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Photopic visual phantom illusion: Its common and unique characteristics as a completion effect

Akiyoshi Kitaoka
Department of Behavioral Physiology, Tokyo Metropolitan Institute for Neuroscience, Musashidai, Fuchu, Tokyo 183-8526, Japan; e-mail: akitaoka@tmin.ac.jp
Jiro Gyoba
Department of Psychology, Faculty of Literature, Tohoku University, Aoba-ku, Sendai 980-8576, Japan
Hideaki Kawabata
Department of Psychology, Faculty of Literature, Kyushu University, Higashi-ku, Fukuoka 812-8581, Japan
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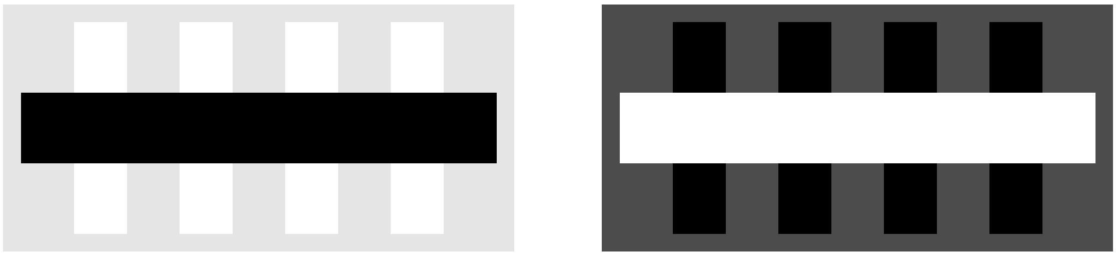
Abstract. An illusion similar to the stationary visual phantom illusion presented earlier by Gyoba (1983, *Vision Research* **23** 205 – 211) is reported. This illusion is visible in photopic vision and we have tentatively named it the 'photopic phantom illusion'. A typical example of this illusion is a white and light-gray square-wave grating occluded by a black region. In this figure, a phantom grating running across the occluder with clear contours but less contrast, is seen. The critical spatial frequencies of photopic phantoms have been measured and compared with those of scotopic phantoms that have been reported previously, revealing a great resemblance between them. We discuss the characteristics of this illusion in terms of transparency, stereoscopic viewing, and perceptual completion.

1 Introduction

The visual phantom illusion is one of a class of perceptual completion phenomena; it bridges the region that occludes a grating pattern. An essential feature of this illusion is that phantoms appear to be continuous with the surrounding grating. This illusion was first discovered by Rosenbach (1902) and later developed by Tynan and Sekuler (1975) who called it 'moving visual phantoms' because of its strong dependence on motion. It was later found that motion is not indispensable; phantoms can be generated by flickering the grating (Genter and Weisstein 1981) or by low-luminance stationary gratings under dark adaptation (Gyoba 1983). The latter illusion is called 'stationary phantoms' since it does not require motion or flicker. We here report an illusion which greatly resembles the stationary phantom illusion but can be seen with relatively high-luminance gratings.

Figure 1 shows two examples. One is a white and light-gray square-wave grating occluded by a black region (figure 1a), the other is a black and dark-gray square-wave grating occluded by a white region (figure 1b). Both examples show a phantom grating running across the occluder with clear contours, but less contrast. Since we can see phantoms without dark adaptation, we have tentatively named this illusion the 'photopic stationary phantom illusion' or simply 'photopic phantoms'. In contrast, we call Gyoba's (1983) version the 'scotopic stationary phantom illusion' since it occurs with low-luminance gratings under dark adaptation. The unique feature of this photopic version is that the contrast of the inducing grating is small and its average luminance is distant from the luminance of the occluder.

In this study, we examine whether the photopic stationary phantom illusion has the same characteristics as the scotopic one with respect to spatial frequency, since spatial frequency of the inducing grating is an important determinant of the scotopic stationary phantom illusion (Gyoba 1983) as well as of the moving phantom illusion (Tynan and Sekuler 1975). In addition, we discuss the characteristics of photopic phantoms from various viewpoints including transparency, stereoscopic viewing, and perceptual completion.



(a) (b)

Figure 1. A demonstration of the photopic stationary phantom illusion. (a) A white and light-gray square-wave grating occluded by a black region. We can see phantoms running across the occluder, in which the contrast polarity of phantoms is the same as that of the surrounding grating. The illusory contours are sharp, though the contrast of the phantom grating is much lower than that of the inducing grating. (b) A black and dark-gray square-wave grating occluded by a white region. The visibility of phantoms in panel (b) seems to be lower than in panel (a) (table 1), though this difference did not reach the 5%-significance level ($t_9 = 1.90$).

2 Visibility of photopic phantoms

Before testing spatial-frequency characteristics, we conducted a preliminary psychophysical experiment to rate the visibility of phantoms, which was defined as follows. Score 0: no phantoms were visible; score 1: phantoms were faintly visible; score 2: phantoms were visible; score 3: phantoms were clearly visible. The phantom figures shown in this paper were all examined. Each figure was drawn in the centre of a white card (29 cm high × 21 cm wide). The occluder (vertical) width was 1.20 deg of visual angle for figures 1, 3, 5a, 6, 7a – 7d, and 1.92 deg for figure 7g. The occluder (horizontal) length was 8.40 deg for figures 1, 3, and 6; 2.70 deg for figure 5a; 3.60 deg for figures 7a – 7d; and 6.72 deg for figure 7g. The size of the occluding squares in figures 7e and 7f was 2.40 deg × 2.40 deg. The size of the surrounding squares in figures 7h and 7i was 4.80 deg × 4.80 deg. One periodicity of a grating was 1.80 deg for figures 1, 3, and 6. The (horizontal) width of a white bar in figure 5a was 0.90 deg. The crossed or uncrossed disparity given to the white bar in figure 5a was 0.24 deg. The horizontal width of a white bar that rotates through 45° from the vertical was 1.20 deg for figures 7a and 7c, and 0.96 deg for figure 7g. The oblique edges in figure 7b tilt through about 18° from the vertical; the base of the (upper) white triangle was 0.80 deg and the top side of the (lower) white trapezium was 1.60 deg. The horizontal widths of the upper bar and the lower one in figure 7d were 0.72 deg and 1.68 deg, respectively. The width of white lines in figure 7e was 0.48 deg. The height and the base of white triangles in figure 7f were 0.72 deg and 0.48 deg, respectively. The width of gray and white bars in figure 7h was 0.48 deg; the size of a white cross was 2.40 deg × 2.40 deg. The radius of the circles in figure 7i was 0.72 deg; the gap between close circles was 0.96 deg. The luminances of the stimulus in figure 1 were 0.96 cd m^{-2} for black, 32.93 cd m^{-2} for white, 2.45 cd m^{-2} for dark gray, and 29.60 cd m^{-2} for light gray. The luminances of the occluder in figures 3a and 3c were 32.50 and 21.50 cd m^{-2}, respectively. The luminance of the gray inducer in figures 3b and 3c was 8.50 cd m^{-2}. The luminances of the stimulus in figure 6 were 30.10 cd m^{-2} for yellow and 23.89 cd m^{-2} for gray. Ten naïve undergraduates participated.

Table 1 shows the results. For example, the visibility scores of figures 1a and 1b were 1.80 (mean) ± 0.40 (SD) and 1.40 ± 0.49, respectively. This means that photopic phantoms were visible but not so clear for some observers, since score 1 indicated that phantoms were faintly visible and score 2 that they were visible. As described later, the visibility of photopic phantoms varied when depth, colour, and figural information were provided. For example, phantoms stereoscopically seen in front of the occluder (figure 5a) were significantly more visible than standard phantoms (figure 1a) ($t_9 = 4.44$, $p < 0.01$),

Table 1. Mean visibility score and SD for individual figures ($n = 10$).

Figure	Mean	SD	Figure	Mean	SD
1a	1.80	0.40	7a	1.30	0.64
1b	1.40	0.49	7b	1.90	0.54
3a[a]	0.60	0.49	7c	0.80	0.75
3b	1.30	1.00	7d	1.00	0.77
3c[a]	2.70	0.46	7e	1.00	0.77
5a[b]	2.70	0.46	7f	1.50	0.92
5a[c]	2.00	0.63	7g	1.00	0.45
6	1.50	0.81	7h	0.40	0.49
			7i	1.80	0.87

[a] The visibility of McCourt's brightness induction was scored. [b] When phantoms were seen in front of the occluder. [c] When phantoms were seen behind the occluder.

whereas the 'phantom disc' (figure 7h) was significantly less visible than the standard phantoms ($t_9 = 6.64$, $p < 0.01$).

3 Measurement of critical spatial frequency

We examined the spatial-frequency characteristics of photopic phantoms and compared them with those of scotopic phantoms.

3.1 *Subjects*

The third author (HK) and five undergraduates who were naïve to the purpose of this experiment participated. They all had normal or corrected-to-normal vision.

3.2 *Apparatus and stimuli*

The stimuli were generated by a computer (Sharp X68000) and displayed on a 15-inch RGB monitor (Sharp CZ603D) which had a 512×512 pixels spatial resolution and a 55.5 Hz noninterlaced raster. A square-wave grating and a sine-wave vertical grating were used as inducers; the whole display was 7.25 deg wide and 5.25 deg high. Each of the gratings was horizontally occluded by a black rectangle; the (vertical) width of the occluder was 0.42, 0.86, 1.30, 1.74, 2.18, 2.62, 3.06, and 3.50 deg. The luminance was 3.2 cd m^{-2} for the occluder, 16.0 cd m^{-2} for the darkest region of gratings, and 80.0 cd m^{-2} for the lightest region of gratings. This means that the luminances of the sine-wave grating changed between 16.0 and 80.0 cd m^{-2} and the luminances of the square-wave grating were 16.0 cd m^{-2} for gray and 80.0 cd m^{-2} for white. The sine-wave grating was generated in virtual 512 black-to-white intensity levels, in which the luminance of one picture element was represented by averaging those of 4×4 pixels (1 pixel had 5 bits or 32 luminance steps), together with a function which linearised the intensity levels. The illumination on the desk supporting the monitor was 180 lx.

3.3 *Procedure*

The procedure was much the same as that of Gyoba (1983). Subjects were individually tested by the method of limits. When they pressed the start key and a grating with a low spatial frequency (the frequency was varied within a small range) was presented for 5 s, they were asked whether phantoms were visible. If the response was "yes", the spatial frequency of the grating was increased by a step of 8% in the next trial. This procedure was repeated until they said phantoms were no longer visible. The ascending limits measured in this way were called 'critical spatial frequencies' (Gyoba 1983). It should be noted that this ascending method of limits might overestimate the critical values. There were eight conditions with respect to occluder widths (see apparatus and stimuli); each of the conditions was presented seven times randomly. A two-way ANOVA (occluder width $\times$ type of waveform) was conducted on log values.

3.4 *Results*

Figure 2 shows the mean critical spatial frequency for six subjects; each subject showed a similar function, which in turn was quite similar to that obtained in the scotopic stationary phantom illusion (Gyoba 1983, figure 3). First, the critical spatial frequency decreased when the occluder width increased ($F_{7,35} = 63.63, p < 0.01$). Second, functions for the sine-wave and square-wave gratings overlapped with each other where the critical spatial frequency was above 2 cycles deg^{-1}. Third, extrapolation of the functions showed that the critical spatial frequency would not exceed 5 or 6 cycles deg^{-1}. These results demonstrate that the photopic phantom illusion belongs to the class of visual phantom illusions.

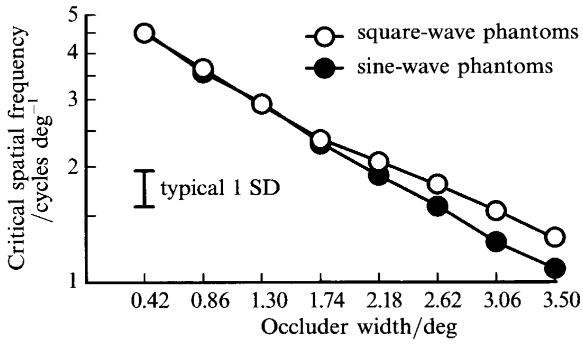
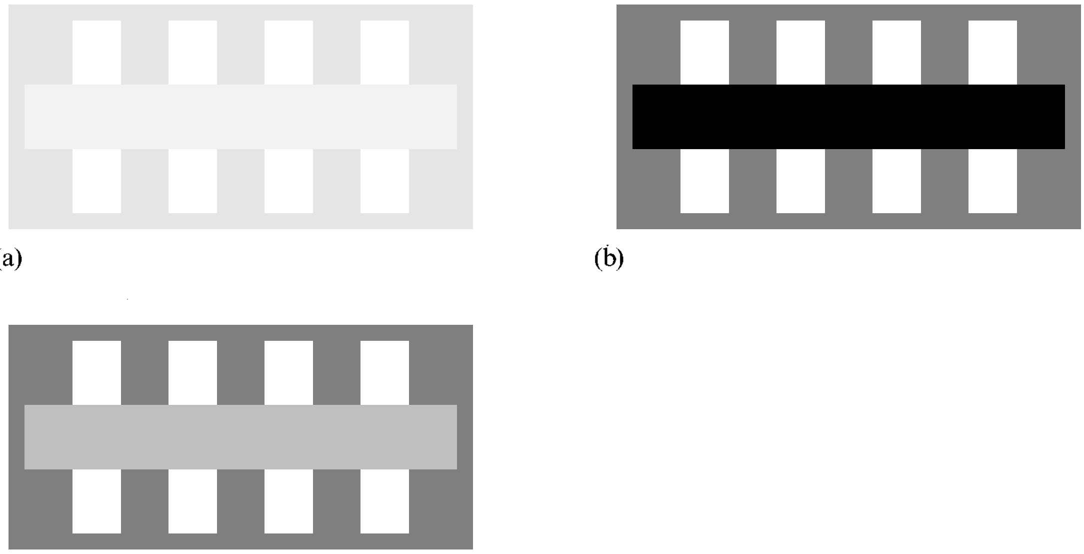


Figure 2. Critical spatial frequencies of photopic stationary phantoms as a function of occluder widths sampled with 0.44 deg intervals. Filled circles represent critical spatial frequencies of phantoms produced by a sine-wave grating and open circles indicate those of phantoms induced by a square-wave grating. Note that both functions overlap with each other when the critical spatial frequency exceeds 2 cycles deg^{-1} or where the occluder width is less than 2 deg. Mean for six subjects.

However, there was one marked difference. Figure 2 shows that the square-wave phantoms gave a *higher* critical spatial frequency than the sine-wave phantoms ($F_{1,5} = 14.69$, $p < 0.05$). This difference seemed to be conspicuous when the critical spatial frequency was below 2 cycles deg^{-1} or the occluder width was larger than 2 deg, though the interaction between occluder width and type of waveform did not reach the 5% significance level ($F_{7,35} = 2.27$, $0.05 < p < 0.10$). Direct comparisons between square-wave and sine-wave phantoms in each occluder width showed 1%-significant differences at occluder widths of 2.18, 2.62, 3.06, and 3.50 deg ($t_5 = 4.36$, 6.47, 9.86, and 9.13, respectively). This result is just the reverse of that obtained for scotopic stationary phantoms, in which the critical spatial frequency of the square-wave phantoms was *lower* than that of the sine-wave phantoms when the occluder width was large (Gyoba 1983). This higher visibility of the square-wave phantoms is unique to the present study since it has been repeatedly reported that square-wave inducing gratings produce weaker phantoms than do sine-wave gratings (Tynan and Sekuler 1975; Genter and Weisstein 1981; Gyoba 1983). This issue should be confirmed in future experiments, in which both photopic and scotopic phantoms are tested with the same subjects, with not only ascending limits but also descending ones measured.

4 Critical factors

What is the critical factor that determines the photopic phantom illusion? There are two possible factors. One is the small contrast of the inducing grating; the other is the large contrast between the average luminance of the inducing grating and the luminance of the occluder. The latter factor is fairly important, since the phantom visibility decreases and the counterphase brightness induction reported by McCourt (1982) is observed when the luminance of the occluder is close to the average luminance of the inducing grating (Sakurai and Gyoba 1985). If we change the luminance of the occluder in figure 1a to the average luminance of the inducing grating, photopic phantoms disappear and McCourt's brightness induction might appear (figure 3a and table 1). If we change the light-gray of the inducing grating in figure 1a to dark-gray, phantoms remain (figure 3b). However, if we change the occluder luminance in figure 3b to the average luminance of the inducing grating, McCourt's brightness induction appears (figure 3c).



(a) (b) (c)

Figure 3. Relationship to brightness induction. (a) If we change the luminance of the occluder in figure 1a to the average luminance of the inducing grating, photopic phantoms disappear. (b) If we change the light-gray of the inducing grating in figure 1a to dark-gray, phantoms remain. (c) If we change the luminance of the occluder in (b) to the average luminance of the inducing grating, McCourt's brightness induction appears in the occluder instead of phantoms.

What about the first factor? This factor does not seem to be so critical, since phantoms can also be seen when inducing gratings show greater contrast (figure 3b and table 1). However, it should be noted that the visibility of phantoms seems to decrease when the contrast of the inducing grating increases. This observation is consistent with the finding that inducing gratings of low contrast give relatively high visibility of the scotopic stationary phantoms (Sakurai and Gyoba 1985).

5 McCourt's brightness induction

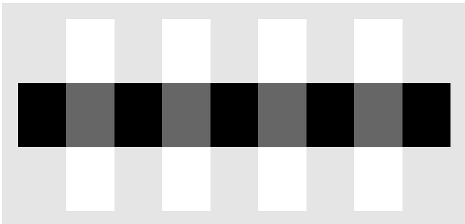
McCourt (1982) found a brightness induction illusion similar to visual phantoms in the occluder (the test field in his terminology) with brightness changes counterphase to the surrounding inducing grating. He criticised the scotopic stationary phantoms and suggested that in-phase phantoms are the misidentified products of his brightness induction (McCourt 1994). In contrast, Gyoba (1994a) claimed that the stationary phantom illusion is restricted to scotopic vision while the brightness induction effect is dominant in photopic vision. He suggested that both phenomena might have a different physiological basis.

By changing only the occluder luminance, we can demonstrate both the figure showing the photopic phantoms (figure 3b) and the one giving the brightness induction (figure 3c). Thus, the important condition for the photopic phantom illusion might be that the luminance of the occluder is higher (lower) than the highest (lowest) luminance of the inducing grating. On the other hand, the significant condition for the brightness induction might be that the luminance of the occluder is located between the highest and lowest luminances of the inducing grating. However, it should be mentioned that we do not intend to exclude the possibility that the necessary conditions for these two illusions overlap with each other to some extent.

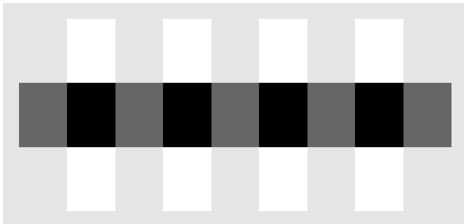
6 Transparency

Transparency is perceived when we observe visual phantoms, whether they are moving or stationary. However, phantoms appear in the occluded region that is homogeneously black or white [cf Masin's (1997) 'neutral' stimuli]. This is curious since luminance steps have been thought to be indispensable to perceptual transparency (Metelli 1974).

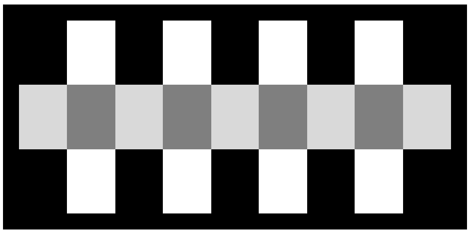
We here hypothesise that perceived lightness, not luminance, is the significant determinant of the perception of transparency. This hypothesis posits that phantoms split the occluder into two regions different in lightness and the interaction between the split occluder and the surrounding inducing grating generates perceptual transparency. For example, figure 1a just corresponds to the transparent figure made up of regions of different luminance shown in figure 4a.



(a)



(b)



(c)

Figure 4. 'Real' figures which show perceptual transparency. (a) The 'bistable' (Anderson, 1997) transparent figure which is thought to correspond to the 'phantom' figure (figure 1a). (b) A figure which follows Metelli's (1974) formula, in which a light-gray grating is seen transparent and perceived as if it were located in front of a horizontal black bar; the black bar appears to be seen through windows or apertures of white rectangles. (c) A figure invalid for perceptual transparency. For details, see the text.

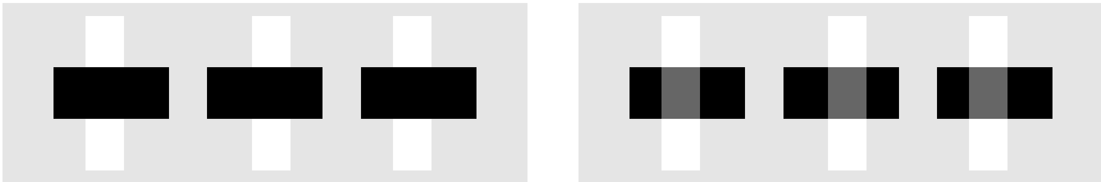
The configuration of figure 4a does not accord with the formula of Metelli's (1974) transparent figure in which one surface is always seen in front of the other (see figure 4b). Instead, it seems to belong in a class of reversible transparent figures (Oyama and Nakahara 1960), in which the perceived depth orders of two layers are reversible or ambiguous (Trueswell and Hayhoe 1993).

We support the idea that the significant factor determining these two types of perceptual transparency may be the arrangement of edge contrast polarity (Anderson 1997). Metelli's transparency occurs when the polarity of the edge contrast is constant along one series of edges and alternates along another series of edges which crosses the former series (figure 4b). On the other hand, reversible transparency including phantom transparency appears when the polarity of edge contrast is constant along every series of edges (figure 4a). If the polarity alternates along both series, the figure is 'invalid' for transparency (Sakurai and Gyoba 1985; Watanabe and Cavanagh 1993) as demonstrated in figure 4c.

According to this classification, the apparent transparency of the visual phantom illusion is of the reversible type or a 'bistable' transparency (Anderson 1997). This means that phantoms can be perceived in front of or behind the occluder.

7 Binocular depth perception

Weisstein et al (1982) and Brown and Weisstein (1991) found that phantom visibility is markedly reduced when the occluder is seen in front of the inducing grating. Figure 5a reveals that this is not the case for the photopic phantoms. When the occluder is seen in front of the inducing grating by crossfusing the right two elements of figure 5a or uncrossfusing the left two, phantoms are visible as clearly as those seen monocularly (table 1). On the other hand, the visibility of phantoms is markedly enhanced by crossfusing the left two or uncrossfusing the right two, when phantoms are seen in front of the occluder. This enhancement was large and seven out of ten observers saw vivid phantoms (table 1).



(a) (b)

Figure 5. (a) When crossfusing the right two elements or uncrossfusing the left two, we observe a white phantom bar behind the occluder, with almost the same visibility as in monocular viewing (table 1). When crossfusing the left two elements or uncrossfusing the right two, we see a white phantom bar in front of the occluder, with enhanced visibility (table 1). (b) A 'really' transparent figure which is thought to be equivalent to (a). When crossfusing the left (right) two elements or uncrossfusing the right (left) two, we observe a white bar in front of (behind) the black bar.

This means that the phantom visibility increases only when phantoms are seen in front of the occluder and that there is little or no suppression by stereoscopic depth perception. This finding agrees with the idea that figure 5a is thought to be equivalent to figure 5b which is composed of regions of different luminance and shows 'bistable' transparency. Figure 5b shows that the visibility of the vertical bar is not suppressed when it is stereoscopically seen behind the horizontal black bar which is supposed to be transparent. This is parallel to the finding of no stereoscopic suppression in photopic phantoms.

8 Colour phantoms

Moving colour phantoms have been reported by Brown (personal communication). Figure 6 demonstrates photopic colour phantoms in that the colour of gratings appears to fill in across the occluder. This colour phantom phenomenon might have some parallels with neon colour spreading (van Tuijl 1975; Redies and Spillmann 1981). However, there are various differences between them. For example, inducing stimuli are thin lines of a limited length for neon colour spreading, while for photopic phantoms inducing stimuli are low-spatial-frequency gratings whose length may not be an important factor. A study to explore their relationship is of great interest in future work.

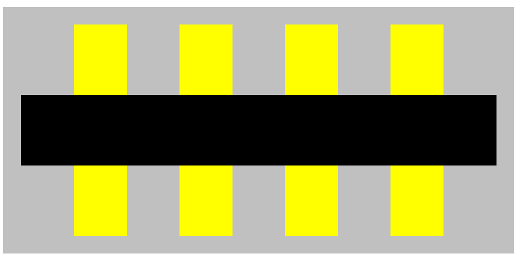


Figure 6. Chromatic phantoms can be observed if the luminance condition is identical to that required in the achromatic phantoms; here, yellow phantoms appear.

9 Perceptual completion

Figure 7 shows examples of perceptual completion produced by photopic phantoms. The shape of illusory contours can be a smooth curve as well as a straight line. Figures 7a – 7d correspond to and give the same shape as Rosenbach's (1902) figures 6, 1, 2, and 4, respectively, though his demonstrations were of moving-edge completion. Figure 7e shows that illusory contours give an appearance of a 'cross'. Figure 7f shows that a large shape can be made up by local completion, in which a star shape is produced.

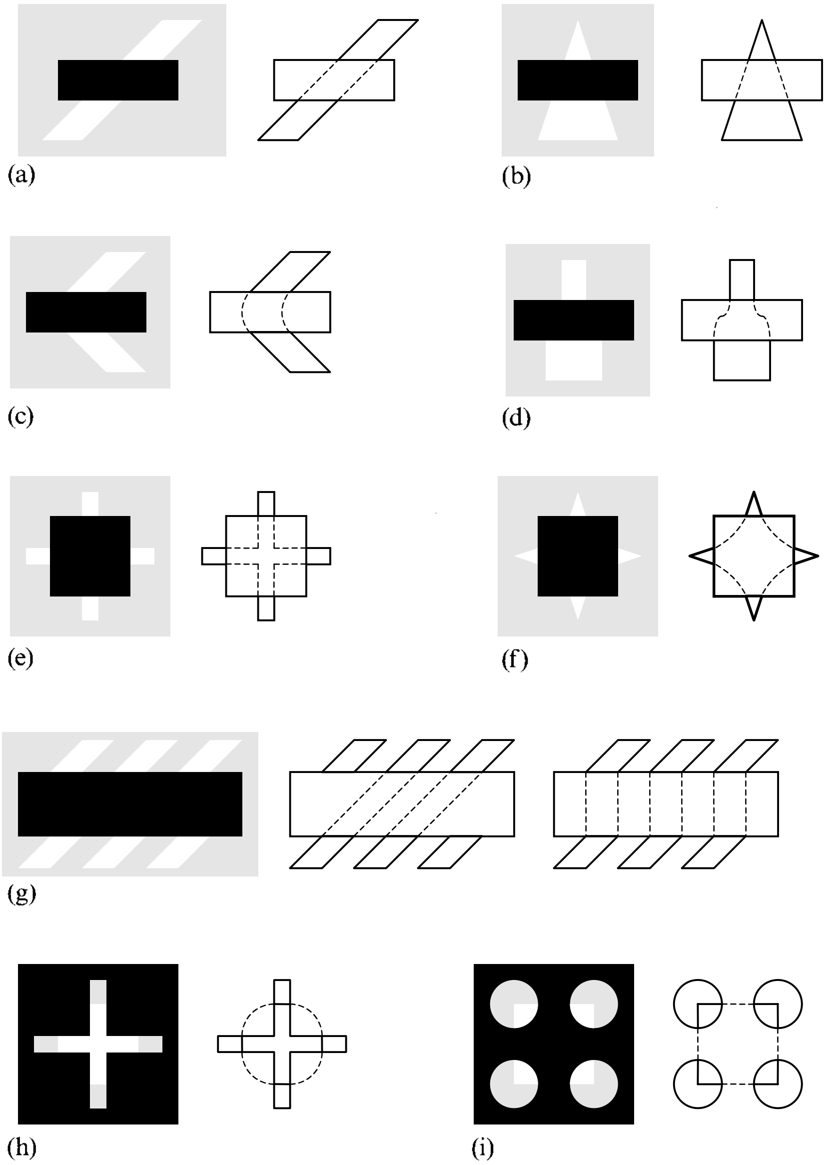


Figure 7. Examples of perceptual completion produced by the photopic phantom illusion. In each panel, the left figure shows perceptual completion and the right figure depicts the frequently perceived contours with broken lines. (a) (b) Aligned oblique edges are linearly completed. (c) Angular edges are completed with smooth curves. (d) Shifted verticals are completed with smooth curves. (e) If inducers are given two-dimensionally, illusory contours show an appearance of a 'cross'. It seems that contours never cross each other. (f) In the same two-dimensional setting as (e), angular changes of inducers generate a star-shaped phantom in which neighbouring inducers are connected to each other. (g) Phantoms are seen here either obliquely in alignment with the oblique inducing grating (aligned phantoms) or vertically without alignment (misaligned phantoms). (h) An illusory disc is seen; it is quite similar to 'neon spreading' described by Nakayama et al (1990). (i) An illusory square is seen; it is quite similar to the Varin figure (Ware 1980).

Figure 7g depicts 'aligned phantoms' and 'misaligned phantoms' named so by Gyoba (1994b) who first discovered this phenomenon in the scotopic stationary phantoms. In this figure, phantoms are seen either obliquely in alignment with the oblique inducing grating (aligned phantoms) or vertically without alignment connecting the nearest corresponding portions (misaligned phantoms). In this study, some observers reported S-shaped contours in misaligned phantoms.

Figures 7h and 7i show striking examples of a close relationship between photopic phantoms and illusory contours such as the Kanizsa triangle, though Genter and Weisstein (1981) thought that phantom contours are different from illusory contours. Figure 7h reminds us of the 'neon spreading' figure presented by Nakayama et al (1990) and figure 7i resembles Varin's figure (Ware 1980).

These phantom figures generally showed less visibility than figure 1 (table 1) and gave more variations in shape. For example, some observers did not find any phantoms in figures 7c, 7d, 7e, or 7h. Some saw a square in figure 7h instead of a disc. It seems that straight-line completion gives higher visibility than does curved-line completion. In general, there seems to exist a variety of individual differences in photopic phantom visibility and completion, in line with a previous study (Brown 1993).

10 Conclusion

In this study we report a new illusion, 'photopic phantoms', which should be attributed to a class of visual phantom illusions that have a long history since Rosenbach (1902). This illusion yields illusory contours with high visibility and can readily produce illusory shapes that have been reported in scotopic stationary phantoms as well as in moving phantoms. Furthermore, photopic phantoms show a close relationship to other types of illusory contours. These characteristics will be powerful tools to clarify the mechanisms of early visual processing.

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