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Subjective figures and texture perception

STEVEN W. ZUCKER and PATRICK CAVANAGH*

Computer Vision and Robotics Laboratory, Department of Electrical Engineering, McGill University, Montréal, Québec H3A 2A7, Canada

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Abstract—A texture discrimination task using the Ehrenstein illusion demonstrates that subjective brightness effects can play an essential role in early vision. The subjectively bright regions of the Ehrenstein can be organized either as discs or as stripes, depending on orientation. The accuracy of discrimination between variants of the Ehrenstein and control patterns was a direct function of the presence of the illusory brightness stripes, being high when they were present and low otherwise. It is argued that neither receptive field structure nor spatial-frequency content can adequately account for these results. We suggest that the subjective brightness illusions, rather than being a high-level, cognitive aspect of vision, are in fact the result of an early visual process.

1. INTRODUCTION

Texture is one of the most prevalent classes of visual patterns. It is rich in clues about surface structure and orientation, but we will show that current models of texture analysis by the visual system are incomplete. Such attempts have been based on definitions of texture posed in terms of distributions of intensity and very low-level features, such as blobs. The main purpose of this paper is to report new experimental evidence that more abstract representations are needed as well. In particular, we show that the representation underlying subjective effects apparent in the Ehrenstein illusion can play an essential role in texture discrimination tasks. These are significantly more abstract features than those previously thought to participate in texture discrimination tasks, thereby raising the level of structure on which texture processing can take place. The discrimination performance that we observed is not readily accounted for by either statistics of intensity distributions or by receptive-field structures. Rather, it would seem that all of the descriptive levels implicit in early visual information processing are capable of playing an active role in texture discrimination tasks.

Perhaps the most complete proposal about texture processing is due to Julesz and his co-workers, who showed that it includes both (i) first- and second-order statistics of intensity distributions (Julesz, 1962), and (ii) first-order statistics of fundamental visual features (called textons). Textons basically consist of oriented blobs, lines, and terminators (Julesz, 1981; see also Beck, 1967, 1972, Marr, 1976; Zucker, 1976). We shall show that neither of these statistics can account for our experimental findings.

2. THE EHRENSTEIN ILLUSION

The Ehrenstein illusion is a classic subjective brightness effect in which the areas bounded by the proximal endpoints of four dark lines appear lighter than their

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*Present address: Department of Psychology, University of Montréal, Montréal, Québec, Canada.

surround (Ehrenstein, 1941, 1954; Spillman *et al.*, 1976). These subjective areas—or discs—distributed over an array, will provide one of the constructive components of our texture discrimination task. The control, or comparison, pattern is identical to the Ehrenstein pattern, except that the horizontal rows have been shifted 0.5 cycles, thereby reducing the subjective brightness discs (see Fig. 1).

Depending on the orientation of the Ehrenstein, two different patterns of subjective figures can be seen—either a rectangular array of discs or a grid of lines or stripes. This second organization can be readily demonstrated by rotating the Ehrenstein pattern in Fig. 1 by 45° and looking at it just to the side of the pattern. Subjective stripes appear when they are within a few degrees of being vertical and horizontal (i.e. when the physical lines are oriented at approximately 45°). These subjective brightness stripes—within the 45° Ehrenstein—are the most salient feature of that pattern. The control pattern, on the other hand, does not undergo any qualitative change as a function of orientation. Thus the moderate difference between the Ehrenstein and the control at 0°, where there are no subjective stripes, becomes very marked at 45°, where one pattern has stripes and the other does not.

2.1. *Oblique effects*

It is not clear what induces this new level of organization in the Ehrenstein pattern at 45°. Although it would be classified as an oblique effect, the fundamental spatial frequency of the subjective stripes in our displays was 4.6 cycles per degree (c.p.d.), well below the spatial frequencies at which substantial oblique effects occur (about 8 c.p.d: Campbell *et al.*, 1966; Berkley *et al.*, 1975). The actual luminance profile that gives rise to the subjective stripes can be seen by tilting the page of Fig. 1 sharply away from you and looking across the pattern along the diagonal. Using this impromptu spatial averaging technique, you should see broad dark bars alternating with narrow light bars. This rectangular luminance profile represents the energy actually in the stimulus along the diagonal. The enhancement of this energy into subjectively brightened stripes

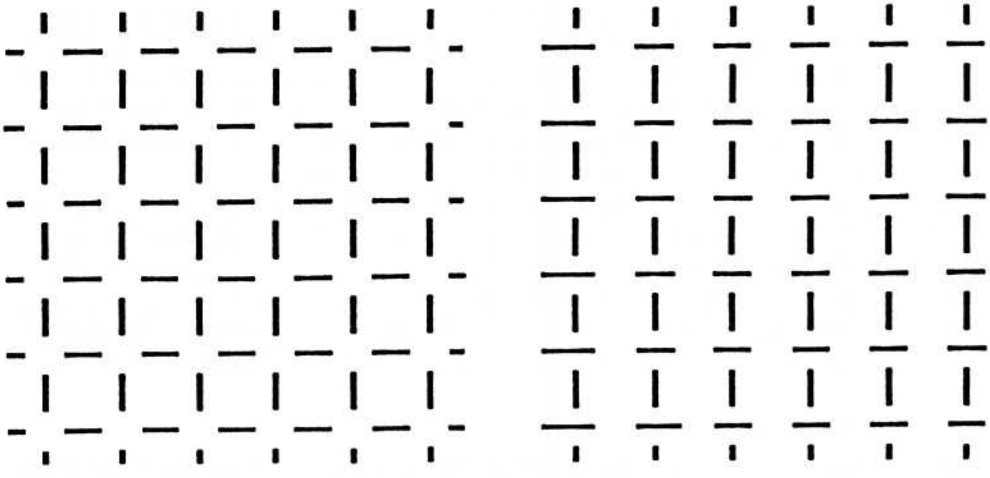

Figure 1. Ehrenstein pattern (left) and the control figure (right). Bright discs should be visible at the line intersections in the Ehrenstein, but may appear to join into bright lines when the figure is held at 45° and viewed extrafoveally. Slant the figure sharply away from you and look along the diagonal to see the actual luminance profiles contributing to these brightness effects.

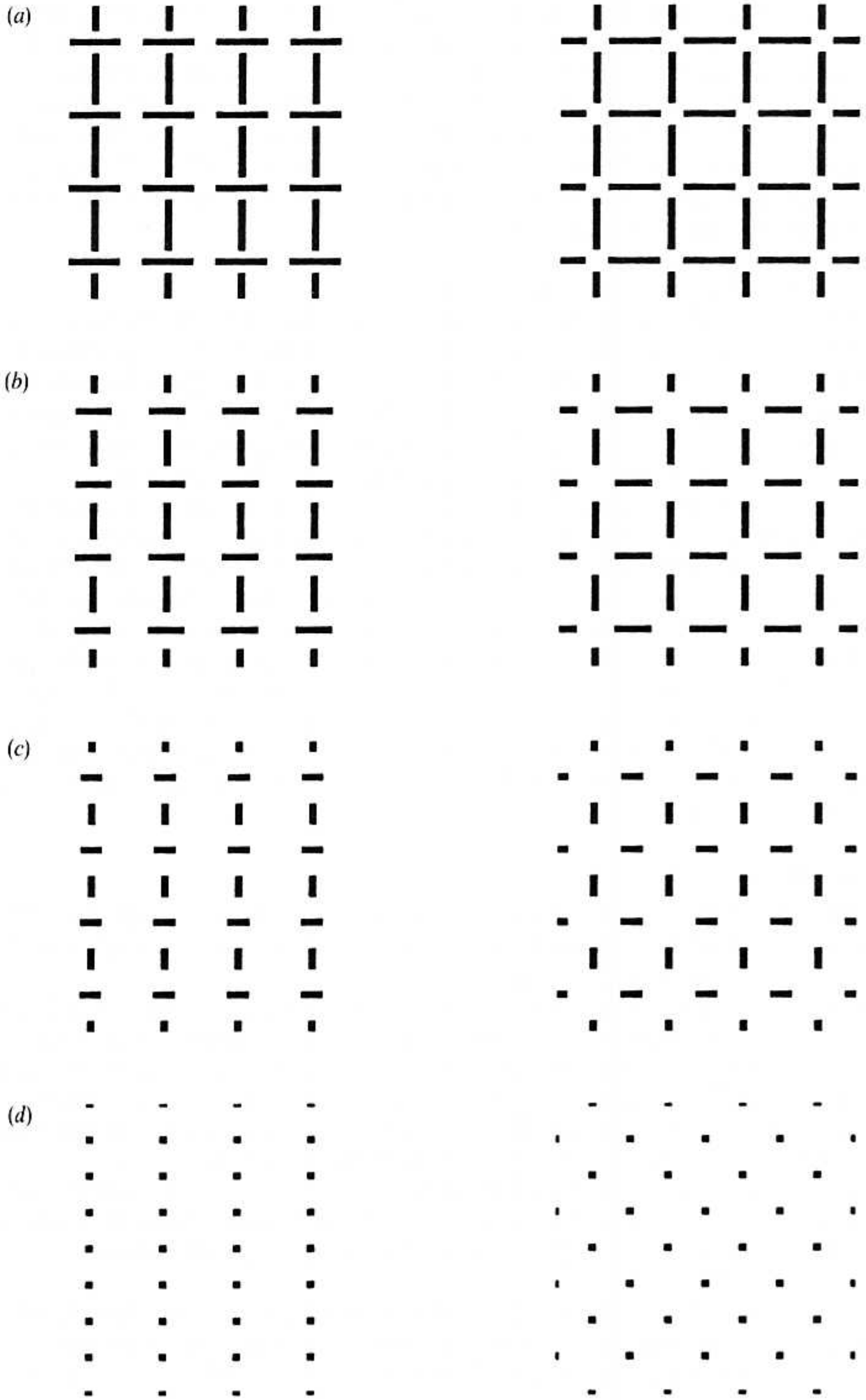

Figure 2. The four gap sizes used for the control and Ehrenstein figures; they are (a) 30%, (b) 50%, (c) 70%, and (d) 90%.

must involve some process beyond simple linear filtering. In terms of the energy in the stimulus, filtered by the visual system's modulation transfer function, there is only a slight advantage for the subjective swaths when they are oriented vertically or horizontally (i.e. when the pattern is at 45°) and this would be limited to the upper harmonics of the stripes' spatial pattern. This slight advantage seems to be quite inadequate to account for the perceived strength of the subjective effects. Perhaps the slight oblique effect gives the subjective swaths a sufficient bias to tip a more abstract grouping process from one organization to another.

2.2. *Subjective figures in texture discrimination*

Although only a slight energy advantage might be sufficient to flip the bias from one grouping to another, we were interested to know whether the discrimination performance would reflect only the slight oblique effect advantage predicted from the spatial frequency data (Campbell *et al.*, 1966; Berkley *et al.*, 1975), or the much more evident subjective figure advantage. In other words, do subjective brightness effects play a direct, influential role in low level tasks like texture discrimination?

We used two manipulations to influence the strength of the subjective figures in the Ehrenstein pattern. First, as already mentioned, we used two orientations of the patterns, one in which the subjective figures were disc-like and the other in which they formed stripes. Second, we varied the size of the gaps in the figures from 30% to 50%, 70%, and 90% of the intersection to intersection distance (Fig. 2). At the 45° orientation, good subjective stripes are seen on the two smaller gap-size figures, but not on the two larger gap-size ones. The gap size has only a very subtle and diffuse effect on the spatial frequency spectra of the figures.* For the discrimination tasks, the manipulations were performed on both the Ehrenstein and the control figures. The task required discrimination of the control and Ehrenstein figures at four gap sizes and at orientations of 0° and 45°.

3. EXPERIMENTAL PROCEDURE

There were 24 subjects in the experiment, each of whom was naïve to its purpose. All were students at the Université de Montréal. Each subject was given 20 practice trials before the actual data collection began.

The two test patterns were presented within circular regions, each 3 degrees of visual angle in diameter. The inclination of the line joining their centres and the fixation point was 22.5° from horizontal, and the centre-to-centre distance was 3.8 degrees of visual angle. The line-to-line spacing within the grids was 0.3° and the line width was 0.03°, black lines on a white background. The test patterns were presented by removing the appropriate gaps from the intact grid and then replacing them after 320 ms.

Each circular region contained either the Ehrenstein or the control pattern, both with the same gap size. The gap sizes were 0.09, 0.15, 0.21 and 0.27 degrees of visual angle. The contrast on the display was approximately 90%, with a mean screen luminance of 50 cd/m^2.

Subjects viewed a fixation point midway between two circular regions of intact grids. The grid of lines was placed on the display primarily to orient the observers. It is possible that some of them adapted to the display, but this should only enhance the

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*That is, the relative weights of the 12 most significant spatial frequency components, i.e. those with the highest energy, are not changed by more than 10% by the gap size manipulations.

visibility of the stimuli, since it would emphasize the differences between the test patterns and the intact grid.

Each subject viewed 80 patterns distributed equally over the four gap sizes, with half of the tests containing the same pattern (either both Ehrenstein or both control), and half different patterns, in the two test grids. After the 320 ms test display, the subject had 5 s in which to indicate whether the two patterns were the same or different. If the subject had not responded within the 5 s, the trial was presented again later in the session.

4. RESULTS

The discrimination results are shown in Fig. 3. The 0° curve displays the data obtained with the patterns oriented as in Fig. 1; the 45° curve shows the data from the rotated display.

The discrimination accuracy was evaluated as a d' measure, where

$$d' = z(P(\text{Yes}\,|\,\text{signal})) - z(P(\text{Yes}\,|\,\text{No signal}))$$

for $z(\cdot)$ a Normal distribution, and $P(\cdot)$ the observed frequency of responses conditioned on the signal. The d' measure shows a substantial advantage for the 45° over the 0° patterns at the two smaller gap sizes. These are the conditions for which the subjective stripes are seen in the 45° Ehrenstein patterns. For the two larger gap sizes, where the subjective stripes are not seen, the advantage actually reverses [planned comparison based on error data, $F(1,22) = 6.43$, $P < 0.02$].

5. DISCUSSION

There are two different theories about texture discrimination: (i) that it is based purely on the statistics of image intensities, and (ii) that it is based on explicit descriptions of the intensity-coded information, or features. We shall now argue that the above experimental results are inconsistent with (i) but are consistent with (ii), provided that the descriptions are abstract enough to include the subjective figures in the Ehrenstein illusion.

The intensity-based theory was founded in an early series of experiments performed by Julesz (1962). By displaying random patterns for short (i.e. approximately 0.5 s)

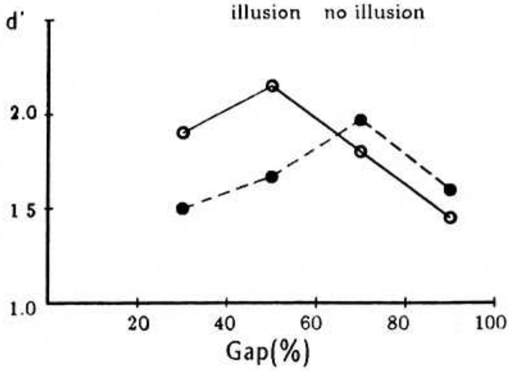

Figure 3. Discriminability (d') of the Ehrenstein and control figures at four different gap sizes and at 0° (●) and 45° (○) orientation.

exposures, he found that human observers were able to discriminate between patterns differing in first- and second-order statistics, e.g. between patterns whose average contrast or power spectra differed; but not between patterns agreeing in these statistics and differing in higher orders; see also Julesz *et al.*, (1973). These results led him to conjecture that only first- and second-order statistics of the intensity distribution mattered for texture discrimination tasks. Such a conjecture was attractive because it implied that texture information could be obtained in a direct and distributed fashion before (even simple) forms were extracted.

Unfortunately, subsequent experiments (Caelli and Julesz, 1978a, b) have shown the intensity conjecture to be false, and a second conjecture—that intensity-statistics, supplemented by first-order statistics of certain explicit local features, are sufficient—now seems more attractive. Julesz has, in fact, named these additional explicit features textons, to denote the elements of texture perception (Julesz, 1981). Another, independent statement of this kind of theory was made by Marr (1976). Both theories are in the classical tradition of computer vision, in which texture has been viewed as 'statistics of local properties' (Rosenfeld, 1969).

The local features involved in this second conjecture are, however, more difficult to specify exactly. The theories, when precise, differ in specifics, but they agree that the local features or tokens should be directly obtainable from the intensities. Both Marr and Julesz were motivated in part by available neurophysiology (e.g. Hubel and Wiesel, 1977) and psychophysics (e.g. Beck 1967, 1972). Julesz claims, in particular, that it is the average number of oriented lines and blobs, and the number of line terminators and crossings, that comprise the list of textons (Julesz, 1981). Our present contribution requires an extension to this theory, and extends the relevant class of image features a step further, to subjective ones, by using textures consisting of highly structured rather than random, patterns.

To show that the above experimental data indicate a more abstract side to texture discrimination, we shall argue in particular that intensity functions do not account for the discrimination results, and that the bright discs (or whatever is responsible for them) should be considered as contributory to texture processing. Thus there is more processing preceding texture discrimination tasks than had hitherto been thought necessary.

5.1. *Insufficiency of second-order intensity distributions*

Spatial frequency representations have been used before to explain subjective effects. Ginsburg (1975) has argued that subjective contours, such as those of the Kanisza triangle, reflect the presence of actual energy components along the contours due to the low spatial-frequency content of the inducing stimuli. Thus, in the instance of the diagonal swaths through the Ehrenstein pattern, cells with elongated on-centre receptive fields will respond when the fields align with the gaps across several intersections. These responses may then contribute to the impression of lines, brighter than the background, joining the intersections. A similar explanation has been given for the presence of subjective diagonal lines in the pincushion grid illusion (Schachar, 1976; Ginsburg and Campbell, 1977; Boulter, 1977; Ochs, 1979), and a related one for the Hermann grid illusion (Spillman and Levine, 1971). It should be noted, however, that several investigators have reported the influence of strictly cognitive factors on the origin of subjective contours (Bradley and Petry, 1977; Brussell *et al.*, 1977; Coren, 1972; Gregory, 1972; Kanisza, 1976; Rock and Anson, 1979).

Spatial frequency content cannot explain the alternation between the two organizations of the subjective figures at 0° and 45°, however. The increased sensitivity to vertical and horizontal contours, as compared to diagonal ones, can be modeled by a frequency domain filter. The response characteristics of such a filter have been measured for the visual system, and are essentially isotropic below about 8 c.p.d. (Campbell *et al.*, 1966; Berkley *et al.*, 1975). Thus this orientation-bias filter would only affect the third and higher order harmonics of our displays. But most of the energy difference between the control and the test patterns was concentrated on the first harmonic, or 4.6 c.p.d. This would certainly be the component responsible for discrimination at this threshold level.

As mentioned in the introduction, the oblique effect has very little influence on the energy of the major component that differentiates the Ehrenstein and control patterns. Any advantage that does exist for the 45° presentation should be present both for the small and the large gap stimuli. The fact that we observe a substantial advantage *only* for the small gap sizes where the illusion is visible argues strongly for a direct role of the subjective figures in the discrimination task.

6. LAWFUL STRUCTURE IN TEXTURE

The previous analysis shows that our results could not be explained 'bottom up'; that is, that the shapes of very early receptive fields were not sufficient to account for all of the mechanisms of texture discrimination. In this section we shall try to work 'top down', by inquiring about the role of texture in visual tasks.

Let us first point out that Julesz developed his texton theory from the analysis of random arrangements of local micropatterns. In our stimuli, on the other hand, the micropatterns are arranged according to macroscopic laws (see Zucker, 1976). This macroscopic organization of texture can carry useful visual information. For example, when one smooth object occludes another, the interruption of the smooth object's texture will conform to a smooth curve (the outline of the occluding object). Analogously, the micropatterns comprising pinstripes and fur satisfy macroscopic laws of organization (Zucker, 1984, 1985), and provide constraints about surface structure. It is the recovery of these smooth curves—the macroscopic structure—that is ecologically important.

Our experimental findings can now be placed in perspective: it was not the number, or average properties of the line segments comprising the displays that was significant; rather, it was their arrangement and the subsequent processing that this triggered. This subjective arrangement may matter at the level of terminators, or at a more abstract level of subjective figures. It has been proposed that terminators can be interpreted as local evidence of occlusion (Coren, 1972); hence it is not surprising that mechanisms exist to organize and use them. In fact, recent physiological evidence points to mechanisms in area 18 that are capable of responding to subjective figures (Von der Heydt *et al.*, 1984).

7. CONCLUSION

Our experiment demonstrated that the subjective figures underlying the Ehrenstein illusion can play a significant role in texture discrimination tasks. Such experimental results cannot be explained readily in terms of simple local features of intensities, such as those signaled by receptive field operators. Rather, it would seem that texture is dependent as well upon structures abstracted from the intensities by various similarity grouping and representation constructing processes (Zucker, 1985) prevalent in early visual information processing. Intensities have been known not to be a sufficient representational basis for texture at the lower end; now the upper limit has been moved to include abstract structural and subjective figures as well.

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