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Light-spot detection on an illusory figure

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Abstract

We investigated how the detection of a light spot was influenced by the presence of an illusory figure. The light spot was presented off-the-border of the illusory figure, either inside or outside the figure. Detection thresholds were lower when the spot was presented inside the figure than when it was presented outside the figure. This facilitatory effect by the illusory figure may be caused by the process of subthreshold contrast summation that is related to the enhancement of apparent brightness in the illusory figure.

Introduction

When four disk patterns with an open-sector are spatially arranged so that the straight lines of the four sectors are aligned with gaps, an illusory figure is perceived in the area between the patterns (Kanizsa, 1976). This illusory figure influences apparent brightness in the area. For example, the contour and the surrounding area look brighter than the background area when the inducers are in lower luminance than the background. What would be the functional characteristics of changes in apparent brightness? Do the changes influence visual performance such as contrast detection? Suppose one conducts a task of detecting a light spot in the brighter area. Is the performance facilitated or suppressed by the presence of the illusory figure?

Findings of several studies that addressed the above issue were not consistent when a target stimulus was presented on the border of an illusory figure. Some studies found a facilitatory effect to be involved while other studies did not (Dresp & Bonnet, 1991, 1993, 1995; McCourt & Paulson, 1994; Rieger & Gegenfurtner, 1999). Some studies also examined similar influences with a target presented inside and outside the illusory figure, and found that the detection was suppressed (i. e. threshold was elevated) in both locations

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(Dresp & Bonnet, 1991 ; Dresp & Bonnet, 1993).

Theoretical accounts about the facilitatory effect of an illusory figure can be summarized in two models. (1) Apparent enhancement of brightness is functionally equivalent to luminance enhancement, and this enhanced luminance of a given target spot adds contrast to the one between the target and the background so that it exceeds the threshold of contrast detection (McCourt & Paulson, 1994 ; Dresp & Bonnet, 1995). This is a case of subthreshold summation of contrast (Legge & Foley, 1980). Details of the subthreshold summation model will be discussed in the Discussion section later. (2) The cortical cells in the visual cortex have long-range connections that respond to two or more stimuli that are separated in space, influencing the activity levels in cells that have receptive fields in the space between the two or more stimuli (Kapadia, Ito, Gilbert & Westheimer, 1995). Lateral long-range interactions activated by inducer patterns are thought to produce the facilitatory effect with an illusory figure (Reiger & Gegenfurtner, 1999).

Compared to the border areas of an illusory figure, the inside area of an illusory figure was not well examined for the influence on target detection. This inside area is especially interesting in terms of the long-range connection model ; inside an illusory figure the line segments are not aligned (e. g. Kanizsa figure, see Figure 1A). The alignment of line segments is a necessary condition for the long-range facilitatory effect. Thus, we would not expect the facilitatory effect by the illusory figure. On the other hand, the area inside the illusory figure looks brighter, when the inducers are black on white background, which can be conditions required to produce contrast summation. We could expect the facilitatory effect by the illusory figure. To test these predictions, we conducted two experiments that measured detection thresholds of a light spot presented in the area of an illusory figure.

General Methods

Stimulus

Four black sector figures (Pac-men) were drawn on a white board. In Experiment 1, they were spatially arranged to induce illusory contours with a square surface (Figure 1 A). In Experiment 2, they were spatially arranged not to induce the illusory contours (Figure 1B). The diameter of the black sector was 1.9 degrees of visual angle. The black sectors were separated 3.9 degrees of visual angle between the centers. Luminance of the black sectors was 0.03 cd/m^2, and luminance of the white background was 50 cd/m^2. A light spot of 30 cd/m^2, 0.36 degrees of visual angle in diameter, was presented on either the inside [referred to as Inside condition] or the outside [referred to as Outside condition] the illusory square in Experiment 1 (or the corresponding location in Experiment 2). The distance from the illusory border to the light spot was 0.5 degrees of visual angle.

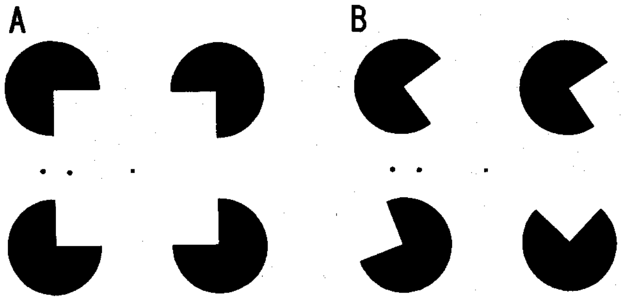

Figure 1. The stimuli used to study the effect of detecting the presence of an illusory figure with a light spot. The dot in the center of the figure is a fixation point. The two dots shown off-the-center in the figure were light spots in our experiments, and one of them was presented in a trial. (A) The stimulus with illusory figure. (B) The stimulus without illusory figure.

Procedures

The stimulus figure was presented for 4 seconds in each trial. The light spot was presented at one of two locations for 8, 10, 12, 14, 16, or 18 milliseconds (ms), 3.5 seconds after the stimulus figure was turned on. These stimuli were presented using a Tachistoscope (Takei Kiki DP4 Type). A small and dim fixation spot was always turned on at the center of the stimulus during each replication of the experiment. Trial intervals, stimulus durations, and stimulus intervals were controlled by a Digital preset timer (Takei Kiki).

Observers stayed in a dark experimental room for 10 minutes to become accustomed to the dark before starting the trials. After a few practice trials, data collection began. Data collection came from two differing locations of the light spot and 6 varying durations, so 12 stimulus conditions were prepared for each replication. For each stimulus condition 20 trials were run, with a total of 240 trials in random order for each observer.

The observer gave a verbal response about seeing the light spot. He/she was instructed to keep the same criterion of judgment throughout the experiment. A brief break was introduced whenever the observer felt tired.

Observers

Seven college students, four females and three males, participated in Experiment 1. Their ages ranged from 21 to 25 years old. Five college students, three females and two males, participated in Experiment 2. Their ages ranged from 21 to 25 years old. Some of the observers in Experiment 1 also participated in Experiment 2. None of the participants were known to suffer from any eye disease.

Results

The results of Experiments 1 and 2 will be presented together. To inspect the general trend of responses, curves showing the probability of seeing the light spot were plotted for each observer in Experiments 1 and 2 for Inside and Outside conditions respectively (Figure 1). The general trends of the curves were similar across individuals and conditions, showing a monotonically-growing function. The curves tend to shift to the right with the panels advancing from A to D, suggesting detection of the light spot was influenced by the location of the spot and the formation of the illusory figure.

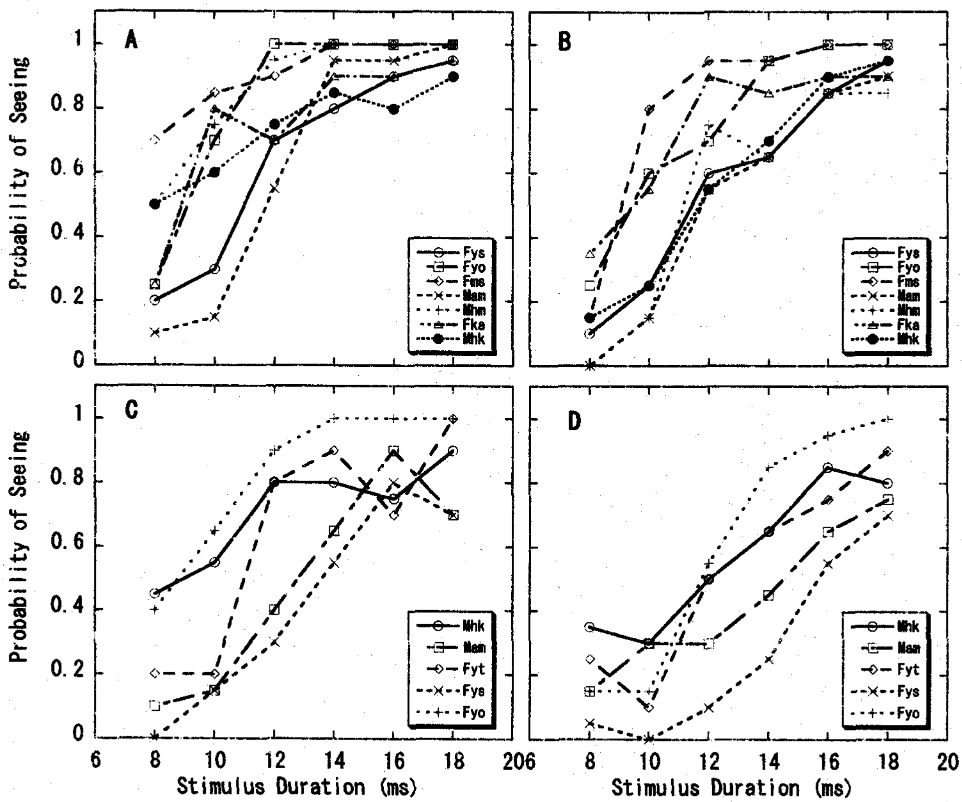

Figure 2. Probabilities of seeing a light spot are plotted as a function of stimulus duration for each observer in four conditions: (A) Inside condition with illusory figure, (B) Outside condition with illusory figure, (C) Inside condition without illusory figure, and (D) Outside condition without illusory figure.

We estimated the stimulus duration with which the observers achieved 0.5 probability of seeing the light spot by applying the cumulative normal function to each individual curve in Figure 2, and refer to it as the threshold for detecting the light spot. The means and standard errors were computed for illusory- and no-illusory-contour conditions, with two stimulus locations (Inside and Outside) respectively (Figure 3). The threshold measure makes the trends suggested in Figure 2 clear; thresholds for inside condi-

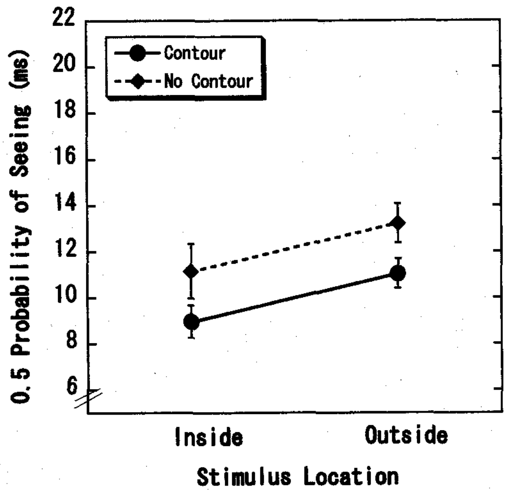

Figure 3. The means of 0.5 probability of seeing a light spot are shown for four stimulus conditions separately. The conditions are combinations of Inside and Outside of inducers, and with and without illusory figure conditions. Error bars indicate ± 1 standard errors of the means.

tions were lower than those for outside conditions, and thresholds for the stimulus with illusory contour were lower than those for the stimulus without illusory contour. Thresholds for the stimulus without illusory contour shifted upward in parallel from those for the one with illusory contour.

Statistical analysis using ANOVA revealed significant difference between two stimulus locations (Inside vs Outside) ($F=21.31$, $df(1,10)$, $p<0.01$), but failed to find significant difference between the stimuli with/without illusory contour ($F=4.05$, $df(1,10)$, $p=0.072$). The interaction of the two factors was also not significant ($F<1.0$).

Discussion

We found a facilitatory effect on detecting the light spot by the presence of the illusory figure. The result is not consistent with the predictions by the long-range interaction model. According to the model, interactive connections between cortical cells (say, A and B) influence the responses of cells (C) that have receptive fields in between A and B. Those cells are supposed to have the same preference for orientation (i. e. all are tuned for vertical orientation), and the receptive fields are spatially aligned co-linearly. The light spot we used in our experiments was presented off-the-border of the illusory figure, and detection cannot be mediated by the co-linear long-range connections of cells.

Our results may be consistent with the predictions made using the subthreshold summation model. When the inducers are darker than the background, the illusory figure is enhanced by the brightness of the surface, which functions to equate the physical increment of luminance. The physical increment of luminance serves as a pedestal for the target (a light spot), elevating the luminance level of the target. Thus, the resulting luminance would produce greater contrast (e. g. for Michelson definition, difference between the target luminance and the minimum luminance in a given area divided by the sum of the target luminance and the minimum luminance), leading to a higher probability of detecting the target.

We should note that there are some issues in regard to the above interpretation. First, the pedestal contrast must be very low to produce the subthreshold summation, and if the pedestal contrast is high, the detection threshold of a target is higher than in the condition for no illusory figure due to contrast masking (Legge & Foley, 1980 ; Akutsu & Legge, 1995). The degree of the pedestal contrast produced by brightness enhancement in our stimulus is unknown. Second, the mechanisms mediating contrast detection in the subthreshold summation model is assumed to be spatial-frequency tuned (i. e. spatial frequency channels in early visual processing, Campbell & Robson 1968; Graham & Nachmias1971). Accordingly, without knowing the power spectra of the stimulus figure, it is difficult to evaluate quantitative plausibility of the model. Third, we did not find significant difference in detection thresholds between the conditions with and without illusory figures. Although the difference was not statistically significant ($p=0.072$), we can observe the trend of difference when both Inside and Outside conditions are compared. This difference may be related to the presence and absence of enhancement in apparent brightness with illusory figure.

In terms of the retinal eccentricity, one could expect lower threshold for the Outside condition, because stimulus locations in our experiments fell in the range that light sensitivity gradually increases as a function of the retinal eccentricity (between $3 \sim 10$ degrees). To the contrary, we found higher detection threshold for the light spot in Outside condition which was located farther from the fovea than that in Inside condition. Thus, a certain property in our stimulus figure produced lower threshold for the stimulus in Inside condition in both those with and without subjective contour.

It is tempting to infer that an apparent surface area produced by the illusory contour drew the visual attention to the area and enhanced sensitivity for the light spot. Visual attention can be thought as a type of beam light that enhances performance of a visual task without any changes of physical properties with the stimulus (a beam light metaphor, Hernandez-Peon, 1966). The four sector patterns might draw the visual attention in the surrounded area to a lesser degree, even if they do not produce the illusory contour, resulting in a higher rate of detecting the light spot in the Inside condition than in the Outside condition. However, this speculation needs further elaboration in both the definition and mechanisms of attention, before applying this to our results.

It is fair to mention that our data is limited in three respects : (1) we used a subjective method in estimating detection threshold ; (2) we only used two locations for the light spot; (3) detection performances were not compared with those for a blank stimulus with a uniform background. Though limited as such, our data provides useful information to understand the nature of illusory figures.

In conclusion, our study found that an illusory contour enhanced detection of a light spot placed in the area, and provided further support to the subthreshold summation model for the enhancing effect.

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