Illusory gray spots and diagonal lines on the Hermann grid

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The present study examines the causal relationship between the illusory gray spots in the so-called Hermann grid figure and the illusory lines connecting the spots diagonally. Eight university students participated as subjects in two experiments. In Experiment 1, the vividness of illusory lines and the darkness of gray spots were rated together. The stimulus variables were three folds; the number of the grid lines, the thickness of the grid lines and the size of every grid cells. The results showed the independence of the two ratings. The hypothesis of inter-inducing effect between the dots and the diagonal lines was concluded untenable. In Experiment 2, factors influencing the vividness of the diagonal lines were examined. The width-height ratio of the grid cells was found stronger in effect than the size. A mechanism sensitive to the stimulus configuration was suggested taking part in the diagonal illusion.

Key words: Hermann grid, illusion, visual system, orientation, size, Fourier analysis.

The Hermann grid illusion (Hermann, 1870) appears in many textbooks on visual perceptions as an example of simultaneous brightness contrast: the simultaneous contrast between grid lines and the background induces the gray spots at the intersections of the grid lines. The leading explanation of this contrast effect is based on well-known properties of visual cells (particularly retinal ganglion cells) having concentric on-center or off-center receptive fields (Jung, 1973; Wolfe, 1984).

Recently, additional illusory lines appearing on the same grid lines have been studied (Schacher, 1976). These illusory lines appear to connect the intersections of grid lines diagonally. When grid lines are white and the background is black, these illusory lines appear darker than the background, and vice versa. This phenomenon has been called the "pin-cushion illusion" after the pin-cushion-like appearance of the inducing pattern (Schacher, 1976), and it has been cited as evidence that the human visual system performs Fourier analysis (De Valois & De Valois, 1980). The Fourier analysis theory on the visual system has however too many problems (Pinker, 1985) to be considered plausible. It is necessary therefore to re-examine the possible mechanism under which illusory lines appear on the Hermann grid.

The purpose of the present study is to examine the possibility that the illusory gray spots produced by the Hermann grid should, in turn, induce the illusory lines connecting the intersections of grid lines. There seemed to be several reasons for examining this possibility. Firstly, gray spots have a relation with the background similar to that of illusory lines. That is, when white grid lines are presented on a black background, gray spots, with illusory lines darker than the background, appear darker than the grids. On the other hand, when black grids are presented on a white background, gray spots, with illusory lines brighter than the background, are brighter than the grids. Therefore, it can be assumed that the apparent gray spots activate a higher process (e.g. interpolation mechanism) and result in the illusory lines

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connecting diagonally the gray spots. Secondly, a similar phenomenon such as diagonal illusory lines in Ehrenstein's figures was explained by the above-mentioned interpolation mechanism (Jung, 1973). Ehrenstein's four black radial lines cause brightness enhancement at the white central gap to which the radial lines are converging, while white radial lines cause darkness enhancement at the black central gap. Then, many Ehrenstein's cross figures are arranged in many rows and columns as if the vertical and horizontal lines are placed in order to be co-linear. Diagonal illusory lines connecting the illusory spots can then be observed. In this respect, Jung (1973) suggested that this diagonal illusion was induced by the enhanced spots.

With these points in mind and examining the validity of the gray spot induction theory, it is necessary to investigate the causal relationship between the illusory gray spots and the illusory lines.

Experiment 1

Method

Apparatus. Stimulus patterns were generated by a micro computer (NEC 9801-m), and displayed on a high-resolution CRT (PC-8853n). The screen was placed at a distance of 72 cm from the eyes of the subject sitting in a chair with a chin-rest in a dark room.

Stimuli and procedure. White grid lines on a black background were used. The same set of 60 stimulus patterns was presented, each five times, both in the “gray spot” session and in the “diagonal line” session. One of the stimulus patterns is shown in Fig. 1. The 60 patterns resulted from the independent variation of the following three factors:

1. The number of grid lines: 4, 6, 8, 10 and 12, both in rows and in columns.
2. The width of grid lines: 3, 6, 9 and 15 min in visual angle.
3. The width of patches surrounded by the grid lines: 28.8, 43.2 and 57.6 min in visual angle. The height of the patches was kept constant at 28.8 min.

Fig. 1. An example of the stimulus patterns. The readers may find illusory lines appearing to connect intersections of grid lines.

As a result, the maximum size of the whole grid pattern was 8.2 (height) x 13.3 (width) degrees, and the minimum one was 1.6 x 1.6 degrees. The reference grid pattern consisted of nine vertical and nine horizontal lines, whose width was 9 min. Both the width and height of the patches, of which the reference pattern consisted, were 43.2 min. The luminance of grid lines was always 117 cd/m².

The subjects served in two sessions: firstly, the “diagonal line” session and secondly, the “gray spot” session. In the “diagonal line” session, subjects were asked to rate the clarity of illusory lines, compared with that of the reference grid pattern which was presented before every block of five stimulus presentations. In the “gray spot” session, the subject was asked to rate the darkness of gray spots at the intersections of grid lines, compared also with that of the reference. In order to rate the darkness of gray spots and the clarity of illusory lines, the subjects were first taught a rating scale. They were told that a rating of “1” indicated no illusory lines or no illusory gray spots, and that
both the clarity of illusory lines and the darkness of illusory gray spots appearing in the reference pattern corresponded to a rating of “5”. Any value greater than 5 was allowed if the clarity or the darkness of illusory regions exceeded that of the reference. The subjects were also allowed to use decimal numbers in the rating. Thus, this rating method can be regarded as a variation of the magnitude estimation method. It was not difficult for the subject to rate these characteristics in this way after 15 practice trials in both sessions. No fixation point was placed, and the subjects were allowed to see the stimulus pattern freely.

Subjects. Eight students (three graduates and live undergraduates) of the University of Tokyo participated in this experiment. All subjects had normal or corrected to normal visual acuity.

Results

Figures 2-a, b, c and d show the results obtained using grid line widths of 3, 6, 9 and 15 min in the “diagonal line” session, respectively, as a function of the number of grid lines for three conditions of the patch width.2 Filled circles indicate the results under the condition of the patch width of 28.8 min, open circle, 43.2 min, and filled squares, 57.6 min. Similarly, Figs. 3-a, b, c and d show the results in the “gray spot” session.

As shown in these figures, both the mean clarity rating of illusory lines and the mean darkness rating of gray spots were increased with the number of grid lines. The effect of the width of grid lines is quite different between the clarity rating and the darkness rating. For example, the former is the smallest for the widest line width, while the latter is the smallest for the narrowest line width. The clarity rating decreases as the patch width increases, while the darkness rating is hardly affected by the patch width.

A standard ANOVA was applied to the present data. This is not only because the rating scale used in the present experiments was assumed to be approximate, at least, to the interval scale, but also because it is now believed that an ANOVA is relatively robust to non-normality (Kendall, Stuart, & Ord, 1983) even when the present data deviate from the exact normality. Thus, a three-way repeated measures analysis of variance was performed on the mean ratings on each attribute: (number of grid lines, NL) x (width of grid lines, WL) x (width of patches, WP). On the mean clarity ratings of illusory diagonal lines, all of these three main factors had significant effects ($F(4, 420)=234.9$, $p<.01$, $F(3, 420)=23.9$, $p<.01$ and $F(2,$

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2 In this experiment, afterimages of the stimulus patterns, which may affect the subject's rating, were not reported.
Illusory diagonal lines on the Hermann grid

Fig. 3. Mean ratings of the darkness of the illusory gray spots as a function of the number of grid lines. Filled circles indicate the results under the condition of the patch width of 28.8 min, open circle, 43.2 min, and filled squares, 57.6 min. The width of the grid lines was 3 (a), 6 (b), 9 (c) or 15 (d) min in visual angle.

420)=97.2, p<.01, respectively). In addition, the interactions (NL×WP, and WL×WP) were statistically significant (F (8, 420)=6.9, p<.01 and F(6, 420)=7.7, p<.01, respectively), indicating that the effect of the patch width on the clarity of illusory lines declined both with decreasing number of lines and with increasing width of lines as shown in Fig. 2.

On the mean darkness ratings of illusory gray spots, both the number of grid lines (NL) and the width of grid lines (WL) had significant effects (F(4, 420)=73.0, p<.01 and F(3, 420)=144.5, p<.01, respectively), while the width of patches (WP) had no significant effect. The interaction (NL×WL) was significant (F (12, 420)=4.1, p<.01), indicating that the effect of number of grid lines diminished when the width of grid lines was 3 min, as shown in Fig. 3-a. Actually, almost no gray spots were observed under this condition, whereas clear illusory lines were observed under the same condition (Fig. 2-a).

Discussion

In this experiment, we examined possibility that the illusory gray spots, produced by the Hermann grid, induce the illusory diagonal lines on the same grid, using the three variables, number of lines (NL), width of lines (WL) and width of patches (WP).

The first variable, the number of grid lines (or the number of intersections), was used in order to examine the global effect. Wolfe (1984) suggested that a purely local model for the Hermann grid illusion (gray spots) was not a complete explanation, and that global factors must be involved. This suggestion was based on his finding that the darkness of gray spots was affected by the number of grid lines. The same is true for the closely related Ehrenstein illusion mentioned before (Spillmann, 1977).

In the experiment reported here, the clarity of illusory diagonal lines was also much affected by the number of grid lines. As a result, both phenomena, the illusory gray spots and diagonal lines, appeared to have a close relation with the number of grid lines. It is possible that eye movements take part in these global effects, since free eye movements were allowed in this experiment. In this respect, however, Spillmann (1971) found that a brief exposure of the Ehrenstein's figures could not deteriorate the global effect, suggesting the eye movement could not serve in this global effect.

The second variable, the width of grid lines, was used to examine its effect on the clarity of the illusory diagonal line, in consideration of its widely known effect on the illusory gray spots (Jung & Spillmann, 1970). Our visual system has certain sized receptive (or perceptive) fields whose concentric on-center or off-center structure
could result in gray spots on the Hermann grid with an appropriate line width. Thus, the width of grid lines should nearly match the size of corresponding receptive (or perceptive) fields so that the gray spots could be induced by the Hermann grid.

The effect of line width on the clarity of illusory lines was definitely obtained, but it was not the same as the effect of line width on the darkness of gray spots. It should also be noted that the gray spots appeared less vivid if the grid lines were too narrow in this experiment, but that was not the case with illusory diagonal lines. On the contrary, under the condition of the narrowest line width (the line width of 3 min), clear illusory lines could be observed. Thus, large differences between the results shown in Fig. 2-a and those in Fig. 3-a suggest that there is almost no positive relation between the clarity of illusory lines and the darkness of gray spots. As a result of this, there is neither a direct nor an indirect causal relation between the illusory gray spots to the illusory diagonal lines. The former part of this conclusion was confirmed by the results of the causal inference by means of partial correlation, which was developed by Simon (1954) and Blalock (1962). This method of inferring causal relationships has been successfully applied to perceptual studies by Oyama (1974, 1977). This was applied to the results of the present experiment and showed a high degree of simple correlation ($r_{CD}=0.47$) but almost no partial correlation ($r_{CD,N}=-0.05$) between the clarity (C) of illusory lines and the darkness (D) of gray spots, when the effect of the number (N) of grid lines was ruled out. This result indicated that there was no direct causal relation between the clarity and the darkness. It also suggested that both the clarity of illusory lines and the darkness of gray spots were affected independently by a common cause. This is the global factor of the increased number of grid lines.

About the effect of the line width on the clarity of illusory diagonal lines, some subjects reported that the illusory lines appeared wider with wider grid lines. Thus, the decrement of the clarity of illusory lines under the condition of wider grid lines (see Fig. 2-d) might be related to the decrement of sharpness of illusory lines, not to the decrement of their amplitude of brightness variation.

Thus, we can conclude that the gray spot induction theory should be thrown out. Here, the results of Experiment 1 should be examined to elucidate the other possible mechanism inducing the observed illusory diagonal lines.

As shown in Fig. 2-a, the clarity of illusory lines decreased with the increasing width of the patches surrounded by the grid lines. The third variable, the width of patches, was used to examine the configuration effect of the grid on the clarity of the illusory diagonal lines. Both the main effect and the interaction (the width of patches×the width of grid lines) were statistically significant. This interaction may reflect the difference between the shape of the patches and that of the intersected part of grid lines which was always square under any condition in this experiment. However, this possibility could be discarded because the decrement of the clarity of illusory lines was much marked even under the condition of square patches, where no shape difference existed, when the grid lines were widest, as shown in Fig. 2-d.

It should be borne in mind that the parameters, which were varied with the changing width of patches in this experiment, included not only the ratio of width to height of the patches, but also the diagonal distance between the opposite corners of the patches. It should be examined therefore whether the ratio or the diagonal distance determines the clarity of the illusory lines. Experiment 2 was conducted for this purpose.
Experiment 2

Method

The same apparatus was used and the same subjects participated in this experiment as in Experiment 1.

Stimuli and procedure. A set of five stimulus patterns was presented, each five times. The five patterns were variations of the pattern in Experiment 1. The number of grid lines was 10, both in rows and in columns, and the width of grid lines was 3 min in all patterns. The width and the height of a patch surrounded by grid lines were varied as shown in Fig. 4. In Fig. 4, patterns (a) to (e) show patches of which stimulus grid patterns consisted. Patterns in the same row in Fig. 4 have the same diagonal distance between opposite corners of a patch, and patterns in the same column have the same width-height ratio of a patch. Therefore, patterns (a), (b) and (c) have the same distance between opposite corners, but the width-height ratio is varied as 1, 1.5 and 2. On the other hand, (d) and (e) are squares with the same width-height ratio, but the diagonal distance between opposite corners is varied as $\sqrt{2} \times n$, $\sqrt{3.25} \times n$ and $\sqrt{5} \times n$, ($n$ means the width of patches of pattern (a), 28.8 min). Diagonal components in Fig. 4 are patches used in Experiment 1. A patch centered in Fig. 4 has the width-height ratio of 1.5 and the distance between opposite corners is $\sqrt{3.25} \times n$. Thus, the effects of this pattern used in Experiment 1 can be divided into two components, one of which is represented by the effect of the pattern (b) and another of which, by the effect of the pattern (d). The same relations will be held when the right bottom pattern in Fig. 4 is compared with the effect of pattern (c) and (e).

The rating method was the same as in Experiment 1, but only the clarity of diagonal illusory lines was rated, referring to the reference pattern of which the rating was "5". The reference pattern was shown to the subject before every block of five stimulus patterns.

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**Fig. 4.** Various patches of which stimulus grid patterns consisted. Patches (a) to (e) were used in Experiment 2.
Results and Discussion

Mean ratings of the clarity of illusory lines for each stimulus pattern are shown in Table 1. It is of importance to compare the results of (b) with those of (d), and the results of (c) with those of (e). This is because these comparisons could make clear which factor of the width-height ratio and the diagonal distance between opposite corners was the main determiner of the clarity decrement of illusory lines observed in Experiment 1. A t-test showed a significantly greater effect of the width-height ratio than the inter-corner distance on the clarity of illusory lines only in the results of (c) and (e) ($t = 2.56, df = 14, p < .05$). In short, the clarity decrement of illusory lines with the increasing patch width in Experiment 1 would be closely related to the width-height ratio rather than the diagonal distance.

Consequently, these results suggest that the mechanism inducing the illusory lines is more sensitive to the configuration of the stimulus pattern than to its size. In this respect, the following subjects' reports should be noted: the illusory lines did not always lie on the diagonal of the grid, but appeared in the orientation of the bisector of an angle between the intersecting grid lines. These reports were obtained in particular when the ratio of width to height of the patch was 2:1. These reports suggest that there is some tendency for the orientation of the illusory lines toward that of the bisector of an angle between intersecting grid lines, not that of the geometrical diagonal. This tendency is assumed to reduce the clarity of the illusory lines when the patch deviates from a square, since these illusory lines with the orientation of the bisector, should be intersected by real grid lines.

General Discussion

The results of the study reported here disputed the possibility that the illusory gray spot appearing on the Hermann grid induced, in turn, the illusory lines on the same grid. This conclusion could be drawn from the results of Experiment 1 where the clear illusory lines were observed even though the gray spots can hardly be observed under the condition of the narrowest line width. It was also confirmed by the results of causal analysis that almost no partial correlation between the darkness of gray spots and the clarity of illusory lines could be obtained, when the effect of the number of grid lines was eliminated.

In this connection, it is possible that the same mechanism which caused the gray spots on the Hermann grid might also induce the illusory lines, though there is no causal relation between the gray spots and the illusory lines. It is well known that the contrast effect, which is usually considered to be based on the concentric properties of receptive fields of visual cells, could also induce illusory gray narrow canals, or inner contrast, on the wider white lines, of which the Hermann grid consisted (Jung & Spillmann, 1970). This phenomenon is, apparently, the result of the brightness contrast between the white lines and the black patches and it should be noted that this inner contrast reduces the brightness of the inner part of the white grid lines. It is also true that this inner contrast reduces the darkness of the inner part of the black grid lines (direct surroundings) with white patches. On the other hand, the illusory diagonal lines in

### Table 1

The mean ratings of the clarity of illusory lines for the stimulus patterns consisting of patches (a) to (e) in Experiment 2

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<thead>
<tr>
<th>Stimulus patches</th>
<th>mean</th>
<th>SD</th>
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<tbody>
<tr>
<td>(a)</td>
<td>6.1</td>
<td>1.6</td>
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<tr>
<td>(b)</td>
<td>4.9</td>
<td>1.6</td>
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<tr>
<td>(c)</td>
<td>3.0</td>
<td>1.0</td>
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<tr>
<td>(d)</td>
<td>5.8</td>
<td>1.7</td>
</tr>
<tr>
<td>(e)</td>
<td>4.6</td>
<td>1.5</td>
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the present experiments were seen inside the black patches and appeared darker than the patches (change in the opposite direction from the inner contrast). Thus, the inner brightness contrast effect and the illusory diagonal lines shown in this experiment cannot be based on the same mechanism. Therefore, the properties of receptive fields of the first- or second-order neurons which have been thought to underlie the inner brightness contrast effect can have no direct relation to these illusory lines.

The results of Experiment 2 suggest that a mechanism sensitive to the configuration of the pattern has a share in inducing these illusory lines. This mechanism is assumed to determine the orientation of the illusory lines. However, we cannot dispute the validity of the Fourier analysis theory of the illusory diagonal lines on the Hermann grid, because Fourier analysis is also sensitive to the orientation of the pattern.

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