Segmenting Textures of Curved-Line Elements

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Abstract

Performance in a segmentation task was measured for a variety of briefly presented textures composed of curved-line elements. It was found that the threshold increase in curvature required for reliable segmentation performance showed a dependence on background curvature similar to that for the *discrimination* of two curved lines. The form of this threshold dependence for segmentation was robust under changes in texture-element orientation and positional jitter. For textures of vertically oriented elements, variations in segmentation performance with background- and target-element curvature were well predicted by a model in which curved-line elements received a discrete representation in magnitude ("straight", "just curved", "more than just curved") and sign ("curved left", "curved right"). For textures of randomly oriented curved-line elements, a marked asymmetry was found in segmentation performance: targets comprising highly curved lines on a background of straight lines were much easier to segment than targets comprising straight lines on a background of highly curved lines. These data and additional computer simulations are shown to reject some traditional explanations of texture segmentation, including those based on local-luminance and on local-orientation differences. It is argued that the representation of curvature information in textures of curved-line elements is based upon the pre-attentive assignment of one of a few curvature labels to each element, each label associated with magnitude and direction information.

1 General Introduction

The "micropattern" texture, in which a foreground and background region contain a number of copies of different texture elements, has been a popular stimulus for studies of texture segmentation (Caelli and Julesz 1978; Gurnsey and Browse 1987; Landy and Bergen 1991). The "texton" theory of Julesz (Julesz 1981, 1984) explained the pre-attentive segmentation of this class of visual textures by suggesting that foreground and

background could be easily distinguished only if the density of a specific set of features – the "textons" – was different in the two regions. The texton theory was later criticized by Nothdurft (1990), who argued that many aspects of texture segmentation apparently explained by texton density differences could be attributed to differences in the luminance or spatial-frequency content of the segregated image regions. One of Julesz's textons, element orientation, proved to be robust under Nothdurft's tests, although Nothdurft (1990) qualified the description of orientation as a texton by noting from his earlier work (Nothdurft 1985b) that local changes in orientation, rather than global differences in region orientation content, provided the most useful information about texture boundaries.

Several models of texture segmentation have emphasized the role of orientation information by modelling the segmentation process as a series of operations performed on the outputs of orientation- and spatial-frequency-tuned filters (Fogel and Sagi 1989; Rubenstein and Sagi 1990; Malik and Perona 1990; Landy and Bergen 1991). None of these models, however, has been able to capture fully all aspects of human performance in texture-segmentation tasks. A particularly problematic class of micropattern textures for such channel-based segmentation models has been the class of textures which comprise simple line figures, such as "L"s, "T"s, "X"s and "+"s. This class of micropattern textures is broadband in both orientation *and* spatial frequency, so complex problems of channel combination must be solved if these textures are to be successfully segmented by multiple-channel models (Landy and Bergen 1991). A further complication has been the existence of performance asymmetries, when the segmentation of a particular micropattern combination depends on which of the pair is foreground or background (Gurnsey and Browse 1987, 1989). These asymmetries have posed problems for segmentation models based on local spatial filtering (Gurnsey and Browse 1989; Malik and Perona 1990; Rubenstein and Sagi 1990).

In psychophysical studies of texture segmentation various quantitative measures of the "segmentability" of textures have been adopted. Some have given demonstrations of textures that "do" or "do not" segment (for example, Nothdurft 1990). Other approaches have included judging whether the two halves of a micropattern texture appear "the same" or "different" (Caelli and Julesz 1978), measuring the effects of different levels of masking on target-region shape discrimination (Nothdurft 1985a; Landy and Bergen 1991), and measuring the effects of masking on target-region localization (Gurnsey and Browse 1987). Few authors have measured thresholds for texture segmentation as a function of differences between target and background elements, the properties of which can be located on a suitable continuum. Such an approach is useful for two reasons. First, segmentation data can be compared directly to discrimination data for individual stimuli parameterized in the same way. Second, differences between target and background are not limited to those that can be characterized by the presence or absence of a particular binary feature, such as a texton, but may assume a range of values, thus allowing a threshold difference to be properly determined. This approach provides information about both the identity and the magnitude of the micropattern differences that are important for texture segmentation.

A spatial parameter that has been neglected in psychophysical studies of texture segmentation is contour curvature, perhaps because of the discouraging evidence of Beck (1973) that line curvature was a poor cue for similarity grouping. Nevertheless, there is agreement that curvature is an important image parameter, particularly for shape discrimination (Attneave 1954; Hoffman and Richards 1984; Richards *et al.* 1986), and there have been many studies of aspects of contour-curvature *discrimination* (Ogilvie and Daicar 1967; Andrews *et al.* 1973; Watt and Andrews 1982; Foster 1983; Watt 1984; Wilson 1985; Ferraro and Foster 1986; Watt 1987; Wilson and Richards 1989; Foster *et al.* 1992). Physiological interest has centred on the question of whether curvature sensitivity is the result of the action of specialized neurones for curvature processing or simply a consequence of orientation sensitivity (Hammond and Andrews 1978; Dobbins *et al.* 1987, 1989; Versavel *et al.* 1990). The question of how curvature-sensitive mechanisms might be constructed from combinations of orientation-sensitive mechanisms has also been addressed in psychophysical studies (Blakemore and Over 1974; Wilson 1985; Wilson and Richards 1989).

Another question pertinent to curvature processing is the possible "discrete" or "categorical" representation of curvature in briefly presented displays (Foster 1983; Ferraro and Foster 1986; Foster and Cook 1989). It has been suggested that in such a representation a curved line is given a discrete label, such as "straight" or "curved", and any further processing of the image has access only to this label information. The implication of this type of representation for texture segmentation is that a given image region could be characterized by the dominant label of the texture elements within it, and segmentation would thus follow automatically. Categorical theories of curvature processing may be related to the "two-process" theories of curvature processing that have been suggested by a number of authors (Watt and Andrews 1982; Wilson and Richards 1989; Versavel et al. 1990).

This study of the segmentation of textures of curved-line elements addressed three questions. First, can psychophysical performance for this class of textures be explained by existing models of texture segmentation? Second, does the processing of such textures demand specialized curvature-sensitive mechanisms? Third, is there evidence of a categorical representation of curvature in the analysis of these textures? Segmentation performance was measured for human subjects who viewed textures of curved-line elements, and performed a target-region shape-discrimination task similar to that used by Nothdurft (1985a). Experiments determined the relationship between curved-line-element texture segmentation and two-curved-line discrimination, the variation in segmentation performance due to texture-element changes that did not affect curvature cues, the importance of the direction of curvature of the texture elements, how curvature-labelling information might be used by segmentation mechanisms, and, finally, the relationship between element curvature and orientation in determining segmentation performance.

2 General Methods

2.1 Stimuli and Apparatus

Each stimulus consisted of a square array of 100 (10×10) curved-line elements. This array subtended 5×5 deg or 7×7 deg of visual angle. Within the array a horizontally or vertically oriented rectangular target patch of eight (4×2) elements was defined. All of the elements within the target patch had the same curvature, but this curvature was different from (either more or less than) that of the elements in the remainder of the array (the "background"; see figure 1). The elements themselves were generated by interpolation between a straight line and a circular arc, and were thus elliptical arcs. Element curvature was defined in terms of a parameter s (the "sag"), which corresponded to the angular distance in minutes of arc visual angle between the mid-point of the chord and the centre of the curve (see Foster 1983). This method of curved-line generation produces a very close approximation to true circular arcs (within 3% for the stimuli used here), and has the theoretical advantage of being directly related to the cue for curved-line discrimination (Foster *et al.* 1992).

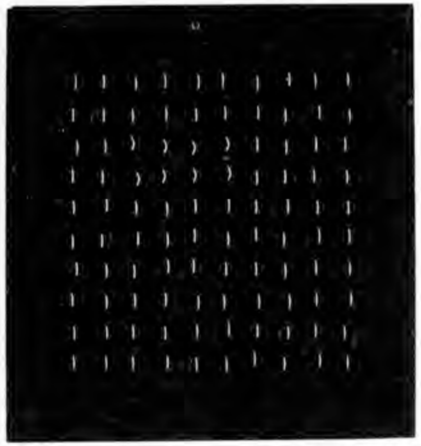

Figure 1: *Example of a curved-line-element texture (see Section 3). The entire array subtended 5×5 deg of visual angle, element chord size was 0.2 deg, background-sag value 0.43 arcmin, target-sag value 2.14 arcmin, and maximum positional jitter ±0.05 deg (±10% of mean element separation). The correct response for this stimulus would be "target horizontal".*

Stimuli were white and appeared superimposed on a uniform white 30×35 deg background with a luminance of approximately 40 cd m^{-2}. At the beginning of each experimental session, the intensity of the stimuli was adjusted by the subject (using a neutral density filter) to be ten times the luminance increment threshold, so that the stimuli were adequately suprathreshold, but not so bright as to produce noticeable afterimages.

Stimuli were presented on the screen of an X–Y display oscilloscope (Hewlett-Packard, Type 1321A) with a P4 sulfide phosphor (decay time approximately 100μs). Experiments were controlled by a laboratory microcomputer through 12-bit DACs and a vector-graphics true-line generator (Sigma Electronics System QVEC 2150). Each curved-line element was drawn within a patch of 1024×1024 endpoint resolution and total extent 24×24 arcmin on the screen. The screen was viewed binocularly at a distance of 170 cm through a view tunnel and optical system that produced the uniform background field.

The curved-line elements each had a constant chord length of either 0.2 deg or 0.4 deg (the reasons for this choice of values are discussed later), and each consisted of eight concatenated straight-line segments or nine adjacent spots. Over the range of curvatures used, the curved-line elements appeared smooth to the eye (spot size 1.3 arcmin, full width at half height). Stimulus presentation time was nominally 100 ms, which corresponded to five refreshes of the display oscilloscope (refresh rate 50 Hz). In some experiments, stimulus presentation was followed by a 500-ms masking stimulus, which consisted of a sampled superposition of target and background elements.

2.2 Subjects

There were in all 14 subjects, each of whom had good acuity (Snellen 6/5 or better) and either fully corrected or no astigmatism. The subjects were paid volunteers and one of the authors (DRS); ages ranged from 19 to 48 yr.

2.3 Procedure

Subjects fixated a central fixation target and, when ready, initiated a trial by pressing a button on a button-box connected to the computer. After a 40-ms delay the stimulus appeared for 100 ms and was followed by a 100-ms blank field, after which the screen either remained blank or the masking stimulus appeared (see above). Subjects maintained central fixation during the presentation period, after which they indicated the orientation of the target patch (either horizontal or vertical) by pressing one of two buttons on a second button-box. The fixation target reappeared after a short delay, signalling that the next trial could be started.

2.4 Experimental Design and Data Analysis

Details are given in the appropriate sections.

3 A Comparison Between Curved-Line-Element Texture Segmentation and Two-Curved-Line Discrimination

Several studies have suggested that curvature discrimination in briefly presented displays is a categorical process (Foster 1983; Ferraro and Foster 1986; Foster and Cook 1989), in that there is an underlying discrete representation of the curved-line continuum. The interpretation of categorical processing (Wood 1976) was based on the presence of sharp peaks and troughs in the plot of increment threshold against stimulus magnitude, and the correspondence of those extrema with the predictions of separate curved-line labelling experiments (Foster 1983). The purpose of the experiments in this section was to determine if arrays of curved-line elements forming textures were processed in a similar discrete way. Measurements of increment threshold for the segmentation of textures of curved-line elements were thus compared with those for the simple discrimination of two curved lines.

3.1 Methods

3.1.1 Segmentation

Stimuli for the segmentation task were generated as outlined in the General Methods section, with curved-line elements formed from eight concatenated straight-line segments. Target-element sag values were always greater than background-element values. For a background sag of s, $s > 0$, target element sag was $s + ds$, $ds > 0$, and thus all elements curved in the same direction (as in figure 1). Chord sizes were 0.2 deg and 0.4 deg, and seven values of background sag were used (0.0, 0.43, 0.86, 1.28, 1.71, 2.14 and 2.57 arcmin for the 0.2 deg chord elements, and 0.0, 0.86, 1.71, 2.57, 3.43, 4.29 and 5.14 arcmin for the 0.4 deg elements). The field size was 5×5 deg for the 0.2 deg chord stimuli and 7×7 deg for the 0.4 deg chord stimuli. Luminance cues to segmentation were disrupted by giving each curved-line element a small amount of random positional jitter, with a maximum value of 0.05 deg, corresponding to 10% and 7% of the average element separation for the 0.2 deg and 0.4 deg chord sizes respectively. Elements were always vertically oriented. Stimulus presentation time was 100 ms with no poststimulus mask.[1]

Data were collected in blocks of 70 trials, preceded by seven practice trials. In each trial the background-sag value was randomly selected from the seven fixed values, but the target-sag value was chosen by an adaptive routine (PEST; Taylor and Creelman 1967; Hall 1981). In each block there were ten trials for each background-sag value. Chord size was randomized between, but not within, blocks. Subjects took approximately five minutes to complete each block, and normally completed eight blocks of trials in a one-hour session. After 16 blocks of trials had been completed, each of the eight subjects had obtained data for 14 psychometric functions (one for each background-sag and chord-size combination), each function based on 80 trials. Each of these sets of data was fitted by a quadratic function, after transformation of the proportion-correct scores by the inverse of a cumulative-Gaussian function. The threshold value was taken for a performance level of 75% correct. A "bootstrap" procedure (Foster and Bischof 1991) was used to estimate the standard deviation on each threshold value. These standard deviations were used to calculate weighted means and standard deviations when averaging over subjects.

3.1.2 Discrimination

In a parallel series of measurements, sag increment thresholds were determined for the discrimination of two curved lines. The task was a spatial two-alternative forced choice (2AFC): subjects were asked to indicate the position ("left" or "right") of the more curved of the curved lines. The curved lines were presented each side of a central fixation cross, at an eccentricity of 1.4 deg. Stimulus duration was 100 ms. Stimulus presentation was followed, after a 100-ms delay, by a 500-ms presentation of a masking stimulus of five randomly oriented straight lines. Curved lines were similar to the curved-line texture elements used in the segmentation experiments, except that each was formed from 12, rather than eight, concatenated straight-line segments. The minor differences in experimental procedure and methods of curved-line generation in the segmentation and discrimination experiments were caused partly by hardware limitations, and partly by the requirements of consistency with other curvature-discrimination experiments. The curved lines in the discrimination experiments were always vertically oriented and were not positionally jittered. Thresholds were obtained for the same range of reference curvatures and chord sizes as in the segmentation experiments.

3.2 Results

Figure 2a shows sag increment thresholds for texture segmentation and for two-curved-line discrimination as a function of background- or reference-sag value. Each point is a weighted combination of the thresholds from the eight subjects. The peaks and troughs in the two sets of data are almost exactly coincident, although there is an evident increase in threshold values of just under 1 arcmin for the segmentation task. Figure 2b shows corresponding data for the larger chord size of 0.4 deg. The threshold minimum in the discrimination data is again coincident with the minimum in the segmentation data, but segmentation thresholds appear to saturate for background-sag values greater than 2.57

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[1] A poststimulus mask was used in later experiments (see Sections 5 and 7), for consistency with other studies of texture segmentation. In a control measurement, however, sag increment thresholds for segmentation under the present conditions were found to be independent of whether the mask was used.

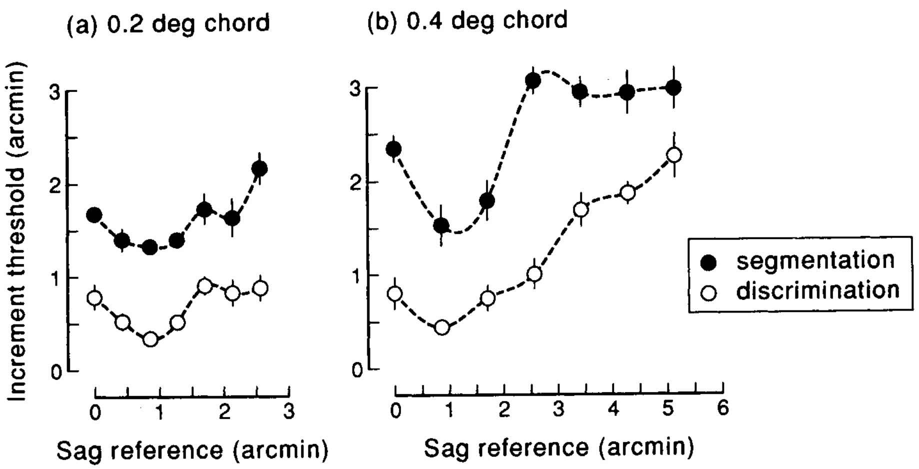

Figure 2: *Sag increment thresholds for curved-line-element texture segmentation (filled circles), and two-curved-line discrimination (unfilled circles), plotted as a function of background or reference sag. Increment threshold corresponds to the increase in sag of the target element or elements (relative to the reference or background elements respectively) required to obtain a performance level of 75% correct. Data points and standard errors are weighted means of thresholds from eight subjects: (a) 0.2 deg chord stimuli, (b) 0.4 deg chord stimuli.*

arcmin. Notice that the peaks in performance (threshold minima) in all four experimental conditions occur at the same value of background or reference sag, namely 0.86 arcmin.

3.3 Discussion

3.3.1 Categorical Segmentation?

Evidence for categorical processing in curved-line discrimination in early vision has been presented elsewhere (Foster 1983; Ferraro and Foster 1986; Foster and Cook 1989). The existence of similar peaks and troughs in the dependence of sag increment threshold on background sag in texture segmentation suggests the possibility of similar categorical processes subserving performance. The lowest thresholds for texture segmentation and curved-line discrimination for both chord sizes occurred at or close to background- or reference-sag values of 0.86 arcmin, which corresponds very closely to the location of one of the peaks in discrimination performance for a slightly different curved-line discrimination task (Foster 1983, Fig 2b). The increase in thresholds on each side of this minimum suggests (Foster 1983) a transition between curved-line categories, the two boundaries of which are close to 0.86 arcmin.

This putative process of segmentation by categorization, which from now on will be called *categorical segmentation*, cannot adequately account for two aspects of the threshold data shown in figure 2. First, if there is only one curved-line category boundary, and it is located at a sag value of about 0.86 arcmin, the segmentation of textures with background sags greater than this value should become increasingly difficult as the probability of the background and target texture elements being assigned to different categories becomes smaller and smaller (Foster 1983; Ferraro and Foster 1986). As shown in the upper graph of figure 2b, sag increment thresholds were approximately constant for background sag values of 2.57 arcmin and larger, and therefore some other segmentation mechanism, perhaps one sensitive to element orientation content, must be involved, at least when background-sag values are large. Second, target-sag values for segmentation threshold were always higher, by about 1 arcmin, than those for discrimination threshold. It has been shown, by means of a computer model based on segmentation by luminance cues (Simmons *et al.* 1991), that this threshold difference is difficult to explain purely in terms of categorical segmentation if only two curved-line labels (for example, "straight" and "curved") were available to the observer; that is, segmentation performance should be as good, if not better, than discrimination performance. If a two-category labelling process did underlie the segmentation of these curved-line-element textures, then there must exist differences between the labelling probabilities for isolated and embedded curved-line elements of a given sag value. A further complicating factor may have been the possible variation in labelling probability with element eccentricity. Some of these issues are considered in more detail later, when the role of categorical processing in segmentation performance is examined more directly (see Section 6).

3.3.2 Element Orientation Content

When there exists a sag difference between two curved lines curved in the same direction and of equal chord lengths, there also exists a difference in their orientation contents (the range of angles turned through by a tangent to the curve moving along the curve). Thus when the chords of all the curved-line elements in a texture are aligned (as in figure 1)[2] orientation-tuned mechanisms should respond differently to target and background regions, and could therefore subserve segmentation performance. (For related material on the role of orientation cues, see Watt 1992.)

It has been shown elsewhere that differences in orientation content are, in fact, a poor cue for isolated curved-line discrimination when presented for long durations (Foster *et al.* 1992). A further argument against differences in orientation as the cue for segmentation is based on the coincidence of the threshold minima in the data shown in figure 2. If orientation differences were the cue for segmentation or discrimination then the positions on the curved-line continuum of any peaks and troughs in performance should scale with the size of the curved lines. Specifically, doubling the chord size from 0.2 deg to 0.4 deg should have resulted in a shift of the threshold minimum to a larger value (approximately twice the size) of the background sag. There was no such shift, suggesting that differences in curved-line orientation content were unlikely to have been the primary cue for either curved-line-element texture segmentation or two-curved-line discrimination in these experiments.

It may be possible to manipulate a texture-segmentation model operating solely on the outputs of orientation- and spatial-frequency-tuned filters so that it accounted for the stability of the positions of the threshold minima in the curved-line-element texture-segmentation data. One possible mechanism for this might be a normalization scheme similar to that described by Gurnsey and Browse (1989). The more parsimonious explanation based on categorical processing of curved-line sag will be discussed later.

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[2] Note the difference between the orientation of the curved-line element itself, which is taken to be the orientation of its chord and is independent of the sag value, and the orientation *content* of the element, which is dependent on both the orientation of the chord and the sag value of the element; the *range* of orientations contained in the element will not vary with chord orientation.

4 Effects of Positional Jitter and Element Rotation

All of the curved-line textures used in the experiments of Section 3 contained vertically oriented elements which had a maximum positional jitter of ±0.05 deg. The experiments presented in this section investigated to what extent segmentation increment thresholds were independent of element orientation and array regularity.

4.1 Methods

Two sets of experiments were performed in parallel. In the first set, maximum positional jitter was kept the same at ±0.05 deg (±3 arcmin; ±10% of mean element separation), but element orientation was allowed to assume four different values: vertical, horizontal, right-oblique (−45 deg) and left-oblique (+45 deg). The curved-line elements in these textures were always aligned, and orientation was randomized between, but not within, presentation blocks (within-texture randomization of orientation is considered in Section 7). In the second set of experiments, the maximum positional jitter of each element was 0.0 deg, ±0.05 deg, or ±0.10 deg, corresponding to 0%, ±10%, and ±20% of the mean element separation, but element orientation was fixed at either vertical or left-oblique.

As in Section 3, data were collected in blocks of 70 trials, preceded by seven practice trials; in each trial the background-sag value was randomly selected from the seven fixed values, but the target-sag value was chosen by a PEST routine, and in each block there were ten trials at each background-sag value. The eight experimental conditions consisted of all four orientation conditions at the intermediate value of maximum jitter (±0.05 deg) together with vertical and left-oblique orientation conditions at the other two maximum jitter values. Subjects normally completed eight blocks of trials in a one-hour session, one block for each condition in a random order. After 64 blocks of trials had been completed, each of the eight subjects had obtained data for 56 psychometric functions (one for each combination of background sag and experimental condition), each function based on 80 trials. Each of these functions was analysed as described in Section 3, and the threshold values obtained were similarly combined.

Stimulus presentation methods were also the same as in Section 3, except that the curved-line elements were made up of nine spots rather than eight vectors. This modification ensured that the total luminance content of each element was independent of its orientation.

4.2 Results

Figure 3 shows segmentation increment-threshold functions for the four orientation conditions. Threshold values and standard errors are weighted means from eight subjects. The graphs for all conditions except the right-oblique show a minimum threshold value for background-sag values of either 0.43 arcmin or 0.86 arcmin. Thresholds for textures with oblique elements were always higher than those for textures with vertical or horizontal elements. Figure 4a shows the effect of different levels of positional jitter on segmentation increment thresholds for textures of vertically oriented elements. Similar results are shown in figure 4b for textures with left-oblique elements. The thresholds in figure 4b show the expected U-shaped dependence on background sag at all values of positional jitter, although the position of the threshold minimum does vary with jitter, moving from 0.43 arcmin to 0.86 arcmin as jitter increases.

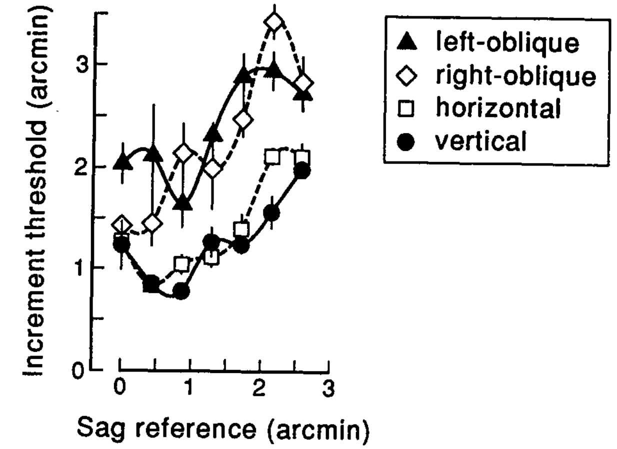

Figure 3: *Sag increment thresholds for curved-line-element texture segmentation plotted as a function of background-sag value for four different element orientations: vertical (filled circles), horizontal (unfilled squares), right-oblique (unfilled diamonds), left-oblique (filled triangles). The chord size was 0.2 deg. The maximum positional jitter of the elements was ±0.05 deg (±10% of mean element separation). Data points and standard errors are weighted means from eight subjects.*

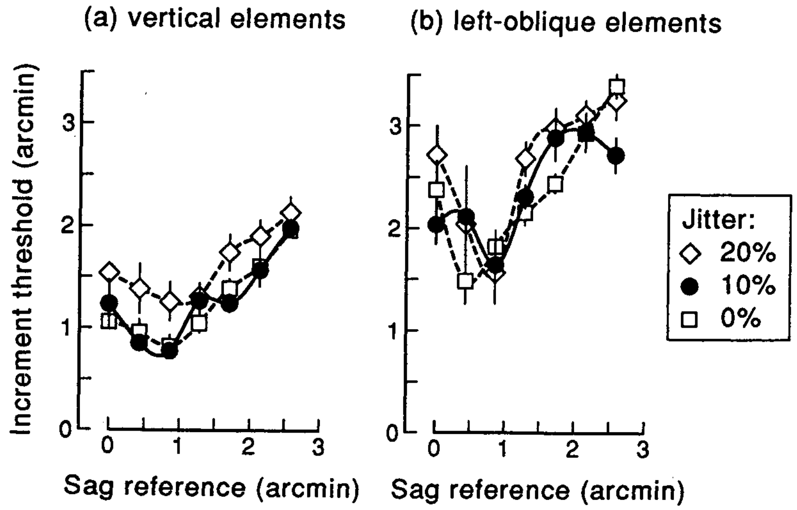

Figure 4: *As figure 3, but for (a) textures of vertical curved-line elements, and (b) textures of left-oblique curved-line elements, at three values of maximum element positional jitter: 0.0 deg (0% of mean element separation; unfilled squares), 0.05 deg (10% of mean element separation; filled circles), and 0.1 deg (20% of mean element separation; unfilled diamonds).*

4.3 Discussion

The form of the increment-threshold function for segmentation did not change with variations in jitter and orientation of the curved-line elements, and in all conditions, except one, there were clear performance peaks (threshold minima) at background-sag values between 0.43 arcmin and 0.86 arcmin. The positions of these peaks, however, did vary with jitter and orientation: threshold minima shifted towards larger values of background sag at larger jitter values, and textures of oblique curved-line elements were more difficult to segment, for a given sag difference, than those of vertical or horizontal curved-line elements. Results for the 10% jitter condition were similar to those from Section 3, suggesting that the different method of curved-line generation (spots rather than vectors) made no significant difference. Thresholds were highest for the largest value of jitter, but the basic shape of the threshold dependence was preserved over all jitter values.

Nothdurft (1990) suggested that the validity of a particular texture-element attribute as a cue for segmentation should be questioned if segmentation by means of this cue could be disrupted by modifications of the texture that did not directly change the cue value. For example, if performance in a segmentation task were based on orientation differences, then random variation in the luminance of the texture elements should not affect the segmentability of the texture. But the fact that image segmentation by orientation differences in the *absence* of global luminance differences is possible, does not necessarily imply that segmentation performance should be the same when luminance cues are present in addition to the orientation cues. Luminance cues themselves could provide alternative valid segmentations of the image, as Nothdurft's own demonstrations have indicated (Nothdurft 1990), although he was careful to reduce the impact of luminance cues as far as possible. Complex questions of cue combination and competition must therefore be addressed before a candidate cue for segmentation is rejected on this basis.

The fact that curvature increment thresholds for segmentation were influenced by positional jitter of the elements does not imply that curvature cues were not used to perform the segmentation. Positional jitter may have introduced additional segmentation cues such as luminance edges that accidentally raised or lowered segmentation thresholds by increasing or reducing the visibility of the texture edges that were already present. The importance of luminance cues to segmentation in textures of curved-line elements, and how these cues are disrupted by element positional jitter, was further investigated in the series of computational control experiments presented in Section 8.

With regard to variations in segmentation performance with element orientation, a number studies have shown that there exists an "oblique effect" for curvature discrimination (Ogilvie and Daicar 1967; Watt and Andrews 1982; Wilson 1985), in that increment thresholds are higher for oblique than for vertical or horizontal curved lines. A reduced segmentation performance with textures of oblique curved-line elements was therefore not surprising. The existence of an oblique effect for curvature discrimination has been used to argue for a representation of curvature information solely in terms of the outputs of orientation-tuned filters (Wilson 1985), but in view of the general decline in discrimination performance along oblique axes it is also possible that more direct representations of curvature could lead to orientation anisotropies, especially if such anisotropies are a consequence of the organization of these representations about horizontal-vertical axes (see Kahn and Foster 1986; Foster 1991, also Foster and Ward 1991b).

The presence of increment-threshold minima at levels of background sag between 0.43 arcmin and 0.86 arcmin for all but one of the eight experimental conditions here is consistent with an explanation based on the categorical segmentation of curved-line textures. The anomalous threshold dependence found for right-oblique elements may represent a sampling problem in that the category boundary may have been between the background-sag values 0.43 arcmin and 0.86 arcmin, so that no clear minimum was detected. If segmentation performance was determined by categorical processes, then, for certain fixed values of the background curved-line sag, it should be possible to detect rapid changes in discrimination performance as the target-sag value crossed from one putative category to another. This behaviour over large variations in target-sag values was explored as part of the following experiment.

5 Effects of Sag Decrements

The experiments described in Sections 3 and 4 were restricted to measurements on textures of curved-line elements with sag values equal to or greater than those of the background. If a division of the curved-line continuum into discrete categories is valid, then performance should be independent of which category is dominant in the target or the background region, and should depend only on whether these categories are different. It is not clear, however, whether curved lines pointing in opposite directions receive different codings, and how such codings might be related to the magnitude of the curvature. In the following experiment, sag increments were allowed to take negative as well as positive values, resulting in textures in which target-sag values were sometimes less than background-sag values, and some elements curved in opposite directions, as shown in figure 5. This extension to the range of sag values also resulted in the interesting situation of target and background containing elements with precisely the same sag values but of opposite signs. This situation provided a further test for texture segmentation models sensitive only to contour orientation differences, for both target and background elements contained the same range of orientations.

5.1 Methods

The adaptive PEST method for setting target-element sag was replaced by a method of constant stimuli, because of the possibility of the stimuli yielding non-monotonic psychometric functions. A post-stimulus mask was also introduced (see Note 1). Data were obtained from a smaller group of subjects and over a longer period of time than in the experiments of Sections 3 and 4, so that within-subject trends could be more easily followed over the larger range of conditions.

Data were collected in blocks of 250 trials. Each block contained 25 presentations of each of the ten background-sag values (0.0, 0.43, 0.86, 1.28, 1.71, 2.14, 2.57, 3.0, 3.43, 3.86 arcmin). The 20 target-sag values were positive-and-negative values taken from the same set of magnitudes as the background-sag values. These 20 target-sag values for each background-sag value were spread across four separate blocks of trials so that only five target-sag values were used for a given background-sag value in a given block. The distribution of target- and background-sag values within each block was organized such that each of the 20 possible target-sag values was presented approximately the same number of times. Each block took approximately 25 min to complete, and subjects completed two blocks in sessions of one-hour duration. Eight replications of each block by each subject yielded 40 trials at each of the background- and target-sag value combinations.

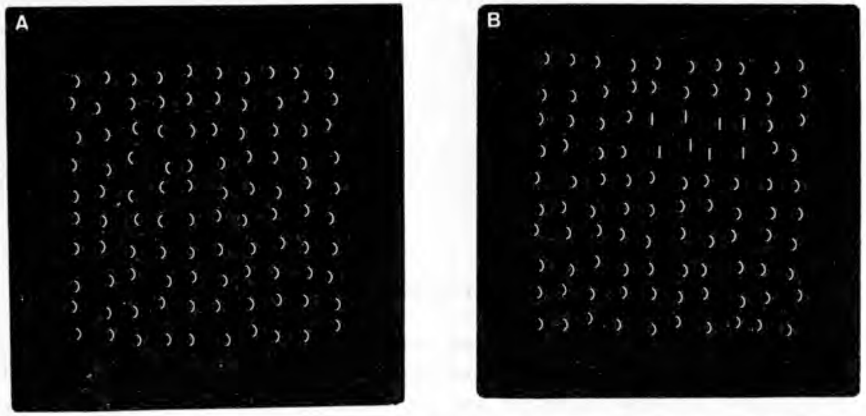

Figure 5: *Examples of curved-line-element textures (Section 5); array and chord sizes are the same as figure 1. (a) Target-sag value −3.86 arcmin, background-sag value 3.86 arcmin. Maximum positional jitter was ±0.1 deg (±20% of the mean element separation). Notice that target and background elements are mirror symmetric. The two subjects scored 80% and 73% correct with this stimulus. (b) Target-sag value 0.0 arcmin, background-sag value 3.86 arcmin. Same positional jitter as (a). Subjects scored 100% and 99% correct with this stimulus.*

Because of the possible very large values of sag increment, a modification was made to the positioning of the curved-lines elements with respect to the underlying texture "matrix". In the experiments described in Sections 3 and 4, the centre of a curved-line element was taken to be the mid-point of its chord. Positional jitter and orientation changes were made in a local coordinate system with the chord mid-point as origin. In the present experiments, which allowed curvature in both directions, this local coordinate origin might have introduced strong luminance cues at the target-region boundary. To reduce such luminance cues, the local coordinate system centre was shifted to the "centre-of-mass" of the curved-lines, which corresponded to a position approximately two-thirds of the distance along the perpendicular bisector of the curved-line element joining the mid-point of the chord to the mid-point of the curved-line element. A randomized positional jitter with maximum values ±0.1 deg (±20% of the mean element separation) was also imposed to disrupt luminance cues further.

5.2 Results

Figure 6 shows, for each subject, the probability of correct performance in the segmentation task as a function of the target-element sag at three representative values of background sag: 0.43, 1.71, and 3.0 arcmin. The piecewise smooth curves are maximum-likelihood linear and quadratic functions (with variable intersections), after transformation by the inverse of a cumulative Gaussian function. Note that the sign of the target-sag value refers to the *relative* direction of background and target elements, so that negative values refer to target elements curving in the *opposite direction* to the background elements (as in figure 5b).

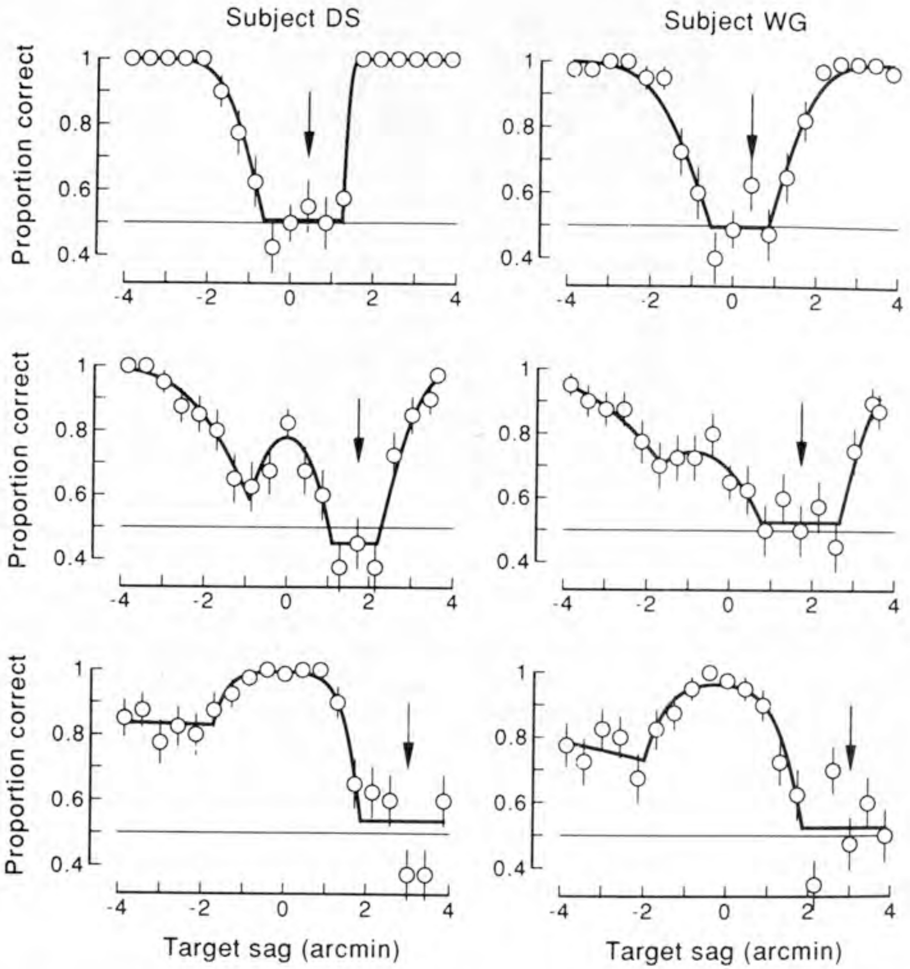

Figure 6: *Proportion-correct performance in the curved-line texture segmentation task for two subjects and three background-sag values plotted as a function of target-sag value. Elements were always vertical. The horizontal line represents chance performance. The vertical arrows indicate the values of the background sag along the continuum. Each data point shows the mean and standard error of 40 trials, assuming a binomial error distribution. The fitted curves are piecewise smooth maximum-likelihood linear and quadratic functions (with variable intersections), after transformation of the proportion-correct data by the inverse of a cumulative Gaussian function. Notice that the sign of the target-sag value refers to the relative direction of background and target elements, so that negative values refer to target elements curving in the opposite direction to the background elements (as in figure 5a). Background-sag values were (top sections) 0.43 arcmin, (middle sections) 1.71 arcmin, (bottom sections) 3.0 arcmin.*

5.3 Discussion

It is evident that segmentation performance does not increase smoothly and monotonically with increase in the difference between target- and background-sag values: there are critical points along the continuum at sag values of approximate magnitudes 0.8 and 1.5–2.0 arcmin where performance accelerates or has an inflexion. These values are remarkably close to the boundary values of 0.87 and 1.81 arcmin reported in the discrimination and categorical labelling of isolated curved lines (Foster 1983).

An explanation of the results in terms of an explicit, categorical representation of curvature in textures of curved-line elements may be formulated as follows, provided that some information about direction of curvature is also included. Suppose (Foster 1983) that there are three curved-line "channels" for a given curved-line orientation: one tuned to straight lines, one to lines that are "just curved", and one to lines that are "more than just curved", and that there are two forms of the second and third channels for the two directions. Suppose also that it is easier to distinguish magnitudes of category labels than their signs, in accordance with the notion of weak sign labels, proposed by Foster (1978) and extended in Kahn and Foster (1986) (see also Foster 1991). When background-sag values are small (0.43 arcmin; figure 6, top), target-sag values in either direction must at least reach the category boundaries, at approximately 1 arcmin and −1 arcmin, before performance is better than chance. When background-sag values are larger (close to 1.71 arcmin; figure 6, middle), target-sag values must be less than 1 arcmin for moderate levels of performance to be obtained, and there is a small *decrease* in performance as the target-sag value passes through the boundary at either −1 arcmin or −2 arcmin. When background-sag values are larger still (3.0 arcmin; figure 6, bottom) performance actually declines at sufficiently large negative values of the target sag, when background and target have the same magnitudes of sag, but different sign. This last result is difficult to interpret in terms of a simple segmentation based on orientation content; for the particular case of the target-sag value of −3.0 arcmin in figure 6 (bottom sections), target and background curved-line elements had identical orientation contents.

Although categorical segmentation appears to provide a plausible explanation for several aspects of performance in the segmentation of textures of curved-line elements, it has not yet been established that the labels assigned in texture segmentation were the same as those used in curved-line discrimination. This issue is addressed in the following section.

6 Target-Region Labelling Experiment

The experiment described in this section made an explicit test of the categorical model of curved-line texture segmentation by requiring subjects to assign curvature labels to the elements within the target region. Labelling performance was then used to predict performance in the 2AFC segmentation task.

6.1 Methods

Methods for the 2AFC segmentation task were the same as for the experiments in Section 5, except that a smaller value of maximum element jitter was used (±0.05 deg; ±10% of mean element separation) to enhance performance levels. Stimuli for the labelling experiment were exactly the same as for the 2AFC task, the only difference between the experiments being that the subjects were given a three-button box, and asked to report the curvature of the curved-line elements in the target region instead of the orientation of the segmented patch. Subjects were asked to push the leftmost button if the elements in the target region appeared to be curved to the left, the rightmost button if they appeared to be curved to the right, and the middle button if they appeared to be straight. In view of the results of the previous experiment, and of Foster (1983), it might be argued that a range of five labels should have been offered, but the purpose here was to keep the demands of the tasks as simple as possible. Some disparity between segmentation performance and the predictions of the labelling model was therefore anticipated at large target-sag values. The full set of 2AFC segmentation data was collected first, followed by that for the labelling task. Both subjects were well practiced in curved-line-element texture segmentation.

6.2 Results

The right-hand column of figure 7 shows one of the subject's proportion-correct responses in the 2AFC segmentation task as a function of target-sag value for three background-sag values. The predictions based on the labelling data are shown in the left-hand column. The predictions were based on the assumption that segmentation was successful if and only if target and background regions were labelled differently.

6.3 Discussion

It is clear from figure 7 that there is good qualitative agreement between 2AFC and labelling data for small (0.43 arcmin) and large (3.0 arcmin) values of background sag, and for the negative part of the continuum at the intermediate background-sag value (1.71 arcmin). A deviation between the labelling and 2AFC data occurred in the positive part of the curved-line continuum, where background and target elements were pointing in the same direction. For the 1.71 arcmin background-sag value, segmentation performance was predicted to be at chance levels, yet the 2AFC data showed a clear improvement in performance with increasing background sag.

The main reason for this disparity between predicted and observed performance was mentioned in the Methods section, namely the need for a third curvature-magnitude category. The evidence from the threshold data in Sections 3 and 4 points to one category boundary at a sag value of about 0.86 arcmin. The proportion-correct data in Section 5 suggested that a second category boundary, at about 1.71 arcmin, was also appropriate. Subjects reported that it was often possible to segment targets with elements of very high curvature (sags of about 4 arcmin) from those of intermediate curvature (sag of about 2 arcmin), even though both were clearly given the label "curved".

A potential general source of disagreement between 2AFC segmentation and labelling data may have been that reported category boundaries were sharper than those truly underlying segmentation performance, for in order to label a target region correctly it was necessary only to identify a single element within that region as being different from the background and label that single element correctly, whereas in order to segment that region considerably more elements (at least three) would have to be correctly labelled. Further quantitative comparison of the data would be better achieved within the framework of a more complete model of segmentation (for example, Proesmans and Oosterlinck 1992). Despite these caveats, it should be noted that labelling data give a good qualitative prediction of several aspects of vertical curved-line-element texture-segmentation performance.

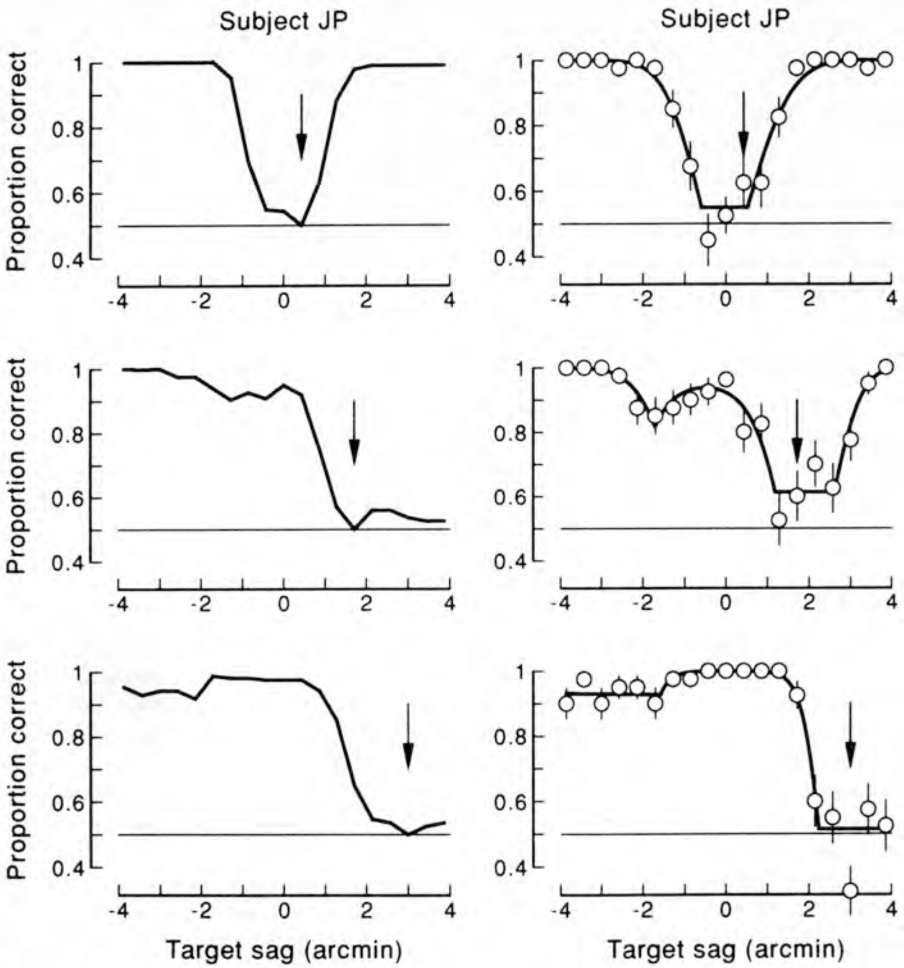

Figure 7: *Similar to figure 6, but with 2AFC segmentation data (right column), and predictions based on labelling data (left column) for one subject (JP). The maximum element jitter was lower than in Section 5 at ±0.05 deg (±10% of the mean element separation). The vertical arrows indicate the values of the background sag along the continuum. Background-sag values were (top sections) 0.43 arcmin, (middle sections) 1.71 arcmin, (bottom sections) 3.0 arcmin.*

The experiments with textures of vertically oriented curved-line elements in Section 5 and this section have indicated the importance of the direction of curvature in the representation of curved lines. The experiments with textures of curved line elements at other orientations (Section 4) showed that sensitivity to curvature differences was reduced at oblique orientations. Physiological studies of curvature-sensitive neurones have indicated that these neurones are sometimes sensitive to both the magnitude and the direction of contour curvature (Hammond and Andrews 1978; Dobbins *et al.* 1987, 1989; Versavel *et al.* 1990). The question that arises is thus: in the segmentation of textures of curved-line elements, to what extent is the representation of curvature independent of the orientations of the elements?

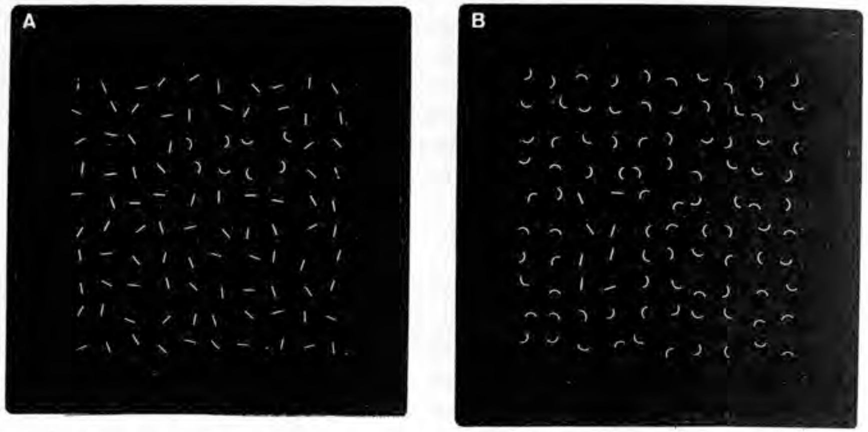

Figure 8: *Example stimuli (Section 7). Array and chord sizes as in figure 1. (a) Target-sag value 0.0 arcmin, background-sag value 3.86 arcmin. Maximum orientation jitter was ±180 deg, maximum positional jitter was ±0.10 deg (20% of the mean element separation). Subjects scored 63% (DS) and 55% (LC) correct with this stimulus. (b) Target-sag value 3.86 arcmin, background-sag value 0.0 arcmin. Other details as in (a). Subjects scored 93% (DS) and 95% (LC) correct with this stimulus.*

7 Textures with Randomly Oriented Curved-Line Elements

With the obvious exception of segmentation by orientation differences, the validity of a particular element attribute as a cue for texture segmentation has been commonly tested with textures of randomly oriented elements (see, for example, Julesz 1981). Measurements of curved-line-element texture segmentation with randomly oriented elements were undertaken to clarify to what extent curvature information is useful for texture segmentation in the absence of orientation cues. Notice that curvature is the space derivative of orientation, and therefore noise in the orientation domain might be expected to interfere with curvature information, leading to reduced performance.

7.1 Methods

Methods were identical to those of Section 5, except that the elements now had a completely randomized orientation (see figure 8).

7.2 Results

Figure 9 shows segmentation performance data for the two subjects at three background-sag values. These background-sag values corresponded to the two limits of the range of sag values used (sag values of 0.0 arcmin and 3.86 arcmin; Figures 9, top and bottom sections) together with one from the centre of the range (1.71 arcmin; figure 9, middle section). There was a clear performance asymmetry. When the target elements were highly curved, and the background elements were straight lines, the target region was easily segmented (target-sag value of 3.86 arcmin; figure 9, top section), but when the target elements were straight lines, and the background elements were highly curved, the target region was much more difficult to segment (target-sag value of 0.0 arcmin; figure 9, bottom section). The two example textures shown in figure 8 illustrate the stimuli that caused this performance asymmetry. Performance levels were considerably lower in these experiments than in those of Section 5: sag increment-threshold values were at least 1 arcmin higher and one subject did not reach threshold performance level for background-sag values of greater than 1.28 arcmin with the range of target-sag values available.

7.3 Discussion

Gurnsey and Browse (1989) argued that asymmetries in visual texture discrimination, in which texture A within texture B is much easier to detect than texture B within texture A, provide *prima facie* evidence against any model of texture discrimination based only on local measurements and comparisons. They proposed that texture-discrimination asymmetries could be explained by assuming that the responses of orientation- and spatial-frequency-selective filters were normalized by the amount to which similarly tuned operators responded elsewhere in the image. As well as adding to the list of asymmetries in texture segmentation (Gurnsey and Browse 1987, 1989), and possibly visual search (Julesz 1981; Beck 1982; Treisman and Souther 1985; Treisman and Gormican 1988; Foster and Ward 1991a, b), the data presented in this section suggest that, if the Gurnsey and Browse (1989) explanation of texture segmentation asymmetries is correct, the responses of *curvature-selective* filters should be similarly normalized across an image.

Results from visual search experiments suggest that visual search for a target that *lacks* a feature among distractors that possess this feature is slower than for a target that possesses that feature among distractors that do not (Treisman and Souther 1985; Treisman 1988; Treisman and Gormican 1988). If curvature is represented in some sort of "feature map" (Treisman 1988), then perhaps the most appropriate labels for the segmentation of textures of randomly oriented curved-line elements are "curved" and "not curved". This type of representation would reduce straightness to being the absence of curvature, and the asymmetry found for this segmentation task would then be consistent with some of those observed in visual search experiments. Such an elaboration of the categorical-labelling model could be related to the Gurnsey and Browse (1989) explanation of asymmetries in segmentation performance in that the meaning of the curved-line label, and possibly also the positions of the category boundaries, might vary if a global normalization of the responses of similarly tuned curvature-selective filters took place.

The fact that the segmentation of textures of randomly oriented curved-line elements was possible provides further evidence that any model of texture segmentation that relies solely on orientation, spatial-frequency, or luminance information is incomplete; curvature information must also be explicitly represented. Yet the increased difficulty that subjects experienced in trying to segment textures of randomly oriented curved-line elements suggests that the representation of curvature is also likely to be directional (that is specifying the orientation and sense of the normal to the chord); therefore the grouping of curved-line elements would be easier when they shared both magnitude and direction of curvature, rather than magnitude of curvature alone.

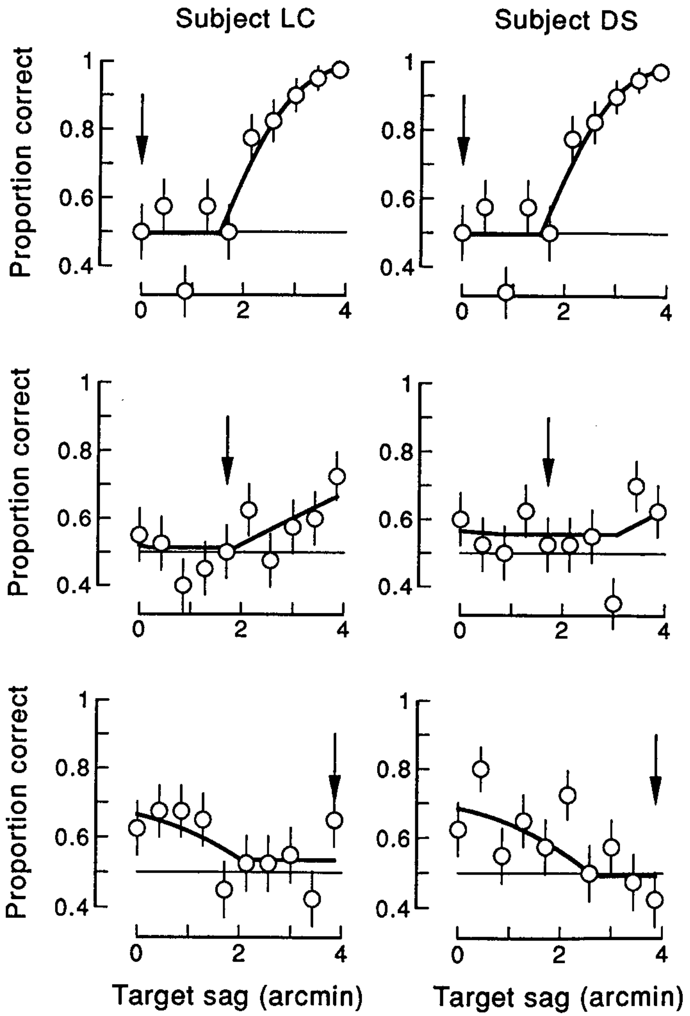

Figure 9: *Proportion-correct performance in the curved-line-element texture segmentation task (Section 7). Data for two subjects are plotted as a function of target-sag value for three representative background-sag conditions. Elements had maximum orientation jitter of 180 deg. Maximum positional jitter was 0.10 deg (20% of the mean element separation). The horizontal line represents chance performance. The vertical arrows indicate the values of the background sag along the continuum. Note that the range is restricted to positive sag values only, as curvature sign has no meaning for randomly oriented stimuli. Each data point shows the mean and standard error of 40 trials, assuming a binomial error distribution. Background-sag values were (top sections) 0.0 arcmin, (middle sections) 1.71 arcmin, (bottom sections) 3.86 arcmin.*

8 The Role of Luminance Cues to Segmentation

The precautions taken in this study against accidental luminance cues to segmentation included matching the curved-line elements for brightness (by generating each of them from equal numbers of vector line-elements or spots); employing positional jitter of the texture elements; and, in some cases, ensuring that the local coordinate system in which element transformations (such as rotations) were performed had its origin at the centre-of-mass of the element. Nevertheless, some additional measurements based on computer simulations were made to control for accidental luminance cues.

8.1 Methods

Textures of curved-line elements were simulated by computer-generated 512×512 arrays of floating-point numbers. They were generated in a similar way to the textures used in the psychophysical experiments in that each curved-line element was constructed from nine adjacent spots with Gaussian intensity profiles. The spot-size was scaled to the correct fraction of the display size for a texture subtending 5×5 deg. Figure 10a shows a scaled example of a computer-simulated curved-line texture, although the number of gray levels has been reduced for ease of reproduction. These texture images were convolved with isotropic Gaussian kernels of unit volume to test for the presence of local variations in the luminance distribution.

8.2 Results

The results of the filtering process were highly dependent on the standard deviation of the Gaussian filter. If the standard deviation was small with respect to the mean element separation, the filter integrated luminance energy only from single curved-line elements, and therefore no differences between target and background elements were obtained. But with filter standard deviations close to half the mean element separation some luminance cues to segmentation became visible. Figure 10a illustrates a curved-line texture with (simulated) background-sag value 0.86 arcmin, and target-sag value 1.86 arcmin (corresponding to 1.7 and 3.2 pixels respectively). There is no positional jitter, and the local coordinate origin is at the centre of the chord (as in the experiments of Sections 3 and 4). After convolution of this image with an isotropic Gaussian filter of standard deviation 30 pixels and unit volume the image shown in figure 10b was obtained. Strong luminance edges are apparent in figure 10b that coincide with the vertical edges of the target region. The amplitude of the simulated luminance difference between the bright and dark patches and the background was approximately 2% of the mean luminance of the image; thus, although the amplitude of the luminance edge was exaggerated in this case by intensity scaling of the computer image, it may still have been detectable in psychophysical experiments.

The texture shown in figure 10c was filtered in exactly the same way as that in figure 10a, and the result is shown in figure 10d. The only difference between the textures in figures 10a and 10c is that the latter contains a small amount of random positional jitter, with a maximum value equal to 10% of the mean element separation (the same jitter level as in the experiments described in Sections 3 and 6, and as in some of those of Section 4). Figure 10d shows that the use of even small amounts of positional jitter was enough to severely disrupt luminance cues to the edge of the target region. Further computational experiments with textures in which the elements had no positional jitter showed that the size of the luminance cue for the location of the edges of the target region was dependent only on the difference in sag between target and background elements. Thus the strength of the luminance cue did not vary with background-sag value for a given sag difference.

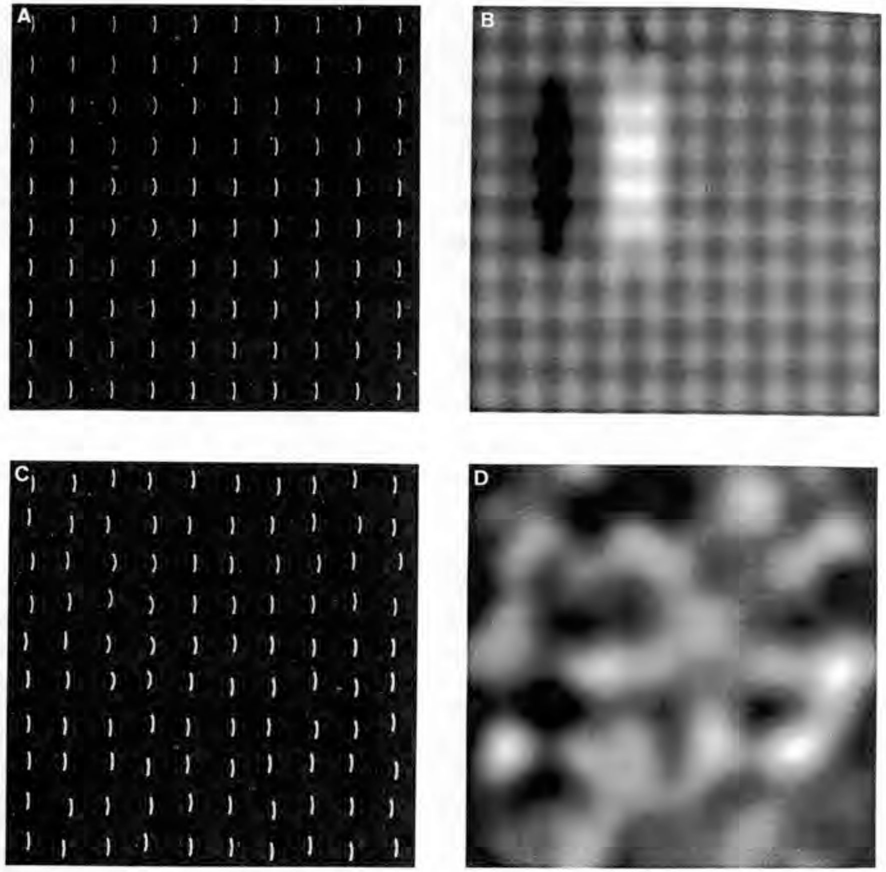

Figure 10: *Illustration of the role of luminance information in assisting target region orientation identification at different levels of positional jitter. (a) Simulated curved-line texture from Section 3. Background sag 0.86 arcmin, target sag 1.86 arcmin, no positional jitter. (b) The same texture filtered with a normalized isotropic Gaussian, standard deviation 1.17 times the mean element separation. The image was re-scaled after filtering. Strong luminance cues to the target region orientation are evident. (c) As (a) except with a small random positional jitter of maximum value ±0.05 deg (±3 arcmin; ±10% of mean element separation. (d) The result of (c) filtered with the same isotropic Gaussian filter as in (b).*

8.3 Discussion

The results of these computer simulations suggested that the use of even small amounts of element positional jitter was enough to severely disrupt luminance cues to segementation of the target region. Moreover, in the unjittered textures, the constancy of the strength of the luminance cue with changes in background-sag value suggested that, if this cue had been used to segment the textures used in the experiments of Section 4, then sag increment-thresholds would have been constant with background-sag value, which manifestly was not so.

9 General Discussion

This study addressed three questions concerning the segmentation of textures of curved-line elements:

1. Can psychophysical performance for this class of textures be explained by existing models of texture segmentation?
2. Does the processing of such textures demand specialized curvature-sensitive mechanisms?
3. Is there evidence of a categorical representation of curvature in the analysis of these textures?

9.1 Implications for Models of Texture Segmentation

Many models of texture segmentation have incorporated stages sensitive to the orientation contents of the texture elements. As is emphasized below, this approach is not sufficient to account for the segmentation of curved-line-element textures. Any model must also be able to explain performance asymmetries, where segmentation performance is different for a given micropattern combination, depending on which of the micropatterns forms the target or background. The performance asymmetry found with textures of randomly oriented curved-line elements (Section 7), together with those considered by Gurnsey and Browse (1987, 1989), provide a challenge for comprehensive models of texture segmentation, such as the scheme described by Malik and Perona (1990). Although an attempt has been made to explain performance asymmetries in visual search in terms of local filtering operations (Rubenstein and Sagi 1990), it has been argued strongly by Gurnsey and Browse (1989) that a global normalization of local filter responses was required for a more complete explanation of asymmetry phenomena. Clearly any texture segmentation model that predicts only the strength of the border between two textures (Malik and Perona 1990; Landy and Bergen 1991) is inadequate.

9.2 Necessity of Curvature-Sensitive Mechanisms

The segmentation of textures of randomly oriented curved-line elements (Section 7) can be possible only if curvature-sensitive mechanisms are involved at some stage of the segmentation process. Furthermore, the segmentation of textures in which target and background curved-line elements were aligned but mirror-symmetric (Sections 5 and 6) suggests that these mechanisms must be sensitive to both the magnitude and the direction of curvature. The existence of performance peaks and troughs exhibited in the increment-threshold functions (Sections 3 and 4), and particularly the coincidence of the threshold minima for different sizes of chord (Section 3), provide further evidence that the segmentation of textures of curved-line elements is likely to be performed by specialized curvature-sensitive mechanisms.

9.3 Categorical Segmentation

Categorical segmentation provides a simple explanation of the existence of the peaks and troughs in performance in increment-threshold functions (Sections 3 and 4), and the coincidence of the optimum values of background sag (where sag increment thresholds were minimum) for different sizes of chord (Section 3). The fact that segmentation performance data for textures of vertically oriented curved-line elements (Section 6) can be predicted, albeit partially, by categorical labelling data suggests that the representation of curvature information may take a categorical form.

With regard to the precise nature of the proposed curvature representation, the labelling data (Section 6) suggest that, for a given curved-line orientation, at least five categorical labels are necessary to predict segmentation performance with briefly presented textures of curved-line elements. These labels would correspond to "straight", "just curved" (in two directions), and "more than just curved" (in two directions). This labelling scheme is an elaboration of that proposed by Foster (1983) to explain performance in a four-alternative forced-choice curvature discrimination task. The boundary between "straight" and "just curved" categories should occur close to a sag value of 0.86 arcmin, and that between "just curved" and "more than just curved" categories should be in the region of 2.0 arcmin, although these values may vary with curved-line orientation and the range of curvatures present within the image. Such a representation scheme is not inconsistent with results from single-cell recording experiments (Hammond and Andrews 1978; Dobbins *et al.* 1987, 1989; Versavel *et al.* 1990).

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