# Contour Integration by the Human Visual System: Evidence for a Local "Association Field"

DAVID J. FIELD,* ANTHONY HAYES,† ROBERT F. HESS†

The Gestalt law of "good continuation" has been used to describe a variety of phenomena demonstrating the importance of continuity in human perception. In this study, we consider how continuity may be represented by a visual system that filters spatial data using arrays of cells selective for orientation and spatial frequency. Many structures (e.g. fractal contours) show a form of redundancy which is well represented by the continuity of features as they vary across space and frequency. We suggest that it is possible to take advantage of the redundancy in continuous, but non-aligned features by associating the outputs of filters with similar tuning. Five experiments were performed, to determine the rules that govern the perception of continuity. Observers were presented with arrays of oriented, band-pass elements (Gabor patches) in which a subset of the elements was aligned along a "jagged" path. Using a forced-choice procedure, observers were found to be capable of identifying the path within a field of randomly-oriented elements even when the spacing between the elements was considerably larger than the size of any of the individual elements. Furthermore, when the elements were oriented at angles up to ±60 deg relative to one another, the path was reliably identified. Alignment of the elements along the path was found to play a large role in the ability to detect the path. Small variations in the alignment or aligning the elements orthogonally (i.e. "side-to-side" as opposed to "end-to-end") significantly reduced the observer's ability to detect the presence of a path. The results are discussed in terms of an "association field" which integrates information across neighboring filters tuned to similar orientations. We suggest that some of the processes involved in texture segregation may have a similar explanation.

Fractal   Orientation   Contours   Visual coding   Psychophysics   Texture perception   Spatial vision

## INTRODUCTION

In the first half of the century, Gestalt psychologists developed a list of "laws" to account for many of the known phenomena of perceptual grouping (e.g. Wertheimer, 1938). Of these, the law of "good continuation" played a central role. The law has been invoked to account for the perception of continuity under a variety of conditions including a number of geometric illusions. Although the phenomena which are described by this law demonstrate an important organizing principle in human vision, the "law of good continuation" is little more than a description of these phenomena. As an explanation, the law has provided little predictive power.

In this study, we take a look at several parameters involved in the perception of continuity and we relate these findings to some current notions of early visual processing. Consider the image presented in Fig. 1. The image shows a tree partially blocked by a regular grid. The reader should find it easy to identify the continuity of the branches even though the grid obscures a significant portion of each branch. At some level, the visual system is able to integrate the information from the different component squares. In this paper, we investigate some of the rules behind this type of integration process.

Several recent papers have investigated the perception of continuity by looking at observers' ability to segregate lines embedded in noise. For example, studies by Uttal (1975), Smits, Vos and Oeffelen (1985) and Beck, Rosenfeld and Ivry (1989) have investigated the detection of straight lines composed of dot elements surrounded by noise composed of similar dots. When the dots form a straight line, the row of dots segregates from the background (i.e. "pops out"). Factors such as the dot spacing and collinearity were found to play an important role in this segregation.

While the above studies restricted themselves to the detection of straight lines, it is clear that segregation of curved lines is also possible. Studies with Glass patterns (Glass, 1969), for example, demonstrate the effectiveness

*Department of Psychology, Cornell University, Ithaca, NY 14853, U.S.A.
†McGill Vision Research Centre, Department of Ophthalmology, McGill University, Montréal, Québec, Canada H3A 1A1.
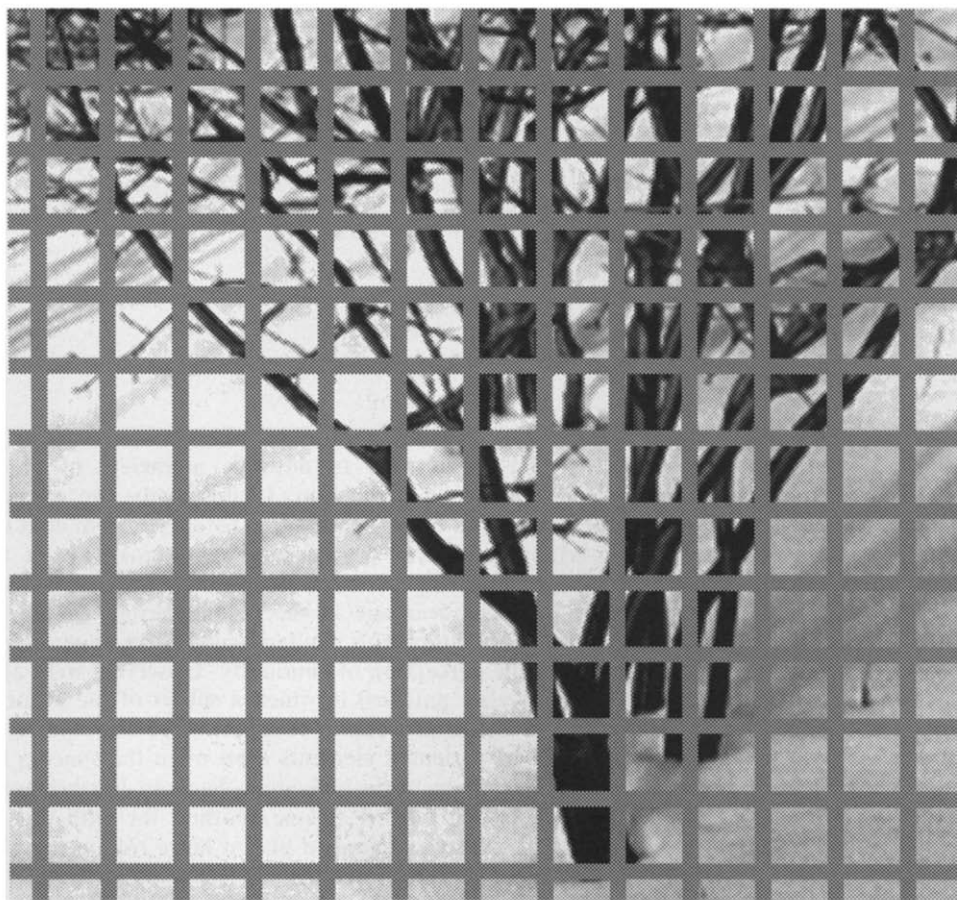
FIGURE 1. A demonstration of the phenomenon of "good continuation". The continuity of the branches is easily identified despite the presence of a disruptive grid.

of local orientation on the global perception of curvature. Several studies have provided demonstrations that curved lines composed of oriented segments can "pop out" under appropriate conditions (Gigus & Malik, 1991; Ullman, 1990). Indeed, several authors have included the representation of curvature in their models of early visual processing (e.g. Watt, 1984; Watt & Andrews, 1982; Wilson & Richards, 1989; Zucker, 1986; Zucker, Dobbins & Iverson, 1989).

Recent computational studies have suggested that a useful segregation process for real scenes may be based on local (rather than global) integration (e.g. Gigus & Malik, 1991; Grossberg & Mignolla, 1985a, b; Morgan & Hotopf, 1989; Parent & Zucker, 1989; Sha'ashua & Ullman, 1988). The general theme of these algorithms is that the points along the length of a curved edge can be linked together according to a set of local rules that allow the edge to be seen as a whole, even though different components of the edge are detected by independent mechanisms. Although these algorithms have been found to be useful for segregating structure from noisy backgrounds, there is little psychophysical or physiological evidence to support the notion that such algorithms are actually employed by the human visual system.

In this paper, we investigate several rules that the visual system uses to integrate the output of early stages of visual processing. In line with previous studies in perceptual grouping (e.g. Beck *et al.*, 1989; Nothdurft, 1991; Uttal, 1975), this study uses stimuli that consist of arrays of oriented line segments. Such stimuli will allow us to determine how the relative alignment of neighbouring elements is related to the perception of continuity.

However, in addition to being locally oriented, the elements in our experiments are also spatially bandpass (i.e. Gabor functions). The use of bandpass functions confers two advantages. First, they limit the types of processes that respond to each element. The spectrum of a line segment is actually quite complex. The ends of each element have energy at a range of spatial frequencies and orientations. With respect to the early stages of visual processing, cells selective to a large variety of orientations and spatial frequencies will respond to such a stimulus. By using bandpass elements, we can be more certain about the mechanisms involved in our segregation tasks.

The second reason for using bandpass stimuli is that they allow us to explore how the grouping processes function at a single spatial scale. We believe that with many natural edges it may be useful to solve the continuity problem separately at each scale. As an example, consider the two edges shown in Fig. 2. Figure 2(a) shows a smooth edge filtered into three spatial frequency bands while Fig. 2(b) shows a fractal edge filtered in the same way.
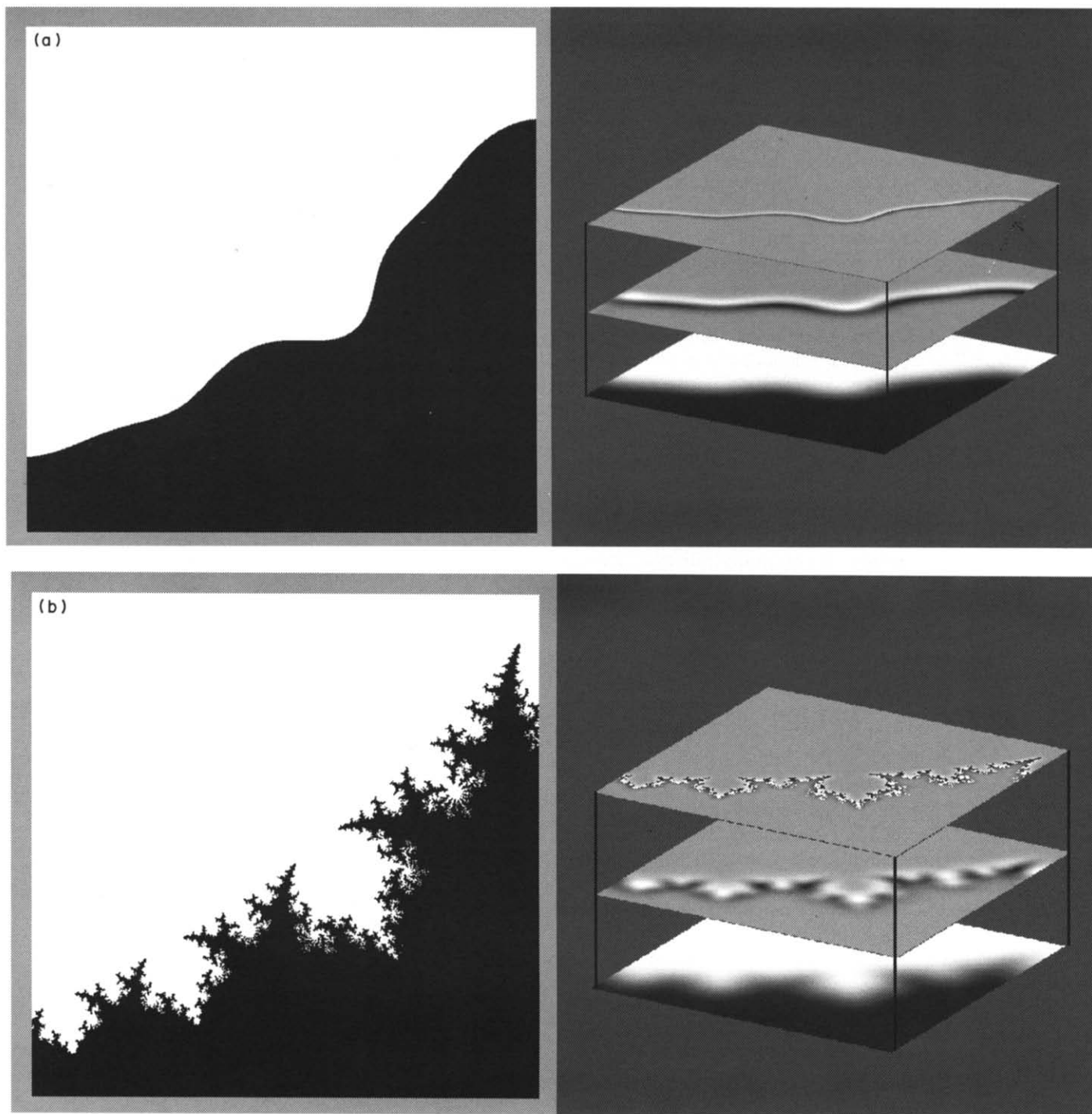
FIGURE 2. Smooth and jagged edges displayed at three spatial scales. (a) Presents a smooth edge (or alternatively a fractal edge with a low fractal dimension) and (b) presents a jagged edge (or alternatively a fractal edge—actually part of the Mandelbrot set—with a high fractal dimension). In the right panel of each figure the three tiers show, from top to bottom, the results of filtering each edge with bandpass filters of high, medium and low peak spatial frequencies. Notice that in (a) the position of the edge is aligned across the three scales. This is not the case for (b).

Smooth edges will show considerable agreement across neighboring frequency bands. Indeed, edge detection proposals like those of Marr and Hildreth (1980), Canny (1986) and Lowe (1988) take advantage of this agreement to identify which image structures represent meaningful edges. However, fractal edges do not show the same consistency across spatial scales. Although the edge is roughly continuous at each scale, the precise position and orientation of the edge changes from scale to scale. At any particular position, the edge may show a particular orientation in only one spatial-frequency band. Indeed, it has been suggested that the bandpass properties of the mammalian visual system provide an ideal mechanism for extracting this locally bandpass structure in natural scenes (Field, 1987, 1992; Hayes, 1989). Thus, the mammalian visual system may solve the

continuity problem at each scale separately, and the use of bandpass elements provides a technique for exploring how the visual system integrates this information.

An example of the type of stimulus used in our experiments is shown in Fig. 3. The image consists of an array of randomly oriented bandpass elements in which a portion of the elements are aligned along a curved path. Although the path is easily identified, there exists no single dimension or parameter that allows the path to be extracted from the background. While it may be possible to explain many texture segregation tasks with reference to a parallel filtering process (e.g. Bergen, 1991; Bovik, Clark & Geisler, 1990; Graham, Beck & Sutter, 1992; Landy & Bergen, 1991), that approach will not work here. For example, if one looks at the response of an array of vertically oriented mechanisms to the stimulus (e.g. convolve the image with an oriented filter), one finds that only a portion of the path will be extracted along with a large number of elements from the background (see Fig. 4). For these types of stimuli, there exists no single parameter (orientation, spatial frequency) which distinguishes the path from the background. The perception of continuity must be derived from a process which integrates along the length of the path. The experiments described in the next section explore some of the processes which underlie this integration.

## METHOD

### Viewing conditions and experimental design

All experiments used a temporal two-alternative forced-choice (2AFC) design. In each experiment, a trial consisted of successively presenting two images: an image containing (1) both background elements and the path elements; and (2) an image containing only background elements. Each image was presented sequentially for 1.0 sec (except in Expt I where a condition was run 0.25 sec stimulus duration and 1.0 sec between the two intervals). The screen was set to the mean gray level between trials. Observers were asked to determine which interval contained the path using the buttons on the computer's mouse.

Observers viewed the images from a distance of 90 cm under conditions of low ambient illumination. At this distance, each image (the array of elements) subtended 8.0 deg of visual angle. The mean luminance of the screen was fixed at 35 cd/m². All images consisted of 512 × 512 pixel images displayed on an RGB monitor driven by a SUN Sparc 2 computer. A look-up table was used to linearize the luminance levels resulting in a look-up table of approx. 7.5 bits (182 gray levels).

Images for all conditions were created before each run and stored on the computer's hard disk (a total of over 800 megabytes of images). Each block of trials consisted of five conditions (e.g. five different inter-element path angles) with 50 trials in each condition. Thus the total number of presentations in any given block consisted of 250 trials. Each block was run four times resulting in a total of 200 trials in each condition. The blocks from each of the five experiments were interlaced and run over a period of 6 weeks.

### Stimuli

The stimuli presented to the observers, illustrated in Figs 3, 6, 8, 10, 12, 14 can be described with three sets of parameters. They are: (a) the parameters describing the individual elements in the stimulus; (b) the positioning of these elements along the feature path; and (c) the parameters describing the relative positions of the background elements.

(a) The elements. All elements, whether part of the path or part of the background elements, are described by the products of a circular Gaussian and an oriented sinusoid (a circular Gabor function). The equation is thus:

$$G(x, y) = e^{-(x^2 + y^2)/2\sigma^2}$$
$$*\cos[2\pi *(\cos\theta * x + \sin\theta * y)/p + \phi] \quad (1)$$

where $\theta$ controls the orientation and $\phi$ determines the relative phase of the elements.

The size of the elements as defined by $\sigma$ was fixed at 4.0 pixels ($\sigma = 4.0$). This results in an element with a full width at half-height ($2\sigma$) of approx. 8.0 pixels. The period of the modulating sinusoid was set to 8.0 pixels ($p = 8.0$). In all experiments, the observers viewed the screen from a distance of 90 cm. These parameters resulted in elements with a peak spatial frequency of 8.0 c/deg and a bandwidth of approx. 1.2 octaves ($\sigma = \frac{1}{16}$ deg). The contrast of each of the elements was the maximum allowed by the screen under these viewing conditions (95%). Since the elements did not have significant overlap, the contrast of the entire 512 × 512 image was the same as that of the individual elements.

(b) The stimulus path. The path on which the elements were placed was created using the rules outlined below and is illustrated in Fig. 5. These rules were followed to ensure that no information regarding the existence of the path was available to the observers other than the relative orientation of the elements defining the path. For example, if the spacing of the elements in the path was not equated with the spacing of the background elements, then it would be possible to identify the path simply on the basis of the relative density of elements around the path.

Each stimulus was constructed by following method. The terms refer to the schematic diagram shown in Fig. 5.

1. The image was divided into a grid proportional to the desired spacing.
2. A starting point for the path was selected (P1). The starting point of the path was always at a point 1.0 deg (64 pixels) from the center of the image.
3. A vector of distance D was projected from P1 to P2 directed towards the center of the image plus or minus a variable angle ($\pm\beta$). For most of the studies described in this paper, the distance between elements was set to 0.5 deg (32 pixels).
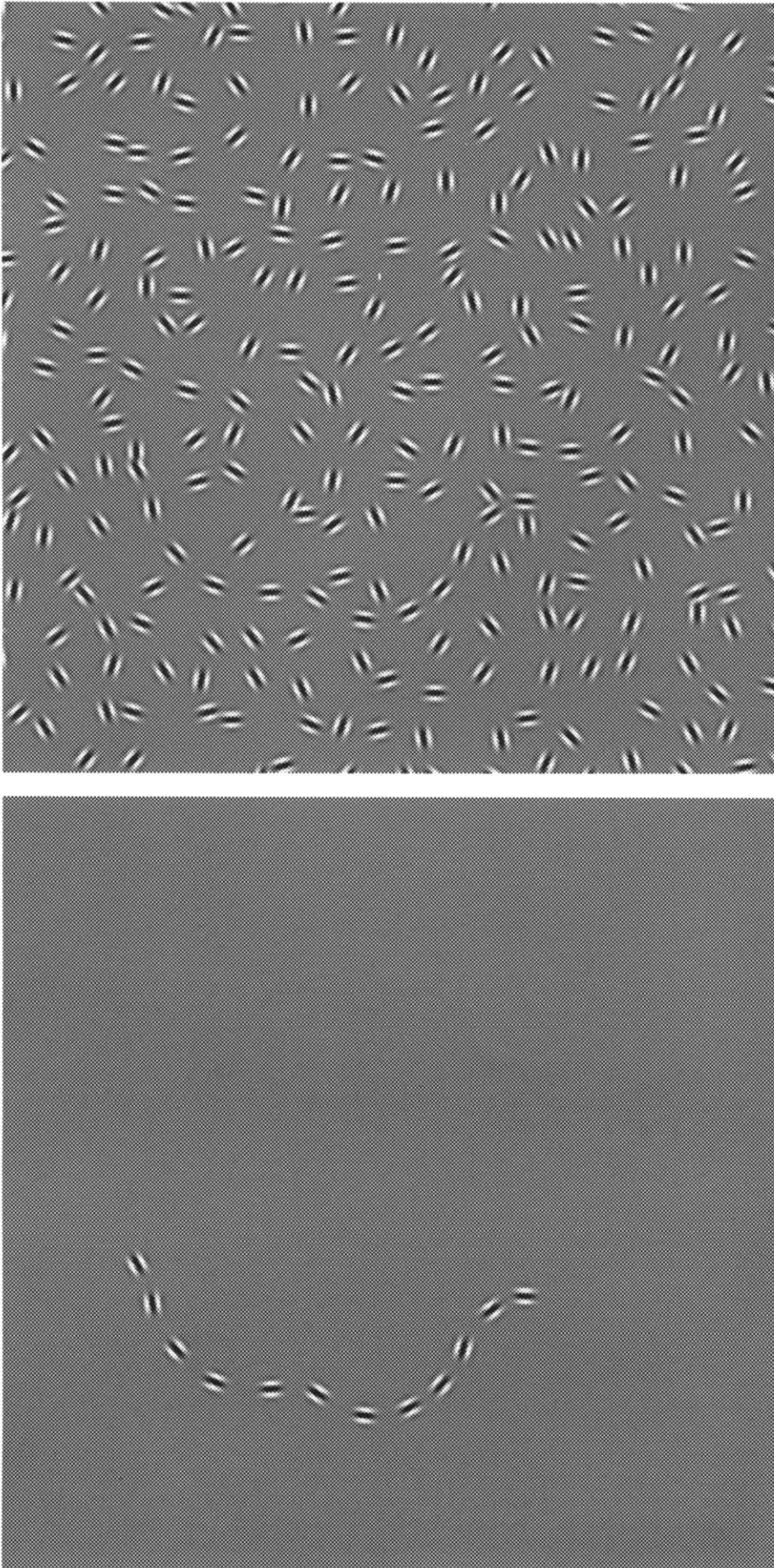
FIGURE 3. An example of a stimulus used in the experiments reported. The left-hand panel shows the path of elements (the stimulus) that the subjects must detect when embedded in an array of randomly oriented elements (the stimulus plus background shown on the right). In all experiments, the stimulus consisted of 12 elements aligned along a path. In this example each successive element differs in orientation by ±30 deg and for this difference in orientation the string of aligned elements is easily detected.
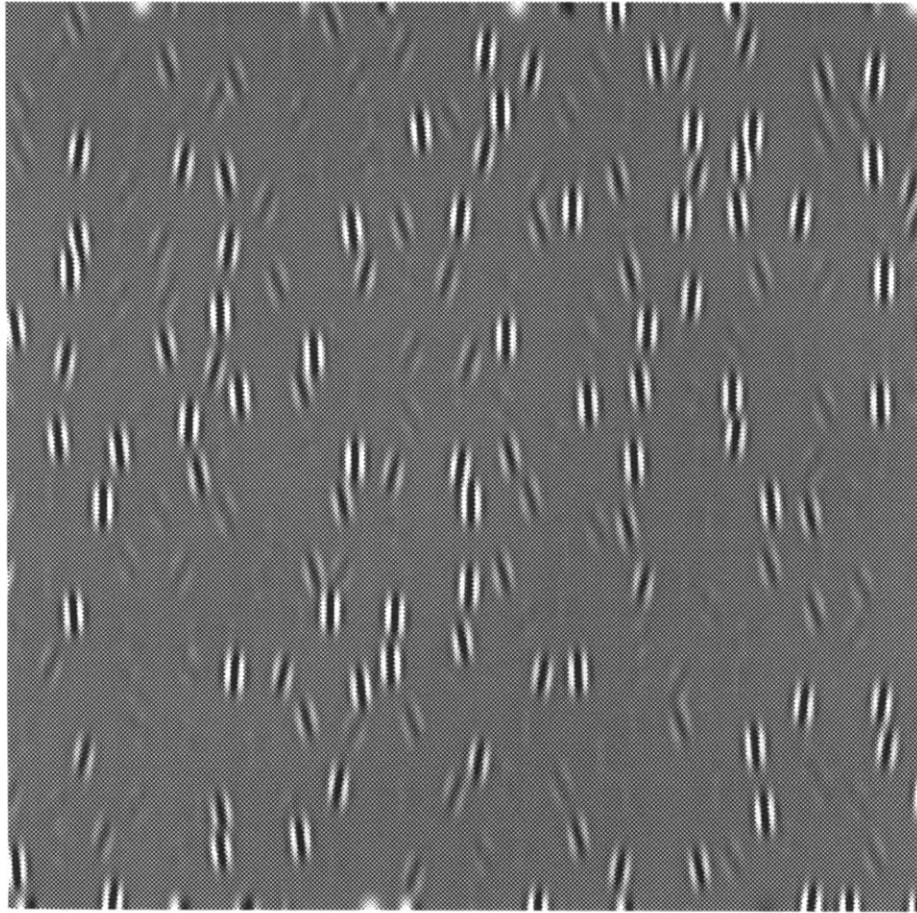
FIGURE 4. An array of elements, containing a path, after filtering with a vertically oriented bandpass filter. The path cannot be segregated from the "noise" background by filtering along a single dimension, such as orientation. See text for details.
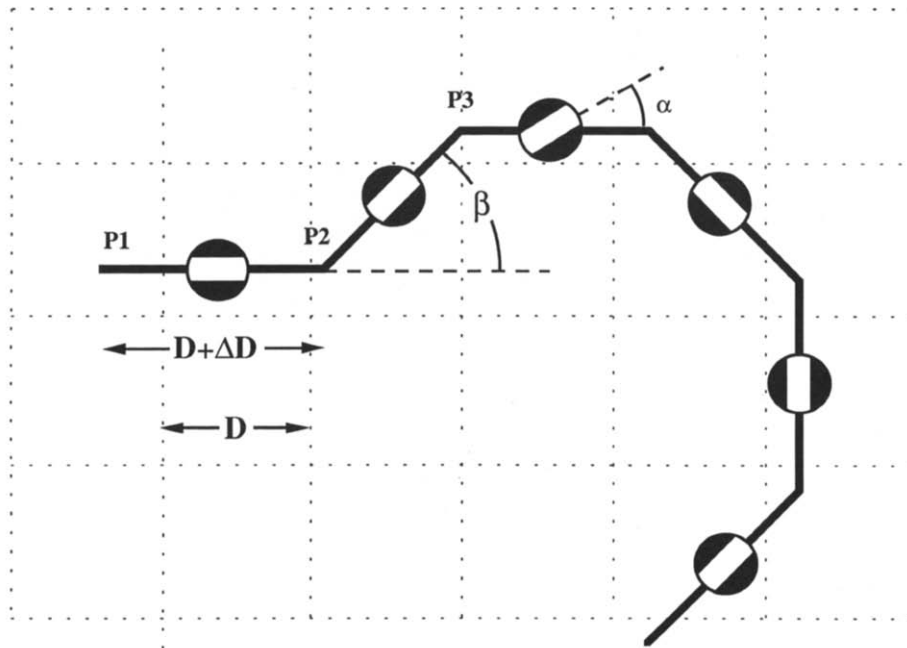


FIGURE 5. Grid showing the placement of path elements. Each stimulus was divided into a grid of 16 × 16 squares each of which contained an element. Each stimulus consisted of a total of 256 elements, 12 path element and 244 background elements. Background elements were not constrained in orientation, but were constrained in position to fall within a square. Path elements were constrained to fall within a square along a pre-determined path; shown as a bold line. The length $D$ is the length of segment on which each element was placed ($\Delta D$ is a small corrective jitter of $\pm 0.25 * D$). The angle $\beta$ is the difference in angle of orientation of each successive path segment ($\Delta \beta$ is a small random jitter between $-5$ and $+5$ deg). The angle $\alpha$ is the angle of orientation of the sinusoid with respect to the path. See text for details.

However, in Exp. IV, we look at the effect of distance by using separations of 0.25 and 0.9 deg.

4. An element was placed at the halfway point between P1 and P2 providing that the square was not already occupied by an element. If the path already contained element, then the path was extended (D/4) to a square that did not contain an element. In most of the experiments, the orientation of the element was set to the orientation of the path ($\alpha = 0$). However, in Exp. II the element orientation was orthogonal to the path orientation ($\alpha = 90$ deg).

5. At position P2, after a rotation by angle $\beta$ or $-\beta$, another vector was projected a distance **D** to P3. In all conditions, the path rotation was one of two angles ($\pm\beta$). For example, in the 60 deg condition, the angle at point $p$ was either $+60$ or $-60$; there was no possibility of a straight continuation of the path. In addition to this fixed rotation, a small random variation around $\beta$ was also added (uniform distribution with a mean of 0.0 deg and a maximum of $\pm 10$ deg). This small addition helped to prevent any geometrical patterns forming in the path.

6. Steps 4 and 5 were repeated until the path was completed.

For all the experiments described in this paper, the path was composed of 12 elements.

(c) *Placing of background elements*. After the path elements had been determined, the background elements were added to the image. An element was added to each square of the grid unless the square already contained an element. The orientation of the element ($\theta$) was selected at random and its position within each square was randomly (uniformly) distributed. With $512 \times 512$ images and the square size set to $32 \times 32$, this resulted in a total of 256 elements in each image. Thus each trial consisted of a stimulus containing the path (12 path elements + 244 background elements) and a stimulus containing only background elements (256 background elements).

*Observers*

Two of the authors served as observers in all experiments. Both are corrected myopes. Both observers were given sufficient practice (typically 100 trials) to reach an asymptote in their performance for each experiment.

### EXPERIMENT I—RELATIVE ORIENTATION OF PATH ELEMENTS

The first experiment investigates the relation between the relative orientation of successive elements along the path and the observer's ability to detect the path. Observers were presented images containing paths in which the orientation of successive elements differed by $\pm\beta$, where $\beta$ was equal to 15, 30, 45, 60 or 75 deg.

Figures 3 and 6 show examples of path orientations of 30 and 60 deg. As noted in the previous section, the relative orientation of successive elements differed by a constant angular difference ($\pm\beta$ rather than a range of angles between $+\beta$ and $-\beta$). Thus, there were no occurrences of two successive elements along the path having the same absolute orientation. In this first study, the five conditions were presented at stimulus durations of both 1.0 and 0.25 sec. The 0.25 sec condition was included in this experiment to determine the role that the stimulus duration played in the segregation process.

*Results*

The results of the first experiment are shown in Fig. 7. Proportion correct is plotted as a function of path orientation ($\beta$). Solid symbols show the results for the 1.0 sec. duration and open symbols show the results for the 0.25 sec duration. Error bars provide the standard error of the mean of the four runs of fifty trials. The results show that with larger angles of relative element orientation, the task becomes increasingly difficult. With the 1.0 sec duration, the observers are still above chance out to 60 deg. The results suggest that under these experimental conditions, the path can be identified when the successive elements in the path differ by 60 deg or less. With the 0.25 sec duration, the subjects found the path more difficult to detect. Since the size of the stimulus was 8.0 deg and the beginning of the path was set at 1.0 deg from the center, the path was not guaranteed to fall in the fovea. With two or three fixations as allowed with the 1.0 sec duration, it was possible to identify the path under conditions where the path could not be identified in the 0.25 condition stimulus. Nonetheless, even with the 0.25 sec duration, the subjects could reliably detect the path even when the successive elements differed by $\pm 45$ deg.

From these results, it is not possible to determine whether the ability to detect the path is a function of the alignment of these elements along the axis of the path or a function of the difference in orientation between successive elements in the path. Experiment II was designed to dissociate these two possibilities.

### EXPERIMENT II—ELEMENTS ORTHOGONAL TO THE PATH

In Expt I, the elements were placed end-to-end as shown in Figs 3 and 6. Consider the hypothesis that the ability to integrate these features is functionally related to the process involved in detecting a continuous but jagged edge. Under such an assumption, one might expect that the ability to detect the path with the end-to-end alignment would be significantly better than ability to detect the path when the elements are aligned side-to-side with respect to the orientation of the path.

A second hypothesis is that the process involved in integrating the path is simply related to the overall difference in orientation between successive elements in
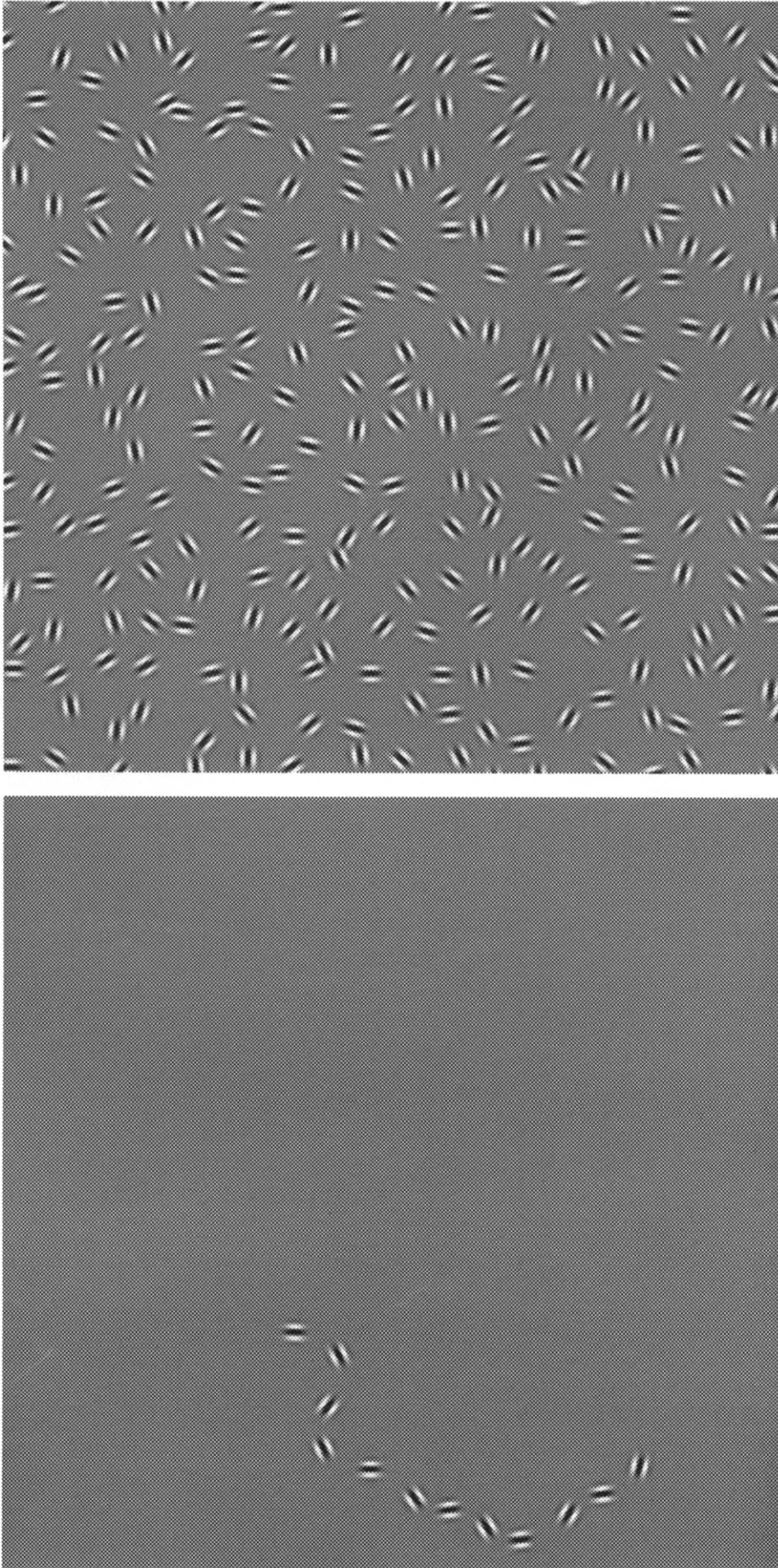
FIGURE 6. The right side of the figure shows an example of a stimulus used in Expt I. In this example, the path orientation variable $\beta$ has the values $\pm 60$ deg. Observers found the task of detecting the path considerably more difficult in this condition than in the condition shown in Fig. 3 ($\beta = \pm 30$ deg).
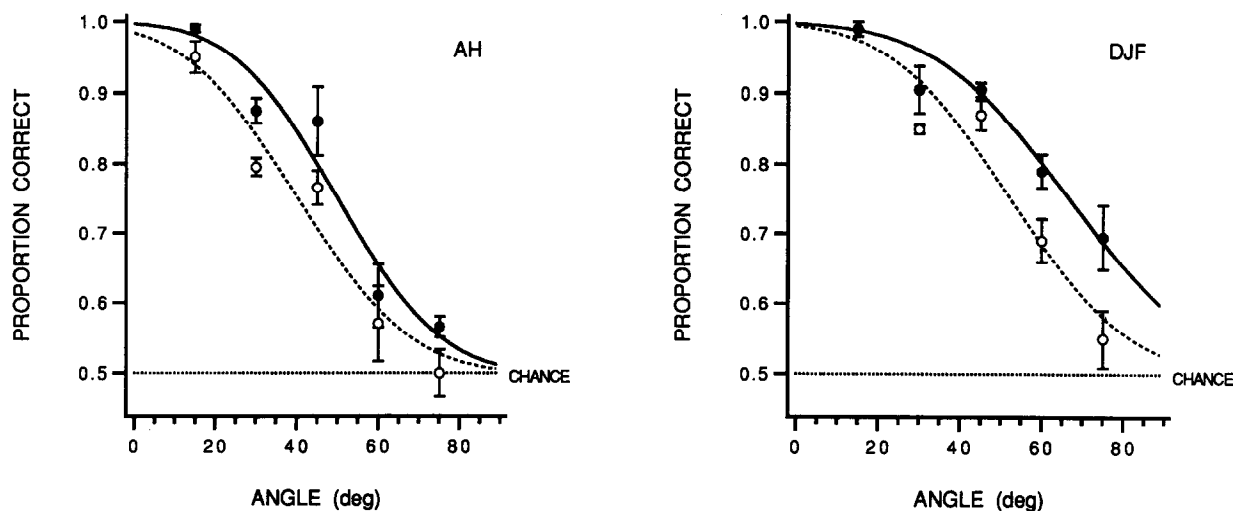
FIGURE 7. Results of Expt I. Path detection performance (two-alternative forced-choice) measured as a function of change in path orientation ($\pm\beta$) for subjects AH and DJF. Each datum is the average of four sets of trials; each trial consisted of 50 presentations. The bars attached to each datum are $\pm 1$ SE. The solid line indicates a weighted error function that was fit to each set of data. The solid symbols show the results for the 1.0 sec stimulus duration (the duration used for Expts II–V). The open symbols and dashed lines show the results for a control condition with a stimulus duration of 0.25 sec.

the path. Under this second hypothesis, one would not expect to see a difference between the end-to-end vs the side-to-side alignment. In this experiment, we repeated the conditions of Expt I, with one important exception. The elements along the path were rotated by 90 deg, resulting in a path where the elements were aligned side-to-side. Since these elements were created using a circular Gaussian [equation (1)], the rotation did not increase or decrease the distance between successive elements along the path. Furthermore, since the elements were separated by a distance that corresponds to eight times the standard deviation (32 pixels) of the Gaussian envelope, there was still no significant overlap between the elements.

An example of a stimulus used in this experiment is shown in Fig. 8. The difference in orientation between successive elements is the same as that of Fig. 3 (i.e. end-to-end alignment). The reader can verify for him/herself that the path is considerably more difficult to detect in Fig. 8 than in Fig. 3.

*Results*

The results of Expt II are shown in Fig. 9. The data for both observers are plotted together with the results of Expt I (dotted lines). One can see that under these conditions, the ability to detect the path is significantly reduced when the relative orientation between successive elements differs by more than 30 deg. The results support the notion that the integration between elements is related to the continuity of edges or lines rather than a more general segregation process based on the redundancy of the stimulus or due to a general linking of features with similar orientation. Our results are in agreement with study of Beck *et al.* (1989) who measured the reaction time to detect a set of vertically oriented elements aligned in a straight line and embedded in a background of non-aligned vertical elements. Observers were found to be significantly slower at detecting the line

when the elements making up the line were placed side-to-side as opposed to end-to-end.

Our results demonstrate that the alignment plays a significant role at all orientations and suggest that the process that mediates the integration of elements shows a strong bias towards the end-to-end alignment.

## EXPERIMENT III—SELECTIVITY ALONG THE PATH

The results of Expt I suggest that it is possible to detect a path even when the elements differ in orientation by as much as 60 deg. This might appear to pose a dilemma. If this integration process can accommodate an angular difference of 60 deg, what makes the path unique among all the potential paths that are found in the randomly oriented background elements? Since the average angular difference between any two random elements is 90 deg, it would appear that there must be a large variety of potential paths available in the background elements.

However, in the experiments described above there is a unique link between the relative positions of the elements and their relative orientations. As shown in Fig. 5, the orientation of the elements is locked to the orientation of the path; a smooth curve passing through the long axis can be drawn between any two successive elements. Does the ability to integrate the elements of the path depend on this joint constraint of position and orientation?

To test this hypothesis, we conducted an experiment in which the orientation of the elements was varied relative to the orientation of the path. The path was constructed in the same way as Expt I. However, the orientation of each element along the path was then given a random change of $\pm\alpha$ where $\alpha$ was either $\pm 15$ or $\pm 30$ deg. An example of the stimuli used in Expt III is shown in Fig. 10.
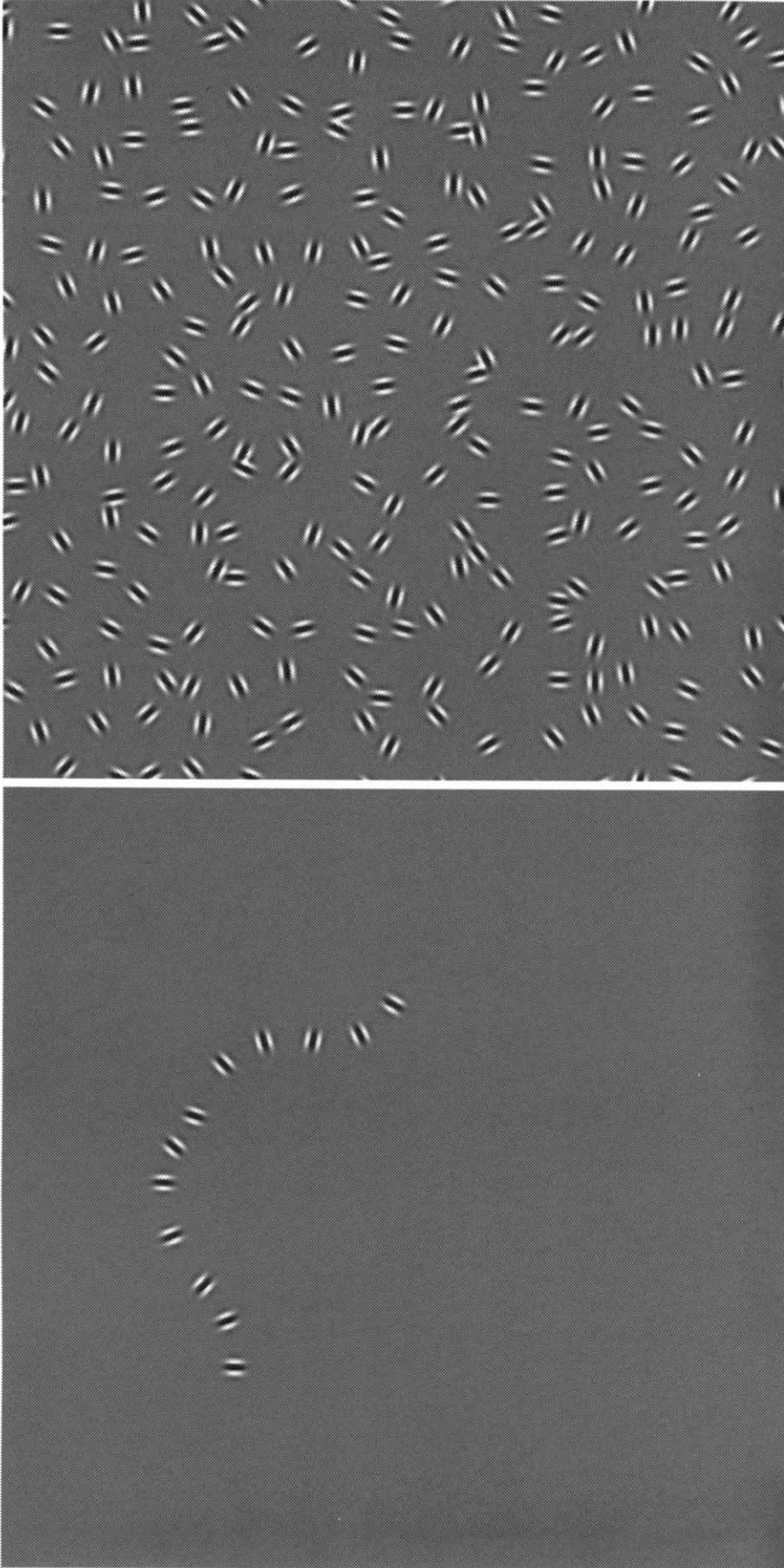
FIGURE 8. An example of a stimulus used in Expt II. In this example the path orientation variable $\beta$ has the values $\pm 30$ deg, and the orientation of the sinusoid of the patch ($\alpha$) is 90 deg with respect to the path. The path has the same parameters as the path depicted in Fig. 3, except the alignment of the Gabor patches is "side-to-side" instead of "end-to-end".
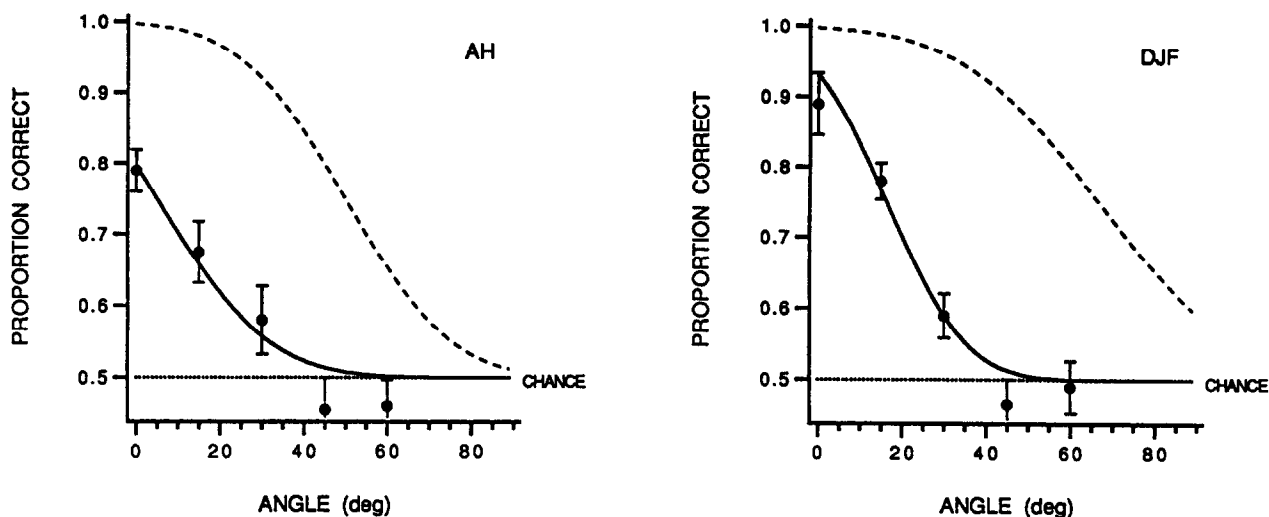
FIGURE 9. Results of Expt II. Details as for Fig. 7 (1.0 sec condition) except that the elements are aligned orthogonal to the path. The dotted line is the weighted error function fit to the results of Expt I, and is used as a basis for comparison for the results of Expts II, III, IV and V.

## Results

The results of this experiment are presented in Fig. 11. Results are shown for both observers using both the $\alpha = \pm 15$ and $\pm 30$ deg (solid lines) along with the results from Expt I where $\alpha = 0$ deg (dotted lines). It is clear that this type of manipulation results in a substantial reduction in the ability to detect the path.

The results support the notion that there is a constraint between the relative positions and the orientations of the elements. The results suggest that the visual system can integrate large differences in orientation only when those differences lie along a smooth path. Consider for example, the 15 deg randomization with the 0 deg path angle ($\alpha = 15$ and $\beta = 0$). The 15 deg randomization makes this task difficult, even though the observers have no difficulty tracking a 15 deg orientation difference when there is no variation ($\alpha = 0$ and $\beta = 15$). We will return to this point in the Discussion.

## EXPERIMENT IV—INTER-ELEMENT DISTANCE

In this experiment we investigate the effects of the spacing of the elements. If the process that mediates the detection of the path is a local process, one would expect some reduction in the ability to detect the path when the elements were spaced relatively far apart. In the two previous experiments, the distance between the elements averaged 0.5 deg (the stimulus array measured 8.0 × 8.0 deg across). In this experiment (IV), the segment length was set to either 0.25 or 0.9 deg (the largest distance possible with our equipment). The total number of elements in the stimulus remained constant (256) as well as the total number of elements in the path (12). Viewing distance and element size remained unchanged. Thus, the change in spacing resulted in stimuli of different sizes. In particular, element spacing of 0.25 deg resulted in a stimulus of 4.0 × 4.0 deg while a spacing of 0.9 deg resulted in a stimulus of 14.4 × 14.4 deg.

Figure 12 shows the 0.25 deg condition relative to the 0.5 deg condition.

## Results

Figure 13 plots the results for each observer as a function of the segment length. Although the observers' performance decreases with distance, it is clear that they are capable of performing this task over a wide range of distances. At the largest inter-element distance (0.9 deg), the path segment is over 16 times the $\sigma$ of the element (8 times the full-width at half-height). These results imply an interaction over relatively large areas of the visual field. Indeed, they provide further support for the notion that these effects are due to some form of interaction between mechanisms rather than to any single mechanism responding to successive portions of the path.

It should be noted that in this experiment, we have confounded the size of the display with the distance between the elements. Thus, the drop in performance at the large distances may be partly due to the fact that many of the elements of the display are now presented in the periphery. It is difficult to avoid this confound without confounding other factors. If the display size remained constant, then the number of elements would have to change under the different conditions. The results we obtained allow us to conclude that the integration is possible at large distances. However, further experiments would be required to determine whether the results were due solely to the distance between the elements.

## EXPERIMENT V—RELATIVE PHASE OF PATH ELEMENTS

In the first four experiments, all the elements were of the same form: even-symmetric Gabor functions. The last experiment was run to determine whether the elements were required to have the same form to achieve path integration. The conditions of this experiment were
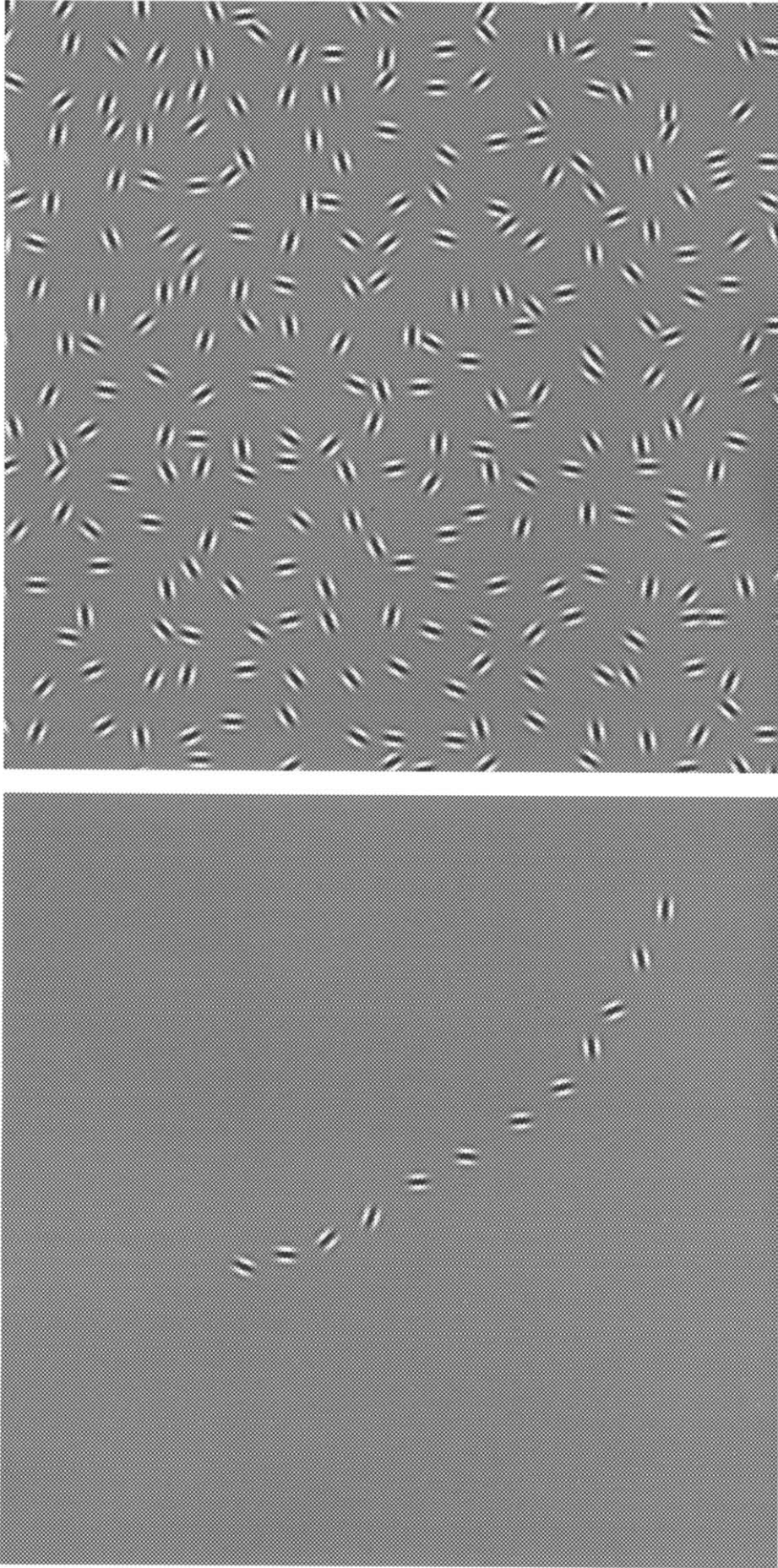
FIGURE 10. An example of a stimulus used in Expt III. In this example the path orientation variable $\beta$ has the values $\pm 15$ deg, and the orientation of the sinusoid of the patch ($\alpha$) is $\pm 30$ deg with respect to the path.
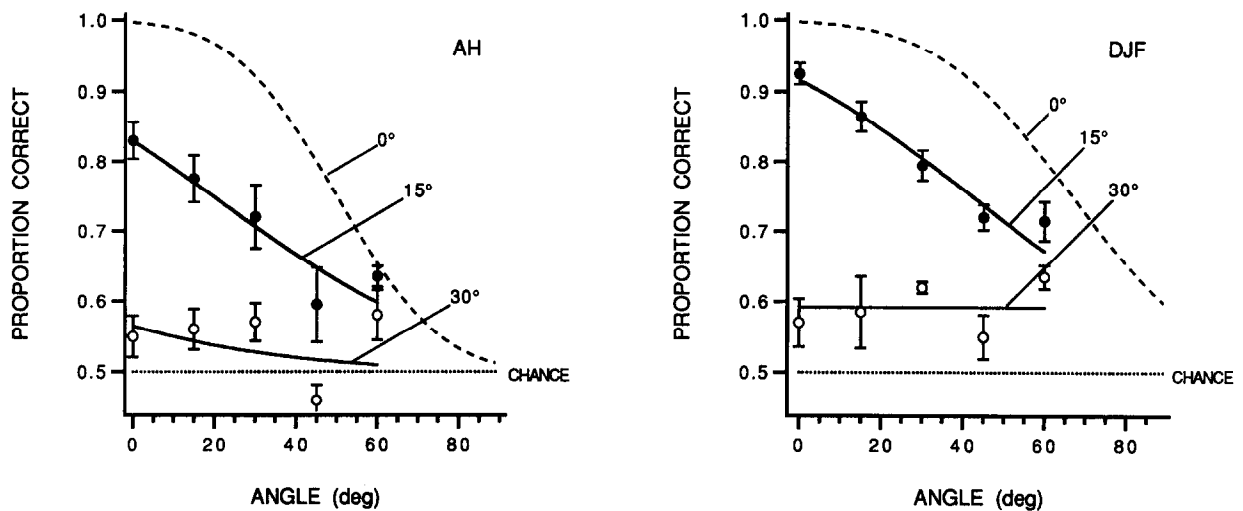
FIGURE 11. Results of Expt III. The solid symbols plot the results for orientations of the element with respect to the path ($\alpha$) of $\pm 15$ deg, and the open symbols for orientations of $\pm 30$ deg. The dashed line shows the results from Expt I ($\alpha = 0$).

the same as that of Expt I, except the relative phase of the elements [$\phi$ in equation (1)] was randomized (uniformly distributed between 0 and $2\pi$). The randomization applied to all the path elements and the background elements. An example of one of the stimuli is shown in Fig. 14.

*Results*

The results of Expt V are plotted in Fig. 15 (solid lines) along with the results from Expt I. These results show no significant difference between this condition and the condition of Expt I. The results suggest that the relative phases of the components are not important to the joining of the segments. With the randomization procedure applied to the phase, the greatest possible difference in phase between two successive elements will be $\pi (+\pi = -n)$ while the average difference will be $\pm n/2$. It is not possible to conclude that phase is irrelevant under all possible conditions. For example, it may be that phase will play a significant role when the bandwidths of the elements are broader than those used in this study. However, these results imply that under the conditions of this experiment, the observers can segregate the path even when the relative phases of the path elements is random.

**DISCUSSION**

The five experiments reported above provide us with a number of insights into the processes that mediate the segregation of a path of elements from its background. In each of these experiments, the elements in the path cannot be identified on the basis of the stimulus properties of the elements. These properties (e.g. spatial frequency, orientation, intensity, contrast, etc.) were the same for the elements in both the path and the background. The path is identified by the relative alignment of its constituent elements. We interpret these results as suggesting a localized linking process or association between the responses to the elements in the path according to a specific set of rules.

Experiments I and IV demonstrate that observers are able to segregate the path from the background when the elements in the path differ up to 60 deg in orientation and when they are separated by distances up to 7 times their width. Experiment II demonstrates that the ability to detect the path is significantly worse when the elements are placed side-to-side as opposed to end-to-end, confirming the finding of Beck *et al.* (1989). If this segregation is due to the association in responses, then the results suggest that the association between elements is stronger along the axis of the element than orthogonal to the axis.

Figure 16(a) provides one way to represent this proposed linking between the responses to each element. For a given element in our displays, there appears to be a region around the element where other elements group together and segregate from the background. We describe this region of association as an "association field".

It would be difficult to provide the precise parameters describing the size of this field. The exact size will be dependent on the particular experimental conditions employed. For example, our results are based on stimuli which have 12 elements in the path and 256 total elements in the stimulus. Significant changes to these parameters are likely to change the proportion correct and would therefore change our estimates of the overall size of this association field. However, such changes should not affect the elongated shape of this field. However these results are interpreted, it is clear that this "association field" covers a considerably wider area than would be covered by the receptive field of a mammalian cortical cell.

The results of Expt III suggest that this association field should not be thought of as a general spread of activation, linking together all types of features within the field. The results show that variations in the orientation of the elements relative to the orientation of the path, result in a significant drop in performance. This suggests that the different parts of the association field show considerable orientation selectivity. Figure 16
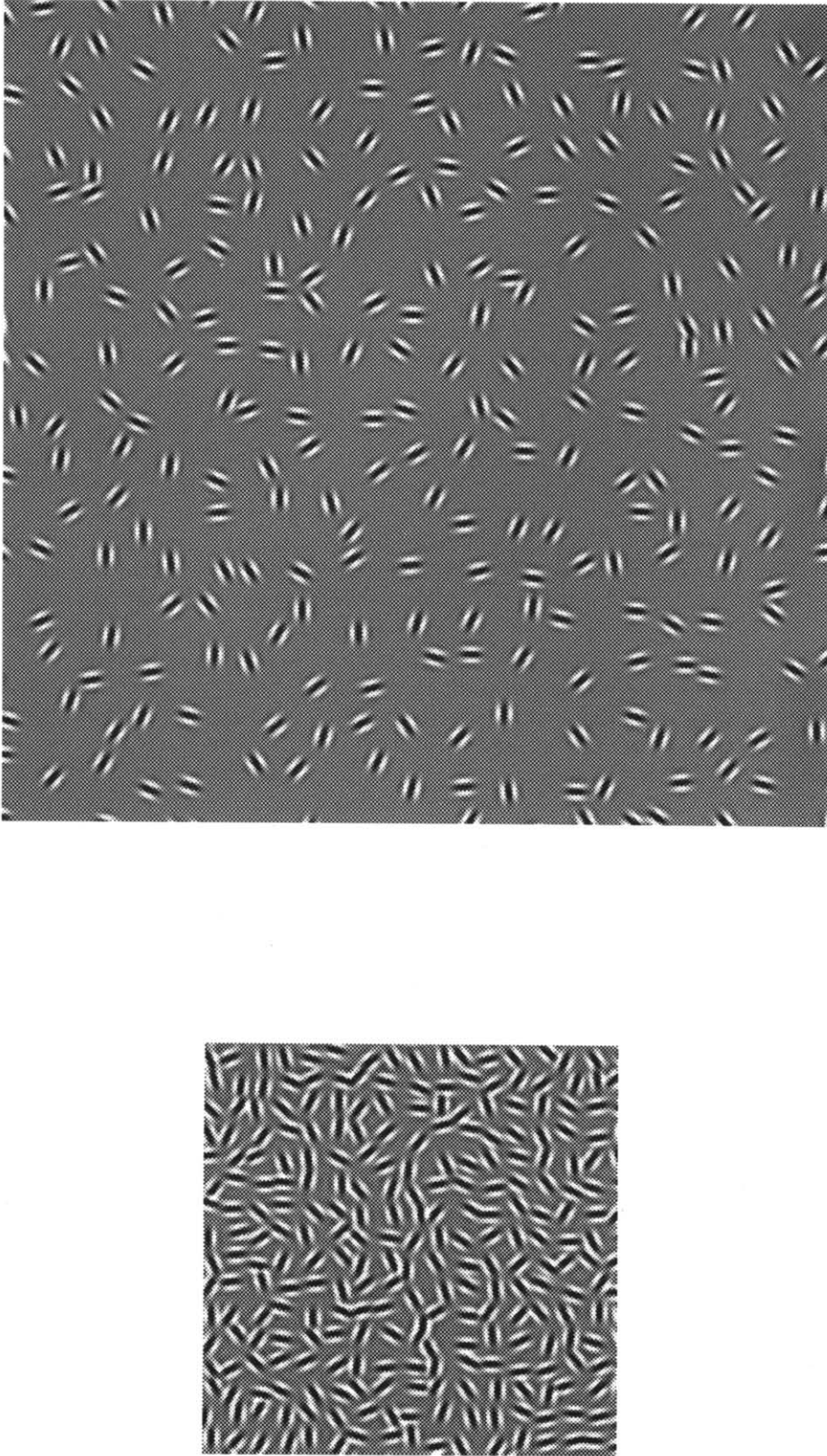
FIGURE 12. An example of a stimulus used in Expt IV. The effects of the element spacing was studied by maintaining the total number of elements but varying the distance between the elements. The right hand panel shows the stimulus when the spacing was set to 0.25 deg (as opposed to the 0.5 deg spacing shown on the left). For these examples the path orientation variable $\beta$ has the values $\pm 15$ deg, and the orientation of the element is aligned with the path ($\alpha = 0$).
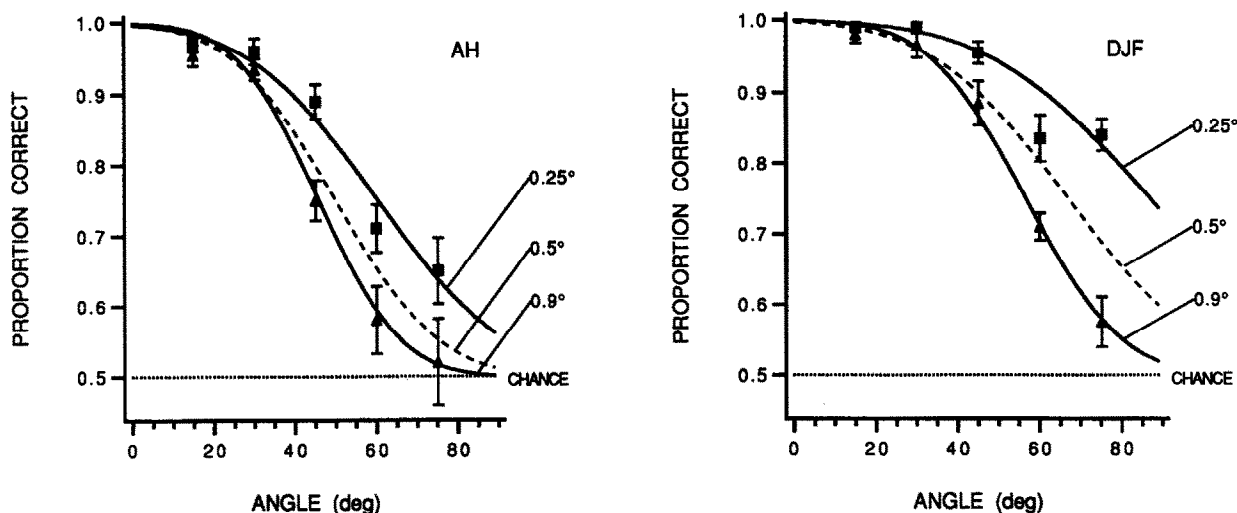
FIGURE 13. Results of Expt IV. The square symbols plot the results for average distances of 0.25 deg between element "boxes", the triangular symbols for 0.9 deg. The average distance between element boxes in Expt I—the dashed line—was 0.5 deg. The space constant of the elements [$\phi$ in equation (1)] was $\frac{1}{16}$ deg for all conditions.

shows our proposal of the preferred orientation in different regions of the field. The rays extending from the ends of the element represent the optimal orientation at different positions relative to the position of the element. As portrayed in Fig. 16(b), elements are associated according to joint constraints of position and orientation.

The results of Expt V suggest that the linking process may be orientation selective but phase invariant. If this holds up under closer scrutiny, this would imply that a mechanism more analogous to a complex cell would be appropriate as the basis of linking. It must be emphasized, however, that this description in terms of an orientation-selective association field is not a necessary model of early visual processing. Although we discuss some interesting parallels in the next section, the association field may represent a grouping strategy at relatively high stages of visual processing. We expect to find correspondence at some level of the visual system, but the description above does not suggest where that correspondence lies.

The five experiments reported in this paper are not meant to represent an exhaustive list of the parameters important in definining the association field. Parameters such as the spatial frequency bandwidth, orientation bandwidth, size, color and relative depth may all have significant effects on the ability to segregate the path from the background. For example, the oriented elements making up the path may only group together when they share similar properties (i.e. color, depth). However, such experiments are beyond the scope of this paper.

*Physiological speculations*

As with most psychophysical studies, it would not be wise to make strong conclusions about the physiological mechanisms which underlie our results. However, there are some interesting parallels between our results and several known properties of the mammalian visual system. In this section, we discuss

these parallels but emphasize the speculative nature of this discussion.

First, a comment about the single detector notion. We believe that the results of our study do *not* support the notion that the detection of the path is mediated by a cell with a receptive field that conforms to the layout of the path. This type of explanation may be conceivable for the case where the elements along the path differ by 0 deg. However, the explanation would have difficulty when the elements differed by more 15 deg. Since there are 12 elements in each path and the orientation difference is always $\pm\theta$, the number of potential paths from each starting point in each condition is $2^{12}$ or 4098. The notion that there might exist 4098 "path detectors" at each location conforming to the range of possible paths seems quite unlikely. Furthermore, it is even unlikely that successive elements along the path are detected by the same mechanism. The bandpass nature of the elements as well as the relative orientation and distance between successive elements should preclude a cell with a classically defined receptive field from responding to successive elements.

If our results are assumed to be a consequence of local interactions between cortical cells, then one must accept that the interactions are occurring at relatively large distances: larger than that represented by a single orientation column. Experiment IV shows interactions at a distance of 0.9 deg for stimuli with a width of 0.125 deg. Near the fovea of the monkey, an orientation column cycles with a periodicity of approx. 1 mm (a hypercolumn) which corresponds in the fovea to a distance of approx. 0.3 deg (Hubel & Weisel, 1974a, b). To account for our results on the basis of interactions between cells in primary visual cortex, interactions between cells in neighboring columns—not just neighboring cells would be required.

It is known that there exist lateral (inter-columnar) connections in primary visual cortex (Rockland & Lund, 1983; McGuire, Gilbert, Rivlen & Weisel, 1991) and there is both anatomical and physiological evidence that
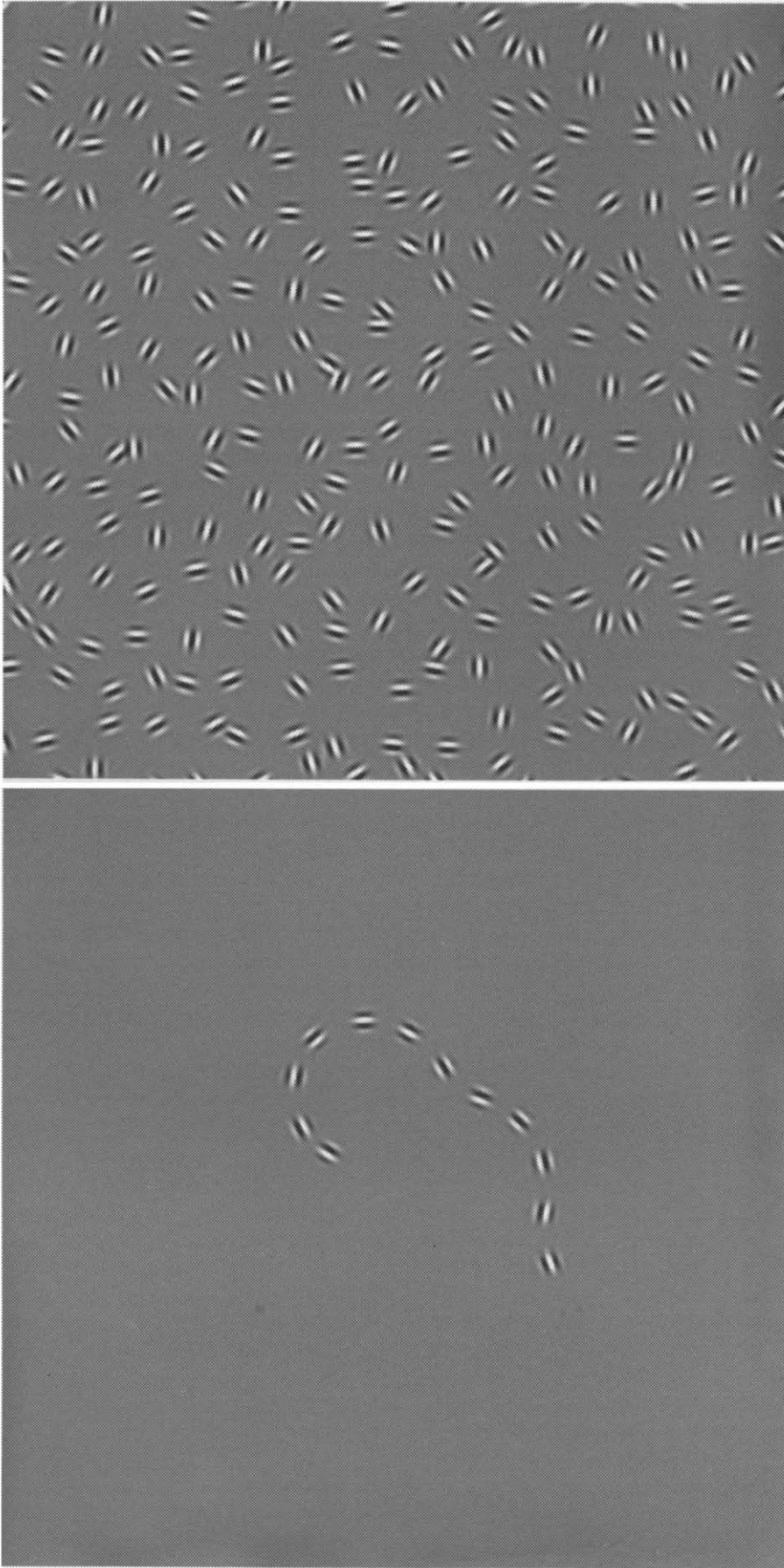
FIGURE 14. An example of a stimulus used in Expt V. In this experiment the phase of the elements [σ in equation (1)] was randomly set. Other than the phase, the parameters were the same as in Expt I.
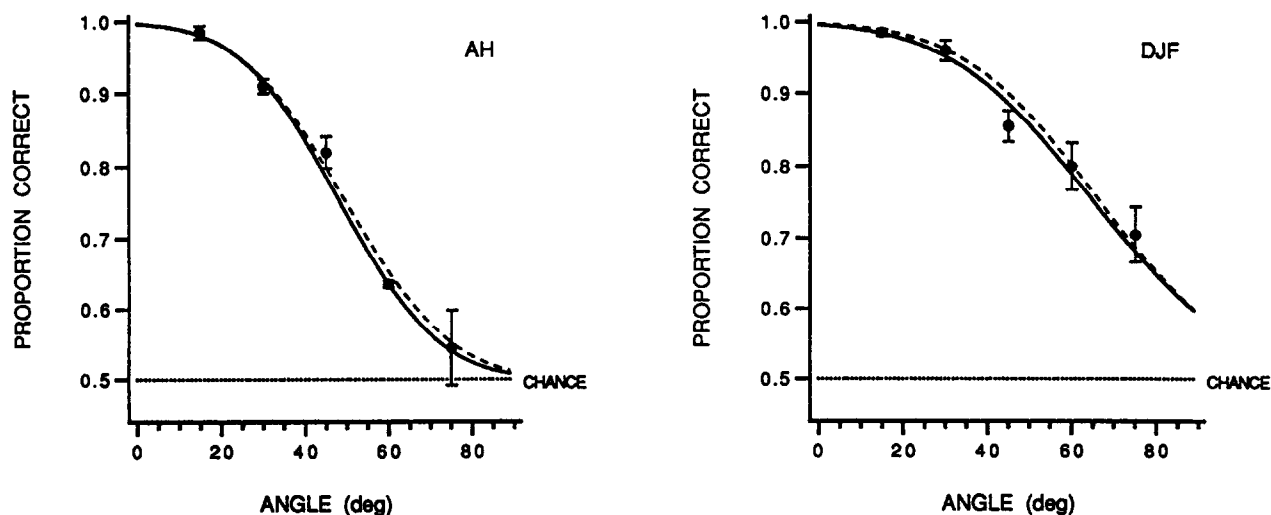
FIGURE 15. Results of Expt V. The data are plotted along with the results of Expt I (dashed line).

cells having similar orientation preference are interconnected (Ts'o & Gilbert, 1988; Gilbert & Weisel, 1989). However, the results of Expts I, II and III suggest that the process that underlies this segregation shows a specific relation between position and orientation. Similar orientations are grouped together only when the alignment falls along particular axes. At the present time there is no evidence that these lateral cortical connections follow these constraints.

Recently, several studies have found evidence for another long-range orientation specific interaction in the visual cortex (e.g. Gray & Singer, 1989; Engel, Konig & Singer, 1991). These studies suggest that there exist coherent oscillations in the activity of neighboring neurons in the visual cortex. The timing between successive action potentials of many cortical cells do not occur at random following the presentation of a stimulus (e.g. moving a bar across the receptive field). For many cells, the probability of response varies cyclically at a frequency of around 50 Hz. The oscillations have been found to be coherent (phase-linked) between cells in neighboring orientation columns (non-overlapping receptive fields) when the orientation tuning of the two cells was similar (Gray & Singer, 1989). Eckhorn, Baur, Jordan, Brosch, Kruse, Munk and Reitboeck (1988) and Engel et al. (1991) have suggested that these oscillations represent a method of linking features in the visual cortex. Further work would be required to determine whether such oscillations play a significant role in the segregation process described in this paper. However, if the coherence in the oscillations was found to conform to the properties of this psychophysically defined association field, a stronger case could be made.

## Computational models of curve extraction

The model that we propose in this paper shows some similarities to the models proposed in the computational literature on curve extraction. A number of studies have suggested an important role for the representation of curvature at quite early stages of the visual system (e.g. Attneave, 1954; Blakemore & Over, 1974; Koenderink & Richards, 1988; Watt & Andrews, 1982; Wilson &

Richards, 1989). Kellman and Shipley (1991) have also proposed a set of rules similar to the association field to account for the perceptual completion of occluded edges in complex objects and images with illusory contours.

Parent and Zucker (1989) as well as Sha'ashua and Ullman (1988) have proposed algorithms for extracting curves which link orientation-selective elements. Our results provide support for the notion that the human visual system utilizes a local grouping process similar to the algorithms suggested by these authors. However, one of the difficulties with their algorithms as a model for human vision is that curves are extracted using a time consuming iterative process based on a relaxation method. As Gigus and Malik (1991) have recently noted, such iterative algorithms are not biologically plausible, requiring multiple feedback loops to extract a curve. Gigus and Malik have shown that it is possible to implement a completely parallel feed-forward algorithm for curvature extraction, which shows properties similar to our proposed association field and is both biologically plausible and computationally efficient.

A second feature of these computational algorithms is that they are principally designed for smooth curves that have well defined tangents. For smooth curves, as shown in Fig. 2(a), the tangent of the edge is relatively constant at different scales. This redundancy across scale can help to define the curve. Although smooth curves are common in a structured (man-made) environment, it should not be assumed that the mammalian visual system is specially adapted to handle such curves.

Fractal curves like the one shown in Fig. 2(b) do not have a well defined tangent. Rather, the orientation of the edge will depend on the particular scale under consideration. As one moves from one spatial frequency band to the next, the orientation of the filtered edge will smoothly change. Indeed, the edge may be continuous at each scale even though the local orientation of the edge changes from scale to scale.

Fractals provide a useful means of creating and representing visual features that have structure at a variety of spatial scales (e.g. Mandelbrot, 1982). In

particular, fractal models have been found to provide an effective description of many natural image phenomena (e.g. Keller, Crownover & Chen, 1987; Pentland, 1984) and fractals are increasingly used in the study of visual processing (e.g. Cutting & Garvin, 1987; Knill, Field & Kersten, 1989; Westheimer, 1991).

In this study, we have data from only a single frequency band. To determine how the human visual system integrates information across neighboring frequency

bands would require further experiments, which we leave for a later paper. However, we should point out that the proposed association field may have a number of parameters other than those of orientation and position.

### Relation to texture segregation

A number of studies have been concerned with the principles by which textures group together and segregate from other textures. The Gestalt rules of organization
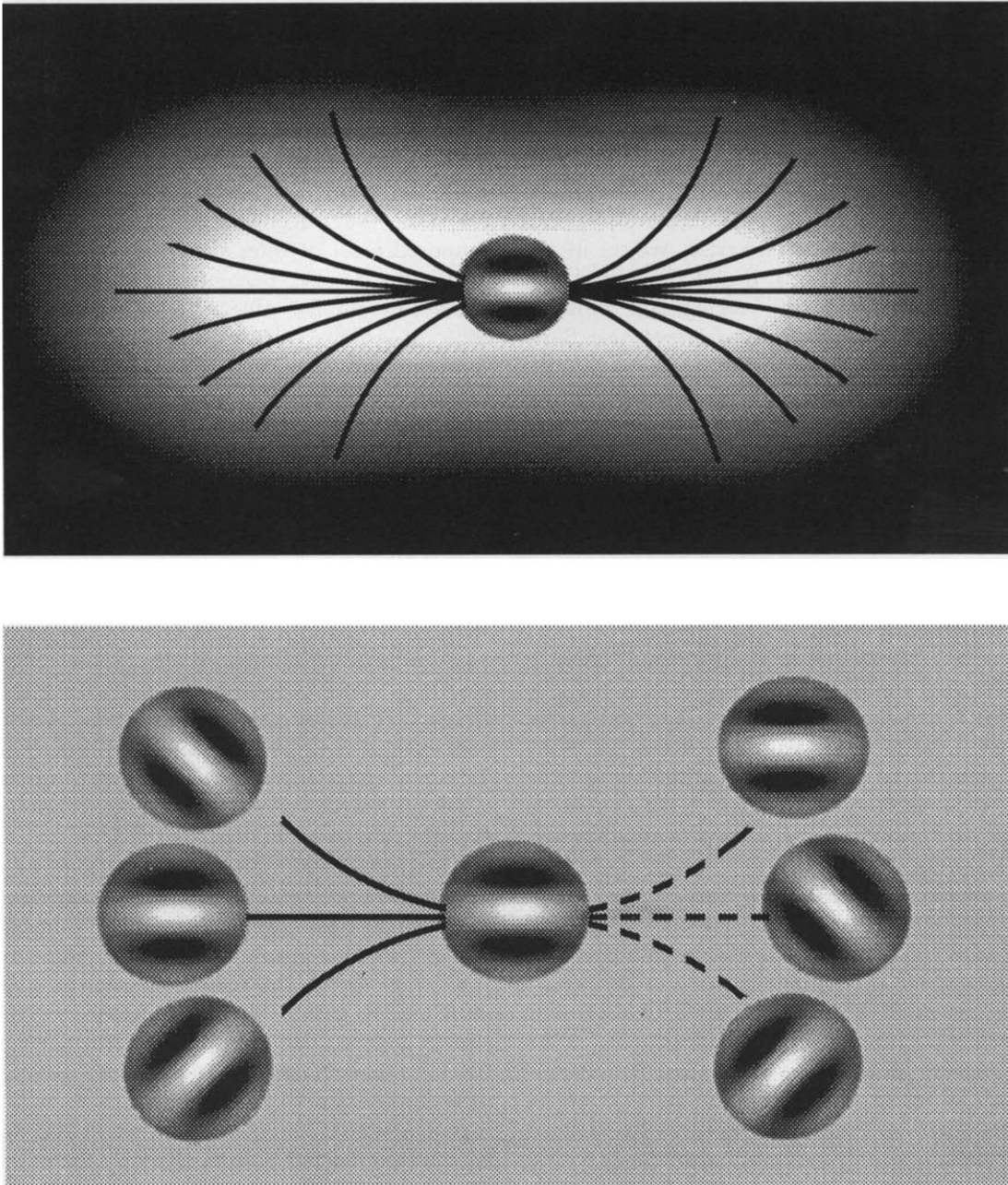


FIGURE 16. The *association field*. The diagram at the top of the figure (a) represents the rules by which the elements in the path are associated and segregated from the background. The precise size of this field would be difficult to determine from this study since it will certainly vary with the particular experimental conditions employed. For example, in this study, the subjects were required to detect 12 elements in a grid of 256 elements. Changing either the path size or the grid size would change our estimate of the association field. The curves in (b) represent the specific rules of alignment. Grouping occurs only when the orientation of elements conforms to first-order curves (i.e. curves with no points of inflection) like those shown by the rays extending from the center of the elements as shown in this figure. The integration process thus appears to show strong joint constraints of position and orientation. Thus, our results suggest that elements with alignment like that shown on the bottom left will be "associated" while elements like that shown on the right will not even though the difference in orientation is the same in both examples.
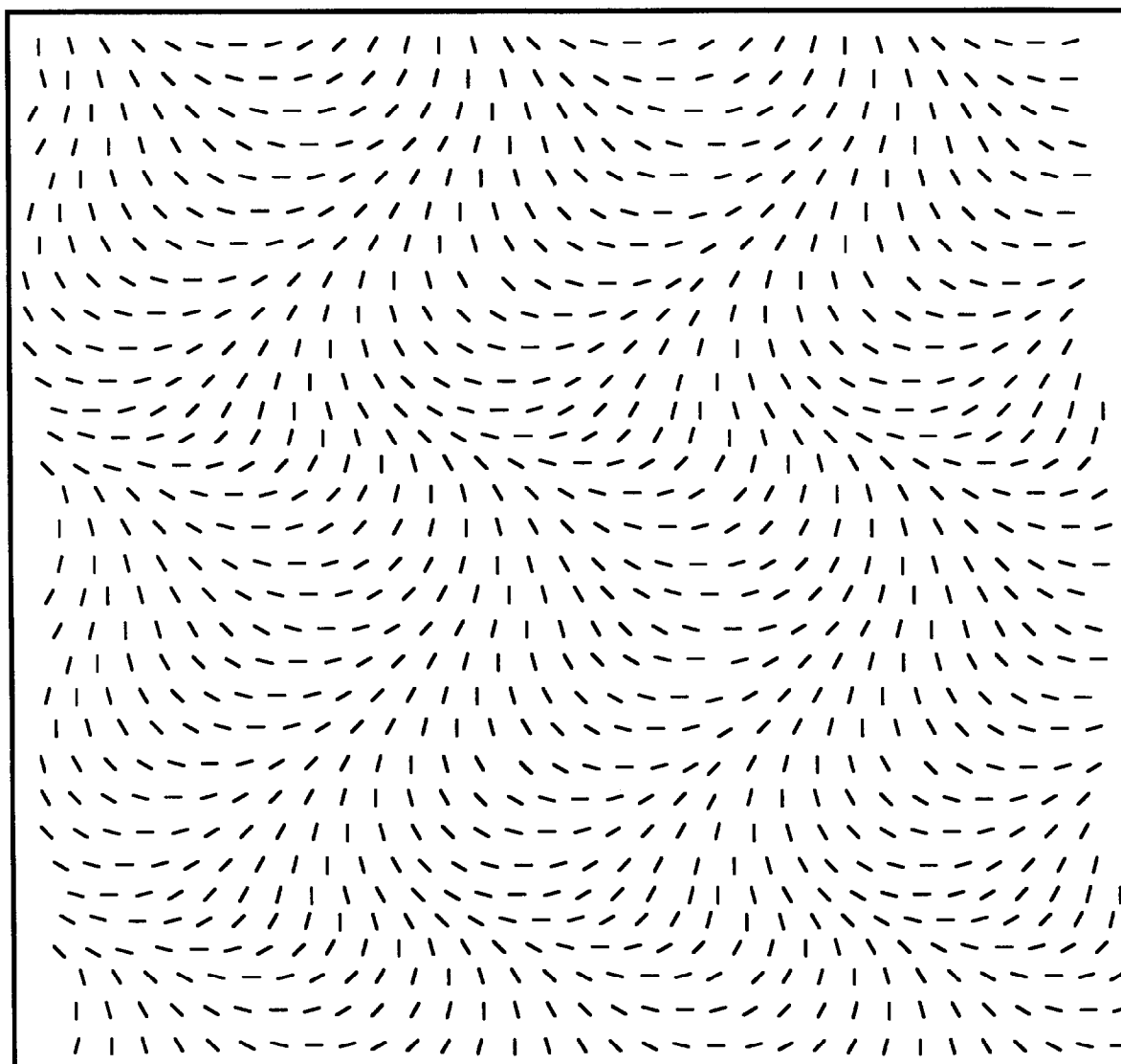
FIGURE 17. This texture contains elements in which the immediate neighbors on all sides differ in orientation by 15 deg. If a perceptual texture was defined only by the feature contrast at the border, then one would not expect to see any grouping in this image. However, the reader will probably notice that the elements that are aligned group together producing a percept of elements flowing smoothly down the image.

(Wertheimer, 1938), as well as studies by Beck (e.g. 1966, 1983) and Julesz (see Julesz & Shumer, 1981 for review), have shown that one structure will segregate from another when the textures differ by an appropriate set of parameters. The identification and classification of these parameters has been the subject of many recent psychophysical studies (e.g. Bovik et al., 1990; Graham et al., 1992; Sutter, Beck & Graham, 1989; see Bergen, 1991 for review). Much of this work has focused on the global nature of the segregation. In these studies, the segregation process is presumed to result from a process involving spatially-parallel filters which are selective along a number of dimensions. Textures that differ in orientation or spatial frequency content, for example, are readily segregated.

In our stimuli, there does not exist any "global" feature that allows the path to be segregated from the background. It is not possible to segregate the path by filtering along any particular dimension. Our results imply that the path segregation is based on local

processes which group features locally. We believe that the recent demonstrations of Nothdurft (1985, 1991) suggest that a similar local process may be involved in many texture segregation tasks. Nothdurft demonstrates that when the orientation of small line elements shift slowly across an image, these elements group together and segregate from the background. His results demonstrate that the global feature-based model is insufficient. However, Nothdurft proposes that the segregation of textures is dependent on the "feature contrast" at the borders of the texture—not the local grouping of structures within the texture. Landy and Bergen (1991) make a similar argument using textures which do not consist of localized elements. Their textures were created by selectively filtering different regions of a noise pattern. They found that the continuity at the border between two textures was important in the ability to segregate the textures.

Consider the image show in Fig. 17. In this image, all elements differ in orientation from their four neighbors

by a constant amount. There are no locations where the difference in orientation is larger or smaller than anywhere else. Thus, by Nothdurft's definition there exist no regions where there exists "feature contrast". Nonetheless, the image does not appear as a uniform texture. The reader will probably see a general "flow" of elements providing the impression of a wave of elements that change direction moving down the image. This demonstration implies that some aspects of texture segregation may be more dependent on local rather than global grouping rules. Whether local processes can account for all segregation tasks remains to be seen.

## Summary

This study has explored five parameters that effect the ability of human observers to segregate a path from the background. In line with several computational studies, we explain our results in terms of an "association field" which groups features according to a specific set of rules. These rules suggest specific constraints for grouping structure with similar orientation content. Although there are some interesting parallels between the grouping of similar orientations and the lateral connections of cortical cells with similar tuning, further work is needed to determine whether these parallels represent more than an interesting coincidence.

## REFERENCES

Attneave, F. (1954). Some informational aspects of visual perception. *Psychological Review, 61*, 183–193.

Beck, J. (1966). Effect of orientation and shape similarity on perceptual grouping. *Perception and Psychophysics, 1*, 300–302.

Beck, J. (1983). Textural segmentation, second-order statistics and textural elements. *Biological Cybernetics, 48*, 125–130.

Beck, J., Rosenfeld, A. & Ivry, R. (1989). Line segregation. *Spatial Vision, 4*, 75–101.

Bergen, J. R. (1991). Theories of visual texture perception. In Regan, D. (Ed.), *Vision and visual dysfunction* (Vol. 10B). New York: Macmillan.

Blakemore, C. & Over, R. (1974). Curvature detectors in human vision? *Perception, 3*, 3–7.

Bovik, A. C., Clark, M. & Geisler, E. S. (1990). Multi-channel texture analysis using localized spatial filters. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 12*, 55–73.

Canny, J. (1986). A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 12*, 679–698.

Cutting, J. & Garvin, J. J. (1987). Fractal curves and complexity. *Perception and Psychophysics, 42*, 365–370.

Eckhorn, R., Baur, R., Jordan, W., Brosch, M., Kruse, W., Munk, M. & Reitboeck, H. J. (1988). Coherent oscillations: A mechanism of feature linking in the visual cortex? *Biological Cybernetics, 60*, 121–130.

Engel, A. K., Konig, P. & Singer, W. (1991). Direct physiological evidence for scene segmentation by temporal coding. *Proceedings of the National Academy of Sciences, U.S.A., 88*, 9136–9140.

Field, D. J. (1987). Relations between the statistics of natural images and the response properties of cortical cells. *Journal of the Optical Society of America A, 4*, 2379–2394.

Field, D. J. (1992). Scale-invariance and self-similar "wavelet" transforms: An analysis of natural scenes and mammalian visual systems. In Farge, M., Hunt, J. & Vassilicos, J. C. (Eds), *Wavelets, fractals and Fourier transforms: New developments and new applications.* Oxford: Oxford University Press.

Gigus, Z. & Malik, J. (1991). Detecting curvilinear structure in images. *U.C. Berkeley CSD Technical Report 91/619.*

Gilbert, C. D. & Weisel, T. N. (1989). Columnar specificity of intrinsic horizontal and cortico-cortical connections in cat visual cortex. *Journal of Neuroscience, 9*, 2432–2442.

Glass, L. (1969). Moiré effect from random dots. *Nature, 243*, 578–580.

Graham, N., Beck, J. & Sutter, A. (1992). Nonlinear processes in spatial frequency channel models of perceived texture segregation: Effects of sign and amount of contrast. *Vision Research, 32*, 719–743.

Gray, C. M. & Singer, W. (1989). Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. *Proceedings of the National Academy of Sciences, U.S.A., 86*, 1698–1702.

Grossberg, S. & Mignolla, E. (1985a). Neural dynamics of form perception: Boundary completion, illusory figures and neon color spreading. *Psychological Review, 92*, 173–211.

Grossberg, S. & Mignolla, E. (1985b). Neural dynamics of perceptual grouping: Textures, boundaries and emergent segmentations. *Perception and Psychophysics, 38*, 141–171.

Hayes, A. (1989) Representation by images restricted in resolution and intensity range. PhD thesis, Department of Psychology, University of Western Australia, Australia.

Hubel, D. H. & Weisel, T. N. (1974a). Sequence regularity and geometry of orientation columns in the monkey striate cortex. *Journal of Comparative Neurology, 158*, 267–294.

Hubel, D. H. & Weisel, T. N. (1974b). Uniformity of monkey striate cortex: A parallel relationship between field size, scatter and magnification factor. *Journal of Comparative Neurology, 158*, 295–306.

Julesz, B. & Sumer, R. A. (1981). Early visual perception. *Annual Review of Psychology, 32*, 575–627.

Keller, J. M., Crownover, R. M. & Chen, R. Y. (1987). Characteristics of natural scenes related to the fractal dimension. *IEEE Transactions on Pattern Analysis and Machine Intelligence, PAMI-9*, 621–627.

Kellman, P. J. & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology, 23*, 141–221.

Knill, D. C., Field, D. & Kersten, D. (1989). Human discrimination of fractal images. *Journal of the Optical Society of America A, 7*, 1113–1123.

Koenderink, J. J. & Richards, W. (1988). Two-dimensional curvature operators. *Journal of the Optical Society of America A, 5*, 1136–1141.

Landy, M. S. & Bergen, J. R. (1991) Texture segregation and orientation gradient. *Vision Research, 31*, 679–691.

Lowe, D. G. (1988). Organization of smooth image curves at multiple scales. *Proceedings of the second international conference on computer vision.* (pp. 558–567). New York: IEEE.

Mandelbrot, B. B. (1982). *The fractal geometry of nature.* San Francisco, Calif.: Freeman.

Marr, D. & Hildreth, E. (1980). Theory of edge detection. *Proceedings of the Royal Society of London B, 207*, 187–217.

McGuire, B. A., Gilbert, C. D., Rivlen, P. K. & Weisel, T. N. (1991). Targets of horizontal connections in macque Primary visual cortex. *Journal of Comparative Neurology, 305*, 370–392.

Morgan, M. J. & Hotopf, W. H. N. (1989). Perceived diagonals in grids and lattices. *Vision Research, 29*, 1005–1015.

Nothdurft, H. C. (1985). Sensitivity for structure gradient in texture discrimination tasks. *Vision Research, 25*, 1957–1968.

Nothdurft, H. C. (1991). Texture segmentation and pop-out from orientation contrast. *Vision Research, 31*, 1073–1078.

Parent, P. & Zucker, S. (1989). Trace inference, curvature consistency and curve detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 11*, 823–839.

Pentland, A. P. (1984). Fractal-based description of natural scenes. *IEEE Transactions on Pattern Analysis and Machine Intelligence, PAMI-6*, 661–675.

Rockland, K. & Lund, J. S. (1983). Intrinsic laminar lattice connections in primate visual cortex. *Journal of Comparative Neurology, 216*, 303–318.

Shas'ashua, A. & Ullman, S. (1988). Structural saliency: The detection of globally salient structures using a locally connected network.

*Proceedings of the second international conference on computer vision* (pp. 321–327).

Smits, J. T. S., Vos, P. G. & van Oeffelen, M. P. (1985). The perception of a dotted line in noise: A model of good continuation and some experimental results. *Spatial Vision, 1*, 163–177.

Sutter, A., Beck, J. & Graham, N. (1989). Contrast and spatial variables in texture segregation: Testing a simple spatial-frequency channels model. *Perception and Psychophysics, 46*, 312–332.

Ts'o, D. Y. & Gilbert, C. D. (1988). The organization of chromatic and spatial interactions in the primate striate cortex. *Journal of Neuroscience, 8*, 1712–1727.

Ullman, S. (1990). Three-dimensional object recognition. *Cold Spring Harbor symposia on quantitative biology* (Vol. LV). Cold Spring Harbor, N.Y.: Laboratory Press.

Uttal, W. (1975). *An autocorrelation model of form detection*. Hillsdale, N.J.: Erlbaum.

Watt, R. J. (1984). Further evidence concerning the analysis of curvature in human foveal vision. *Vision Research, 24*, 251–253.

Watt, R. J. & Andrews, D. P. (1982). Contour curvature analysis: Hyperacuities in the discrimination of detailed shape. *Vision Research, 22*, 449–460.

Wertheimer, M. (1938). *Laws of organization in perceptual forms*. London: Harcourt (Brace & Jovanovich).

Westheimer, G. (1991). Visual discrimination of fractal borders. *Proceedings of the Royal Society of London B, 243*, 215–219.

Wilson, H. R. & Richards, W. A. (1989). Mechanisms of contour curvature discrimination. *Journal of the Optical Society of America A, 6*, 106–115.

Zucker, S. W. (1986). Early processes for orientation selection and grouping. In Pentland, A. P. (Ed.), *From pixels to predicates: Recent advances in computational and robotic vision* (pp. 170–200). Norwood, N. J.: Ablex.

Zucker, S. W., Dobbins, A. & Iverson, L. (1989). Two-stages of curve detection suggest two styles of visual computation. *Neural Computation, 1*, 68–81.