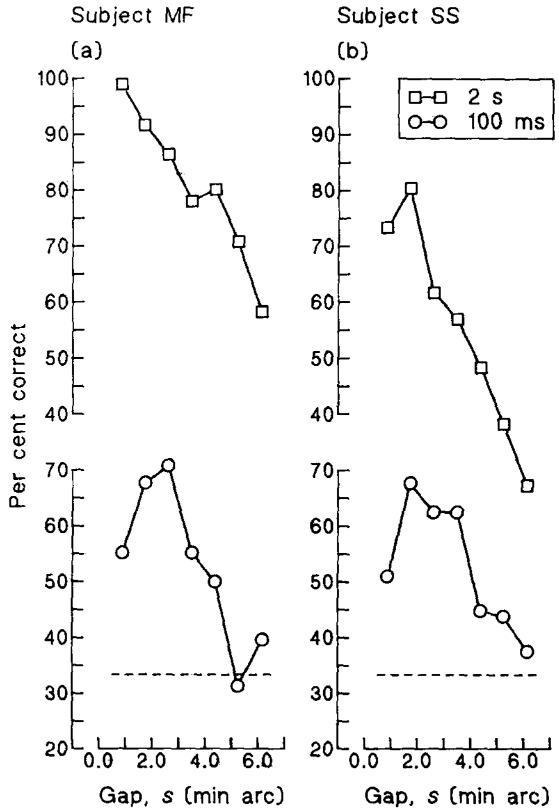

Figure 2. Performance in discriminating line-segment pairs with varying reference gap size s in an array of three line-segment pairs for two durations of stimulus display. (The magnitude of the [half] discrimination step ds was fixed at 0.59 min arc for the 2-s display and at 0.88 min arc for the 100-ms display. Chance-level performance for a 3-AFC task is shown by the horizontal broken line.)

Discussion

The effects of stimulus duration were similar to those obtained with curved-line displays (Ferraro & Foster, 1986; Foster, 1983). For the long-duration display, discrimination declined almost monotonically with gap size s, whereas for the short-duration display, performance was strongly peaked at around s values of 2.6 min arc. As has been noted elsewhere (Foster, 1983), the peak in performance with the short-duration display could not be attributed to a nonuniformity in the stimulus continuum or to some general configurational effect associated with the presentation of three like stimuli in similar orientations.

Were the differences in performance in the two conditions due to the choice of the discrimination step $2ds$? It seems unlikely. First, the reason for decreasing the value of ds with the long-duration display was to reduce the mean level of performance to where it might overlap, over some portion of the range, with performance obtained with the short-duration display. If the values of ds were not decreased, performance with the long-duration display would saturate. Second, in separate measurements of curved-line discrimination in which a range of *ds* values was used for long- and short-duration displays, the same pattern of performance (expressed as reciprocal spatial threshold) was obtained (Foster & Cook, 1989). Some analyses of size effects of *ds* have been considered in Ferraro and Foster (1984).

Could the effects of reduced stimulus duration be regarded as a spatial threshold-scaling effect? That is, could the short-duration discrimination functions be brought into coincidence with the long-duration functions by scaling the parameter axis (expanding the long-duration one or contracting the short-duration one) according to some characteristic spatial threshold (see Ferraro & Foster, 1984, for related technical discussion)? Such a simple proposal is appealing, but may not suffice here, for the spatial thresholds under the two exposure conditions were not very different (and for one subject actually overlapped). To achieve coincidence of the two functions, some nonlinear scaling of the parameter axis would probably be needed.

Given, for the moment, that the peak in discrimination performance obtained with the short-duration display was the result of the effectively discrete processing of longitudinally displaced line segments, the next step attempted to identify their supposed underlying internal characterizations. The following experiment tested three competing sets of potential descriptors, each defining different partitions of the stimulus continuum and each offering different perceptual identities for those partitions.

Experiment 2: Labeling of Longitudinally Displaced Line Segments

Previous experiments on a variety of labeling scales with briefly presented curved lines (Foster, 1983) suggested that a natural, "Fechnerian," categorical-identification scale might offer the most appropriate labeling regime, preferable, for example, to a uniform categorical-rating scale (using neutral ordinal labels such as *1*, *2*, *3*). (Scales based on discrimination steps have found a particular use in color vision; see references in Boynton, 1988.) For the discrimination of line segments with gaps, suitable candidate labels could be *no gap*, *just a gap*, and *more than just a gap*. Subjects experienced no difficulty in the use of these kinds of labels and applied them consistently and lawfully (see e.g., Foster, 1983). In Experiment 1, the peak in discrimination performance for the short-duration display was centered about gap sizes of approximately one or two discrimination steps (*2ds*), suggesting that the peak might mark a boundary between characterizations of the stimuli of the from *no gap* and *just a gap*. For completeness, all three labels were considered, but in different combinations to form three different categorical-identification scales. These scales had the sets of labels *no gap* and *just a gap*; *just a gap* and *more than just a gap*; and *no gap*, *just a gap*, and *more than just a gap*. With each of the scales in turn, subjects assigned the given labels to the stimuli of Experiment 1. Given that the resulting labeling performance reflected the characteristics of the discrete processes assumed to determine discrimination performance with the short-duration display in Experiment 1, a theoretical performance was calculated and tested against the observed performance. Three such performances were obtained, one for each of the three categorical-identification scales.

Method

Subjects. The subjects who participated in Experiment 1 also participated in Experiment 2.

Stimuli and apparatus. The stimuli and apparatus used in Experiment 2 were the same as in Experiment 1.

Procedure and experimental design. The subjects fixated the central fixation target, and, when ready, initiated a trial by pressing a switch on the push-button box connected to the computer. After a 500-ms delay, the line-segment display appeared for 100 ms, followed by a blank field for 100 ms, after which a small arrow (of extent 0.21°) appeared for 500 ms in the center of the display field pointing to the location previously occupied by the odd pair of line segments. The subjects maintained central fixation during the presentation period, after which they indicated the appearance of the cued pair of line segments and then that of the other two pairs of line segments in the display in terms of one of the given labeling scales, the scale being fixed in each block of runs. (An advantage of this design over that in which subjects first perform a discrimination and then an uncued labeling is that identification performance is not contingent on, or bounded by, discrimination performance.) Responses were signaled on the push-button box connected to the computer. All other details of procedure and experimental design were the same as in Experiment 1.

Results and Discussion

Categorical identification. Figures 3a–3f show, for each subject, labeling performance (based on responses to all the stimuli in each display) for each of the three categorical-identification scales, as a function of the gap parameter s for the pair of line segments. The results shown in Figures 3a and 3d are for the labels *no gap* and *just a gap*; Figures 3b and 3e are for the labels *just a gap* and *more than just a gap*; and Figures 3c and 3f are for the labels *no gap*, *just a gap*, and *more than just a gap*. Each data point was based on 96–192 trials. (The number depended on the distribution of $s - ds$ and $s + ds$ values in Experiment 1. The middle half of the range was necessarily sampled twice as often as the ends to preserve equal sampling of the reference values s.)

The subjects' performances were similar, and the variation of percentage of assignments of a given label with gap size showed regular behavior (which preserved the ordinal character of the categories) with each of the three categorical-identification scales. For the scale with the labels *no gap* and *just a gap* (Figs 3a and 3d), the boundaries of the categories (defined by the points at which assignment percentages for the categories crossed over) were at 2.1–2.5 min arc; for the scale with the labels *just a gap* and *more than just a gap* (Figures 3b and 3e), the boundaries shifted, appropriately, to larger gap values, 3.8–4.0 min arc; and for the scale with all three labels (Figures 3c and 3f), the boundaries were at 1.4–2.6 min arc and at 4.5–5.1 min arc, showing a small shift away from each other and more noticeably for subject SS (Figure 3f).

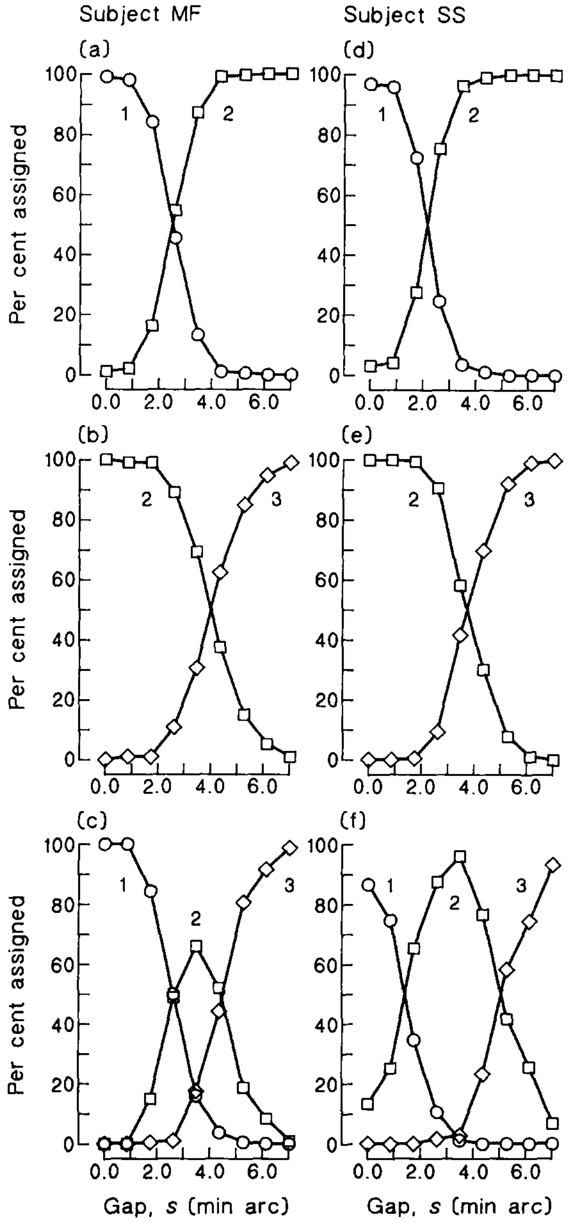

Figure 3. Performance in labeling line-segment pairs with varying gap size according to three categorical-identification scales. (Categories: 1 = *no gap*, 2 = *just a gap*, 3 = *more than just a gap.*)

Predicted discrimination performance. A method for deriving a predicted discrimination performance from a set of categorical-identification data was described in Foster (1983). The method was based on a generalized-distance scheme in which each stimulus element was represented, in terms of labeling performance, as a point in an n-dimensional Euclidean space. Thus, an element with parameter value s was represented by an n-tuple $(p_1(s), \ldots, p_n(s))$, where $p_i(s)$ is the probability that label i is chosen from the n labels available. The discriminability of two stimulus elements was assumed to be determined by the separations of their images in this space. Without loss in generality, distances were defined according to the city-block metric, that is, an l_p metric with $p = 1$. (If the $p_i(s)$ are first linearized by applying the inverse of the standardized normal integral, the distance measure may be related directly to the signal detection theoretic measure d'; Foster & Ferraro, 1989.) Some other schemes for predicting discrimination performance from labeling data have been considered in Foster and Ferraro (1989). For a given set of labeling data, however, predicted performance does not depend (up to a quadratic scaling factor) on the particular discrete scheme chosen (Foster & Ferraro, 1989). Cutting (1982) has summarized some of predictive schemes used in auditory modeling. The method used here was the same as that in Foster (1983), and predictions were based on subjects' responses to all the elements in the display.

Figures 4a–4f show, for each subject, predicted discrimination performance (continuous lines) and actual discrimination performance (broken lines, replotted from Figures 2a and 2b, 100-ms data). Each categorical-identification scale with two labels yielded a single-peaked predicted discrimination performance, whereas that with three labels yielded a double-peaked predicted discrimination performance. The greater separation of the double peaks for subject SS (Figure 4f) reflected the greater separation of the category boundaries (Figure 3f).

Mean levels of predicted and observed performance were very close for both two-labels scales (differences did not exceed 1.2%), but less close for the three-labels scale (differences reached 10.3%). An indication of the more important goodness of fit may be derived from the root-mean-square error (*RMSE*), a measure advocated by Massaro (1987). Performance predicted by the categorical-identification scale with the labels *no gap* and *just a gap* (Figures 4a and 4d, *RMSE* 7.6% and 10.9%, respectively) was evidently the most closely congruent to observed performance, the theoretical performance showing a sharp well-located peak for both subjects. Predicted performance for the scale with the labels *just a gap* and *more than just a gap* (Figures 4b and 4e, *RMSE* 19.4% and 16.0%, respectively) also showed a single sharp peak, but it was shifted too far (by about 1.7 min arc) toward large gap values. Predicted performance for the scale with all three labels *no gap, just a gap,* and *more than just a gap* (Figures 4c and 4f, *RMSE* 17.2% and 17.7%, respectively) was clearly incompatible with observed performance.

Although *RMSE* gives a direct measure of lack of fit, it does not distinguish between deviation due to differences in shape and deviation due to differences in general response level. To assess these effects, the two measures of comparison proposed by Cutting (1982) were computed: *proximity*, which, like *RMSE*, measures the point-wise closeness of obtained and predicted functions, and *shape*, which is an ANOVA trend test and which measures the overall congruence of the two functions. The predicted performances from all scales showed significant failures in proximity ($\chi^2(7) \geqslant 16.1$, $p < .05$), but the deviations were least for those in Figures 4a and 4d. The most significant trends in shape ($z \geqslant 5.1$, $p \ll .001$) were also obtained for those scales in Figures 4a and 4d. In summary, for both subjects, all three measures of concurrence showed that the scale with the labels *no gap* and *just a gap* gave better predicted performances than either of the two other scales.

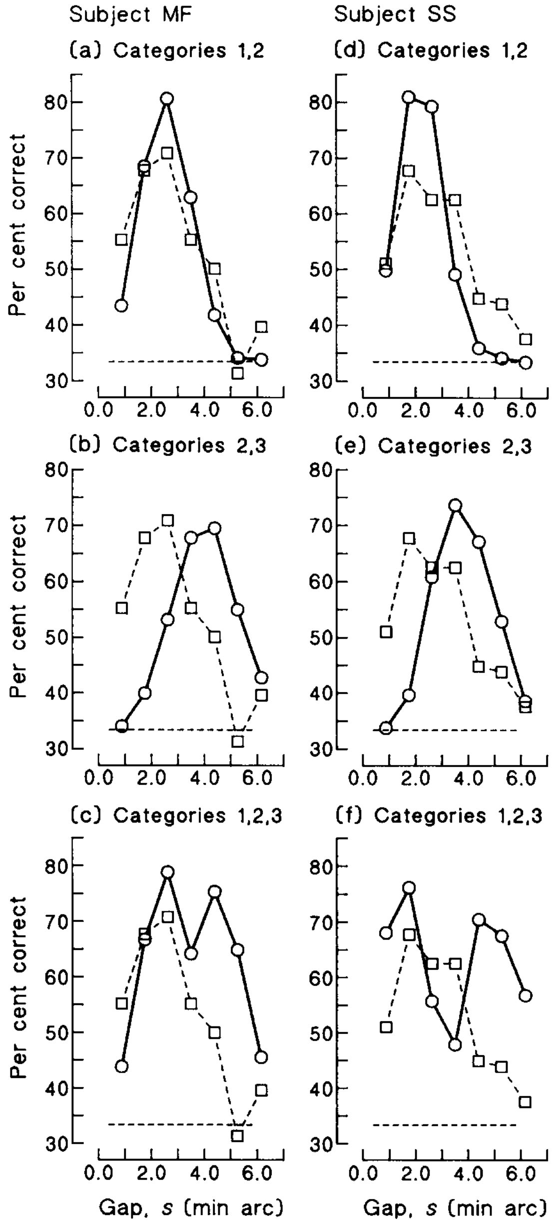

Figure 4. Predicted performance (continuous line) and observed performance (broken line, replotted from Figure 2) in discriminating line-segment pairs with varying reference gap size *s* in a 100-ms-duration display. (Predicted performances in a and d were obtained from the two-interval-scale data of Figures 3a and 3d; in b and e from the two-interval-scale data of Figures 3b and 3e; and in c and f from the three-interval-scale data of Figures 3c and 3f. Open circles are connected with continuous line = predicted from labeling. Open squares are connected with broken line = observed.)

Despite the a priori plausibility of the present threshold-based labelings of line segments with gaps, their suitability in offering characterizations of the supposed underlying discrete processes was assessed solely on the basis of the scale's ability to generate accurate predictions of discrimination performance. In principle, other labeling scales may be contrived that will yield similar predictions. This issue is considered later. The next two experiments considered discrimination and categorical identification of line segments that were subjected to lateral displacements.

Experiment 3: Discrimination of Laterally Displaced Line Segments

In this experiment, which was analogous to Experiment 1 except for the direction of displacement, the discriminability of parallel nonoverlapping pairs of line segments with different amounts of offset was measured at steps along a continuum of such pairs, a sample of which is shown in the inset to Figure 5. The size of the offset was specified by the parameter *s* in min arc. The overall extent of each pair of line segments was fixed at 0.40°. Arrays of three such pairs of line segments with offsets, the lines with common orientation, were presented as illustrated in Figure 5. In each display, two of the pairs of line segments were identical, each with offset $s - ds$ (or $s + ds$), and one pair was "odd," with offset $s + ds$ (or $s - ds$, respectively). The discrimination step $2ds$ was fixed and independent of *s*. The task of the subject was to locate the odd pair of line segments, the position varying pseudorandomly from trial to trial. There were again two durations of the stimulus display, 100 ms and 2 s.

Method

Subjects. The same subjects who participated in Experiments 1 and 2 also participated in Experiment 3.

Stimuli and apparatus. The continuum of pairs of line segments with offsets was produced by fixing the two terminal members of the range and generating intermediate members by varying the amount of offset linearly. The overall extent of each pair of line segments was 24 min arc (0.40°), and the widths of the line segments were approximately 1.0 min arc. The length of each of the line segments in each pair was 10 min arc, so that the ends of the line segments were never

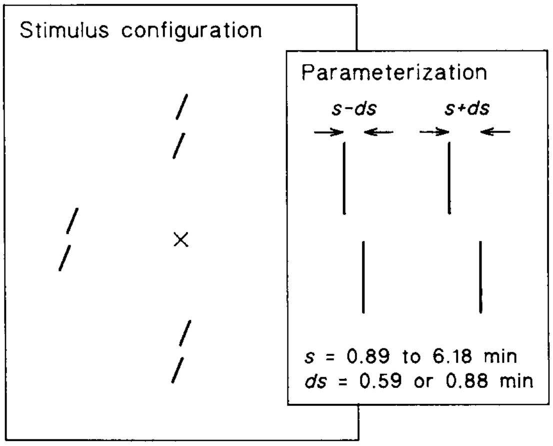

Figure 5. Example of stimulus display (and stimulus parameterization) used in Experiment 3. (The main figure is to scale, except that the line-segment pairs are shown 100% larger. The "odd" line-segment pair had offset $s + ds = 4.41$ min arc, and the two identical line-segment pairs had offset $s - ds = 2.65$ min arc.)

closer than 4 min arc, thereby (a) eliminating possible confounding effects due to their apparent continuity or discontinuity near zero offset and (b) reducing any influence of the length of the line segments on the general level of performance. As Westheimer (1981, p. 12) has noted in hyperacuity measurements, when the endpoints are separated by 2–4 min arc, the segments can be shrunk to points with little detriment in performance.

As in the earlier experiments, the three pairs of line segments in each display were presented at three of the four positions defining the vertices of an imaginary diamond of side 2.0° (as illustrated in Figure 5, in which the line segments are shown 100% larger than their true scale). A fixation cross was present at the center of the imaginary diamond. Stimulus eccentricity was thus 1.4°. The assignment of pairs of line segments to vertices varied pseudorandomly from trial to trial. In each display, two of the pairs of line segments had offsets $s - ds$ (or $s + ds$), and the third had offset $s + ds$ (or $s - ds$, respectively), with the value of ds being fixed at 0.88 min arc for the 100-ms display, and at 0.59 min arc for the 2-s display (see inset to Figure 5). For subject MF, the reference value of the offset parameter s ranged from 0.89 to 6.18 min arc, and for subject SS, on the basis of pilot studies, the range was shifted toward slightly larger values, from 1.77 to 7.05 min arc.

The details of stimulus generation, spatial precision and timing, and adjustment of intensity were all the same as in Experiment 1.

Procedure and experimental design. The procedure and experimental design were the same as in Experiment 1, except that for subject SS the number of blocks was four and five for the 100-ms and 2-s displays, respectively.

Results

Figures 6a and 6b show, for each subject, discrimination performance for the two durations of the stimulus display. In each panel of the figure, the percentage of correct responses corresponding to the correct discrimination of the odd pair of line segments (offset parameter $s + ds$ or $s - ds$) from the two identical pairs of line segments (offset parameter $s - ds$ or $s + ds$, respectively) is plotted against the reference value of the offset parameter s. Each data point was based on 96 trials for subject MF (Figure 6a), and on 128 and 160 trials for subject SS (upper and lower parts of Figure 6b, respectively). Chance-level performance based on a 3-AFC task is shown by the horizontal broken line.

Although there were detailed differences in performance by the 2 subjects, the forms of the dependencies of discrimination on s were similar and analogous to those of Experiment 1. Thus for the 2-s display, discrimination declined almost monotonically with s (with highly significant linear trends, $z \geqslant 5.75$, $p \ll .001$, for both subjects), whereas for the 100-ms display, performance was strongly peaked at $s = 3.5$–4.4 min arc (with highly significant quadratic trends, $z \geqslant 3.33$, $p < .001$, for both subjects). The same pattern of performance was obtained from a second d' analysis. As in Experiment 1, for neither display duration was there any evidence of a tradeoff between percentage correct and RT.

Discussion

The results of this experiment paralleled those of Experiment 1. For the long-duration display, discrimination of laterally displaced line segments declined almost monotonically with offset s, whereas for the short-duration display, performance showed a marked peak. The position of this discrimination peak at s values of 3.5–4.4 min arc was, however, shifted relative to the peak at about 2.6 min arc for gap discrimination in Experiment 1. The reason for this shift in peak position may be related to the different attributes associated with the variable s in the two experiments: When the line segments are displaced longitudinally, there is physically no gap between them for all $s \leqslant 0$; when the line segments are displaced laterally, they are physically not offset only for the singular value $s = 0$. If there were some intrinsic visual noise in early processing that superimposed a jitter on effective s values (see Andrews *et al.*, 1973), judgments about the presence of an offset near $s = 0$ might be made with much less precision than judgments about the presence of gap. This notion is considered further after the next experiment.

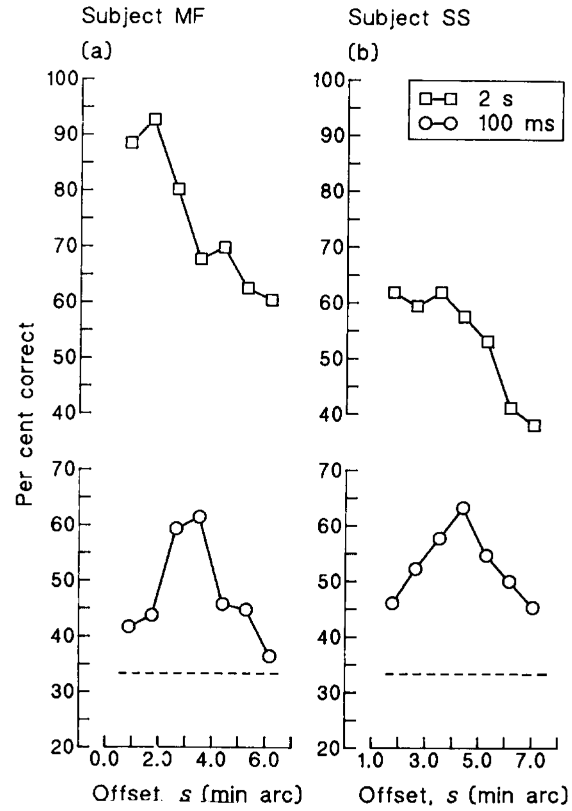

Figure 6. Performance in discriminating line-segment pairs with varying reference offset size s in an array of three line-segment pairs for two durations of stimulus display. (The magnitude of the [half] discrimination step ds was fixed at 0.59 min arc for the 2-s display, and at 0.88 min arc for the 100-ms display. Chance-level performance for a 3-AFC task is shown by the horizontal broken line.)

Given, again, that the peak in discrimination performance with the short-duration display resulted from the effectively discrete processing of the laterally displaced line segments, the next experiment tested three competing sets of potential descriptors for the supposed underlying discrete internal characterizations.

Experiment 4: Labeling of Laterally Displaced Line Segments

This categorical-identification experiment applied the same rationale for choosing possible labeling regimes as that in Experiment 2. For laterally displaced line segments, suitable candidate labels were *not offset*, *just offset*, and *more than just offset*. In Experiment 3, the peak in discrimination performance for the short-duration display was centered about offsets of two or three discrimination steps, somewhat greater than those in Experiment 1, suggesting that the peak might also mark a boundary between characterizations of the stimuli of the form *just offset* and *more than just offset*. As in Experiment 2, all three labels were considered, but in different combinations to form three different categorical-identification scales. These scales had the sets of labels *not offset* and *just offset*; *just offset* and *more than just offset*; and *not offset*, *just offset*, and *more than just offset*. With each of the scales in turn, subjects assigned the given labels to the stimuli of Experiment 3. Given that the resulting labeling performance reflected the characteristics of the discrete processes assumed to determine discrimination performance with short-duration displays in Experiment 3, a theoretical performance was calculated and tested against observed performance. Three such performances were obtained, one for each of the three categorical-identification scales.

Method

Subjects. The subjects were the same as those in Experiments 1-3.

Stimuli and apparatus. The stimuli and apparatus were the same as those of Experiment 3.

Procedure and experimental design. The procedure and experimental design were identical to those of Experiments 2 and 3.

Results and Discussion

Categorical identification. Figures 7a-7f show, for each subject, labeling performance for each of the three categorical-identification scales as a function of the offset parameter *s* for the pair of line segments. The results shown in Figures 7a and 7d are for the labels *not offset* and *just offset*; Figures 7b and 7e are for the labels *just offset* and *more than just offset*; and Figures 7c and 7f are for the labels *not offset*, *just offset*, and *more than just offset*. Each data point was based on 96-192 trials (see Experiment 2).

The subjects' performances were again similar, and the variation of percentage of assignments of a given label with offset size showed regular behavior with each of the three categorical-identification scales. For the scale with the labels *not offset* and *just offset* (Figures 7a and 7d), the boundaries of the categories (defined by the points at which assignment percentages for the categories crossed over) were at 2.6-3.7 min arc; for the scale with the labels *just offset* and *more than just offset* (Figures 7b and 7e), the boundaries shifted appropriately to larger offset values at 3.7-5.2 min arc; and for the scale with all three labels (Figures 7c and 7f), the boundaries were at 2.4-2.5 min arc and 4.5-6.3 min arc, showing, as in Experiment 2, a small shift away from each other, again more noticeably for subject SS (Figure 7f).

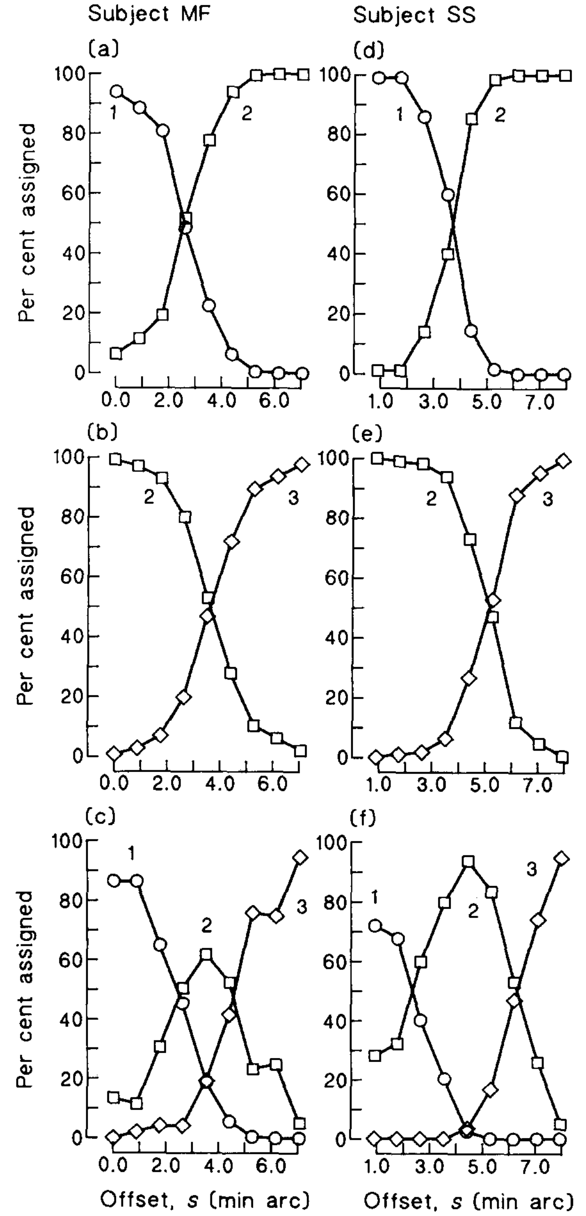

Figure 7. Performance in labeling line-segment pairs with varying offset size according to three categorical-identification scales (Categories: 1 = *not offset*, 2 = *just offset*, 3 = *more than just offset*.)

Predicted discrimination performance. As in Experiment 2, each of the three sets of categorical-identification data were used to derive a predicted discrimination performance.

Figures 8a-8f show, for each subject, predicted discrimination performance (continuous lines) and actual discrimination performance (broken lines, replotted from Figures 6a and 6b, 100-ms data). Categorical-identification scales with two labels yielded single-peaked predicted discrimination performances, whereas the scale with three labels yielded a double-peaked predicted discrimination performance. The greater

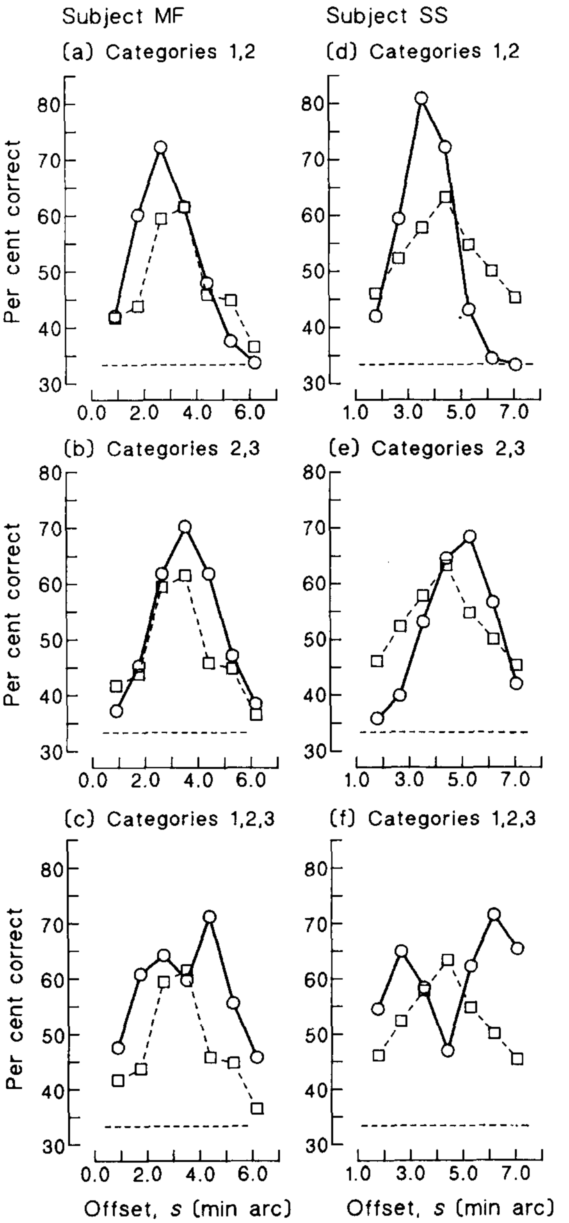

Figure 8. Predicted performance (continuous line) and observed performance (broken line, replotted from Figure 6) in discriminating line-segment pairs with varying reference offset size s in a 100-ms-duration display. (Predicted performances in a and d were obtained from the two-interval-scale data of Figures 7a and 7d; in b and e from the two-interval-scale data of Figures 7b and 7e; and in c and f from the three-interval-scale data of Figures 7c and 7f. Open circles connected with continuous line = predicted from labeling. Open squares connected with broken line = observed.)

separation of the double peaks for subject SS (Figure 8f) again reflected the greater separation of the category boundaries (Figure 7f). Mean levels of predicted and observed performance were again very close for both two-labels scales (differences less than 4.1%), but less close for the three-labels scale (differences reached 10.2%).

Performances predicted by the categorical-identification scales with the labels *not offset* and *just offset* (Figures 8a and 8d, *RMSE* 8.4% and 13.1%, respectively) and the labels *just offset* and *more than just offset* (Figures 8b and 8e, *RMSE* 7.3% and 8.8%, respectively) were both congruent to observed performance, although each was slightly shifted along the s-axis by not more than about 0.9 min arc with respect to the best position. Predicted performance for the scale with all three labels, *not offset, just offset,* and *more than just offset* (Figures 8c and 8f, *RMSE* 13.1% and 14.2%, respectively) was again clearly incompatible with observed performance.

These informal comparisons were supported by a quantitative analysis of the kind performed in Experiment 2. All of the predicted functions showed significant failures in proximity ($\chi^2(7) \geqslant 13.9$, $p < .05$), but the effects were least for the scales in Figures 8b and 8e. The most significant trends in shape occurred for the scales in Figures 8a and 8d ($z \geqslant 2.94$, $p < .01$) and in Figures 8b and 8e ($z \geqslant 2.55$, $p < .01$). Thus, for both subjects, the scale with the labels *not offset* and *just offset* and the scale with the labels *just offset* and *more than just offset* each provided a more congruent fit than the three-label scale, but neither was clearly better than the other.

One possible explanation for the closeness of the two sets of predictions might be based on the role of the singular value $s = 0$ in judgments of line-segment offset and the vulnerability of effective s values in this region to internal visual noise (see Discussion section of Experiment 3). In the presence of such noise, the label *not offset* ($s = 0$) may be normally perceived to be inapplicable in discriminating nonoverlapping offset line segments, all judgments being effectively based on the labels *just offset* and *more than just offset.* The peak in discrimination performance that might otherwise be anticipated at a *not offset–just offset* boundary (compare Experiment 1) would be displaced to larger s values. Although for any two-labels scale the distribution of responses would be dominated by this boundary, only when three labels were imposed would a possible *not offset–just offset* boundary emerge.

As with longitudinally displaced line segments, the best categorical scale for predicting discrimination of laterally displaced line segments need not be unique. For example, an imaginary line might be drawn from the centers of the two parallel line segments comprising each stimulus pair, or from their nearer endpoints, and a labeling scale devised on the basis of just detectable differences in relative tilt (compare Sullivan et al., 1972; Watt, 1984b; Westheimer, 1981). The present experiments were not intended to distinguish between different labeling scales that yielded identical predicted functions.

General Discussion

Review of Experiments 1–4

Two classical acuity tasks were used to test processing of relative line position in early vision. Stimulus continua were defined that were physically uniform with regard to the amount of longitudinal or lateral line-segment displacement, and the discriminability of adjacent pairs of stimuli drawn from each of these continua was measured at successive points along them. Experiments 1 and 3 showed that the mode of performance in discriminating both longitudinally and laterally displaced line segments was strongly influenced by stimulus duration. For a 2-s display, performance in discriminating an increment in displacement declined essentially monotonically. For a 100-ms display, there was a marked peak in discrimination, which for line-gap discrimination was at gap sizes of about 2.6 min arc, and for line-offset discrimination was at offset sizes of about 3.5–4.4 min arc.

Experiments 2 and 4 tested the suitability of candidate labeling scales in the identification of the briefly presented line segments. Theoretical discrimination performances were computed from each set of labeling data, and the congruence of theoretical and observed performances was then used to determine the best scales: *no gap* and *just a gap* for longitudinally displaced line segments, and *just offset* and *more than just offset* (or possibly *not offset* and *just offset*) for laterally displaced line segments.

The principal inferences were as follows: (a) In early vision, there appear to exist discrete mechanisms that are sensitive to relative line position and that are qualitatively different from mechanisms determining traditional acuity performance. (b) These discrete mechanisms have spatial characteristics that can be identified in terms of perceptual labels with simple threshold descriptors. (c) Two such descriptors are sufficient to represent relative position either along a longitudinal displacement axis or along a lateral displacement axis.

Previous investigations of early visual form processing, including those by Beck (1966, 1982), Beck and Ambler (1972), and Treisman and Gormican (1988), found no evidence for the existence of preattentive mechanisms sensitive to line arrangement. One possible explanation, alluded to earlier, is that the present findings are due to choice of experimental design, in particular sampling from a larger continuously parameterized stimulus set rather than from a small finite set. Another possible explanation has been offered by Treisman and Gormican (1988, p. 40) in a slightly different context, namely that not all feature codings are activated whenever a particular stimulus is presented, and that, rather than being processed in parallel, some precedence on codings may be imposed (Treisman, 1982). It is possible that minimizing the variation in stimulus properties within a display (Foster, 1980) helped reduce the risk of competition between possible alternative codings.

These experiments raise other issues concerning early visual processing of line arrangement. One question of theoretical interest is whether the recorded performance results strictly from the categorical perception of the stimuli. If it does, or at least appears to, why should it occur in early vision, and what kinds of visual mechanism might underlie it? These and related issues are considered in the following sections.

Categorical Perception

The notion of categorical perception has received a variety of interpretations in the literature (see Harnad, 1987, and Macmillan, Kaplan, & Creelman, 1977, for reviews). In its most general form, categorical perception can be considered as the treating of a set of stimuli, usually continuously parameterized, as equivalent in some way (Bornstein, 1987). Categorical perception has been intensively investigated in color perception and wavelength discrimination (Boynton & Gordon, 1965; Kaiser, 1968; Kolers & von Grunau, 1975; Luria, 1967; Mullen, in press; Uchikawa & Boynton, 1987; Uchikawa & Ikeda, 1987; see reviews in Boynton, 1975, 1988), in the perception of speech sounds, particularly stop consonants (Carney, Widin, & Viemeister, 1977; Liberman et al., 1957, 1961; Pisoni, 1977; Repp, Healy, & Crowder, 1979; Samuel, 1977; Studdert-Kennedy et al., 1970; see Harnad, 1987, and Repp, 1984, for reviews), and in the perception of nonspeech sounds, such as plucks and bows (Cutting, 1982; Cutting & Rosner, 1974; Miller, Wier, Pastore, Kelly, & Dooling, 1976; Pisoni, 1977; Rosen & Howell, 1981). Categorical modes of visual discrimination have also been reported in some high-level form-perception tasks, for example, in associating speechlike sounds and circular sectored figures (Cross, Lane, & Sheppard, 1965), in discriminating closed curve figures with pictorial interpretations (Cermak, 1977; Shepard & Cermak, 1973), and in learning geometric shapes (Rosch, 1973).

The basic experimental paradigm for the investigation of categorical perception is similar to the paradigm used here: Discrimination and identification performances are obtained for a set of stimuli drawn at intervals from a physical continuum. Comparison of the two kinds of performances leads to inferences about the nature of the underlying sensory and perceptual processes. A critical issue in studies of categorical perception has been the choice of criteria against which the relationship between discrimination and identification performances should be assessed. In auditory perception, a set of operational criteria have been proposed for what might be called the strong version of categorical perception (Pastore, 1987; see Macmillan et al., 1977, and Studdert-Kennedy et al., 1970). Thus, with reference to the stimulus continuum, there should be (a) distinct labeling categories with sharp boundaries, (b) regions of chance performance in the discrimination of stimuli drawn from the same labeling category, (c) a discrimination performance peak at the category boundary, and (d) a close correspondence between the actual discrimination performance and the discrimination performance predicted from the labeling results based on the assumption of absolute categorization. As Macmillan (1987) noted, Liberman et al. (1957) found that discrimination reached a peak between phoneme categories, but performance was systematically better than predicted, a result that many others also found (but note the discussion of context effects in Repp et al., 1979).

In other tasks and modalities, categorical perception has been less strictly defined, centering mainly on criterion (c); in this weak form, categorical perception is closer to the *category boundary effect* (Wood, 1976). Operationally, the important differences between the strong and weak forms of categorical perception have been summarized in the two measures of comparison for discrimination and labeling functions described by Cutting (1982). The two measures, of proximity and shape, were essentially those applied here.

Whether categorical perception really occurs and what form it takes have been the subject of a sustained discussion in the auditory perception literature. It is not the purpose of this report to attempt any further review (for which see the references cited earlier). It is, nevertheless, useful to draw attention to a particular model of categorical perception proposed by Pastore et al. (1977) in which the presence of a single common factor (depending on task and modality) caused both a peak in the discrimination function and a categorical dichotomy in the labeling function, and thus the close correlation between the two. The model was used successfully to explain data from an experiment on the visual discrimination and labeling of flickering lights of different temporal frequencies (in the region of the flicker-fusion threshold) and from an experiment on the auditory discrimination and labeling of a sinusoid of varying intensity.

Was categorical perception then obtained in the present experiments? In that there were significant departures from coincidence in the observed and the best fitting predicted discrimination functions, as assessed by the proximity measure, the answer is apparently not. (Manipulating the metric used to compute the predicted discrimination performance had negligible effect on fit.) It should be noted, however, that discrimination and identification data were obtained under slightly different experimental conditions (involving a post-stimulus cue and increased visual memory load in the labeling task). In speech perception, evidence has been found for stimulus-context effects in vowel labeling, and by taking context effects into account, discrimination performance has been accurately predicted from labeling data (Repp et al., 1979). The disparity here between observed and best predicted functions as quantified by *RMSE* was small, less than 11% in all cases, and the similarity of these functions as quantified by the shape measure was highly significant. Operationally, the data satisfy the formal criteria for weak categorical perception. In the following section, we briefly consider some specific visual processes that might underlie this kind of performance.

Discrete Processing Schemes and Stimulus Duration

There are a number of processing schemes that may be invoked to explain sharp peaks in discrimination performance with short display durations. These schemes differ in the level at which the critical processing is assumed to occur, and in the detailed nature of that processing, but they do have an important common feature, namely, that at some stage they have a discrete structure (Foster & Ferraro, 1989; compare Miller, 1988). For example, the discrimination of briefly presented stimuli might be determined by the sampling properties of a small number of peripheral spatial-frequency sensitive mechanisms whose temporal responsiveness was associated with low center spatial frequencies (e.g., Graham, 1981; Thomas, 1985; Watson & Robson, 1981; Wilson & Bergen, 1979). Given two such mechanisms, with different spatial periodicities, discrimination would be best at line-segment separations intermediate between the two periodicities, and worse at very small or very large displacements (compare analyses of traditional hyperacuity performance by Wilson, 1986). The congruence of observed and predicted discrimination functions would then result from a common-factor process, in the sense of Pastore et al. (1977).

Alternatively, independent of the precise nature of the initial spatial sampling, discrimination might be determined by a small number of internal labels available at some higher level, possibly in short-term visual memory, to characterize the stimuli (Rosch, 1978; Treisman, 1979). Performance would be controlled by a resource-constraint bottleneck (Foster, 1983; Newell, 1980; Pylyshyn, 1989), and discrimination would be strictly categorical. Temporal dependence could be explained by an iterative process such as successive approximation, previously proposed (Ferraro & Foster, 1986) in connection with the discrimination of curved lines. This process could be achieved by *relaxation labeling* (Kuschel, 1982; Zucker, Hummel, & Rosenfeld, 1977; see Rosenfeld & Kak, 1982, for an introduction). This is a probabilistic and iterative process by which a description is successively updated according to a given set of compatibilities among (local) labels attached to neighboring points in the region of the stimulus element. Relaxation would be a highly efficient process, achieving substantial improvements in classification in just the first few iterations.

Despite fundamental differences in the structures of these discrete schemes, and in the algorithms used to compute their responses, it is possible to show that under a small number of assumptions they give remarkably similar predictions (Foster & Ferraro, 1989). Thus, although a generalized-distance model with a particular index (unity in the city-block metric) was used to generate the numerical data used here, predicted performances from other models in the family (including a probabilistic combinatorial model) were found to be closely congruent, and the schemes differentiated similarly among the empirical data. The compatibility of their detailed predictions has led to the suggestion that they are all examples of a class of general coding processes whose behavior is determined by a single parameter, the *number of degrees of freedom* associated with the process, here corresponding to the number of categories in the chosen labeling scale (Foster & Ferraro, 1989).

Image Segmentation

Threshold-based descriptors specifying gap size and offset size may have a particular role in the analysis of visual scenes when there is little opportunity for image scrutiny. An analogy may be drawn from machine-based vision. An early step in the machine processing of a pictorial image is an operation of segmentation that yields a classification of image pixels into say *edge* and *not edge*. After edges (or lines or curves) have been extracted from the image, they may be linked together to form more global entities. The criteria for linking two edges can include good continuation and mutual alignment (Rosenfeld & Kak, 1982, p. 129). Threshold-based descriptors could be used in the corresponding visual analysis, the labels *no gap* or *just a gap* being attached to longitudinally displaced line segments, and *just offset* or *more than just offset* to laterally displaced line segments, prior to their being tested for concatenation in some higher-level description of the scene.

The same kinds of labeling might also be involved in more detailed contour processing in early vision. Segmentation has been argued to be important in hyperacuity tasks with curvilinear stimuli (Watt, 1986), for which the existence of certain critical image features may constrain the integration of high-precision shape information along the stimulus contour. Watt (1986) suggested that the effect of these features was to determine an inflexible segmentation of the contour before more detailed analysis took place. Given the present findings, the labels *no gap* and *just a gap* could be used to describe whether the physical segmentation of a contour was effective, and the labels *just offset* and *more than just offset* could be used to describe the relationship of contours that have already been segmented. The fact that the peak in gap discrimination fell much closer to the displacement origin than the peak in offset discrimination might then be interpreted in terms of the priority attached to the accurate and early segmentation of contours in visual scenes.

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