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Discrete and continuous modes of curved-line discrimination controlled by effective stimulus duration*

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Abstract—In previous experiments two extreme modes of visual discrimination performance have been investigated by measuring small differences in pattern shape at points along a continuum of pattern shapes. These two modes, associated with discrete and continuous encoding processes, were obtained by simultaneously manipulating the number of pattern components in the display and the effective duration of the display. In this experiment, discrimination performance was measured for a fixed number of pattern components, namely three, and variable display time course. The stimuli used were curved lines drawn from a continuum with curvature parameter s. There were three stimulus time courses: (1) 2-s stimulus display, (2) 100-ms stimulus display, and (3) 100-ms stimulus display followed by a post-stimulus mask. Discrimination performance declined smoothly and monotonically with s for (1), but varied non-monotonically with s revealing a central peak for (3). Performance for (2) was intermediate between that for (1) and that for (3). A reduction in effective stimulus duration alone was thus sufficient to cause a transition from continuous to discrete modes of discrimination performance, a result which may be compatible with an explanation of variable discrimination modes based on a method of successive internal approximations of the stimulus.

INTRODUCTION

Fundamentally different modes of visual form or pattern discrimination performance may be revealed by measuring, within a suitable paradigm, the detectability of small differences in pattern shape at successive points along a continuum of pattern shapes parametrized by a single variable. Studies carried out by Foster (1980b, 1982b, 1983) demonstrated the existence of two extreme modes of visual discrimination performance that depended on the number of pattern components or subpatterns comprising the display and on the effective duration of the display. One mode of performance was characterized by the existence of a sharp maximum at one or more points on the continuum; the other mode of performance was characterized by a smooth, often monotonic, variation over the continuum. These qualitative changes of performance over the same continuum could be related to changes in the underlying type of pattern representation assumed to be used by the visual system. Thus, a sharply peaked discrimination performance was associated with the use of coarse *discrete* encodings and a smoothly varying discrimination performance was associated with the use of fine-grained *continuous* encodings. A theoretical rationale for this interpretation has been given elsewhere (Foster, 1980b; Ferraro and Foster, 1984).

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The studies cited above involved experiments on the discrimination of 3-dot figures varying systematically in their departure from collinearity (Foster, 1982b) and on the discrimination of curved lines varying systematically in curvature (Foster, 1983). There were two different types of stimulus condition: in the one, two subpatterns were presented and display duration was long, namely 2 s; in the other, four subpatterns were presented and display duration was short, namely 100 ms, and the display was followed by a post-stimulus mask. The mask was used to curtail the effective display duration by disrupting further possible processing of the fading visual image (Sperling, 1960; Estes and Taylor, 1964, 1966; Eriksen and Spencer, 1969; Lupker and Massaro, 1979). In the first stimulus condition, discrimination performance was found to be smoothly varying or essentially monotonic over the range of stimulus variation, reminiscent of performance obtained in some conventional acuity and hyperacuity tasks (Ludvigh, 1953; Andrews *et al.*, 1973; Westheimer and McKee, 1977; Westheimer, 1979, 1981; Watt, 1984). In the second stimulus condition, discrimination performance was found to be non-monotonic and sharply peaked.

Further investigation of the nature of the processes underlying discrete modes of discrimination performance was carried out in an experiment on curved-line discrimination (Foster, 1983) in which subjects assigned labels to the curved-line stimuli according to various categorical-identification and categorical-rating schemes. One scheme used the labels 'straight', 'just curved', and 'more than just curved', and the data obtained were used to compute a theoretical discrimination performance that closely matched the empirical discrimination performance, thus supporting the hypothesis that the latter was indeed the result of discrete encoding processes and, in particular, suggesting possible characterizations of the representations involved.

These results on discrete encodings are analogous, at a formal level, to the findings in auditory perception by Liberman and his colleagues (Liberman *et al.*, 1957, 1961) on the phoneme-boundary effect. These authors showed that as certain speech-like stimuli were 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. A theoretical rationale for the analogous existence of peaks and troughs in visual pattern discrimination was proposed (Foster, 1979, 1980a, b) as a necessary consequence of the hypothesized discrete internal encoding of the stimuli. To test this hypothesis, a *spatial perturbation* technique (Foster, 1979, 1980b) was developed in which a continuum of patterns was generated by a formal procedure based on the use of a 1-parameter group of transformations that secured a *transformational uniformity* (Foster, 1979, 1980b) of the range. Each pattern was assumed to give rise, with a certain probability, to one of a small number of discrete internal representations. Discrimination of adjacent pairs of patterns was assumed to be poor at points on the parameter range where the probability was high that the patterns were assigned the same internal representation. Discrimination of adjacent pairs was assumed to be good at points on the parameter range where the probability was high that the patterns were assigned different internal representations. These points thus corresponded to the 'boundaries' of the internal encodings. It was this rationale that led to experiments on discrete encodings for collinearity-noncollinearity (Foster, 1979, 1982b), for angle (Foster, 1980b), and for curvature (Foster, 1983).

Discontinuities or rapid changes in performance have occasionally been observed in some traditional hyperacuity tasks (e.g. Westheimer and McKee, 1977, Fig. 5; Watt and Andrews, 1982, Fig. 10). In the present context, however, the question of the uniformity of the stimulus range was particularly relevant. The existence of peaks and troughs was not sufficient to imply unequivocally the operation of discrete encoding processes: the continuum itself could in some sense have been non-uniform, and disconfounding the separate contribution of such a non-uniformity to overall performance may have been difficult, as has been noted for some auditory perception tasks (Pisoni and Lazarus, 1974; Macmillan *et al.*, 1977). One approach to the problem of range non-uniformity may be to define performance against a hypothetical ideal processor (Andrews *et al.*, 1973; Watt and Andrews, 1982). Empirically, however, the problem of range non-uniformity is obviated if both discrete and continuous modes of performance may be obtained over the same continuum. A variety of techniques (Foster, 1982a, pp. 335-337; Foster, 1983) may then be used to assess uniformity and derive an estimate of the contribution to discrimination performance of discrete encoding processes alone.

The conditions of stimulus presentation in the spatial-perturbation experiments outlined above (Foster, 1982b, 1983) were chosen to clearly elicit either continuous or discrete modes of discrimination performance by simultaneous manipulation of time course and the number of subpatterns in the display. The purpose of the present experiment was to determine whether, with a suitably fixed number of subpatterns, it was possible to reveal continuous and discrete modes of discrimination performance by manipulating stimulus time course alone. Such a result would possibly have implications for an explanation of these varying modes of discrimination performance based on a method of successive internal approximations of the stimulus, described more fully later.

The stimulus subpatterns used in this experiment were curved lines drawn from a continuum, a sample of which is shown in Fig. 1(b). Display time courses were as follows:

(1) 2-s pattern display, no post-stimulus mask;
(2) 100-ms pattern display, no post-stimulus mask;
(3) 100-ms pattern display, post-stimulus mask.

The number of subpatterns in each display was fixed at three. This number was chosen on the basis of preliminary experimentation: using less than three subpatterns reduced the task to a conventional acuity or hyperacuity task, and, for short display durations, the major change in form of the discrimination performance occurred when the number of subpatterns in the display was increased from two to three, rather than from three to four.

METHODS

Stimuli and apparatus

The continuum of curved lines was produced by fixing the two terminal members of the range (both arcs of circles, one with infinite radius), and generating intermediate members by the action of a 1-parameter group of transformations, which amounted here to a process of horizontal scaling. Curvature was specified by the parameter s which measured the perpendicular distance between the chord and the midpoint of the curved line (Fig. 1a). The two terminal members of the range had s values of 0 and 3.43 min arc (Fig. 1b). The chord of each curved line subtended 12 min arc visual angle and the width of the line approximately 1.2 min arc. Pattern displays comprised three

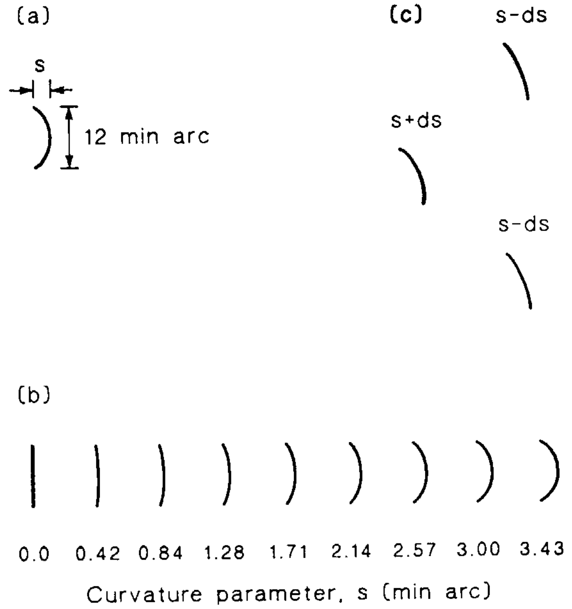

Figure 1. (a) Definition of the curvature parameter s; (b) illustration of the curved-line stimuli with constant increment ds in s of approximately 0.43 min arc; (c) illustration of typical stimulus configuration with reference value $s = 1.28$ min arc, $ds = 0.43$ min arc (i.e. $s - ds = 0.84$ min arc, $s + ds = 1.71$ min arc). The separations of the curved lines are not to scale, and the fixation target is not shown.

curved lines presented at three of the four positions defining the vertices of an imaginary diamond of side 2.1° (as shown in Fig. 1c). A fixation cross was present at the centre of the imaginary diamond. Stimulus eccentricity was thus 1.5°. The assignment of curved lines to vertex varied randomly from trial to trial. In each display, two of the curved lines were identical, each with curvature parameter $s - ds$ (or $s + ds$), and the third was 'odd' in that it had curvature parameter $s + ds$ (or, respectively, $s - ds$) (Fig. 1c). In any particular condition, the magnitude of the increment ds was fixed and independent of s so that the difference in curvature between the identical curved lines and the odd one was constant over the range of s; $2ds$ constituted the *discrimination step*. The value of s about which the increments were made was called the *reference value*. The position of the odd curved line and the (common) orientation of all the curved lines in each display varied randomly from trial to trial (see below). The stimuli were white and appeared superimposed on a uniform white 20° × 20° background field, luminance 40 cd m^{-2}.

The intensity of the curved-line stimuli was adjusted by each subject at the beginning of each experimental session to ten times 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.

The post-stimulus mask used in this experiment consisted of three separate random line-segment subpatterns each covering the area of the field occupied by each of the three curved lines. Each random line-segment subpattern comprised 18 2.4-min-arc line-segments, each of approximately the same point intensity as the curved-line stimuli.

The stimuli were produced on the screen of an X–Y display oscilloscope (Hewlett-Packard, Type 1321A) with P4 sulfide phosphor (decay time 50 μs) controlled by a minicomputer (CAI Alpha LSI-2) through 12-bit DACs and a vector-graphics (Sigma Electronics System QVEC 2150) true vector generator with 10-bit resolution. Each curved line was composed of ten concatenated straight-line segments, and over the range of curvatures used here appeared smooth to the eye. To achieve the required spatial fidelity, each curved line was drawn within a patch of 1024 × 1024 resolution of extent 24 × 24 min arc on the screen. Each patch containing each curved line could be positioned anywhere on the screen to within 4096 × 4096 resolution over the 14° × 10° CRT display. All curved-line displays could be presented within 20 ms, and displays of varying duration were produced by refreshing the display at 20-ms intervals. A nominal 100-ms display thus comprised five refresh cycles. This fine temporal structure was not visually apparent to the subject. The display screen was viewed binocularly, with natural pupils, at a distance of 1.7 m through a view tunnel and optical system which produced the uniform background field.

Procedure and experimental design

The subject fixated the central fixation target and, when ready, initiated a trial by pressing the appropriate switch on a push-button box connected to the computer. After a 500-ms delay, the curved-line display appeared. The display time course, constant throughout a particular session, was one of those summarized earlier: (1) 2-s curved-line display, no post-stimulus mask, (2) 100-ms curved-line display, no post-stimulus mask, (3) 100-ms curved-line display, followed, after a 100-ms blank field, by the random line-segment masking field, duration 500 ms. The fixation target then disappeared. The subject maintained central fixation during the presentation period. The task of the subject was to indicate, after each presentation period, the position of the odd curved line. When the subject had signalled his or her response on a push-botton box, the fixation target reappeared after about 2-s delay, indicating that the next trial could be started. The occurrence of 'illegal' responses, corresponding to locations within the imaginary diamond array at which no curved line appeared, was monitored; in fact, no illegal responses were obtained.

Trials were performed in sequences of 28. In each such run, the curved lines in each display had seven different reference values of the curvature parameter s (0.43–3.00 min arc), and eight different orientations to the vertical (22.5°, 67.5°, 112.5°, 157.5°, with additional orientations being obtained by rotations through a further 180°). The increments $+ds$ and $-ds$ occurred equally often. In each session, each subject carried out one set of eight runs, preceded by one practice run. In each set, the display time course and the magnitude of the increment ds were fixed. On the basis of pilot experiments, the magnitude of ds was fixed at 0.43 min arc for the 100-ms curved-line displays and 0.29 min arc for the 2-s curved-line display. The sequence of presentations in each run was chosen pseudo-randomly but balanced over runs to offset stimulus carry-over effects and response bias by subjects. The same run sequences were used in each of the three time-course conditions. Subjects carried out three or four sets of eight runs for each of these conditions (two sets each day). Subjects were not given trial-to-trial feedback on their performances.

Subjects

Two subjects participated in the experiment. One subject, KW, was female aged 22 yr and the other, MF (coauthor), was male aged 34 yr. Each had normal visual acuity (Snellen acuity at least 6/5). KW was unaware of the purpose of the experiment. Both subjects were well practised in the experimental procedure.

RESULTS

Figures 2 and 3 show, for each subject, discrimination performance for the three different time courses of the stimulus display. In each section of the figures, the percentage of correct responses is plotted against reference value of the curvature parameter *s*. Chance-level performance is shown by the horizontal dotted line.

Individual discrimination performances were similar: for the long-duration display, performances declined monotonically; for the short-duration display and no post-

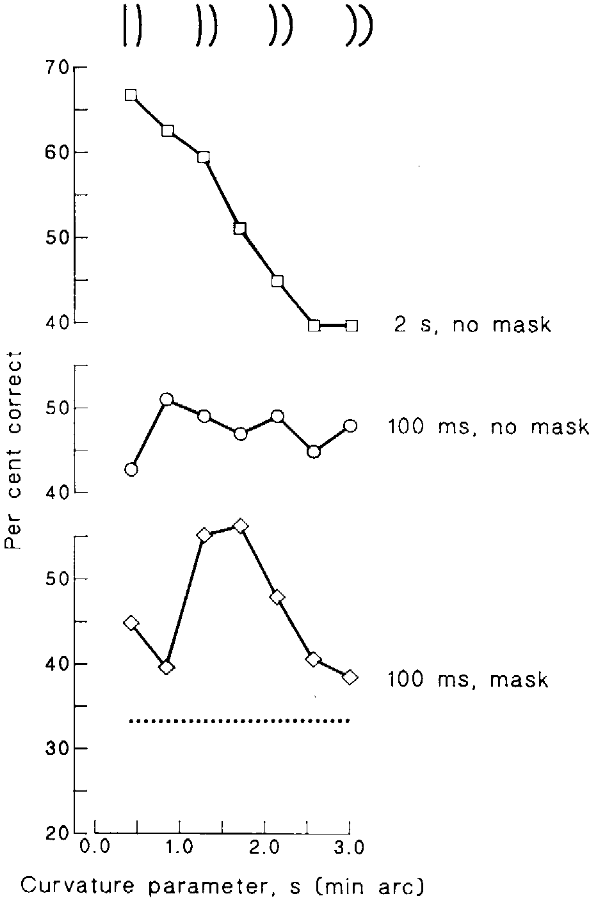

Figure 2. Curved-line discrimination performance. The percentage of correct responses for discriminating curved lines differing by a constant increment *ds* in the curvature parameter *s* (Fig. 1) is plotted against the reference value of *s*. Illustrations of pairs of curved lines to be discriminated are shown at the top of the figure. The three stimulus time courses are indicated: (□) 2-s curved-line display, no post-stimulus mask; (○) 100-ms curved-line display, no post-stimulus mask; (◇) 100-ms curved-line display, followed, after 100-ms blank field, by 500-ms random line-segment mask. The magnitude of the increment *ds* was fixed at 0.29 min arc for the 2-s display and at 0.43 min arc for the 100-ms displays with and without the mask. Number of trials per point 96. Subject KW.

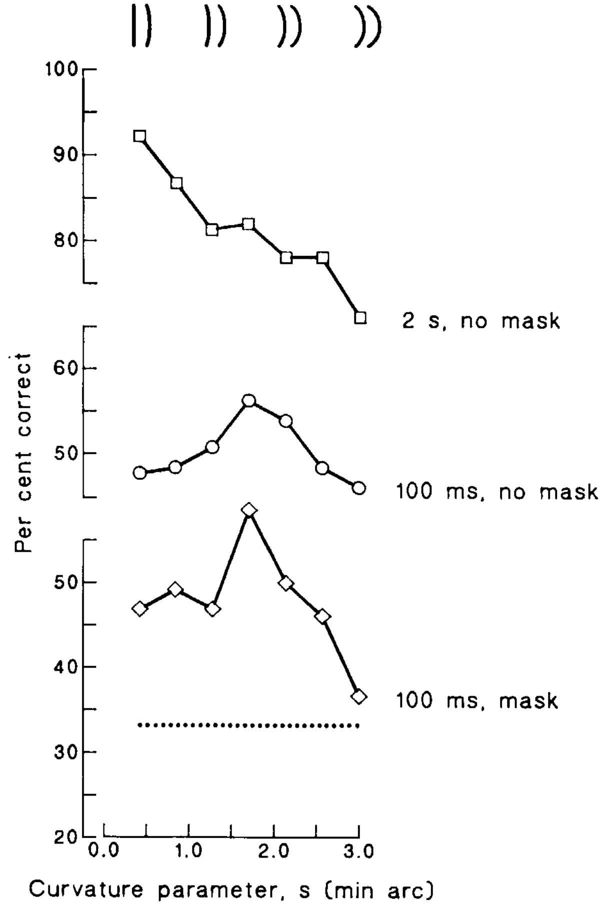

Figure 3. Curved-line discrimination performance. Main details as for Fig. 2. Number of trials per point 128. Subject MF.

stimulus mask, performances were nearly constant or weakly peaked; and for the short-duration display with post-stimulus mask, performances were strongly peaked, each at or close to $s = 1.71$ min arc.

Trend analysis

To quantify the form of the discrimination performance for the three conditions of stimulus time course, a (logistic) trend analysis was performed. For the 2-s display, there were highly significant linear trends ($z = 5.17$, $P < 0.0001$, for KW; and $z = 4.48$, $P < 0.0001$, for MF; two-tailed tests here and elsewhere), whereas quadratic trends were not significant ($z \leqslant 1.08$, $P > 0.2$, for both subjects). For the 100-ms display without post-stimulus mask, there were no significant linear trends ($z \leqslant 0.12$, $P > 0.5$ for both subjects), and no significant quadratic trends ($z \leqslant 1.73$, $P > 0.05$ for both subjects). For the 100-ms display with post-stimulus mask, there were significant quadratic trends ($z = 2.50$, $P < 0.02$, for KW; and $z = 2.64$, $P < 0.01$, for MF), and no significant linear trends ($z \leqslant 1.45$, $P > 0.1$, for both subjects).

Reaction time

Although reaction time (RT) was not used as the principal measure of performance, values were recorded to provide a general monitor of responsiveness and to test for trade-off effects. RT values were accordingly pooled over the three experimental conditions for each subject. Mean RT ± SEM for a correct response was 755 ± 57 ms for KW and 724 ± 84 ms for MF. RTs tended to decrease with increase in per cent correct. (gradient ± SEM was: -10.74 ± 7.26 ms $\%^{-1}$, $z = 1.44$, $P > 0.1$, for KW; and -15.15 ± 4.00 ms $\%^{-1}$, $z = 3.79$, $P < 0.0001$, for MF). Thus, rather than there being a trade-off, the reverse tended to occur. No correlation was observed between mean RT for an incorrect response and per cent incorrect (gradient ± SEM was 6.57 ± 7.18 ms $\%^{-1}$, $z = 0.91$, $P > 0.2$, for KW; and -4.00 ± 9.59 ms $\%^{-1}$, $z = 0.42$, $P > 0.5$, for MF).

DISCUSSION

As shown by the present experiment, it is possible to elicit qualitative changes in visual discrimination performance by manipulation of stimulus time course alone. When display duration was long, curved-line discrimination performance was smooth and monotonic with curvature parameter s; when display duration was short and effectively limited by a post-stimulus mask, discrimination performance was relatively coarse with s, showing a pronounced central peak. In previous experiments involving similarity judgements of curved lines in texture-like displays, such discontinuities in performance were not observed (Beck, 1973).

It was suggested earlier that, in general, different modes of discrimination performance could be related to different modes of pattern encoding: a coarse, non-monotonic performance could be associated with the operation of discrete encoding processes and a smooth, usually monotonic, performance could be associated with the operation of continuous encoding processes. Some indication of the possible perceptual identity of discrete encodings for curved-line stimuli was obtained in a previous study (Foster, 1983) of curved-line discrimination in which the stimuli were of dimensions similar to those used here. In that study, two explorations of the stimulus range were undertaken: the one using the first half of the full stimulus range and reference values of s set at approximately 0.22-min-arc intervals, and the other using the full stimulus range and reference values of s set at 0.47-min-arc intervals. In the first experiment a peak in discrimination was found at $s = 0.87$ min arc and in the second experiment a peak was found at $s = 1.81$ min arc. These observed performances were congruent with theoretical performances computed from separate labelling data obtained with the labels 'straight', 'just curved', and 'more than just curved'. The peak in performance in the first half of the stimulus range was interpreted as corresponding to a 'boundary' between internal encodings characterized by the labels 'straight' and 'just curved'; the second peak was interpreted as corresponding to a boundary between internal encodings characterized by the labels 'just curved' and 'more than just curved'. In the present experiment, the peak in discrimination performance obtained with short effective display duration (i.e. 100 ms with post-stimulus mask) occurred at or close to $s = 1.71$ min arc. Because the range of variation of s and the sampling density of reference values were also similar to those used in the previous experiment (Foster, 1983) with the full stimulus range, it seems reasonable to suppose that the putative discrete encodings of the present experiment were also characterized by the labels 'just curved' and 'more than just curved'. It should be noted, however, that in general these characterizations and presumably the corresponding boundaries between internal encodings are not fixed and may vary with the overall sizes of the stimuli and the effective complexity of the display.

Encoding by successive approximations

The occurrence of different modes of discrimination performance depending on stimulus time course may result from an internal encoding process that acts in an iterative fashion analogous to the 'successive approximation' procedures used in some electronic digital-to-analogue signal-conversion devices. Suppose that in any particular pattern discrimination task there is a large, but finite, set of internal labels available for the internal representations of the various stimuli. Let A be a set of subpatterns (such as that in Fig. 1b) and let J be the finite set of available internal labels. The process of encoding defines a mapping from A to J, so that A can be subdivided into subsets, each subset a_j comprising all those subpatterns that are assigned the same label j. The collection of all subsets a_j formed in this way defines a partition of A. In the present case the assignment of a particular subpattern to a subset must be considered a probabilistic rather than a deterministic event; that is, each subpattern is assigned a given label with a certain probability (Foster, 1979, 1980a). The notion of the partition of a set can, however, be extended to the probabilistic case (see for instance Cornfeld *et al.*, 1982, Appendix 1). Let $N(a_j)$ be the number of subsets forming the partition; this number determines the fineness of the encoding. Thus, a discrete encoding should be characterized by small values of $N(a_j)$, whereas a continuous encoding should be characterized by large, but finite, values of $N(a_j)$, the latter limited only by the spatial sampling characteristics of the retina.

The process of pattern encoding can be thought of as a dynamical process (compare Massaro, 1975, Chapter 18; Lupker and Massaro, 1979) that in an interval of time Δt performs a sampling of the stimulus and from this sampling constructs an internal representation of the stimulus. In the sense that the representation captures certain properties of the stimulus, it may be regarded as an 'approximation' of some full description. When the duration of the display is short, few iterations of this sampling operation can occur and the resulting internal representation therefore defines a poor approximation of the stimulus; when the duration of the display is increased, a greater number of iterations can be applied and the resulting internal representation then defines a better approximation. In this way, successive iterations determine finer encodings, so that the sharp peak in discrimination performance obtained with short-duration displays becomes less pronounced as the duration of the display is increased, the limit of this sequence being a smoothly varying dependence.

For a smoothly varying discrimination performance, the form of the variation then depends strongly on the nature of the parametrization. In the present experiment, if the discrimination step $2ds$ were allowed to increase with the parameter s, the decline in performance with long-duration displays might be reversed. For short-duration displays, less effect on performance, at least in the position of the peak, would be anticipated (compare discrimination performances of 3-dot figures in Foster, 1979 and 1982b).

The time required for each iteration of this hypothesized approximation process depends on factors such as the number and the type of subpatterns present in the display. For sufficiently complex configurations and types of subpattern, a post-stimulus mask may not be necessary to limit effective stimulus duration, although in this experiment the presence of a mask was needed to clearly elicit discrete discrimination performance.

There are superficial analogies between the successive approximation scheme and the multiple resolution scheme proposed by Koenderink (1984) for the structural description of images. In the present case, however, the variation of resolution with time was monotonic, and, for any given display time course, performance was presumably determined by the finest level of resolution available with little or no contribution from coarser levels of the representation.

Generality of discrete modes of discrimination

In addition to discrete modes of discrimination performance obtained with curved-line displays, discrete modes of discrimination performance have been found with 3-dot figures when the collinearity of the dots was varied (Foster, 1979, 1982b), and with chevron figures when the angle between the connecting lines was varied (Foster, 1980b). For 3-dot figures the discontinuities in discrimination performance were tentatively interpreted as evidence for the operation of discrete encodings related to the labels 'collinear' and 'non-collinear', and, for chevron figures, for the operation of discrete encodings related to the labels 'acute' and 'obtuse'.

These results have formal similarities to the findings by Caelli and Julesz (1978) and Caelli *et al.* (1978) in experiments on the discrimination of textures with identical second-order statistics. These texture displays were presented for 50 ms. Most of the texture pairs were indistinguishable from each other, but micropatterns with properties of 'quasi-collinearity', 'corner', and 'closure' could be discriminated among a set of micropatterns with identical second-order statistics. Caelli and Julesz (1978) and Caelli *et al.* (1978) proposed that there existed a class of detectors for quasi-collinearity, corner and closure (and other possible geometrical features) that might be the fundamental units for detecting figure from ground (but see Julesz, 1981, for further discussion).

The importance of simple geometrical features in determining the discriminability of texture-like displays has also been shown in other experiments on perceptual grouping effects, particularly in peripheral vision. Beck and others have shown that variables such as differences in the slopes of the lines forming the display elements may be more effective in producing similarity grouping than differences in the arrangement of the component lines (Olson and Attneave, 1970; Beck, 1972; Beck and Ambler, 1972, 1973; see also Bergen and Julesz, 1983). Beck proposed that simple features such as line slope and line location could be linked to form textural units that affected textural segmentation by modifying the salience of existing features differences and introducing new feature differences (Beck, 1983; Beck *et al.*, 1983; compare Julesz, 1981).

There are, however, important differences, both in methodology and in the underlying processes tested, between these texture-discrimination measurements and the present and previous experiments using the pattern-perturbation technique. In the pattern-perturbation experiments the number of subpatterns in the field was small and never exceeded four, presentation was always foveal, and discrimination was always performed pairwise at steps along a continuum of shapes. Apart from the obvious differences between these simple, sparse displays and dense, textured fields, the method of testing discrimination, used for example by Caelli and Julesz (1978) and Caelli *et al.* (1978), was designed to emphasize the discriminability of patterns differing in the presence or absence of some structural feature rather than the discriminability of patterns with common structural features that varied smoothly along some parameter range.

Because of the spatial density of textural elements and their role in forming the surfaces of objects in a natural environment, the corresponding internal encodings may not be the same as those associated with the contours defining the boundaries of objects, although the former may give rise to the latter (compare Marr, 1982, pp. 93–96). The discrete and continuous encodings investigated here by the pattern-perturbation technique may have more relevance for foveal contour discrimination in natural scenes. Discrete modes of operation may be used to detect basic features of the environment glimpsed during fixational pauses as the eye moves over the scene, and continuous modes may provide a finer analysis when the gaze in directed to local regions of interest.

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