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Psychophysical Measures of Illusory Form Perception: Further Evidence for Local Mechanisms

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Detection thresholds for a small light spot were measured at various distances from configurations (Kanizsa squares and other) consisting of white inducing elements on a dark background. Threshold distributions as a function of target position, number, size and spacing of contrast inducing elements were established. The data show that thresholds are elevated when the target is located close to one or more inducing element(s). Furthermore, threshold elevations diminish with increasing distance of the target from the configurations, increasing spacing and decreasing size of their inducing elements. When the target is flashed upon an illusory contour, no threshold elevation is observed in any of the conditions tested. Within incomplete illusory figures (only half of the square visible), the threshold gradients show the same tendencies. The present observations add further empirical support to the idea that illusory figures are built up by way of local mechanisms at early stages of processing.

Illusory contours Brightness induction Increment thresholds

INTRODUCTION

Many authors have stressed the hypothesis that illusory contour perception and the associated brightness phenomena are generated by two distinct mechanisms (Spillmann, Fuld & Gerrits, 1976; Day & Jory, 1980; Spillmann, Fuld & Neumeyer, 1984; Grossberg & Mingolla, 1985; Shapley & Gordon, 1987; Dresp, Lorenceau & Bonnet, 1990; Dresp & Bonnet, 1991) which may cooperate at critical stages of form genesis where local operations of the visual system are integrated into a more global perceptual process. The idea that illusory contours result from the processes which are designed to build up contour information in general finds support in psychophysical data (Zucker & Davis, 1988) and in results obtained with single unit recordings in area V2 of the primate cortex (Peterhans & Von der Heydt, 1989; Von der Heydt & Peterhans, 1989). These recordings show that responses of orientation selective cells are triggered by stimuli eliciting the perception of illusory contours in the Kanizsa square and in similar figures.

Some data (Dresp, 1993; Dresp & Bonnet, 1991; Spillmann, Fuld & Neumeyer, 1984; Coren & Theodor, 1977) suggest that illusory forms might, to some extent, be the result of contrast mechanisms which are supposed to be underlying phenomena that are generally referred to as simultaneous contrast (Heinemann, 1972) or also Mach band phenomena (Fiorentini, 1972). The question to which degree local contrast might be important to understand the processes which gives rise to the perception of illusory contours has been raised in a previous paper (Dresp & Bonnet, 1991). We reported observations which show that the threshold for the detection of a small light spot is higher when the target is flashed on a position close to a configuration of white inducing elements presented on a dark background than when it is presented on a homogeneous dark field. These threshold elevations occur in configurations with and without illusory contours, however, when the target is flashed right upon an illusory border, the detection threshold decreases abruptly. We concluded from these observations that contrast and contour must be generated by way of two separate mechanisms at early stages of processing.

Local brightness (or darkness) enhancement observed within illusory contour patterns as well as in displays which do not give rise to illusory border perception [Dresp *et al.*, 1990; see Fig. 1(a, b)] might to some extent be a consequence of diffusive brightness mechanisms which rely upon the principle of lateral interaction between systems of luminance specific operators (cf. Gerrits & Vendrik, 1970; Jung, 1972). Such interactions are supposed to be underlying various brightness phenomena. Their perception depends upon the intensity and the spatial distribution of contrast generated through luminance and size of the inducing surfaces

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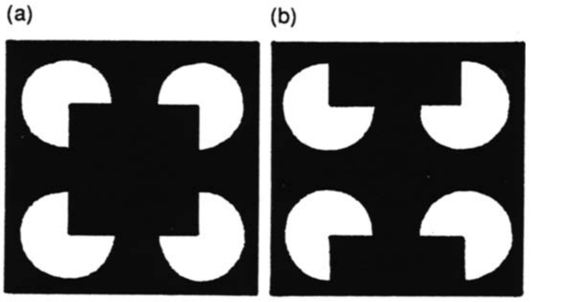

FIGURE 1. (a) A Kanizsa square with illusory contours and enhanced surface darkness. (b) A control figure which does not give rise to the perception of a closed surface.

(see Wyszecki, 1986, for a review on achromatic induction effects).

The following series of experiments provides a set of psychophysical data which may help us to understand how illusory figures are built up from local information about brightness and orientation. The previous study mentioned above (Dresp & Bonnet, 1991), has shown that local measures obtained through increment threshold procedures [yes/no and two-alternative forced-choice (2AFC)] seem to reflect different effects of brightness- and orientation-specific processes on the sensitivity of the visual system (see Fiorentini, 1972, for a review on brightness phenomena and increment thresholds). Local threshold elevations seem to be related to mechanisms which give rise to brightness or darkness effects within illusory contour stimuli. On the other hand, the abrupt decrease in thresholds upon illusory borders might be a consequence of another type of mechanism contributing to the genesis of an illusory contour.

To gain further insight into the way in which local informations about brightness and orientation might be combined and integrated into a global process of perceptual organization, we investigated the influence of some spatial parameters on increment detection within different stimulus configurations. Thresholds were measured in figures consisting of white inducing elements on a dark background. We have demonstrated earlier with three different observers that an adaptive yes/no method and a 2AFC procedure lead to essentially the same observations in this type of experiment. In the present study, we have given preference to an adaptive yes/no procedure because it leads to a more rapid convergence of the grey values near the asymptotic threshold level. Experiments of the type reported here are extremely time-consuming and the adaptive threshold procedure devised from Tyler (1987) represents, in this respect, a considerable advantage to 2AFC methods.

EXPERIMENT 1

The first experiment was run to confirm earlier findings which have shown that a bright surface induces a threshold elevation in its neighbouring dark surround (cf. Fiorentini & Zoli, 1966; Wildman, 1974). These elevations diminish when the distance between the target and the border of the inducing surface increases (Van Essen & Novak, 1974).

Within a Kanizsa square, threshold variations as a function of the distance of the target from the inducing elements are presumably much more complex. The Kanizsa figure consists of four inducing surfaces which form a "closed" configuration. This closure phenomenon may introduce other processes that might have an effect on the increment thresholds which is not immediately predictible. Before measuring further series of increment thresholds in figures with illusory contours, we wanted to gain some parametric information about the rate of decay of the effect of a simple inducing surface (a single disk) on the detectability of the target and about the maximal distance over which this effect can be observed as a function of the size of the inducing surface.

Subjects

One observer (the first author) participated in this experiment. The subject has normal vision.

Material

The stimuli were presented binocularly on a high resolution video monitor (Visionor model M 51 CHR No. 1007, Lille, France). They were generated through a PC compatible computer (Olivetti M 24) using a special graphics adaptor (GALAXY ref. SA-1019A, Evroz, Tel Aviv) providing a display of 1024 (horizontally) $\times$ 768 (vertically) pixels at 60 Hz frame rate (non-interlaced). Pixel size was 0.33×0.33 mm, the surface of the target spot was 1 pixel (1 pixel = 1.51 min arc). The background patterns were three single disks [see Fig. 2(a)] with different diameters 20, 60 and 100 pixels). The displays were exposed continuously in the centre of the screen. Luminance of the white pixels forming the disks was 21 cd/m^2, that of the black pixels of the background 2 cd/m^2. Grey levels of the test pixel were obtained by combinating R–G–B signals by means of a special interface. Careful calibration of each R–G–B combination was realized with a CS 100 Minolta photometer and cross-checked with another device that has been standardized to a Pritchard photomultiplier. The subject was placed in front of the screen at a viewing distance of about 75 cm.

Procedure

Thresholds were measured at 5 different points away from the border of each disk. Distances from disk border were 2, 4, 8, 16 and 32 pixels (1 pixel = 1.51 min arc). A small grey circle at liminal contrast to the background served as the fixation mark between trials.

The subject's head position was stabilized by means of a head and chin rest. Exposure time of the test pixel was set at about 170 msec (10 frames). Within each session one or more (depending on the length of the session) thresholds were measured on a blank field of the same luminance as the one of the background of the disks. The purpose of these controls was to neutralize possible effects of fluctuations of the physical luminance output of the screen and/or of incidental sensitivity variations. Each threshold measured near a disk was related to a

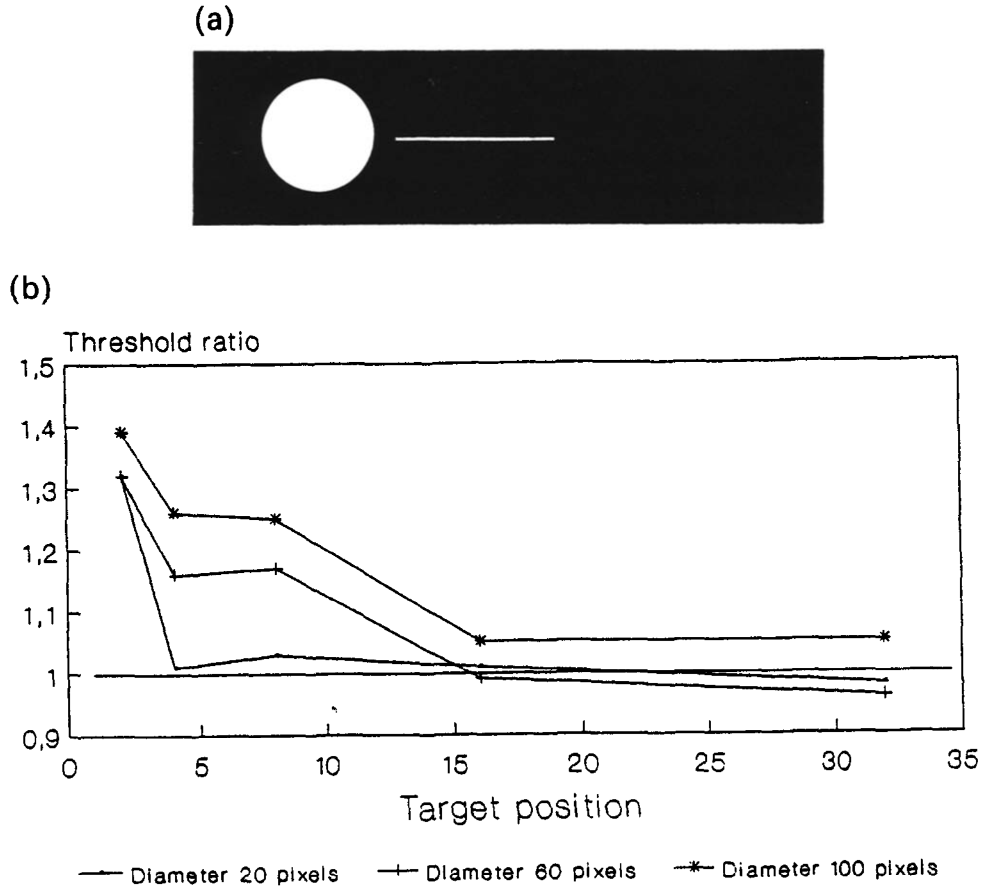

FIGURE 2. (a) The inducing element used in the first experiment. Increment thresholds were measured on the horizontal median axis of a disk at several distances from its border. The effects of three disk sizes were tested. (b) The results of Expt 1. Threshold ratios are plotted as a function of the target position and the size of the inducing disk. Each point in the graph expresses a test threshold (measured with the inducing element) divided through a threshold measured on a homogeneously dark background within the same experimental session.

control threshold established within the same experimental session. Later on, the results will be expressed as ratios (test threshold/control threshold). The experiment was run under mesopic conditions and the subject was dark-adapted at the beginning of each session.

Thresholds were measured by means of an adaptive yes/no procedure devised from Tyler (1987). This staircase procedure was developed in order to obtain rapid convergence of the grey values near the asymptotic threshold level. On each trial the test pixel could be present or absent with equal probability. The subject gave his response ("pixel present" or "pixel absent") by means of two response keys. The grey values of the pixel were determined by the subject's response on the previous trial: "pixel absent" was followed by an increment of the grey value, "pixel present" was followed by decrement. The first five trials of the series served to determine the starting grey value of the test pixel by means of a halving procedure which permits to start measurement as close as possible to the threshold. After those first trials, step amplitude was constant (about 0.05 cd/m^2). After fifteen trials, stopping criteria were calculated, trial after trial, according to the following principles. A threshold was obtained when two conditions were met: the slope of the function relating the values of the stimulus to the rank of the trial had to be equal to zero ± 0.1; the percentage of correct detections had to be $75 \pm 10\%$. An average of 50 trials was necessary to reach a threshold. At each target position, three thresholds were measured in different sessions.

Results and discussion

The mean results of the experiment are presented in Fig. 2(b). Each point reflects the mean value of three threshold ratios (background pattern/blank field). Forty-five thresholds were obtained within figure conditions and fifteen measurements were taken on the blank field. Detection performances were quite stable within and between experimental sessions. The mean of the thresholds measured on the blank field was 4.76 cd/m^2 with a standard deviation of 0.52 cd/m^2.

Increment thresholds are elevated when measured near the disk border. These elevations decrease with increasing distance of the target spot from the disk border and with decreasing size of the disk surface. Analysis of variance reveals that both effects are statistically significant [$F(4,8) = 6.830$; $P < 0.05$ and $F(2,4) = 6.952$; $P < 0.05$, respectively]. The interaction between both factors is significant at $P < 0.001$ [$F(8,16) = 8.537$]. The data suggest that the best fit is obtained with a power function. The exponent appears to be constant over size conditions ($\alpha = -0.11$) while the intercept increases with the diameter of the disk.

As a whole, the results of this experiment are consistent with earlier threshold data obtained within square- or ring-configurations and across luminance steps (Cornsweet & Teller, 1965; Fiorentini, 1966; Wildmann, 1974; Van Esen & Novak, 1974).

EXPERIMENT 2

In this experiment, increment detection is systematically investigated in Kanizsa figures. Increasing the angular size of the inducing elements and/or reducing their separation increases the subjective darkness of the illusory square (cf. Dresp *et al.*, 1990). Furthermore, darkness enhancement is stronger in Kanizsa squares than in control figures without illusory contours [see Fig. 1(b)]. This result suggests that the brightness mechanism interacts with the processes which give rise to the perception of closure within the figure. This has been assumed earlier by Day and Jory (1980).

Previously (Dresp & Bonnet, 1991), increment thresholds were measured in both types of figures. The results have shown that threshold elevations are observed in both displays at target positions close to the inducing elements. These elevations decrease with increasing distance between the target and the inducing elements. On the illusory contour itself, thresholds do not differ from those obtained on a homogeneously dark background. At the equivalent position in the control figure where no illusory contour is visible, such a threshold decrease does not occur. These results have been obtained with two different types of threshold procedure: The adaptive staircase method described above and a two-alternative temporal forced-choice (2AFC) procedure. Both methods have been shown to lead to essentially the same results.

The results of Expt 1 provide evidence for an effect of the size of contrast inducing surfaces on the increment threshold at different distances from their borders. In this study, increment thresholds were measured as a function of size and spacing of the inducing elements across one of the illusory contours in the Kanizsa square. Taking into account previous results, we expect increment thresholds to increase with increasing size and proximity of the inducing elements. On the illusory contour, no threshold elevation is expected (cf. Dresp & Bonnet, 1991). If orientation is processed separately from brightness (e.g. Shapley & Gordon, 1987), then the thresholds measured on the illusory border should not vary with size and spacing of the inducing elements.

Subjects

One highly trained observer (the first author) underwent 357 threshold measurements covering all the stimulus conditions of this experiment. The subject still has normal vision.

Material and procedure

The screen and the luminance conditions were the same as those of Expt 1. The background stimuli were Kanizsa squares giving rise to illusory contour perception. Nine Kanizsa squares were used in separate sessions. They were fabricated by combinating different inter-pacmen gaps with different pacman sizes. The gaps (number of black pixels between two pacmen at each side of the square) were 20, 60, 100 and 140 pixels and the diameters of the pacmen were 20, 60 and 100 pixels (1 pixel = 1.51 min arc). Thresholds were measured at 10 different points away from one of the illusory contours of each Kanizsa square as well as right on the illusory border itself (see Fig. 3). The test pixel was shifted horizontally across the median axis of the figures. The same experimental procedure as the one described for Expt 1 was used for threshold measurements.

Results and discussion

Sixty measurements were taken on a homogeneously dark background within several sessions. With a mean value of 4.33 cd/m^2, the coefficient of variation was 18.9% which indicates a relatively good reliability of the measurements taken over a 2 month period.

As in Expt 1, every threshold measured within a Kanizsa square was divided through the mean threshold obtained on the homogeneous field within the same session. The average threshold ratios are shown in Figs 4–6. As expected from the previous experiment (Dresp & Bonnet, 1991) the results show two main features: at target positions away from the illusory contour, threshold elevations decrease with increasing distance of the target spot from the contour in all Kanizsa figure conditions. Furthermore, thresholds measured right on the illusory contour (position 0) are not elevated and even, in some cases, slightly reduced.

Thresholds on either side of the illusory contour

As seen in Figs 4, 5 and 6, for equivalent distances to the illusory contour, threshold elevations are larger outside the Kanizsa square than inside of it. To obtain a factorial design for analyses of variance we took into account only six target positions at three distances (2, 4 and 8 pixels) from the illusory contour. The analysis reveals that the effect of the target position (inside or outside the square) is statistically significant [$F(1,2) = 42.189$; $P < 0.05$]. In both cases, the thresholds tend to decline when the distance between target and illusory contour increases, the effect being not statistically significant in this experiment. Threshold elevations

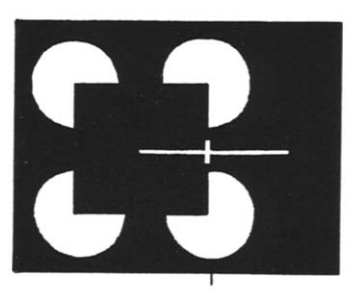

FIGURE 3. The inducing configuration used in Expt 2. Increment thresholds were measured on the horizontal median axis of the figure at several positions within and outside the illusory square as well as right upon one of the illusory borders.

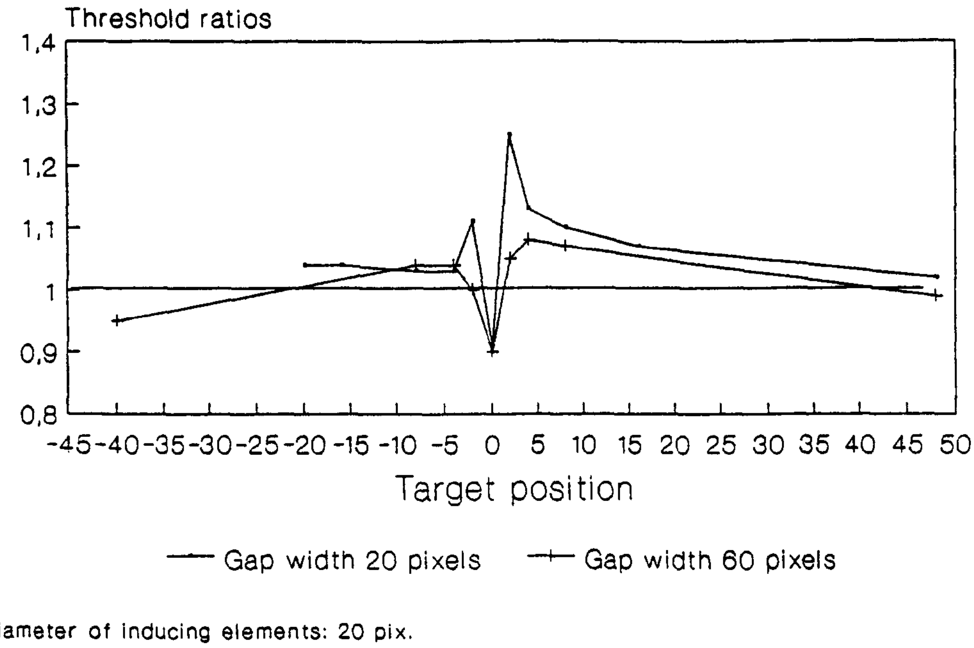

FIGURE. 4. The results of Expt 2. Threshold ratios are plotted as a function of the target position, the gap width between inducing elements and their diameter. The legends of the x-axis should be read as follows: negative values refer to target positions within the illusory square, positive values refer to target positions outside the illusory square. "0" Refers to the situation when the target was presented right on the illusory border.

increase with the diameter of the inducing elements. This result tends to confirm the predictions derived from Expt 1 and is revealed to be statistically significant [$F(2,4) = 7.411$; $P < 0.05$]. Furthermore, mean threshold elevations increase when the gap between inducing elements increases. For the smallest diameter, the effect disappears at 60 pixels inter-pacmen gap. With medium diameter, threshold elevations disappear at a gap of 140 pixels and for the inducing elements with the biggest size, all gaps generate threshold elevations on either side of the illusory border. Analysis of variance, taking into account the two gap sizes (20 and 60 pixels) that were matched with all the diameter conditions, shows that the effect is significant for these modalities [$F(1,2) = 36.472$; $P < 0.05$]. The interaction between the diameter of the inducers and these two gap sizes is also significant [$F(2,4) = 6.971$; $P < 0.05$].

For each figure condition, the decay of the relative threshold as a function of the distance to the nearest inducing element is best described by a power function (see Expt 1). The mean exponents are lower for thresholds measured inside the Kanizsa Square than for those measured outside. The mean exponents and intercepts are higher for bigger diameters. For a given

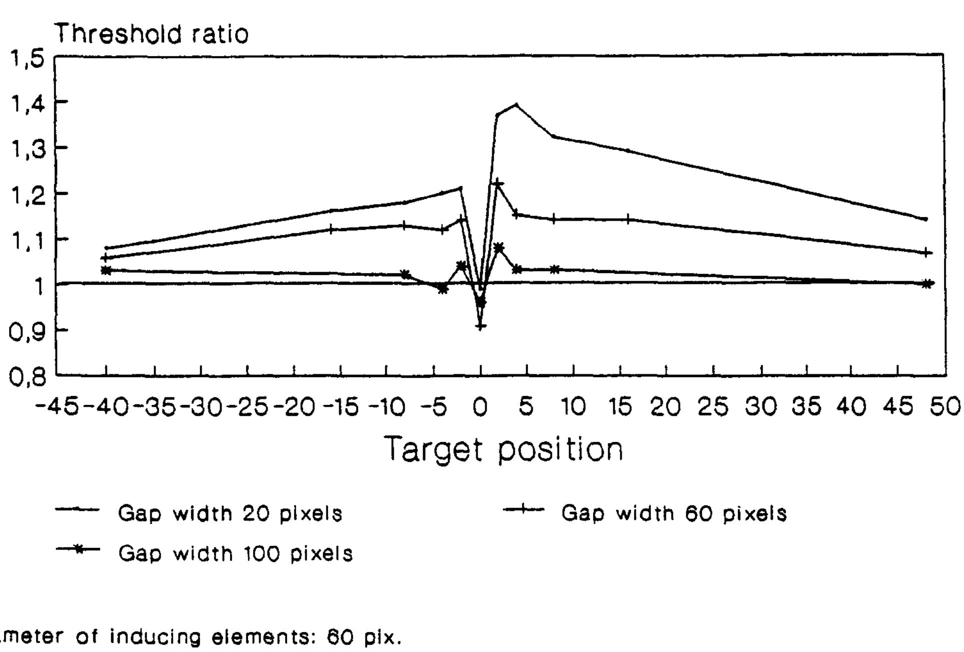

FIGURE. 5. See caption for Fig. 4. Results obtained with inducing elements of 20 pixels diameter.

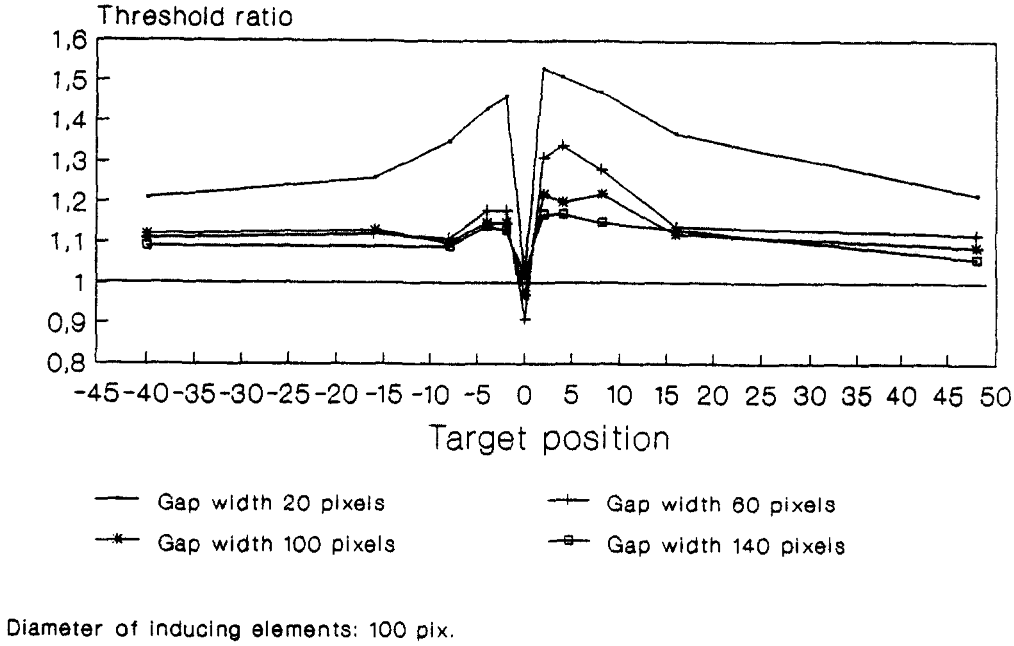

FIGURE 6. See caption for Fig. 4.

pacman size, exponents and intercepts increase with increasing inter-pacmen gap (see Tables 1 and 2).

Thresholds on the illusory contour

No threshold elevations are observed on the illusory contour itself. This finding confirms the results of previous experiments (Dresp & Bonnet, 1991). Furthermore, in most of the cases thresholds appear to be slightly lower than those obtained on a homogeneous field. The results show no systematic variation as a function of the diameter or spacing of the inducing elements. This observation adds support to the idea that brightness and orientation are processed separately and excludes the possibility that variations in thresholds measured on either side of an illusory contour as a function of the diameter of the inducers might be essentially due to changes in the general level of illumination.

EXPERIMENT 3

The next experiment was designed to check whether there is any specific effect of figure closure on the threshold gradient. If the effects reported above reflect consequences of locally operating mechanisms, they should occur even when only parts of the illusory figure are visible. TWO collinear inducing elements should provide sufficient inputs of brightness and orientation to trigger the specific processes that give rise to threshold elevations on one hand, and to a decrease in thresholds on the illusory contour, on the other. In other words, if our assumptions are in the right direction, threshold gradients should not be altered qualitatively within an incomplete illusory figure.

Subjects

Two subjects took part in the experiment. One was highly trained (the first author), the other one less. Subject AJ was run in some conditions only (see Fig. 9). Both observers have normal vision.

Material and procedure

The screen, the luminance conditions and the experimental procedure used for threshold measurements were the same as those described for Expt 1. The background stimuli were either a single inducing element (pacman) or two collinear inducing elements (see Fig. 7). Their diameter was 100 pixels and the inter-pacmen gap was 20 pixels. With the two collinear inducing elements, an illusory contour is clearly perceived. Thresholds were measured at target positions equivalent to those in Expt 2.

TABLE 1. Exponents of the decay functions (functions relating to threshold elevations to distance of the target from the nearest inducing element)

Gap diameter	Inside 20	Inside 60	Inside 100	Inside 140	Outside 20	Outside 60	Outside 100	Outside 140
20	0.04	—			0.09	0.15		
60	0.08	0.09	—		0.15	0.20	0.19	
100	0.11	0.04	0.03	0.03	0.21	0.39	0.49	0.76

TABLE 2. Intercepts of the decay functions (functions relating threshold elevations to the distance of the target to the nearest inducing element)

Gap diameter	Inside 20	Inside 60	Inside 100	Inside 140	Outside 20	Outside 60	Outside 100	Outside 140
20	1.16				1.45	1.77		
60	1.46	1.55			1.94	2.32	2.28	
100	1.85	1.34	1.25	1.32	2.43	4.85	8.41	29.66

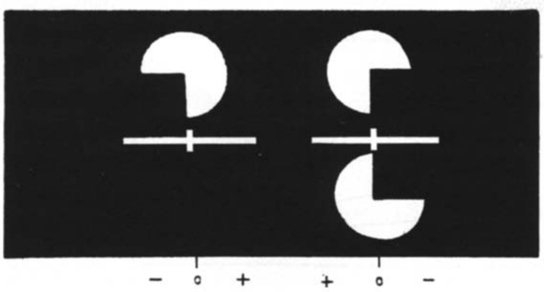

FIGURE 7. The inducing configurations used in Expt 3. The target positions were equivalent to those of the second experiment. In one condition, a single inducing element was presented. In the other condition, two collinear inducing elements were presented and a single illusory contour was clearly visible within the configuration. The diameter of the inducing elements was 100 pixels, in both conditions.

Results and discussion

Individual results of both observers are displayed in Figs 8 and 9 for comparable conditions. Intra-individual variability estimated by the ratio of the standard deviation over the mean of the thresholds measured on homogeneous background was 5% for AJ and 11% for BD. The total number of these control measures was greater for BD (n = 12) than for AJ (n = 7). The inter-individual consistency of the results can be evaluated in comparing Figs 8 and 9.

Figure 8 shows the results for subject BD, Fig. 9 represents data obtained with AJ. The graphs show the same tendencies as those that have been observed in the previous experiments with complete illusory figures. Thresholds are slightly elevated on either side of an illusory border and decrease when the target is flashed on that border, even when only two collinear inducers are present. The most striking observation is that this same tendency is still there when a single inducer is present and no illusory contour can be seen in the display. Analysis of variance on BD's data shows that the threshold decrease with increasing distance of the target from the inducers is statistically significant [$F(4,8) = 4.495$; $P < 0.05$]. The difference between configurations (one or two inducers) and the effect of the target position (inside or outside the configuration) are not statistically significant here. Nevertheless, the interaction between the distance of the target from a contour and its position within the configuration is significant [$F(4,8) = 9.500$; $P < 0.01$]. The results of this experiment indicate that a single inducer provides sufficient information of brightness and orientation to generate specific effects on increment thresholds.

GENERAL DISCUSSION

The aim of this investigation was to provide further psychophysical data which might sustain the idea that illusory figures are generated at early stages of processing. The results tend to indicate that local inputs of brightness and orientation contribute to the genesis of forms such as the Kanizsa square in the following manner.

Local differences in darkness may be partly due to spreading lateral interactions which generate an oriented diffusion of darkness in directions away from the borders of the inducing elements. Elevations in increment thresholds may reflect, to some extent, the effects of such a diffusive mechanism. The fact that thresholds are systematically lower inside an illusory square indicates that the increment threshold is somehow correlated with darkness generated inside the illusory square, close to the contour. Given that the threshold distribution is not homogeneous within the square, it is difficult to say to which degree a diffusive process may account for *global* darkness enhancement, since the latter appears to be homogeneous (see also Dresp, 1993) .

Information about orientation and collinearity seems to create the basis for illusory contours. Competitive

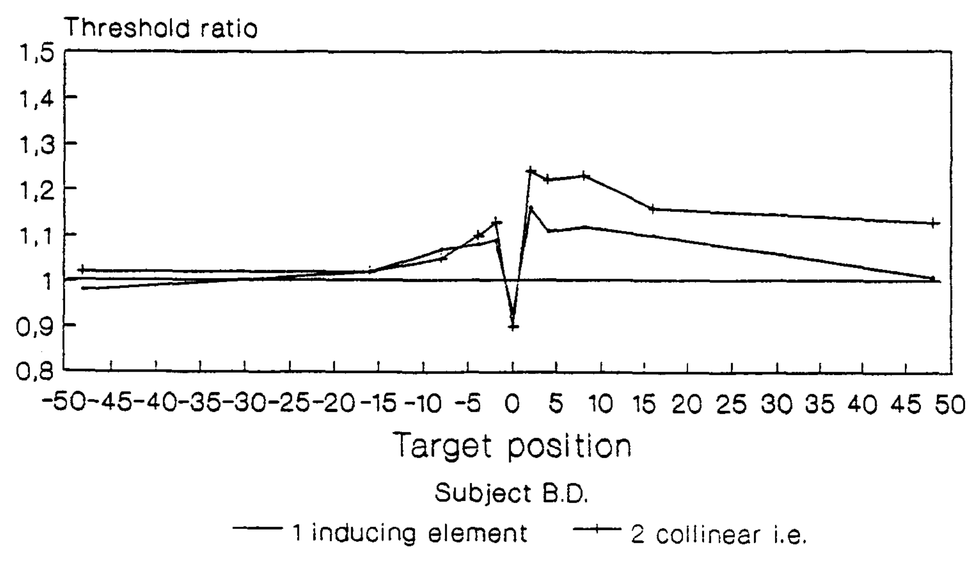

FIGURE 8. The results of Expt 3. Threshold ratios are plotted as a function of the target position and the number of inducing elements presented. Subject BD.

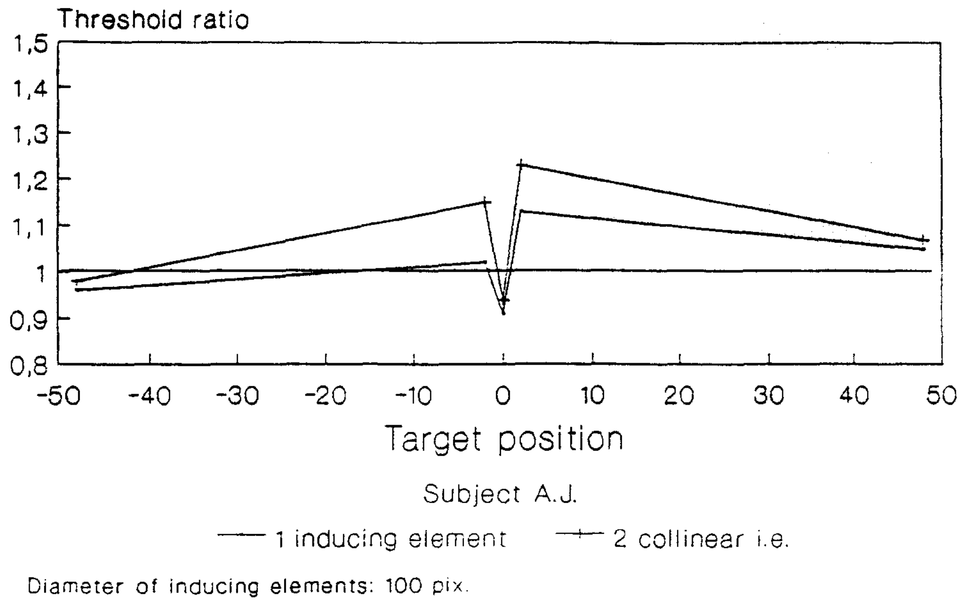

FIGURE 9. Same as Fig. 8. Subject AJ.

interactions between orientational- and brightness mechanisms could explain why increment thresholds are not elevated on the axis which prolonges the edge of one or more inducing elements. Processes signalling orientation might locally inhibit the processes which generate a spreading of brightness or darkness. An illusory contour would become visible when, at least two, oriented processes come to cooperate and to bridge the gap between collinear edges.

The results of Expt 3 show that the consequences of both brightness- and orientational-mechanisms occur locally without figure closure or visibility of an illusory contour. This is further, and in our view important, empirical support for explanations relating illusory brightness and contour to early stages of processing. A single inducer seems to provide to the visual system the essential information which, combined with other local inputs, triggers the mechanisms creating the neurosensory basis for illusory form.

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