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Research Note

Subthreshold Summation with Illusory Contours

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Results from three experiments using spatial forced-choice techniques show that an illusory contour improves the detectability of a spatially superimposed, thin subthreshold line of either contrast polarity. Furthermore, the subthreshold line is found to enhance the visibility of the illusory contour. Stimuli which do not induce illusory contours, but reduce uncertainty about the spatial position of the line, give rise to a slight detection facilitation, but the threshold of 75% correct responses is not attained. The data indicate that superimposing illusory contours and subthreshold lines produces interactions which are similar to classic subthreshold summation. They thus provide psychophysical evidence for the functional equivalence of illusory contours and real lines suggested by recent neurophysiological findings.

Contour Illusory contours Threshold Subthreshold summation

INTRODUCTION

Illusory contours are fine apparent lines or edges which cannot be defined in terms of local variations in luminance, as shown on the example of the Kanizsa square (Fig. 1). Recently, an increasing number of authors have emphasized the possible significance of these phenomena with regard to adaptive neurophysiological processes, and the evidence that neurons in the visual cortex of the monkey start firing when an illusory contour is presented within their receptive field (Peterhans & Von der Heydt, 1989; Von der Heydt & Peterhans, 1989; Grosof, Shapley & Hawken, 1993) suggests that these contours are functionally equivalent to real lines or edges.

Data from psychophysical studies using increment threshold techniques to measure the detection of small, non-oriented, light targets presented upon and alongside illusory contours (Dresp & Bonnet, 1991, 1993), have suggested that facilitatory neural interactions may be the key to a deeper understanding of how these illusory perceptions are generated in the human brain. The most striking result of these experiments was that the threshold for the detection of the target was lowered when the latter was presented on an illusory contour as defined by the prolongation of the lines of pixels which constitute the inner borders of two collinear inducing elements in the Kanizsa figure.

It appears that the nature of the effects which determine increment detection facilitation should be investigated further, given that the previous results obtained in the Kanizsa square strongly suggest that the facilitatory effects are a consequence of the mechanism that underlies illusory contour formation. Some earlier psychophysical experiments (Kulikowski & King-Smith, 1977) have revealed that the contrast threshold at which a fine line target is detected by human observers is reduced when the target is superimposed on an invisible line of the same orientation. This threshold facilitation effect has become widely known as "subthreshold summation", and is interpreted in terms of additive neural activity in the visual cortex. Although it is not consciously perceived, the subthreshold line is effectively processed in the brain by the same neurons as those that respond to the target line. When both lines are strictly superimposed, the neural responses to these two stimuli add together and a lower contrast is needed for a threshold response.

The assumption of a functional equivalence of real lines and illusory contours, and the similarity between line summation effects and the increment threshold facilitation effects briefly described above suggest that a subthreshold technique similar to the one used by Kulikowski and King-Smith (1972) might provide further insight into the functional characteristics of the mechanisms that generate illusory contour formation. In the present study, we investigated the spatial interactions that may occur between subthreshold lines and illusory contours. In fact, if the hypothesis of a functional equivalence of real and illusory lines holds, a

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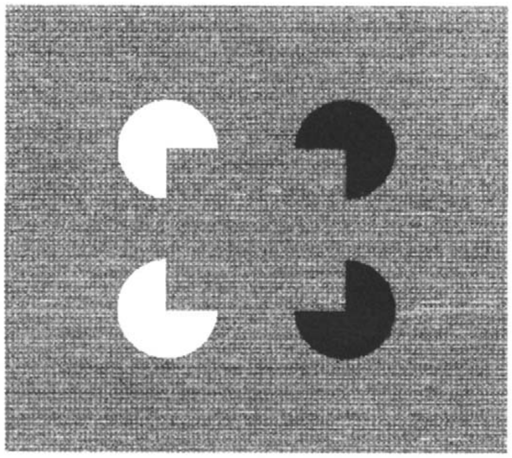

FIGURE 1. A Kanizsa square induced by stimulus elements of opposite contrast polarity. Although there is no physical difference in luminance between the figure in the centre of the stimulus and the background, four illusory contours, delineating an apparent square, are perceived.

subthreshold line should sum with an illusory contour in a similar way as it does with a real one. We tested both the effects of a subthreshold line on the strength of an illusory contour, and the effects of an illusory contour on the detectability of a subthreshold line.

EXPERIMENT 1

A first question that arises with this approach is the one of contrast polarity of an illusory contour. Since such contours cannot be defined physically in terms of differences in luminance, this issue appears to be somewhat problematic. The naive observer might say that white inducing elements should engender a dark illusory contour, and black inducing elements should give rise to a light illusory contour, but in fact, as the example given in Fig. 1 shows, the inducing elements do not have to share the same contrast polarity to produce the phenomenon. Is the illusory contour that results from such a combination of black and white inducing elements a dark, or a light one?

The observation that illusory contours can arise from configurations with inducers of alternating polarity has been discussed earlier by Prazdny (1983), and it has been suggested that their genesis must therefore, at some stage, involve mechanisms that are insensitive to the sign of contrast (e.g. Grossberg, 1994; Shapley & Gordon, 1987). Neurophysiological data tend to support this assumption, given that a certain number of the neurons in V2 of the macaque monkey which responded to stimuli eliciting the perception of illusory contours were reported to respond equally well to bars or edges of either contrast polarity (e.g. Peterhans & Von der Heydt, 1989).

If the genesis of illusory contours does not depend on contrast polarity, we predict that the effect of a subthreshold line of any polairty should sum with the effect of an illusory line. In a first experiment, we determined whether a dark subthreshold line would enhance the visibility of an illusory contour induced by white stimulus elements.

Subjects

Two observers, both trained in psychophysical tasks and naive to the purpose of the present study, participated in the experiment. They both had normal vision.

Stimuli

The stimuli (see Fig. 2) were presented binocularly on a monochrome computerscreen (60 Hz, non-interlaced). They were generated with an IBM compatible PC (HP 486), equipped with a VGA Trident graphic card. The size of the white inducing elements was 30 min arc, and their luminance 20 cd/m^2. The edges of two collinear inducers were separated by a gap of 1 deg of visual angle. Background luminance was 6.7 cd/m^2. The subthreshold line had the same length as the illusory contour upon which it was added (1 deg of visual angle), and five different luminance intensities, presented in random order within an experimental session according to the method of constant stimuli. The five luminance levels of the subthreshold line were: 6.7, 6.6, 6.5, 6.4 and 6.3 cd/m^2. The illusory contours and the subthreshold line appeared simultaneously on the screen for about 350 msec at each trial. The inter-stimulus interval was about 800 msec.

Procedure

The dark subthreshold line was added randomly to one of two illusory contours presented simultaneously on the screen (see again Fig. 2), and the observers had to press one of two response buttons to indicate whether it was the left, or the right illusory contour that appeared more visible to them. Each response that corresponded to the perception of a stronger illusory contour on the side where the subthreshold line was

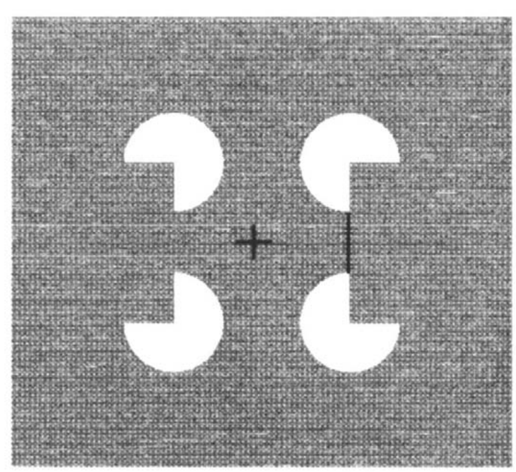

FIGURE 2. In the first experiment, we added a dark subthreshold line to one of two illusory contours induced by white stimulus elements. The subthreshold line and the figural context were flashed simultaneously for a brief duration. Naive observers had to decide whether the illusory contour was stronger to the right, or to the left of the fixation mark. In a preliminary experiment we had verified that the subthreshold line was not detectable when presented out of context.

added, was counted as a "correct detection". The luminance of the subthreshold line varied randomly within an experimental session, which consisted of 50 trials. Each observer went through 10 sessions. In a preliminary experiment, with the same observers, we had verified that the subthreshold line could not be detected when it was presented alone.

Results and discussion

The results are shown in Fig. 3(a) (subject CM) and Fig. 3(b) (subject VF). When the subthreshold line is presented out of context on a plain background, the percentage of correct detections, computed for each of the five lumininance levels, is situated around 50% (chance level). When the line is presented on an illusory contour, performance rises, as a function of the intensity of the subthreshold line, from chance level to 95% correct detections. These data indicate that the presence of the subthreshold line enhances the visibility of the illusory contour.

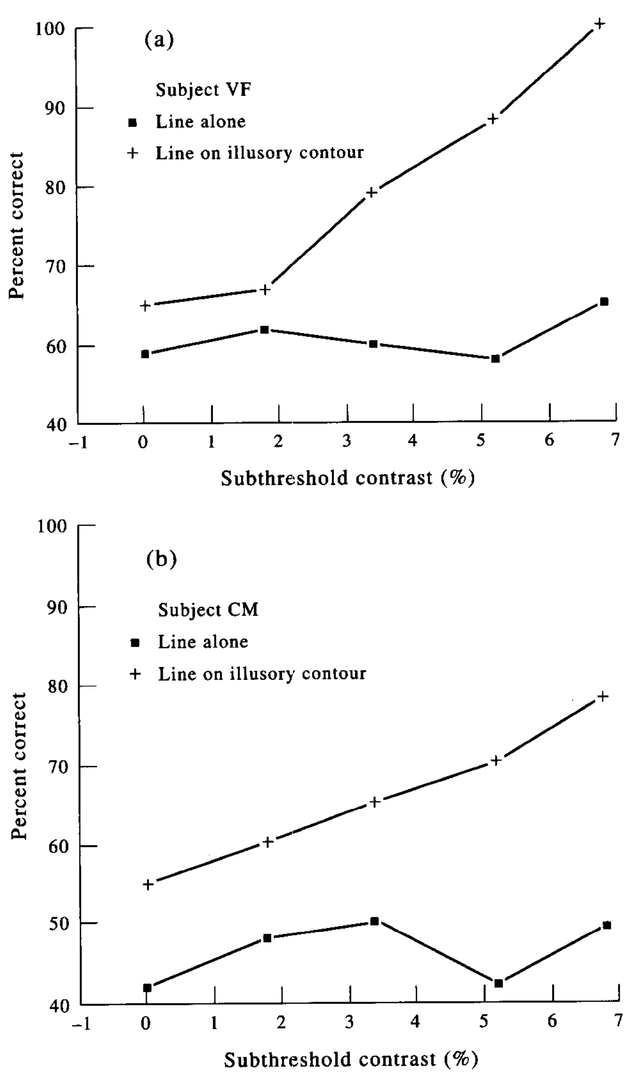

FIGURE 3. These figures show percentages of "correct detections" as a function of the contrast intensity of the subthreshold line, presented out of context (■), and presented upon an illusory contour (+), (a) Data for VF, (b) data for CM. When the subthreshold line is presented alone on a plain background, performances do not exceed the chance level. When it is presented upon an illusory contour, performance rises, as a function of the intensity of the subthreshold line, from 50% (chance level) to 82% (subject CM), and 95% (subject VF) "correct detections".

One possible explanation of this finding would be that the luminance contrast of the inducing elements, and not the illusory contour, determines the effect. Such an interpretation is, however, unlikely to hold here. Luminance contrasts of opposite polarity are known to trigger suppressive spatial interactions rather than facilitation, as demonstrated by results from spatial probability summation experiments (e.g. Wilson, Phillips, Rentschler & Hilz, 1979), studies using lateral masking techniques to investigate the detection of foveal Gabor signals (Polat & Sagi, 1993), or from more recent work investigating the effects of 'luminance pedestals' on increment detection of small, non-oriented light targets presented at the ends of lines (Dresp, 1993; Morgan & Dresp, 1995).

A more likely explanation for the effect observed in the present experiment is that the subthreshold line adds some kind of energy to the illusory contour and thus enhances its visibility. This would imply that the illusory contour and the subthreshold line are detected by a common mechanism, and that the latter is insensitive to contrast polarity. We ran a second experiment to investigate this issue further.

EXPERIMENT 2

If the mechanism that generates the illusory contour is insensitive to the polarity of contrast, and if the subthreshold line adds energy to specifically that mechanism, it should be expected that a line of any polarity would do so, regardless of the contrast sign of the inducers. In this experiment we presented dark and light subthreshold lines on illusory contours induced by black or white stimulus elements. We furthermore investigated the effect of lineillusory contour length on both the detectability of the lines and the strength of the illusory contour.

Subjects

Two trained observers, including the first author, participated in this experiment. Both had normal, or corrected-to-normal vision. One subject was naive to the purpose of the study.

Stimuli

The stimuli were generated with the same display as described above. The size of the stimulus elements which induced the illusory contours was maintained. They were either white (11 cd/m^2), or black (4 cd/m^2), and presented in random order to the left or to the right of the fixation mark (see Fig. 4). The luminance of the gray background was 6.73 cd/m^2. The 12 luminance intensities of the dark and light subthreshold lines, randomly presented on one of the two illusory contours, were 6.15, 6.20, 6.26, 6.32, 6.37, 6.43, 7.03, 7.09, 7.15, 7.21, 7.28 and 7.34 cd/m^2 for subject IM, and 6.26, 6.32, 6.37, 6.43, 6.49, 6.55, 6.91, 6.97, 7.03, 7.09, 7.15 and 7.21 cd/m^2 for subject BD.

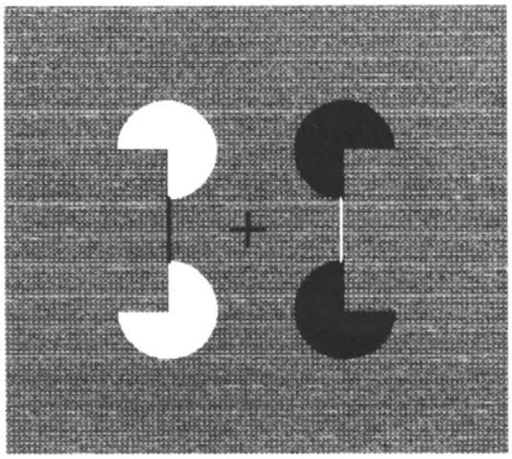

FIGURE 4. In the second experiment, we randomly presented subthreshold lines of either contrast polarity on illusory contours induced by stimulus elements of either sign. As in the first experiment, the subthreshold line appeared either on the contour to the left, or on the contour to the right of the fixation mark.

The length of the lines was identical to the length of the illusory contours, and varied within an experimental session. Five parameters, were used: 37.5, 52.5, 67.5, 82.5 and 97.5 arc min. As in the previous experiment, the illusory contours and the subthreshold line appeared simultaneously on the screen for about 350 msec on each trial. The duration of the inter-stimulus interval was the same (about 800 msec).

Procedure

The procedure was similar to the one used in the first experiment. However, this time the observers, neither of whom had participated in the first study, had to accomplish different tasks. Subject IM (the naive observer) was asked to indicate whether the left or the right illusory contour appeared stronger to her, whereas subject BD (the first author) had to detect the contour on which the subthreshold line was presented. In the control condition, both observers had to detect the subthreshold line presented on a plain grey background, and appearing randomly to the left or to the right of the fixation mark.

Results and discussion

Generally, the results of this experiment show that presenting a subthreshold line of any contrast polarity upon an illusory contour induced by stimulus elements of any contrast polarity both enhances the visibility of the illusory contour (task of subject IM), and facilitates the detectability of the line itself (task of subject BD). The effects of the subthreshold line on both types of performance, identification and detection, are very similar.

The data from the contour enhancement task (subject IM) are represented in Fig. 5(a, b, c). When the subthreshold line was presented alone (the control condition for both the contour enhancement task, and the detection task), both subjects accomplished, in fact, a detection task. The data of subject IM show that, in the

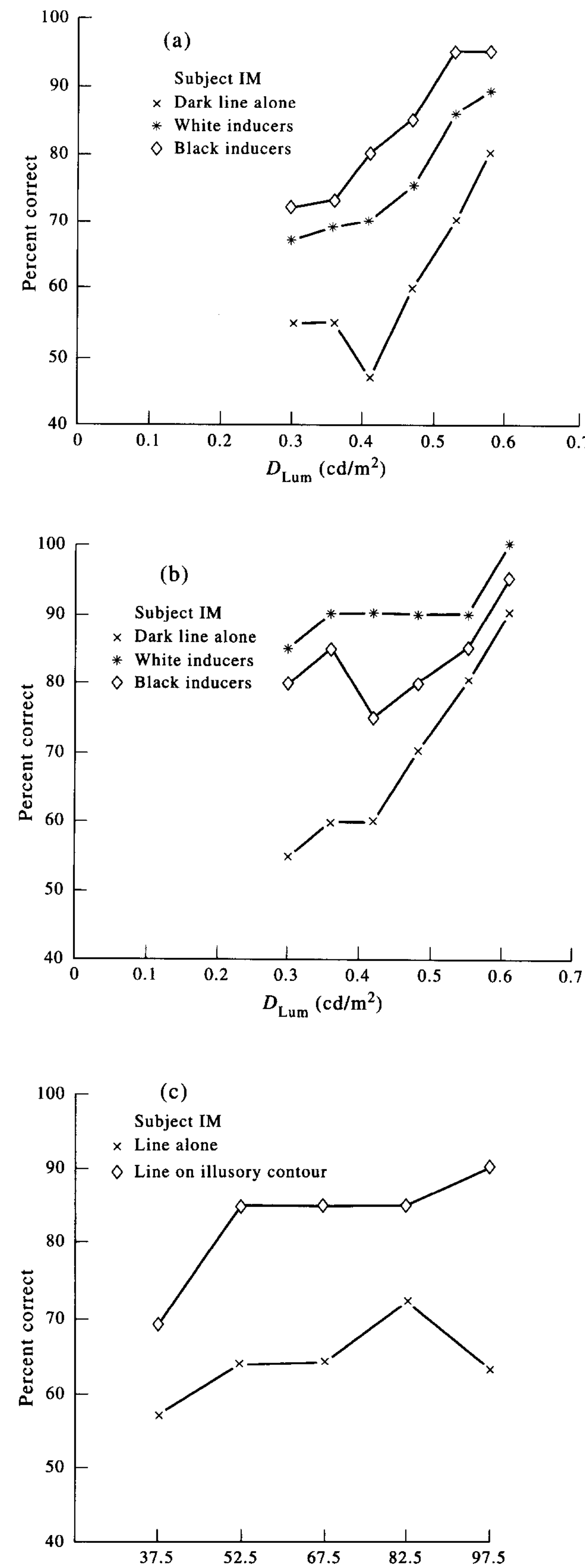

FIGURE 5. The results of subject IM, who had to decide on illusory contour strength, in the second experiment. (b, c) The percentage of "correct responses" is plotted as a function of the difference in luminance between the subthreshold line and the background in the different experimental conditions. (c) Percentages of "correct responses" as a function of the length of the subthreshold line.

control condition, the white line is detected only at the two highest luminance intensities, the dark line only at its lowest intensity, the threshold being defined at 75% correct detections. However, when the lines are presented on the illusory contours, the visibility of the latter is enhanced by all intensities, including the subthreshold levels. Mean performances in the contour enhancement task increase from 80% to 90% "correct detections" for a white line presented on illusory contours [Fig. 5(a)], and from 70% to 92% for a dark line presented on illusory contours [Fig. 5(b)]. The performances reveal that the effect of the subthreshold line on illusory contour enhancement is systematically stronger when the line and the stimulus elements which induce the illusory contour have the same contrast polarity. Very similar results are observed with subject BD in the detection task, as can be seen in Fig. 6(a, b).

Effects of line length on performances in the contour enhancement task are shown in Fig. 5(c), effects on performances in the detection task are shown in Fig. 6(c). When the subthreshold line is presented alone, its detectability slightly increases with the length of the line until an optimum is reached at a length of approx. 1.3 deg of visual angle, but the threshold of 75% correct detections is never attained. When the subthreshold line is presented upon an illusory contour, mean performances increase with line/illusory contour length from below 70% to over 90% in both the contour enhancement task, and the detection task. Moreover, the effect of line/illusory contour length persists at 1.3 deg of visual angle. We assume that this result can be related to the size of the receptive field of the mechanisms that generates the illusory contour. Such an interpretation is consistent with neurophysiological and psychophysical findings indicating that the spatial limits of illusory contour integration are beyond 2 deg of visual angle (e.g. Von der Heydt & Peterhans, 1989; Dresp, Lorenceau & Bonnet, 1990; Dresp, 1992; Lesher & Mingolla, 1993).

The results shown in Figs 5(a, b) and 6(a, b) also reveal that the visibility of an illusory contour is even further enhanced when the subthreshold line and the stimulus elements which induce the contour have the same contrast polarity. Furthermore, the subthreshold line itself becomes even more detectable. These findings are likely to be explained by a specific effect of the inducing elements which seem to provide a 'luminance pedestal' (e.g. Foley & Legge, 1981) facilitating even more the discrimination of both the illusory contour and the subthreshold line added on that contour. Such pedestal effects occur with targets and inducing stimuli of the same polarity and low contrast intensity, and it has recently been found that they contribute to lower increment thresholds for small targets presented at the ends of lines (Morgan & Dresp, 1995).

However, the facilitatory interaction between the subthreshold line and the illusory contour is clearly not reducible to a simple pedestal contrast effect generated by the inducing elements. Pedestal effects are polarity specific, the one observed in our experiment is not.

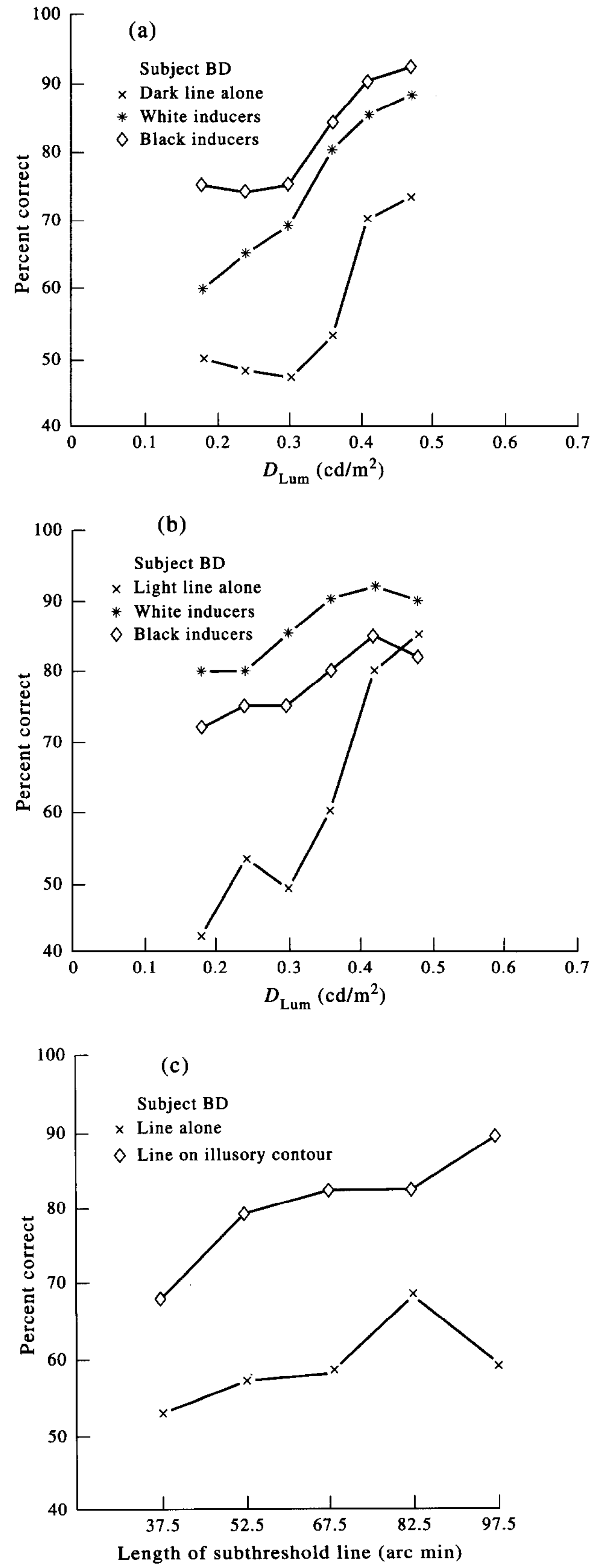

FIGURE 6. The results of subject BD, who always had to detect the subthreshold line, in the second experiment. The graphs reveal similar tendencies in the results of the two observers, who had been given different instructions in the experimental condition where the subthreshold line was presented on the illusory contour. A subthreshold line of any contrast polarity is found to enhance the strength of an illusory contour (IM's data), and to be better detected when presented on an illusory contour (BD's data). This holds for contours induced by stimulus elements of any contrast polarity.

Subthreshold lines of any polarity are better detected when presented on an illusory contour, regardless of the polarity of the stimulus elements which induce that contour.

It might still be objected that the mere presence of the inducing elements at positions adjacent to the subthreshold line reduces uncertainty about the spatial location of the line, and thus facilitates its detection. Although we think that such an interpretation can hardly explain why the subthreshold line enhances the strength of the illusory contour on which it is added (results of subject IM), we ran a third experiment to evaluate the extent to which reduced spatial uncertainty may account for the data of our first two experiments.

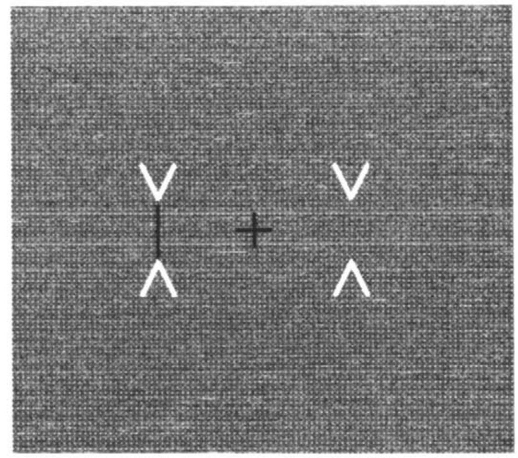

FIGURE 7. In the third experiment, we tested the extent to which reduced uncertainty about the spatial position of the subthreshold line may account for the results in Expts 1 and 2. Therefore, we added a control condition with stimulus elements that induced local reference contrasts at the ends of the subthreshold line, but no illusory contour.

EXPERIMENT 3

To test whether the mere presence of stimulus elements at positions adjacent to the ends of the subthreshold line can explain why the latter becomes detectable, we used a control configuration which does not generate illusory contours but should reduce spatial uncertainty in the same way as the illusory contour configuration may do. We compared performances in three experimental conditions: (1) subthreshold line presented alone; (2) subthreshold line added on an illusory contour; and (3) subthreshold line presented in the control configuration. Since we wanted to avoid the pedestal effect observed in Expt 2, which would only have added unnecessary noise to the results in this control experiment, we left out the conditions where the subthreshold line and the inducing elements have the same contrast polarity. As in the first study, we presented a dark subthreshold line, either alone or within configurations made of white stimulus elements, generating or not illusory contours.

Subjects

The subjects (IM and BD) were the same as in Expt 2.

Stimuli

The size and the luminance of the white inducing elements of the illusory contour configuration were the same as in the previous experiments. The control configuration (see Fig. 7) was made of two collinear "V" stimuli with the same luminance as that of the inducing elements of the illusory contour configuration. The stimulus elements in all figure conditions were separated by a gap of approx. 80 arc min. The length of the subthreshold line was identical to that gap size. The luminance levels of the dark subthreshold line were 6.37, 6.43, 6.49, 6.55 and 6.61 cd/m^2 for subject BD and 6.26, 6.32, 6.37, 6.43 and 6.49 cd/m^2 for subject IM. The luminance of the background on which all stimuli were presented was 6.73 cd/m^2.

Procedure

The procedure was basically the same as in Expt 2. In the condition where the subthreshold line was presented on the illusory contour, subject IM had to accomplish the contour enhancement task, as in the previous experiment, and subject BD the detection task. In the other conditions, both observers had to detect the subthreshold line, randomly presented to the left or to the right of the fixation mark. In addition to the number of correct detections, we also recorded response times in this experiment.

Results and discussion

The percentage of correct detections was calculated for each observer and experimental condition. The probabilities where then transformed into logit values and plotted as logistic functions of the difference between the luminance intensity of the subthreshold line and the luminance intensity of the background. For the transformation of the data, the following formula was used: $\text{logit}_\pi = \ln \pi/1 - \pi$, where π is the probability of correct detection of the subthreshold line for a given observer within a given experimental condition.

The data of subject IM, who had to decide on the strength of the illusory contours, are shown in the Fig. 8(a, b). The data of BD, who accomplished a detection task in all experimental conditions, are represented in Fig. 9(a, b). The psychometric functions relating the transformed probabilities of correct detection to the differences between the luminance intensity of the subthreshold line and the luminance intensity of the background reveal that the best performances are obtained when the subthreshold line is presented on an illusory contour, regardless of the instructions given to the observer [cf. Figs 8(a) and 9(a)]. In this condition, the theoretical threshold where $\pi = 0.75$, in other words the point where the subthreshold line is, or would be, detected correctly in 75% of the trials, corresponds to a luminance difference of 0.23 cd/m^2 for observer BD and to a difference of 0.39 cd/m^2 for observer IM. In the control condition where the subthreshold line is

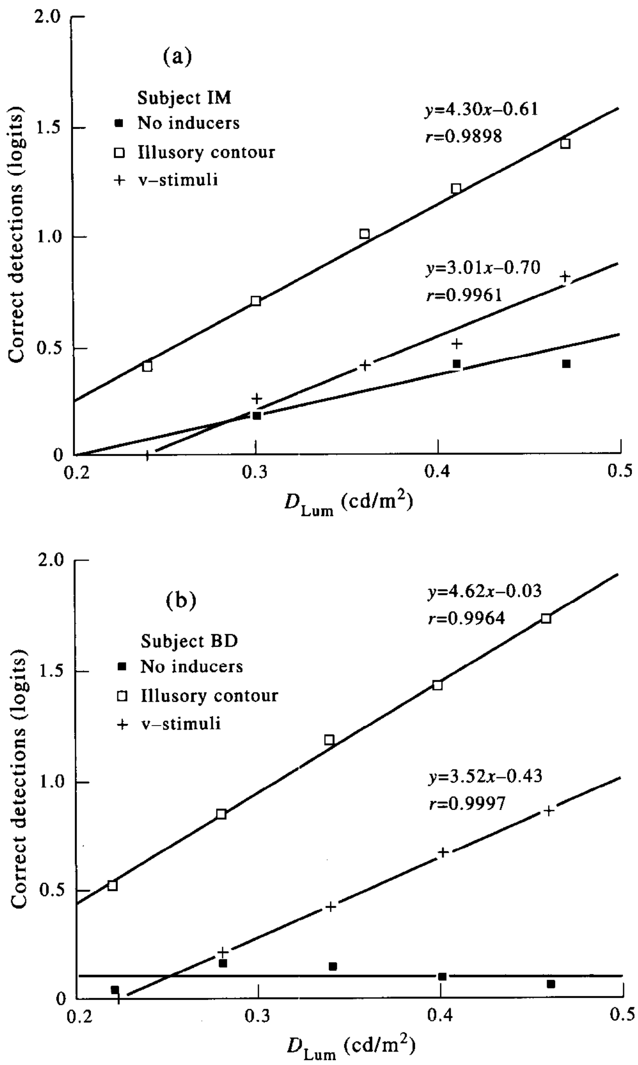

FIGURE 8. The data from the third experiment. (a) Results of subject IM, who had to decide on illusory contour strength. The data of subject BD who accomplished a detection task in all conditions. The probability of "correct detection" of the subthreshold line is plotted as a logistic function of the difference in luminance between the line and the background (a). The graphs indicate that performances are slightly better when a reference contrast is added at the ends of the line (the control condition with the "V-stimuli"), however, they are far from being as accurate as in the condition where the subthreshold line is presented on the illusory contour. Response times as a function of the difference in luminance between the subthreshold line and the background (b), reveal a consistent relation between speed and accuracy, comparing the different experimental conditions: when the percentage of correct detections is higher, response times are found to be systematically shorter.

presented within stimulus elements which induce local contrast but no illusory contour, the theoretical threshold lies, for both observers, beyond the luminance values used in this experiment. For subject BD, it corresponds to a luminance difference (between subthreshold line and background) of 0.43 cd/m^2, and for subject IM to a difference of 0.60 cd/m^2. As shown in the graphs, the slopes of the psychometric functions fitted to the data of the illusory contour condition and the control condition are roughly parallel. In the condition where the subthreshold line was presented alone, performances are situated around chance level for all the luminance intensities of the subthreshold line that were used in this experiment.

Figures 8(b) and 9(b) show response times of each observer in the different experimental conditions. The graphs reveal a consistent relation between speed and accuracy: response times are the longest in the condition that yields the lowest percentages of correct detections (i.e. when the subthreshold line is presented alone), and the shortest in the condition that yields the highest percentages of correct detections (i.e. when the subthreshold line is presented on an illusory contour).

The results of this third experiment show that the facilitatory effect of illusory contour configuration on both the detectability of a subthreshold line and the strength of the illusory contour upon which the line is added cannot be explained solely in terms of reduced uncertainty about the spatial position of the line. Although the mere presence of contrast elements at positions adjacent to the ends of the subthreshold line slightly improves detection performances, as compared to the situation where the line is presented alone, it does not engender a facilitation effect as strong as the one produced by the illusory contour configuration.

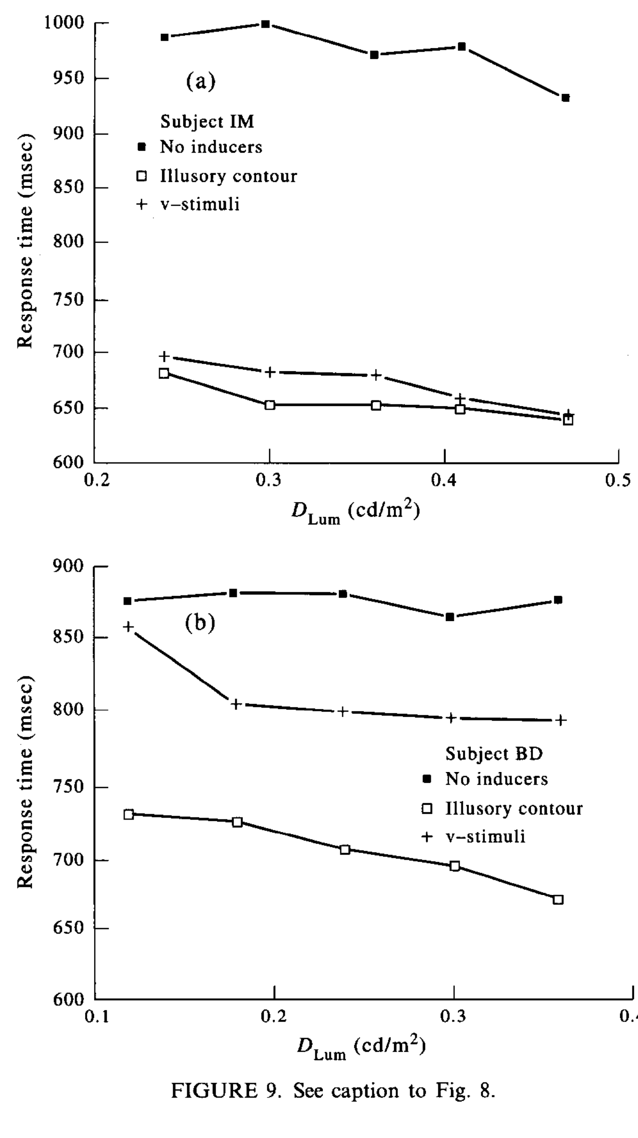

FIGURE 9. See caption to Fig. 8.

CONCLUSIONS

The data from our three experiments suggest that illusory contours and subthreshold lines tend to sum their energies in the same way as real lines and subthreshold lines, as demonstrated in the original subthreshold summation experiments by Kulikowski and King-Smith (1972). Their subthreshold line technique appears to provide an indirect measure of illusory contour integration, showing that "illusory contour detectors" are insensitive to contrast polarity and integrate over larger distances than classic line detectors. These observations are consistent with neurophysiological findings (e.g. Von der Heydt & Peterhans, 1989), and they support models of form perception which emphasize the role of polarity insensitive processes in contour completion (e.g. Grossberg, 1994).

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