Illusory motion in Enigma: A psychophysical investigation

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Experiments to determine the optimum conditions for perceiving illusory motion in Engima-like patterns have also demonstrated that the illusory motion is not the result of unintended motion of the image on the retina due to microsaccades or accommodative changes in the lens of the eye but instead has a cortical origin. The perceived illusory activity is believed to be a consequence of neural signals emanating from high-contrast bars and edges in the image that emit randomly fluctuating signals, as expected from spiking cortical neurons. These fluctuations may induce illusory motion in the channels by a mechanism similar to that responsible for the Omega effect, in which sequences of random patterns of black dots presented in an annular channel produce the perception of illusory rotation of these dots within the annulus.

cortical noise | Omega effect | visual illusion

There are many examples of static pictures that produce the illusion of movement. One of these, the Enigma, was painted by I. Leviant in 1981 (1). Viewers of that painting report seeing fluid-like forms in the painting, although the painting itself is completely static. The static image consists of radial black and white lines with three concentric circular annular channels superposed on the radial grating.

A gray-scale image based upon the Enigma is shown in Fig. 1. Most observers report seeing some fluid-like activity in the circular channels moving randomly clockwise or counterclockwise within the channels. The perceived direction of motion changes from time to time with no discernible regularity. Leviant (1) described the steps that led him to execute the Enigma and provided some simple rules that he developed to enhance the "illusion." A very similar work of his is also on display at the Exploratorium in San Francisco as the "Traffic Illusion," so-named, "because moving forms seem to follow avenues" (1).

Zeki *et al.* (2) investigated the illusion using positron emission tomography and found a strong correlation between seeing the moving forms and an increase in the activity of cortical area V5, which is thought to be involved in the perception of motion. R. L. Gregory (refs. 3 and 4) attributed the perception of moving forms to accommodative changes in the lens of the eye or to microsaccades. He based these suggestions upon his finding that no motion is seen when the radial black and white lines in the MacKay illusion (refs. 5–7) are viewed through a 2-mm circular aperture. Zeki tested these suggestions for the Enigma image by demonstrating that the moving forms could still be seen when viewed through a 2-mm pupil, or when he treated his eyes with atropine to diminish or abolish the accommodative power of his lens. He therefore suggested a cortical mechanism for perceiving the moving forms (refs. 8 and 9). C. Fermuller *et al.* (10) presented a computational explanation of the moving forms and suggested that "eye movements and/or accommodation changes cause weak retinal motion signals, which are interpreted by higher-level processes in a way that gives rise to these illusions." (10). Fermuller *et al.* (10) viewed movements of the eyes as "triggers" to provide actual motion stimuli to higher-level processes that extract motion information interpreted as if in a 3D environment from the input available in the 2D images on the retinas. Mon-Williams and Wann (11) suggested that small rototranslational movements of the eye are responsible for the illusion.

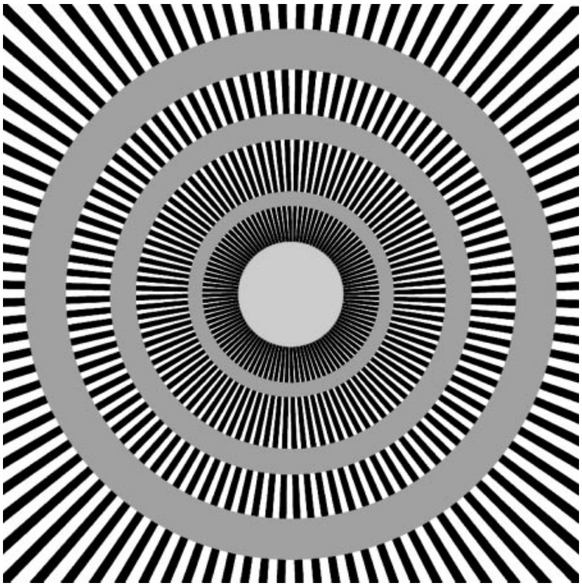

Fig. 1. A gray-scale image based on Enigma by I. Leviant (1).

Rose and Blake (12) suggest that the mechanism responsible for motion seen in the Enigma is almost certainly related to the generation of "complementary images" by the repetitive pattern of high-contrast bars. Radial lines fanning out from a point are said to generate "rosettes" and concentric circles to generate "petaloid" patterns. These repetitive patterns also induce motion at right angles to the contours and produce a prominent motion after effect (refs. 5 and 13). Rose and Blake (12) draw a distinction between these illusions and the "Omega effect," in which circular motion is seen when the "snow-like" noise produced by a detuned television set is viewed through a circular annular mask. However, the motion seen within the annulus in the Enigma is much more rapid than that seen in the Omega effect, is "shimmery and incoherent," and disappears near the fovea. When viewing radial lines, the shimmer people report is usually something like "petals," with the center coinciding with the center of the radial line pattern and "shimmer" flaring out like petals. In his original paper of 1957, MacKay (5) described rosettes or petaloids as the complementary images of radial lines, so that the display of the rosette-like figure with dark lines produces a shimmer that resembles radial lines.

Normally, the eyes are never truly stationary and exhibit some jitter all the time (14), and stationary images do not normally stimulate the perception of noticeable coherent motion. Cortical mechanisms are probably responsible for stabilizing the world in the

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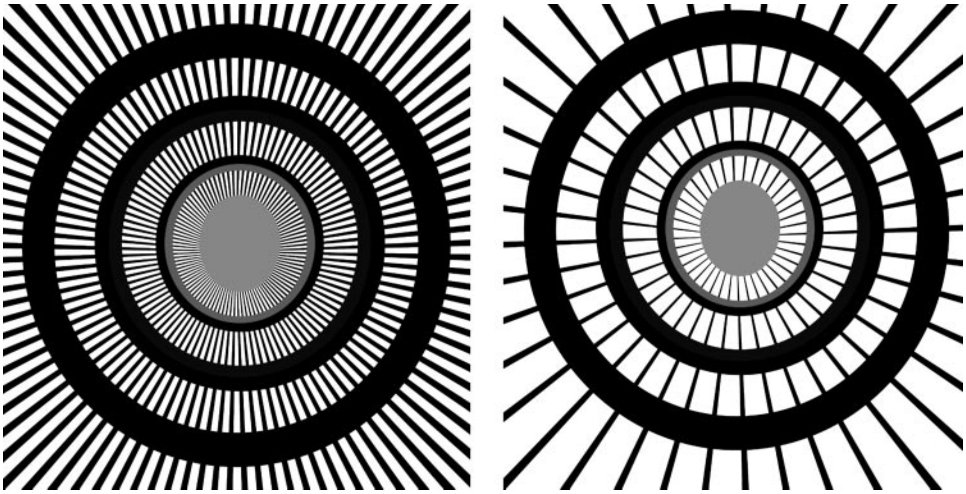

Fig. 2. Two of a set of eight images with various angular separations between black spokes: 3.6° (*Left*) and 15° (*Right*).

presence of normal eye jitter. Attributing the "shimmer" seen in the McKay illusion (5) to microsaccades or accommodative changes in the lens in the presence of the high-contrast radial lines implies that cortical mechanisms do not fully compensate for mechanical jitter when viewing high-contrast repetitive patterns. However, not all figures consisting of high-contrast lines produce a shimmer, and not all images that do produce a visual shimmer elicit the perception of illusory motion. It has been suggested that some figures produce illusory motion, whereas others do not, because normal eye movements that occur when viewing certain figures produce weak real movement signals on the retina, which are then interpreted by the cortex as real visual motion (10, 11).

Leviant (1) suggested that the numerous high-contrast edges near the circular annuli in the Enigma cause intense activity in contour-signaling neurons, which excite motion-sensitive neurons whose preferred direction is orthogonal to the local contours. This mechanism is proposed to explain why the direction of the illusory motion is perpendicular to the high-contrast grating lines used in the various figures. This suggestion discounts the effect on the retina of unintended signals produced by the jitter or accommodation of the lens of the eye and instead favors an explanation based on cortical interactions among edge-, contour-, and motion-detecting neurons.

To establish constraints on possible mechanisms for the illusion, we investigated Enigma-like images psychophysically to determine the conditions for perception of the illusion. To test whether a strong real motion signal overwhelms weak movement signals that might be generated by movement of the eyes, we displayed a rotating Enigma-like image and found that the illusory motion is seen just as for a stationary Enigma-like pattern.

To find the conditions for perception of illusory motion in Enigma-like patterns, we systematically varied the spatial frequency of the repetitive pattern, the width of the uniform channel within which illusory motion appears, the angle at which the lines in the repetitive pattern intersect the channel, and the color and contrast of the lines and channels. Observers were asked to rank the strength of the illusory motion as these parameters were changed on a five-point scale (no, weak, average, moderate, and strong activity). Our data suggest that the underlying mechanisms are cortical and are not caused by unintended motion on the retina.

We consider the illusory motion in the Enigma to be a consequence of the cortical activity stimulated by high-contrast gratings. Rose and Blake (10) point out that the motion induced at right angles to the lines in repetitive high-contrast patterns like the Enigma contains much higher temporal frequencies than seen in the Omega effect. The Omega effect demonstrates that observers can experience random noise in a "channel" as net motion within the channel. The cortical activity generated by repetitive patterns may act like noise that is similarly experienced as net motion in the Enigma illusion. Illusory motion in Enigma-like patterns is suppressed by high-contrast features located within the channels in which the illusory motion is normally seen. The difference in frequency between the Enigma and Omega illusory motions might be due to the different noise-generating mechanisms. We examine the possible connection between the illusory motion seen in the Enigma and that seen in the Omega effect and report those results separately.

Experiments and Results

Experiment 1: Effect of Separation Between the Black Spokes. The center-to-center angular separation between adjacent black spokes was varied from 1.8° to 15° of arc, and the width of the black spokes was always 1.2° of arc, which yields a good sensation of illusory motion. In Fig. 2, the image on the left corresponds to an angular separation of 3.6°, and the image on the right corresponds to an angular separation of 15° in image space. The images were viewed from a distance of 1.5 m, so that the diameter of the outermost circular annulus was 9° of arc on the retina. The average responses of eight observers are shown in Fig. 3. Illusory motion is perceived strongly when the angle of separation between neighboring spokes is approximately three times the width of the spokes and falls fairly rapidly when the separation is decreased or increased. This agrees

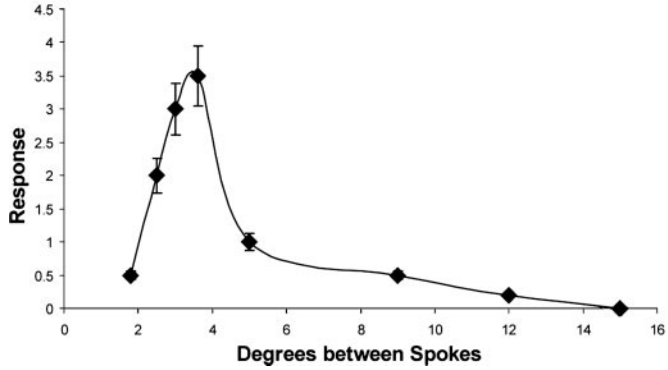

Fig. 3. Illusory motion is seen best for an angular separation of 3.6° between the black spokes (see Fig. 2 *Left*).

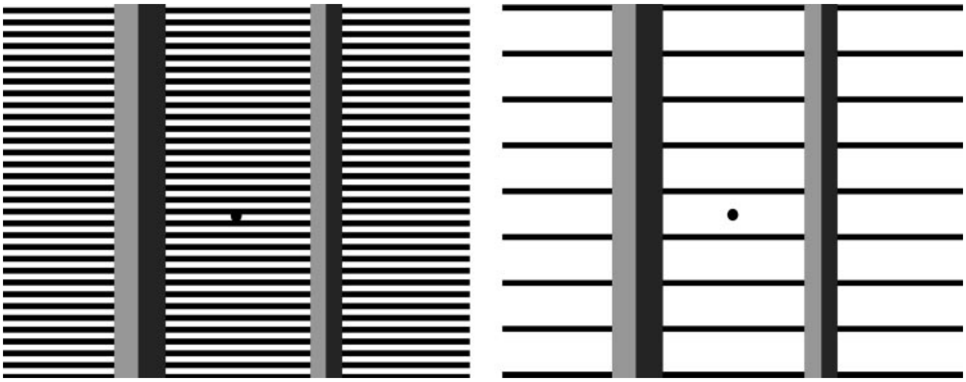

Fig. 4. Two of a set of seven images with various separations between the black bars.

with Leviant's observations (1) concerning the optimal separation of lines or spokes for achieving good illusory motion.

The strength of the illusory motion is the same for black spokes on a white background as for white spokes on a black background. The width of the spokes in the circular geometry of the Enigma is a critical parameter, and the range of the spoke widths that could be tested was limited by the number of spokes that could be fitted into a circle. Observers reported no illusory motion for spoke widths >15 min for any angular separation between the spokes. To avoid this constraint imposed by the circular geometry, the dependence of the strength of the illusion on the separation between the spokes was also measured for a rectangular geometry. The stimulus consisted of a grid of uniformly spaced horizontal black bars 6 min of visual angle thick, with various values of the vertical separation between the bars. Two of the images are shown in Fig. 4. Two vertical channels were superimposed upon the horizontal bars, and a fixation dot was placed at the center of the image. Observers were asked to judge the quality of the illusory motion they perceived in the channels. The illusory motion was the strongest for a gap of 15 arc minutes at the eye between the horizontal bars (Fig. 5). This is about the same as the separation between the spokes at the outer perimeter of the middle circular annulus in the Enigma-like images.

Experiment 2: Effect of Luminance Contrast. In this set of stimuli, the luminance of the background spaces between the spokes was varied, whereas the luminance of the "black" spokes and the innermost and outermost annuli was held constant at a "dark" level of 0.9 cd/cm^2 A set of six images was constructed in which the background luminance of the spaces between the spokes varied from 3 to 55 cd/cm^2, and the average luminance of the two parts of the middle annulus was constant at 15 cd/cm^2. Two of these images, corresponding to the 8- and 55-cd/cm^2 background luminance values, are shown in Fig. 13, which is published as supporting information on the PNAS web site. The perceived illusory motion in the middle annulus was strongest when the background luminance was the highest (Fig. 6).

Luminance contrast between the spokes and the background is essential for producing illusory motion, although illusory motion is perceived in the middle annulus even when its average luminance, 15 cd/cm^2, equals the luminance of the background.

Experiment 3: Effect of Luminance Contrast Within the Circular Annuli. In this experiment, the luminance of the two concentric circular regions of the middle annulus that had slightly different brightness in Experiment 2 was varied, so that the luminance contrast between the two regions varied from 0 (i.e., the two regions had the same luminance) to 10. This was done first when the luminance of the outer ring of the annulus was 3 cd/cm^2 and then repeated when the luminance of the inner ring of the annulus was 3 cd/cm^2. A luminance of 33 cd/cm^2 for the brighter ring yielded a luminance contrast of 10 between the two rings of the annulus. The strength of the illusory motion averaged over observers was very similar for the two conditions, and the results shown here are the averaged results for the two conditions (Fig. 7).

Thus, if there are sufficiently high contrast features in the annuli, the illusory motion is negligible. Leviant (1) reported that if he

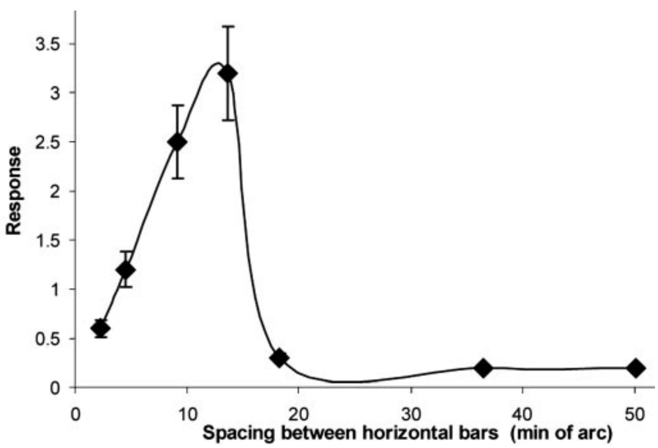

Fig. 5. Illusory motion is seen best for a separation of 15 min of arc between the black bars for a bar thickness of 6 arc min (see Fig. 4).

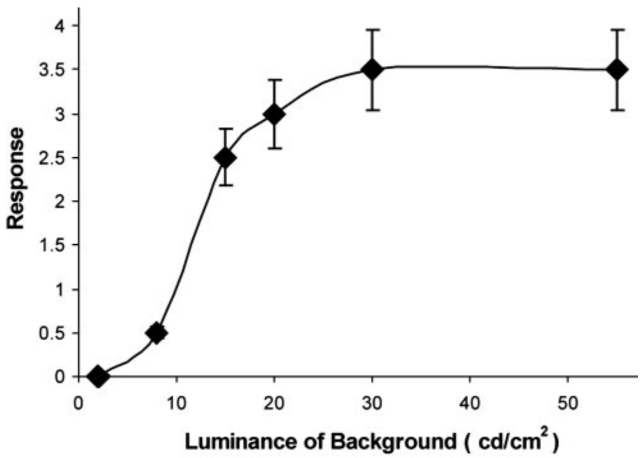

Fig. 6. The perception of illusory motion becomes stronger as the contrast between the black spokes and the background increases. The luminance of the black spokes was 0.9 cd/m^2, and the average luminance of the middle annulus was 15 cd/cm^2 for this experiment.

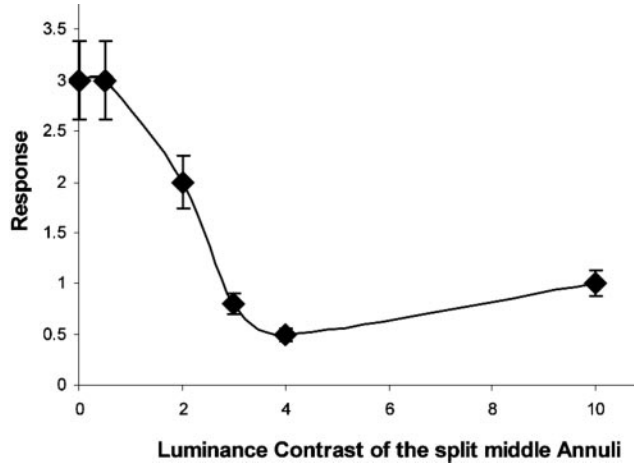

Fig. 7. Illusory motion is best seen when the middle annulus is uniform. The middle annulus was split into two concentric rings. The luminance of one of the rings was held constant at 3 cd/cm^2, whereas the luminance of the other was varied. The luminance contrast is defined as the difference between the luminance values of the two rings divided by 3.

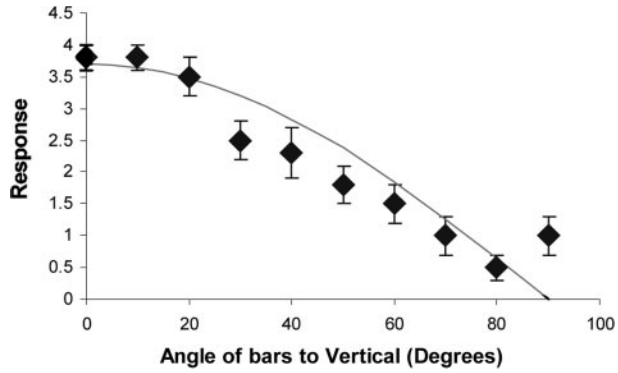

Fig. 9. The strength of the illusory motion increases smoothly as the angle between the black bars and the vertical channel increases. The fitted curve is the sine of the angle $\times$ the response at 90°.

either placed a mesh in front of the enigma painting or put circular spots in the annuli, no illusory motion was seen in the circular channels. We confirmed his finding by displaying an image in which there are many features in the channel imposed upon a high-contrast grating (Fig. 8). The observers see illusory motion when the features have low luminance contrast but not when they have high luminance contrast, which is consistent with the results shown in Fig. 7. The presence of the high-contrast black dots in the channel completely suppresses the illusory motion seen in the absence of the dots or when the dots have low-luminance contrast.

Experiment 4: Dependence of Illusory Motion on Orientation of the Background Grating. Leviant (1) reported that the illusory motion was strongest when the channel was at right angles to the grating. In this experiment, we determined the sensitivity of illusory motion to the orientation of the grating with respect to the channels. Two vertical channels were superimposed upon a high-contrast grating with various orientations with respect to the channels. The gratings consisted of black lines 5 arc min wide and white background lines 10 arc min wide, producing four cycles of the grating per degree. A set of 10 images was used with the angle of the grating lines with respect to the vertical channels ranging from 0° to 90° in increments of 10°. Two of these images are shown in Fig. 14, which is published as supporting information on the PNAS web site, and the strength of the illusory motion averaged over observers is shown in Fig. 9. The smooth curve in Fig. 9 is the sine function, which seems to fit the data reasonably well, so that the strength of the illusory motion seems to be proportional to the component of the length of the grating bars that is perpendicular to the channels. Experiment 6 measures the effect of the length of the bars directly.

Experiment 5: Effect of Orientation of a Channel and Perpendicular Grating Combination with Respect to the Vertical. Is the angle between the black bars and the channel the main factor in determining the strength of the illusory motion, or does the orientation of bars and channels with respect to the laboratory play a role? The whole display is presented at various orientations with respect to the horizontal while keeping the bars perpendicular to the channels. The channel and gratings were displayed within a circular patch of 10° of arc in diameter. Seven different orientations of the same combinations of a channel and grating were tested. The orientation is defined as the angle between the grating bars and the horizontal direction; an orientation of 0° means that the channels are vertical, and the bars are horizontal; an orientation of 90° means that the channels are horizontal, and the bars are vertical. Two of the seven orientations used are shown in Fig. 15, which is published as supporting information on the PNAS web site, and the strengths of the illusory motion are shown in Fig. 10. The strengths of the illusory motion are seen to be independent of the direction of the

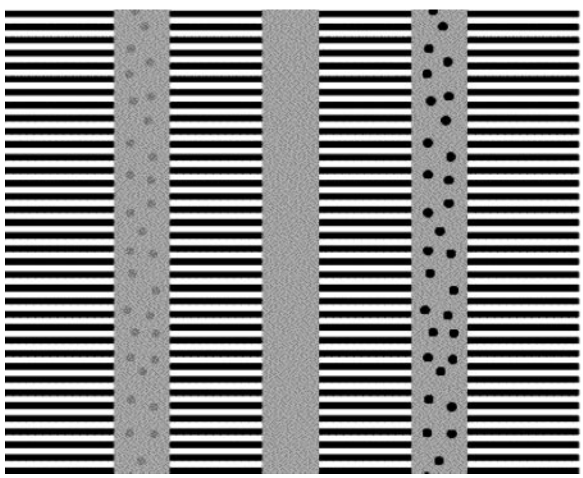

Fig. 8. High-contrast features within the channel suppress illusory motion activity.

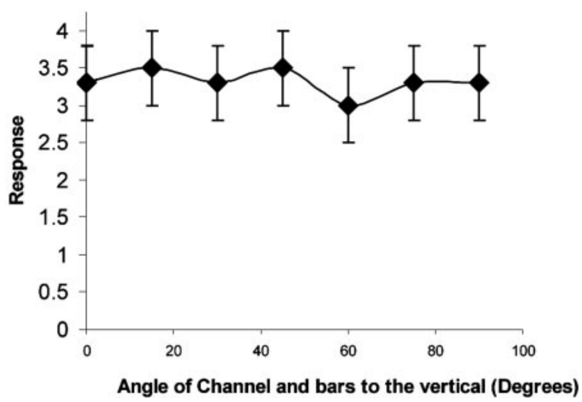

Fig. 10. The strength of the illusory motion is independent of the orientation of the grid of parallel lines when it is perpendicular to the channels. The abscissa is the angle between the grid lines and the laboratory horizontal direction.

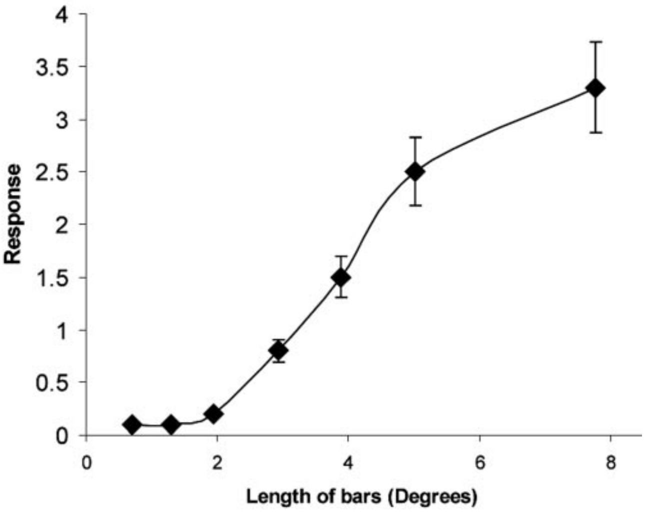

Fig. 11. The bar must be longer than 2° of arc on either side of the channel to produce very strong illusory motion. These bars are longer than motions on the retina because of microsaccades, and their effect increases with increasing bar length.

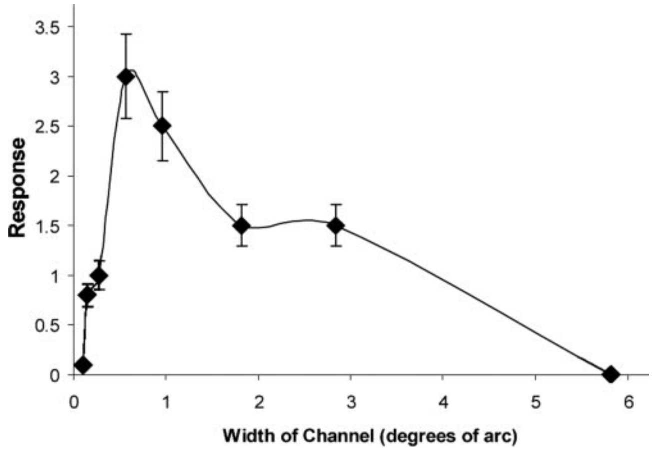

Fig. 12. Very little illusory motion is perceived for channels narrower than 15 arc min and for channels >3° wide, and most of the illusory motion is localized in a narrow strip near the edges of the widest channels.

grating of black bars when the channels are perpendicular to the bars.

Experiment 6: Effect of the Length of the Background Grating Bars. A high-contrast grating oriented perpendicular to the channels produces illusory motion. Is this effect the result of local processes, or is an extended part of the image involved? If microsaccades, tremors, or other miniature movements of the eyes are the dominant cause of illusory motion, the grating needs to extend only a small distance beyond the uniform channel to produce the effect. Unintended motions in the retina are usually ascribed to microsaccades or accommodative changes in the lens of the eye. Such eye motions produce only local motion on the retina, normally on the order of 1–5 min of arc (14). But if the strength of the illusory motion depends strongly on the bar length beyond the range of local eye motions, the dominant cause of illusory motion is likely to be cortical. High-contrast gratings with seven different bar lengths were used. Two of these images are shown in Fig. 16, which is published as supporting information on the PNAS web site, and the averaged strengths of the illusory motion observed are shown in Fig. 11.

The bar lengths shown in Fig. 11 are the extent of the grating on either side of the vertical channel. Perception of illusory motion is very weak when the grating extends <1° beyond the edge of the channel and very strong when the grating extends >2° from the edge of the channel, suggesting that the cause of the illusion is cortical and not limited by the small motions on the retina that are usually attributed to eye microsaccades and accommodative changes of the lens of the eye.

Experiment 7: Effect of Varying the Width of the Channels. The spacing of the horizontal grating lines used in the images was three cycles per degree, with the black lines being 8 arc min wide and the white lines 12 arc min wide. Seven different channel widths used were 6′, 9′, 19′, 34′, 1.8°, 2.8°, and 5.8°. Illusory motion was weak in the three narrowest channels, especially in the weakest one. The illusory motion was strongest in the 34′ channel and became weaker for wider channels. The motion was "localized" within a narrow strip near the edges of the widest channel, with no motion seen in the middle of the channel. An attempt was made to measure the width of this active strip, but the estimates varied widely even for the same observer on different days. Reported widths of the strip ranged from a few arc minutes to the full width of the channel. Despite this variation in reported localization of the motion activity, estimates of the strength of the illusory motion were consistent for data collected on different days. The averaged strength of the illusory motion is shown in Fig. 12.

Experiment 8: Effect of Rotating the Enigma. One way to gauge the effect of the weak motion signals generated on the retina by eye motions is to add much larger external real motion signals, so that the total real motion is the sum of the ocular "micromotions" and the external motion signal. If these external and ocular motions are processed by similar mechanisms, the ocular motions may have reduced visual effects in the presence of large external motions of the stimulus. In this way, the effect of the ocular motions can be compared with the effect of the real motion. For example, if the Enigma pattern is physically rotated, then observers may not see any illusory motion in the circular annuli if the physical rotary motion overwhelms the effects of retinal motion due to eye jitter, or they may see the illusory motion only in one direction with no changes in direction, as seen with stationary Enigma images. Fig. 1, which stimulates good illusory motion in the circular annuli, was printed on high-gloss photographic paper, 8.5 × 11 in in size, and mounted on a turntable so that it could be rotated while being viewed. Four observers were asked to view the rotating Enigma and judge the strength of the illusory motion for three rotational speeds, 5, 10, and 15 rpm (see Movies 1, 2, and 3, which are published as supporting information on the PNAS web site, respectively). These observers all see illusory motion in a stationary Enigma. All of the observers also saw illusory motion with respect to the spokes when the Enigma image was rotated at 5 and 10 rpm, and the illusory motion appeared to change direction erratically as for a stationary Enigma image. At 15 rpm, the illusory activity appeared to be stationary with respect to the physical features of the image. Instead of illusory motion around the annuli, the middle annulus appeared to be covered with a faint "transparent illusory texture" or "nonuniform shading" that rotated with the Enigma. We reproduced these observations using computer displays and a "movie" of a rotating Enigma, although in these displays, some observers were able to see the illusory activity even at 25 rpm.

Discussion

These experiments establish the following conditions for producing the strongest illusory motion in Enigma-like images. (*i*) Bars in the gratings should be 6–10 arc min wide for "rectangular grids," and spokes should be 1–2° wide for Enigma-like geometry for the strongest illusory motion effects. Wider or narrower elements produce weaker illusory motion. (*ii*) The bars and spokes should have the highest possible luminance contrast with respect to the background. (*iii*) The optimal width of the white (black) lines is 0.6–1.5 times the width of the black (white) lines. (*iv*) The grating bars should be approximately perpendicular to the channels. (*v*) The grating should cover as large an area of the visual field as possible, and the bars should be at least 2° long on both sides of the channel in which the illusory motion is to be seen. (*vi*) The channels superimposed upon the grating should be uniform, and any texture within them should be of very low luminance contrast. (*vii*) The width of the channels should be between 15 and 60 arc min.

The small differences between these rules and those given by Leviant (1) may be due to the fact that he used canvas and paint to present the images, whereas we used a computer monitor (cathode ray tube). Illusory motions seen with printed images are less reproducible than those obtained from images on the monitor and depend on the type of paper and the ambient light.

To test one of these rules, we designed an Enigma-like image that satisfied all of the rules, except that the spokes were very thin, and no illusory motion was seen. A similar result was obtained with a rectangular grid pattern.

Experiment 8, showing that the illusory motion is present even when the entire image is rotated, and Experiment 6, showing that high-contrast bars of lengths $>2°$ of arc at the retina are required for the strongest illusory motion, suggest that small eye movements play no significant role in generating the illusory motion seen in the Enigma.

We therefore agree with Zeki (8) that cortical mechanisms are primarily responsible for the illusory motion seen in images like the Enigma. The finding that illusory motion is stronger for gratings extending many degrees of arc beyond the region of the channel containing illusory motion and the elimination of the illusion by changing the width of the background lines also strongly support the view that cortical mechanisms are primarily responsible for the illusion. These cortical mechanisms appear to operate within high luminance-contrast gratings that border "empty" channels of uniform luminance free of texture. This might be due to the high activity of edge-detecting neurons, which have fairly large receptive fields that overlap the regions containing both the uniform channels and the high-contrast gratings. High-contrast features within the uniform region suppress or regulate this neural activity, but in their absence, this neural activity appears to induce illusory motion. The dynamics of this neural activity reflects the dynamics of internal neural mechanisms, because the external stimulus is stationary.

In our view, the illusory motion seen in Enigma-like images is stimulated by neurons whose receptive fields contain the contrast edges of bars or spokes that intersect channels with uniform contrast. Extended portions of these edges, as well as their endings at the channel boundaries, play a role in stimulating illusory motion if the channels are "empty" and of uniform contrast. The neural signals emanating from these bars are stronger for longer bars and fluctuate over time. These fluctuations may induce illusory motion in the channels by a mechanism similar to that responsible for the Omega effect, in which the motion-inducing stimulus is a sequence of random dot patterns of high luminance contrast with a fixed "refresh" rate. Because the dynamics of the noise in the Enigma-like configurations and the Omega stimulus is different, the pattern of reversals of direction of motion is expected to be different.

We model the illusory motion seen in Enigma-like images using the excitable neuronal array (ENA), a 2D array of interconnected neuronal elements based on the architecture of the primary visual cortex (15, 16). When a pattern of neuronal excitation mimicking the Enigma is imposed on an ENA, circular waves of neuronal activity arise at the center of the pattern and spread radially outward. When they encounter an empty circular annulus like an annulus of the Enigma, circular motion appears in the annulus as in the original Enigma. This motion occurs only when the spacing between the radial lines in the model has certain values in analogy with psychophysical measurements (see Fig. 3).

The appearance of such neural activity in the model is interpreted as being related to the global motion seen when a time sequence of random dots is displayed in a circular annulus. A sequence of random dot patterns presented in a large uniform area does not usually elicit any perception of global motion but appears as twinkling visual noise. However, when the same dot patterns are viewed through a circular annular aperture, circular motion is seen, and it alternates irregularly between clockwise and counterclockwise directions. Results of our study of this configuration will be reported elsewhere.

Materials and Methods

All of the images were presented in a dimly lit room on a 22-in (diagonal) cathode-ray tube monitor with a resolution of $1{,}280 \times 1{,}024$ pixels and a viewing area of 40×30 cm viewed at a distance of 1.5 m. For each image, observers were asked to rank the strength of the illusory motion they perceived on a five-level scale of perceived activity: none (0), weak (1), average (2), moderate (3), and strong (4). The observers controlled the time spent viewing each image and how many images they ranked in a sitting. Each of the eight observers ranked the entire set of images at least three times. The observers were 20–50 years old and had normal or corrected-to-normal vision. Two of the observers initially saw little or no activity in the images but began perceiving activity after viewing the set of images twice. Data from the initial runs of these two observers are not included in the averages presented in this paper.

The pictures were also printed by using a Hewlett–Packard DeskJet 970 printer on 8.5×11-in glossy or matte paper and shown to some of the subjects. Images printed on high-gloss photographic-quality paper generally produced a stronger illusory motion than those printed on matte paper. The strength of the illusion depended on the ambient light. The averages used in this paper include only the responses to images on a cathode-ray tube monitor in a dimly lit room, because they showed less variability than responses to printed images.

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