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Contrast sensitivity and appearance in briefly presented illusory figures

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Abstract—We examined the contributions of brightness enhancement, illusory figure formation and figural completion to changes in contrast sensitivity in contour gaps. The brightness on the border of a Kanizsa-square and an outline square was measured as the point of subjective equality with the background (PSE) for small line targets. Increment and decrement thresholds were measured at the same location. We found that contrast thresholds were lower than in a control condition without inducers, and that the threshold reduction was independent of the contrast polarity of the inducers. This reduction cannot be explained by a simple summation of stimulus contrast and induced brightness. In a second experiment the inducers that define the contour of the Kanizsa and the outline square were changed so that the figure was no longer closed, keeping the local stimulus surround constant. Thresholds were equally reduced for all conditions, independently of whether the figure was completed or not, or whether an illusory contour was perceived or not. The results suggest that the reduction of contrast threshold in contour gaps is independent of the brightness perceived in these gaps and of the formation of an illusory figure. Processes that cause contrast threshold reduction in contour gaps also seem to operate independently of figural completion.

Keywords: Illusory contours; Kanizsa-square; brightness; contrast thresholds; contrast sensitivity.

INTRODUCTION

Illusory figures like the Kanizsa-square elicit several perceptual phenomena: the central square is perceived as brighter than the surround, and appears located in front of the surround. In addition, physically nonexistent contours are perceived that delineate the illusory square. Different theories on the perception of illusory figures have been developed arguing either for top-down influences of illusory figure formation (Gregory, 1972; Rock and Anson, 1979; Wallach and Slaughter, 1988), or for a low level, feed-forward processing of illusory contours (Shapley and Gordon, 1987; for a review see Petry and Meyer, 1987; Dresp and Bonnet, 1991, 1993, 1995;

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Spillmann and Dresp, 1995; Lesher, 1995). Evidence pointing towards a low level processing of illusory figures comes from physiology (von der Heydt *et al.*, 1984; Redies *et al.*, 1986; von der Heydt and Peterhans, 1989; Peterhans and von der Heydt, 1989; Grosof *et al.*, 1993; Hirsch *et al.*, 1995) and psychophysics (Shapley and Gordon, 1987; Dresp and Bonnet, 1991, 1993, 1995; McCourt and Paulson, 1994).

Psychophysically, contrast thresholds are lower for small test targets presented on the illusory border of a Kanizsa-square, in the gap between the inducers, than at locations near the border (Dresp and Bonnet, 1991, 1993; McCourt and Paulson, 1994). These results are often related to subthreshold summation (Kulikowski and King-Smith, 1973); the contrast threshold for a target is reduced when it is superimposed on a subthreshold contrast pedestal of the same contrast polarity. It is increased when the pedestal and target have opposite contrast polarities. The changes in contrast threshold as a function of the pedestal contrast can be explained by summing target and pedestal and applying a positively accelerated transducer function (Foley and Legge, 1981; Yang and Makous, 1995). This explanation assumes that illusory contours are functionally equivalent to subthreshold stimuli, and as such can serve as a pedestal for the target (Dresp and Bonnet, 1995; Spillmann and Dresp, 1995; McCourt and Paulson, 1994).

The hypothesis that the percept of illusory figures might be due to low level processes is further supported by physiological findings. Cells in macaque extrastriate area V2 (von der Heydt *et al.*, 1984) respond to stimuli that elicit in humans the percept of an illusory contour. Grosof *et al.* (1993) found cells in primary visual cortex V1 that responded to some types of illusory contours. However, it is not clear to what extent the neuronal responses to these stimuli covary with the perceived strength of the illusory figure. Rather, the responses might be the neural substrate of more elementary contour interpolation mechanisms. In experiments where the influence of the stimulus surround on contrast sensitivity was investigated a good correlation was found between behavioral data of humans and changes of firing rates of macaque cortical neurons (Kapadia *et al.*, 1995; Polat and Sagi, 1993, 1994; Dresp, 1993; Gilbert *et al.*, 1996). Kapadia *et al.* (1995) found that the response of many cells in macaque area V1 increased when a low contrast bar in the cell's classical receptive field was accompanied by a high contrast flanking bar outside the cell's classical receptive field. The strength of facilitation of the neuronal response depended on the orientation difference, lateral displacement and distance between target and flanking line. The same factors influenced the strength of facilitatory effects of a high contrast surround stimulus on contrast sensitivity in behavioral measurements (Polat and Sagi, 1993, 1994; Kapadia *et al.*, 1995). Also, perpendicular structures at the end of the line reduced the facilitatory effect in the behavioral (Dresp, 1993) and physiological experiments.

However, several other physiological studies suggest that the link between physiology and psychophysics might not be as close as suggested by the results of Kapadia *et al.* (1995). Both Levitt and Lund (1997) and Knierim and van Essen (1992) found that the effect of iso-oriented surrounds is mainly suppressive. Facilitatory effects were mainly found when target and surround differed in orientation (Sillito *et al.*, 1995) and depended on the relative contrast of target and surround (Levitt and Lund, 1997). Polat *et al.* (1998) used a Gabor-patch flanked by two colinear Gabor-patches in their recordings in cat primary visual cortex, the same stimuli they had employed in their psychophysical experiments (Polat and Sagi, 1993). They found facilitatory effects for low target contrasts and suppressive effects for high contrast targets.

These results indicate that the basis for spatial long-range contextual influences on contrast sensitivity may be found at an early processing level such as striate cortex. However, they leave unclear the processing levels at which the perceptual phenomena associated with illusory contours are represented. Our aim was to clarify the relationship between the appearance of briefly presented illusory figures, such as brightness enhancement along the borders of an illusory figure, and contrast sensitivity for small test line segments along these borders. Specifically we aimed to test the hypothesis that brightness enhancement along illusory contours is functionally equivalent to subthreshold stimuli and can serve as a pedestal for target detection. In the second experiment, we considered whether configuration-dependent contrast threshold changes depend specifically on subjective contours or figural completion. Our results imply that brightness enhancement and the increase of contrast sensitivity on an illusory contour are independent phenomena. The processes that increase contrast sensitivity in contour gaps also seem to be unaffected by the formation of an illusory contour and figural completion. This implies that the process responsible for the increase of contrast sensitivity in contour gaps is independent of the process responsible for the formation of an illusory figure.

EXPERIMENT 1: BRIGHTNESS ENHANCEMENT IN CONTOUR GAPS

The objective of the first experiment was to investigate the relationship between brightness enhancement on illusory contours and the reduction of contrast thresholds for targets that are presented in the gaps between the inducers. Threshold reduction could either be due to subthreshold summation of the target and the illusory 'pedestal' or due to contour interpolation processes between the inducers. To evaluate these two (non-exclusive) alternatives we measured in the same subjects both contrast threshold and brightness enhancement in several stimulus configurations.

For testing these hypotheses, it is necessary to separate the influence of the stimulus surround on contrast thresholds from the influence of brightness enhancement. It has been shown that contrast thresholds for a target can be influenced by a single inducer if the target is presented colinear to the inducer (Dresp, 1993; Morgan and Dresp, 1995; Wehrhahn and Dresp, 1998). At moderate inducer contrast and short inducer-target distance (up to 15′) an increase of contrast sensitivity can be observed only when the inducer and target have the same contrast polarity (Dresp, 1993; Morgan and Dresp, 1995; Wehrhahn and Dresp, 1998). However, with larger gaps between the inducer and the target (about 20′) and high inducer contrast the contrast sensitivity for a target can be increased by inducers of any contrast polarity (Zenger and Sagi, 1996; Yu and Levi, 1997; Wehrhahn and Dresp, 1998). This property permits the separation of the effects of brightness enhancement and stimulus surround.

We determined the strength of the brightness enhancement in the gaps between pacmen inducers, where an illusory contour is perceived, and between line segments that do not elicit the percept of an illusory contour. Then we measured increment and decrement thresholds under the same conditions. From these data we can then draw conclusions about the functional relationship between brightness enhancement and contrast threshold reduction.

Methods

Equipment. The experiments were run on a Silicon Graphics Indigo Workstation. The monitor was 38.5 cm wide and 28.5 cm high. Subjects were seated at a viewing distance of 130 cm and viewed the screen binocularly through natural pupils. The monitor was run at a refresh rate of 72 Hz, allowing stimulus exposures durations which were multiples of 13.88 ms.

To determine contrast thresholds we used a set of 65 calibrated luminance levels within the range of 6.7 cd/m^2 below and 7.1 cd/m^2 above background luminance (15.1 cd/m^2). The Luminance levels were measured using a Graseby Optronics Model 370 radiometer with a model 265 photometric filter at each of the locations where the target was displayed. For the analysis we used the luminance values of the appropriate location. In this way we obtained a high accuracy and compensated for possible luminance heterogeneity at different locations of the monitor. In all experiments, except as noted, the luminance of the inducers was 49.7 cd/m^2. This corresponds to 53.4% Michelson-contrast.

Subjects. Four subjects, including one of the authors (JR), participated in all experiments. All subjects had normal or corrected to normal visual acuity.

Stimuli. All stimuli were based on a square shape with a side length of 2.5 deg visual angle (Fig. 1). The target was a short line, 2.4′ (3 Pixels) wide and 10′ long. Contrast thresholds were determined in three different configurations (Fig. 1A–C):

(A) In the control condition only the target was displayed.

(B) Lines: the target was presented in the gaps of a square made up of lines. The lines were 50′ long and 3.2′ wide. The gaps in the square were 50′ wide.

(C) Pacmen: the target was presented in the gaps of a Kanizsa-square where observers perceive a subjective contour. The square consisted of discs with a radius of 50′ and a 90 deg sector missing. We will refer to this inducer type as pacmen. The gap length was also 50′ as in the condition above.

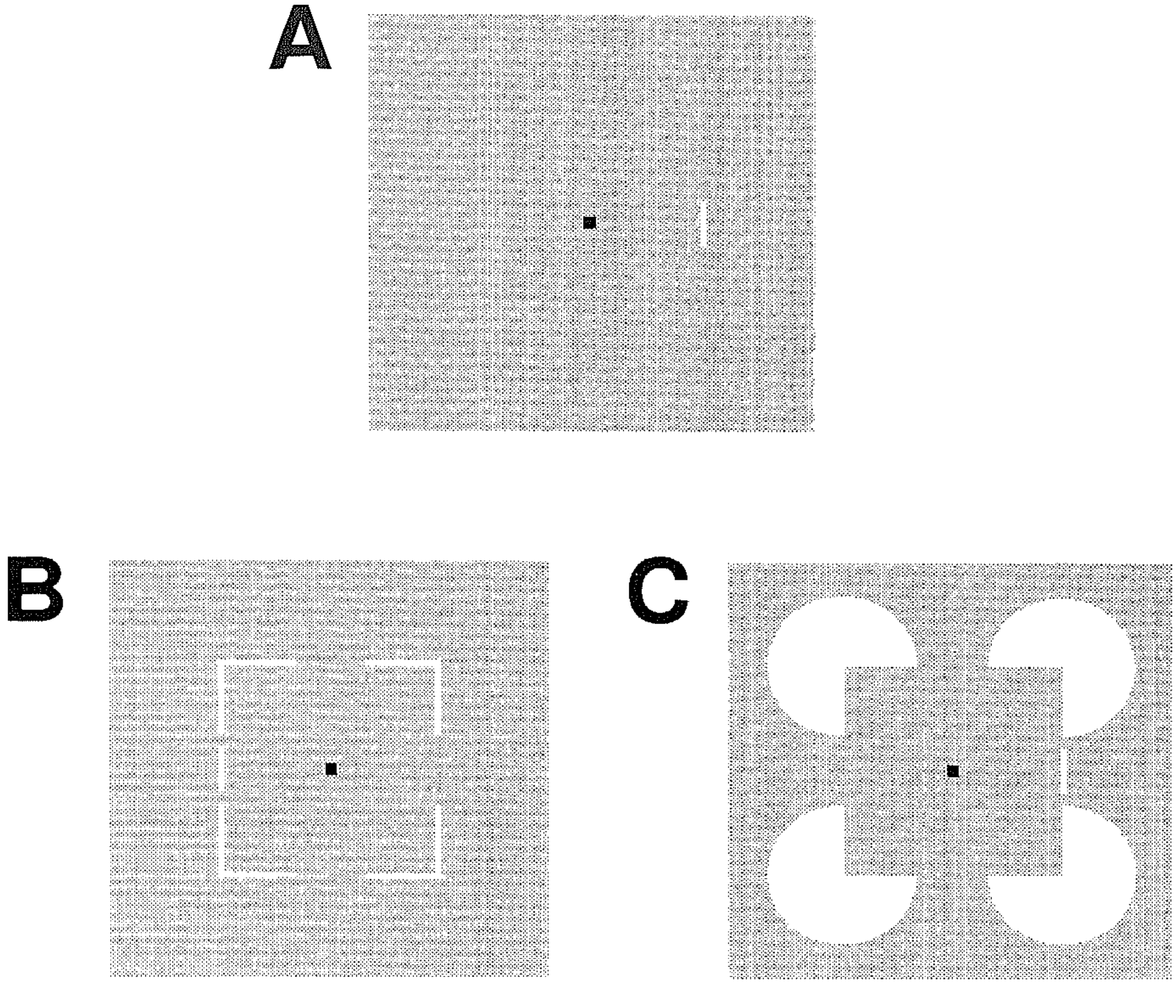

Figure 1. The Stimuli used in the experiments. The target was a short line with variable contrast, presented either on the left or on the right of a fixation point. In the control condition (A) only the target was displayed. To test the influence of the stimulus configuration and brightness on the contrast thresholds for the line target we used two additional stimuli. The target was presented in a square made up of lines (B), where no illusory figure is perceived, or in the gaps of a Kanizsa-square (C) where observers perceive an illusory square.

Our goal was to investigate the effect of brightness by measuring decrement and increment threshold separately and to compare them with the predictions of a summation model (Kulikowski and King-Smith, 1973; Foley and Legge, 1981). The target was a 10′ long line in the 50′ long gap between the inducers, leaving a gap of 20′ between target and inducer.

Procedure. At the beginning of each trial a fixation spot was displayed for 500 ms (Fig. 2). The fixation screen was followed by the stimulus screen, in which the fixation spot persisted. Then the target was displayed either on the left side or right side of the square for 110 ms, followed by a blank screen. From this moment on the response of the subject was registered. The next trial started automatically after the observer responded, with an inter-stimulus-interval of at least one second.

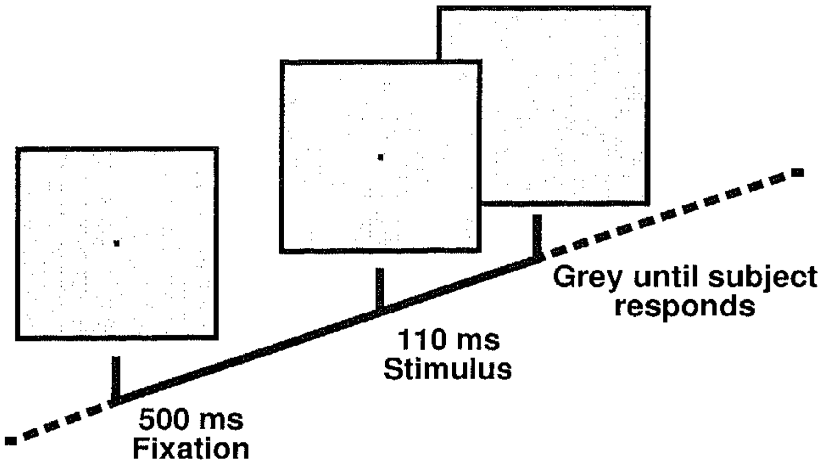

Figure 2. At the beginning of a trial subjects had to fixate for 500 ms. Then the stimulus appeared for 110 ms. The target contrast was randomly chosen from a set of 5 contrast levels. It was presented randomly either in the left or in the right gap of the square. After stimulus presentation the screen was switched to a uniform grey until the subject responded by pressing a key. In one block of trials (20 repetitions of each contrast level) only one stimulus type (Fig. 1A–C) was used.

Contrast thresholds. The objective was to determine the target contrast the subjects needed to reliably detect the target. The target was displayed with equal probability either on the left or the right side of the square. The observers indicated the position by pressing the left arrow key for the left side and the right arrow key for the right side on a standard keyboard (spatial two alternative forced choice method). Trials in which the subject's response was wrong were indicated by a click-tone.

The method of constant stimuli was used. For each stimulus configuration (Fig. 1A–C) the contrast threshold was determined with a set of five target contrasts. One contrast level was chosen so that the subject never saw the target and another one clearly above detection threshold. The remaining three contrast levels were grouped around the individual threshold in this configuration. The contrast thresholds were determined in a separate block for each stimulus configuration (i.e. pacmen, line and control). In each block every contrast level was presented 20 times in a random order. The blocks for the three stimulus configurations were combined into an experimental session, which lasted about 30 min. At the beginning of each session the subjects adapted for five minutes to the background luminance of the monitor (15.1 cd/m^2). Each subject participated in five experimental sessions. The first one was a training session and was excluded from further analysis. From the data of the remaining four sessions we calculated the proportion of correct responses at each contrast level (80 repetitions per contrast level). Then we fitted a cumulative Gaussian-function with the lower asymptote at 50% correct responses (guessing level) and the upper asymptote at 100% correct responses to these values. The contrast level at which the subject obtained 75% correct responses was extracted as an estimate for the contrast threshold. All contrast thresholds in this study were determined with this procedure.

Brightness. For the measurement of the brightness perceived in the gap some deviations from the procedure described above were necessary. First, the target was presented at nine contrast levels, four levels below and four above background luminance. At the ninth contrast level no target was displayed. The subjects (except the author JR) were not informed about the later. For the measurement of brightness enhancement we did not want the subjects to compare the perception of the gap in which the stimulus was displayed with the percept that was elicited by the other gaps. Therefore we split the square vertically and presented only one half (e.g. the left pair of inducers) with a target in its gap. By pressing the up- or down-arrow key subjects had to indicate whether they saw something brighter or darker than the background in the gap between the inducers. For each contrast step we calculated the percentage of answers 'brighter than the background' and fitted a cumulative Gaussian-function to these data. The value for which the subject chose both alternatives with equal frequency was extracted as the point of subjective equality with the background (PSE).

Results

In Fig. 3 the averaged PSEs, decrement, and increment thresholds for four observers are plotted for the Kanizsa-square configuration and the outline square configuration. As expected, the PSE was shifted to values below background luminance in the gap between the inducers of the Kanizsa-square (pacmen: 0.59 cd/m^2, $t_3 = 9.0$; $p < 0.01$). This indicates that the space between inducers was perceived to be brighter than the background. However, the PSE was also shifted below background luminance in the gap of the square made up of lines (lines: 0.73 cd/m^2, $t_3 = 4.22$; $p < 0.025$), confirming our earlier informal observations that for short presentation times brightness enhancement also appeared in the gaps between the lines. In the control configuration none of the subjects showed a significant deviation of the PSE from the background luminance. This shows that none of them had a significant bias that influenced the measurement of the PSE.

In the analysis of the contrast threshold data a paired t-test did not show a significant difference between the effect of the inducer types (pacmen, lines: $t_7 = 1.75$, $p > 0.1$). Although the absolute values of the decrement thresholds are slightly lower than the increment thresholds (pacmen, decrement: 1.61 cd/m^2; increment: 1.65 cd/m^2; lines, decrement: 1.38 cd/m^2; increment: 1.63 cd/m^2; control, decrement: 1.88 cd/m^2; increment: 2.01 cd/m^2), this difference between the decrement and the increment thresholds was not significant ($t_7 = 1.27$, $p > 0.1$). Both, the increment and the decrement thresholds, were significantly lower when measured between the inducers (pacmen, lines) than in the control configuration (increment: $t_7 = 8.6$, $p < 0.001$, decrement: $t_7 = 3.1$, $p < 0.025$).

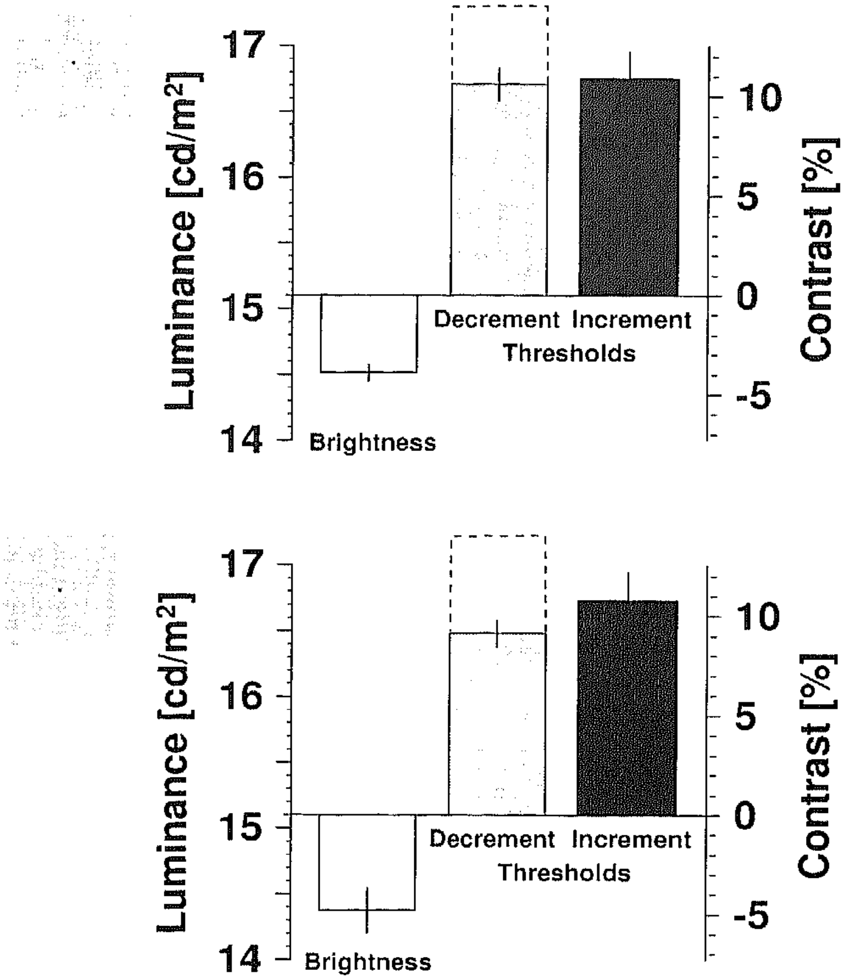

Figure 3. The average responses of four observers in the first experiment. The corresponding stimuli are shown on the top left of each graph. The open bars show the point of subjective equality for the target. The values below background luminance indicate that the space between the inducers was perceived to be brighter than the background. The grey and the black bars plot decrement and increment thresholds. For a better comparison the decrement thresholds are plotted as absolute values. The dashed bar depicts the decrement thresholds that would have been expected according to a subthreshold summation model. Note that both, decrement and increment thresholds are reduced compared to the control condition (see text). Vertical bars represent ±1 standard error of the mean.

Discussion

The results of the first experiment suggests that the brightness perceived in the gap of an illusory contour is functionally different from a luminance pedestal. According to an energy summation model (Kulikowski and King-Smith, 1973; Dresp and Bonnet, 1995; Yang and Makous, 1995) where the induced brightness and the target are summed, the decrement thresholds should have been elevated compared to the increment thresholds, as long as the pedestal is subthreshold (bumper effect) (Kulikowski, 1976; Bowen and Cotten, 1993; Yang and Makous, 1995). The dotted lines in Fig. 3 show the prediction of a subthreshold summation model, in which the output of the system is simply the sum of the target and the brightness pedestal. This prediction does not work, as decrement thresholds do not exceed increment thresholds. It might be that our method led to an underestimation of the brightness between the gaps. But with a pedestal above threshold (subjects did perceive an increase in brightness) one would expect, according to a summation model, an increase of contrast thresholds compared to the non-pedestal case (Yang and Makous, 1995), which we did not observe.

We conclude that contrast threshold reduction is independent of the brightness effects seen in the gap between the inducers. The brightness effects are mediated by different, maybe later processes that do not seem to interfere with processes that mediate contrast threshold reduction. Watanabe and Oyama (1988) used the causal inference method to investigate the role of brightness enhancement in illusory contour formation and arrived at the conclusion that subjective brightness appears at a late processing stage. It should be noted here that in Watanabe and Oyama's study the subjects rated the brightness increase of the whole area framed by the illusory contour relative to its surrounding, while in our study the point of subjective equality for a line target near the border was determined. Although our study was not designed to draw inferences about the hierarchy of processing stages, our results are consistent with the assumption of a late formation of brightness.

The reduction of decrement and increment thresholds we observed confirms recent findings that for large separations between inducer and target, and for high inducer contrasts, the inducer's effect on contrast thresholds is independent of the inducer contrast polarity. Inducers lead to an increase in contrast sensitivity for targets of any contrast polarity as long as the targets are colinear to the inducers (Zenger and Sagi, 1996; Yu and Levi, 1997; Wehrhahn and Dresp, 1998).

We believe that we obtained a meaningful estimate of the strength of induced brightness because the measurements were taken at the same location where contrast thresholds were determined. This was important as brightness is not necessarily constant over all locations in a contour gap. Interestingly, brightness enhancement was not only present in the gap between the inducers of a Kanizsa-square, but also in the gap between the line inducers. The subjects reported that they perceived a thin white line bridging the gap between the lines with a decrease in brightness to the middle of the gap. This is interesting for two reasons. First, it has been argued that illusory contours appear only roughly perpendicular to line end inducers (e.g. Lesher, 1995). Our results show that induced brightness can also run in parallel to line inducers. Second, the effect seems to exist only for a very limited period of time as no brightness enhancement is perceived in a static display. When looking at Fig. 1B normally no bright stripes connecting the lines are perceived.

The dynamics of illusory contour formation have been subject to several investigations (Reynolds, 1981; Kojo *et al.*, 1993; Rubin *et al.*, 1995; Ringach and Shapley, 1996; Gegenfurtner *et al.*, 1997). Reynolds (1981) reported time limited appearance of a subjective figure. In his study, a Kanizsa-triangle configuration was displayed on a background that obstructed the formation of an illusory contour under normal viewing conditions. The author could show that the triangle was initially perceived for processing times up to 300 ms. For longer presentation times this percept disappeared, the illusory triangle was no longer visible. The time-limited perception of brightness enhancement, or of the illusory figure as a whole, indicates that initially generated percepts might undergo changes as processing proceeds.

EXPERIMENT 2: FIGURAL COMPLETION

In Experiment 2 we tested the possible influence of figural completion processes on the enhancement of contrast sensitivity in contour gaps. In particular, we compared the contrast thresholds obtained in a stimulus configuration where the inducers could be integrated to an illusory or outline square to the contrast thresholds obtained in a configuration where this was not the case.

Methods

The stimuli that were used in this experiment can be seen in Fig. 4. The stimuli in the closed configuration (Fig. 4A) were identical to the ones with which contrast thresholds were determined in the previous experiment, except for the following changes: the luminance of the inducers was 30.6 cd/m^2, which corresponds to 34% Michelson-contrast, and the target line was 33′ long. In the open configuration (Fig. 4B) the inducers were changed in a way to keep the ratio of the lengths of the luminance defined contour and the gap (‘support ratio’) constant. For the line stimuli this was achieved by omitting the horizontal lines. The pacmen were replaced by half disks with a diameter that was equal to the radius of the pacmen used in the previous experiment. We also employed a control condition where only the target and the fixation spot were displayed. The data for the open and the closed condition were collected in different sessions, as described in the procedure section of the first experiment.

Normalized contrast thresholds were calculated by dividing the individual thresholds obtained in each stimulus configuration by the thresholds obtained in the control condition. The subjects were the same as in Experiment 1.

Results

The average normalized contrast thresholds for the four configurations are shown in Fig. 5. Inducers had a marked effect on contrast thresholds: thresholds were significantly lower when the target was displayed in the gap between two inducers than when they were displayed alone (lines, open: $t_3 = 4.12$, $p < 0.05$; closed: $t_3 = 3.54$, $p < 0.05$; pacmen, open: $t_3 = 9.51$, $p < 0.01$; closed: $t_3 = 7.85$, $p < 0.01$). A comparison of thresholds obtained in the open and the closed configuration showed no significant difference between the effect of the inducers for the outline squares and the Kanizsa-squares (pacmen: $t_3 = 1.33$, $p > 0.25$; lines: $t_3 = 0.58$, $p > 0.25$). Interestingly, the decrease in threshold was nearly identical for the Kanizsa-squares (Fig. 4A), which elicit a strong percept of an

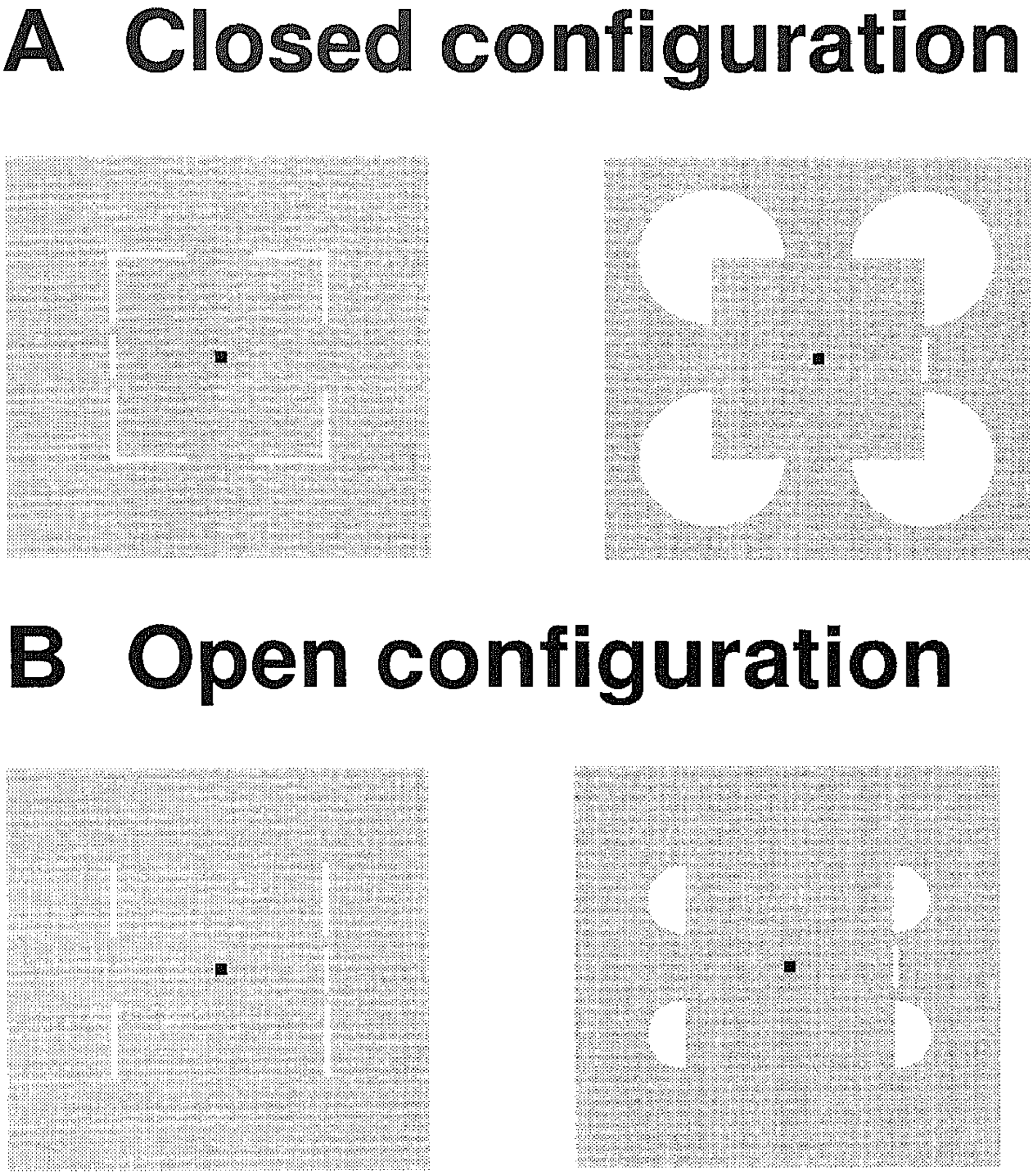

Figure 4. The stimuli used to study the effect of figural completion on contrast sensitivity. The stimuli of the closed configuration (A) were the same as in the first experiment. In the open configuration (B) the luminance defined length and the gap length were held constant.

illusory figure, and the outline squares, where no subjective figure is perceived (Fig. 4). The difference between these conditions was not significant, neither for the closed ($t_3 = 0.81$, $p > 0.25$), nor for the open ($t_3 = 0.66$, $p > 0.25$) configuration.

Discussion

The amount of threshold reduction was independent of both figural completion and the percept or presence of an illusory figure. We found no difference in the effects of open versus closed figures, and no difference between Kanizsa-squares and outline squares. This indicates that the processes that mediate contrast threshold reduction in contour gaps act independently of the processes in which figural completion is

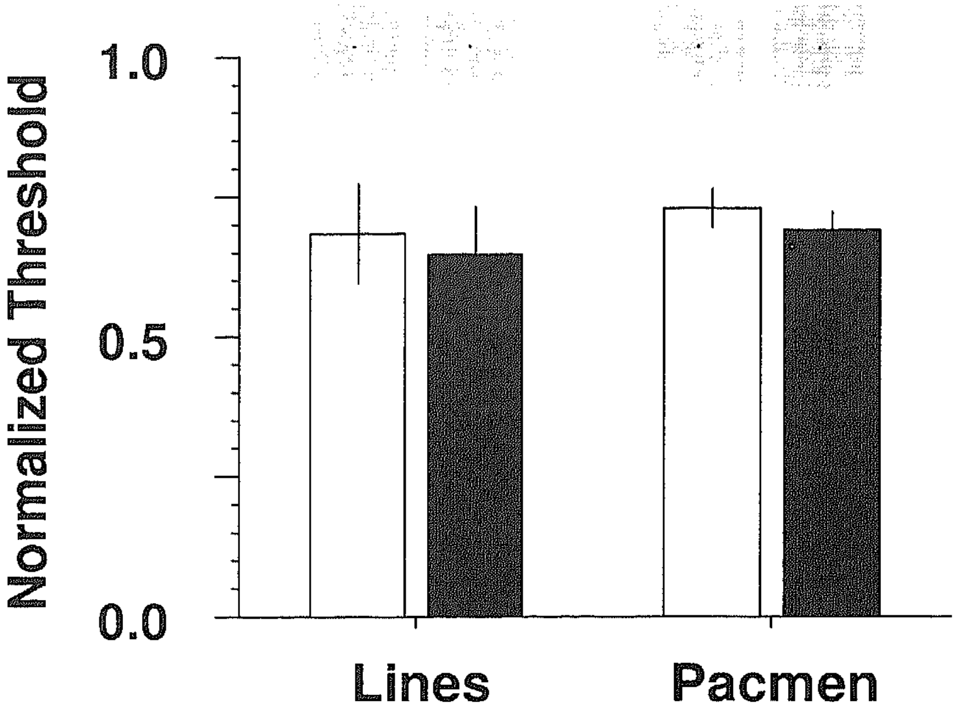

Figure 5. Comparison of averaged increment thresholds from four observers obtained in the open and in the closed configuration. Example stimuli are plotted at top of the corresponding bars. White bars represent normalized thresholds from the closed configuration, and black bars from the closed configuration. Normalized contrast thresholds were calculated by dividing the absolute thresholds by the threshold in the control configuration.

obtained and illusory figures are generated. This agrees with the results of the first experiment, where we found that contrast threshold mechanisms were independent of brightness enhancement. Both illusory contour and brightness are features of an illusory figure. The results of the two experiments therefore indicate that the processes that mediate contrast threshold reduction in contour gaps are independent of the processes that generate the perceptual phenomena of illusory figures, and that these perceptual phenomena are generated at a different, presumably later processing stage. Dependent processes would have produced a difference between the configurations with and without the percept of an illusory figure.

The conclusion that early processes supporting contour interpolation are independent of the formation of an illusory figure is in good agreement with the results we obtained in a recent study using a different approach (Gegenfurtner *et al.*, 1997). There, we investigated the dynamics of the processes that bridge the gaps between inducers of figures, comparable to the ones used in this study. We determined the presentation time that was necessary to reliably detect a Kanizsa- or a line-segment triangle in a field of randomly oriented inducers of the same type. Thresholds increased as a function of gap length, indicating that the gaps between the inducers need to be interpolated. There was no difference between the interpolation speed in the Kanizsa- and the line-segment triangle, indicating that the interpolation process is independent of the formation of an illusory contour.

GENERAL DISCUSSION

In summary, the results of our experiments suggest that the processes that mediate contrast sensitivity in the vicinity of a suprathreshold stimulus act independently of the processes underlying the formation of an illusory contour and the brightness enhancement. We suggest that the effect of the surround on contrast sensitivity is mediated at an early level in visual processing, which is not affected by figural completion. The perceptual phenomena that accompany illusory figures seem to be generated by different processes, which can be affected while processing of the stimulus proceeds.

The finding that brightness enhancement and the formation of illusory contours have no effect on contrast sensitivity sheds new light on the conclusions about the functional relationship between perceptual phenomena like illusory figures and induced brightness, and the increase of contrast sensitivity in contour gaps (Dresp and Bonnet, 1991, 1993, 1995; Dresp, 1992; McCourt and Paulson, 1994). The effects that we obtained in the Kanizsa-square are comparable in magnitude and polarity specificity to earlier results, where Kanizsa-squares were used as stimuli (McCourt and Paulson, 1994; Dresp and Bonnet, 1995; Dresp and Grossberg, 1997). Our results do not support the notion that the increase of contrast sensitivity is due to a summation of the target stimulus with the illusory contour (Dresp and Bonnet, 1995) or brightness (Dresp, 1992; Dresp and Bonnet, 1993). Neither did we find a stronger decrease in contrast thresholds if an illusory contour is perceived (Dresp, 1997). It seems to be more likely that lateral long-range interactions activated by aligned stimuli provide the basis for contrast facilitation. These processes might determine the features of an illusory figure, like the contour and the brightness, but the phenomenal emergence of these features seems to require further processing. We have shown this by disentangling the effect of induced brightness and illusory contours on contrast sensitivity from the effects of lateral interactions that appear in contour gaps.

It has been argued that long-range horizontal connections between neurons could signal contour closure and mediate contrast thresholds at the same processing level (Kovacs and Julesz, 1993; Gilbert *et al.*, 1996; Yen and Finkel, 1998). In our experiments we did not find an effect of contour closure on contrast thresholds. However, our contours were based on a square shape and the contour elements were perfectly aligned. Since the neural horizontal connections are strongly orientation tuned, path integration is easily disturbed when the orientation between the elements in the path diverges too far (Field *et al.*, 1993). Also Pettet *et al.* (1998) have shown that the visibility of a closed contour is decreased when it contains sharp corners. This indicates that the smoothness of a contour is an important parameter for the pop-out effect in path integration. Our results indicate that the facilitation between two adjacent and aligned inducers is not necessarily enhanced by an additional closure of a figure.

It may be objected that the contrast threshold reduction we obtained in the presence of inducing elements (lines or pacmen) is due to the reduction of uncertainty about the spatial position of the target by the aligned inducers. For several reasons we do not believe that our results, especially the failure to find differences in the strength of the effects in the Kanizsa- and the line-segment square, can be explained by this assumption. First, Dresp (1993) obtained reduced contrast thresholds for a small target spot of light presented at the end of a line or the edge of a single pacman compared to the case when the target was presented on a plain field. When the line ends were stopped by a perpendicular line added adjacent to the target (L- or T-shape) the contrast threshold reduction diminished. The same effect happens when a circle is added to the pacman shape closing the outline of the disk. Furthermore, a suprathreshold light spot presented in the vicinity of the target failed to reduce contrast thresholds (Dresp, 1993) although it reduced spatial uncertainty about the target position. The dependency of facilitatory effects on the shape of the line endings was also observed by Kapadia *et al.* (1995) in their psychophysical and physiological studies. A second effect that cannot be explained by the spatial uncertainty hypothesis is that the increase in contrast sensitivity diminishes or reverses when a target is presented close to an inducer of opposite contrast polarity (Dresp, 1993; Morgan and Dresp, 1995). Third, Dresp and Bonnet (1995) and Dresp and Grossberg (1997) used a control configuration in their measurements of contrast sensitivity on illusory contours in which the target was presented between two V-shaped flankers to reduce spatial uncertainty. Note that the V-shaped flankers provide information about the target position but, unlike our line-segment configuration, no information about contour continuation. Comparing the contrast thresholds obtained in the V-shape configuration to the contrast thresholds obtained when the target was presented alone revealed that the positional uncertainty alone cannot account for the observed contrast threshold reduction.

We did not find an effect of figural completion on contrast thresholds, with or without the presence of an illusory figure. This indicates that illusory figures are generated at a different processing stage: their appearance can be influenced by both high-level processes (e.g. Rock and Anson, 1979; Reynolds, 1981; Wallach and Slaughter, 1988) and by low-level determinants like inducer spacing (Banton and Levi, 1992; Dresp, 1992; Ringach and Shapley, 1996), alignment (Kellman and Shipley, 1991) and contrast (Watanabe and Oyama, 1988). These low level determinants are also important determinants for the influence of the stimulus surround on contrast sensitivity (Dresp, 1993; Polat and Sagi, 1993, 1994; Zenger and Sagi, 1996; Wehrhahn and Dresp, 1998; Kapadia *et al.*, 1995) but unlike illusory figure perception, contrast sensitivity does not seem to be influenced by high-level processes.

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