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Illusory displacement of equiluminous kinetic edges

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Abstract. A stationary window was cut out of a stationary random-dot pattern. When a field of dots was moved continuously behind the window (a) the window appeared to move in the same direction even though it was stationary, (b) the position of the 'kinetic edges' defining the window was also displaced along the direction of dot motion, and (c) the edges of the window tended to fade on steady fixation even though the dots were still clearly visible. The illusory displacement was enhanced considerably if the kinetic edge was equiluminous and if the 'window' region was seen as 'figure' rather than 'ground'. Since the extraction of kinetic edges probably involves the use of direction-selective cells, the illusion may provide insights into how the visual system uses the output of these cells to localize the kinetic edges.

1 Introduction

Most object boundaries in the real world are defined by a luminance difference across their border. However, in many cases edges can be defined without such luminance differences, and these equiluminous edges have interesting properties (Ramachandran and Gregory 1978; Livingstone and Hubel 1987; Trościanko 1989, personal communication). Examples include: an equiluminous chromatic edge, where two areas of the same luminance but different hues meet; or a texture edge such as the border between fine and coarse textures of the same mean luminance; or a kinetic edge (Julesz 1971; Nakayama 1983) such as the border between two random-dot textures which are identical save that one is moving and the other is stationary. We have recently observed that equiluminous texture borders and kinetic edges tend to fade completely on prolonged steady fixation even though the elements defining the edges remain clearly visible (Ramachandran 1988; 1989; Ramachandran and Gregory 1991). Perhaps the fading occurs because of selective adaptation or fatigue of neural channels that are specialized for extracting such edges (Albright 1987).

Since most object boundaries in the world have luminance edges associated with them, one wonders why the visual system takes the trouble of extracting all these different kinds of edges. One possibility is that using multiple mechanisms allows the visual system to defeat camouflage, and to cope with 'noisy' images (Ramachandran 1990). For example, consider a leopard seen against a screen of fluttering foliage while chasing one of our arboreal ancestors. The leopard may be completely invisible when it is standing still but as soon as it starts moving its shape becomes instantly visible as a result of the kinetic edges associated with its borders.

While studying kinetic edges we came across a striking new visual illusion that forms the subject of this paper. To create the edges, we began with a stationary window cut out of a stationary random-dot pattern. Behind the window we displayed a random-dot pattern 'conveyor belt' that moved continuously to the right. Surprisingly, the moving dots appeared to drag the window with them so that it appeared to move in the same direction—an example of a class of illusions that we call 'motion capture' (Ramachandran and Inada 1985; Ramachandran 1985, 1987). It was almost as though the strong luminance-based motion signals from the drifting dots were being misapplied to the edges of the stationary window, so that they appeared to move as well. Furthermore, the window also appeared to be displaced to the right (Ramachandran and Anstis 1987). This striking positional displacement occurred optimally at equiluminance, that is, when the moving and static regions shared the same mean luminance.

2 Experiment 1: Drifting dots affect perceived position

Stimuli were displayed on a monitor screen, 25 deg wide × 18 deg high, under the control of a microcomputer, and were viewed from a distance of 57 cm in a dimly lit room. The entire screen was filled with sparse grey random dots on a black background. Each dot (pixel) subtended 4.7 min arc. A central fixation spot was provided. Four small square windows, each of side 1.5 deg, were arranged at the corners of a larger square of side 6 deg which was centered on the fixation point. Each square window was stationary, but contained a field of sparse random grey dots that continually appeared at one edge of the window, drifted horizontally across it at a speed of 2.3 deg s^{-1}, and disappeared. About twenty-four grey dots were visible within a window at any one time. The edges of the windows were defined only by motion; if the dots were stopped the windows vanished. The dots in the upper two windows drifted inward toward the midline, while the dots in the lower two windows drifted outward away from the midline (figure 1). It was found that the square array looked trapezoidal, with the two upper windows appearing closer together than the two bottom windows. In other words the static positions of the windows appeared to be displaced in the direction of the dot drifts. The display was shown to sixty-two naive subjects who were unaware of the purpose of the experiment, and all of them reported seeing the displacement. The perceived spatial offset is not an artifact of the mean position of sparse dots within each window over time, because when the dot drift direction was reversed by reversing the time sequence (keeping the spatial patterns the same) the perceived offset was in the opposite direction.

This apparent static misalignment was measured by a null method on twelve naive subjects. Note that the dots in the top left and bottom right windows in figure 1

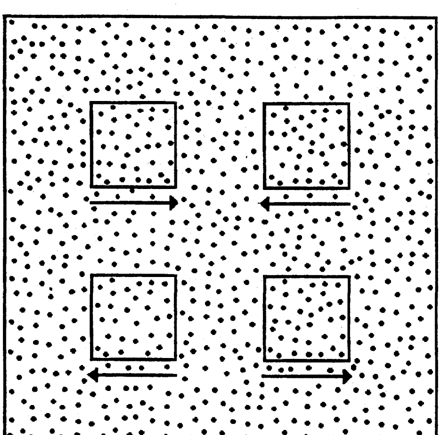

Figure 1. The stimulus used in the experiment. The four small squares were actually windows cut out of a stationary random-dot pattern through which one could see dots moving either towards the midline (upper two windows) or away from the midline (lower two windows) as indicated by the arrows. This caused the static positions of the windows to appear displaced in the direction of the moving dots. Note that the margins of the windows are visible only as a result of relative motion, so that if the moving dots were stationary the windows would become invisible. The outlines of the windows shown in the illustration here were not present in the original display.

drifted to the right; these two windows were always kept in a fixed position on the screen. The dots in the other two windows (bottom left and top right) drifted to the left, so these two windows both appeared to be statically displaced to the left. The subjects were able to adjust the position of this pair of windows on the screen by moving a hand-operated mouse. By moving the mouse to the left (or right) they could make the separation between the two upper windows greater (or smaller) than the separation between the two lower windows. Each subject adjusted the mouse, maintaining central fixation, until satisfied that the separations were equal such that the four windows lay at the corners of an imaginary square. The setting was then recorded. To avoid any positional bias the entire display was mirror-reversed top to bottom in half the trials.

The dots in the windows were always grey (7 cd m^{-2}). However, three different surround conditions were used; the surround dots were either grey (7 cd m^{-2}), white (15 cd m^{-2}), or black, that is, invisible. Twenty readings per subject were obtained for each background luminance setting.

We found that the windows always appeared to be displaced in the direction of the dot drift (figure 2). Each datum point on the graph represents the mean of two hundred and forty readings (twelve subjects and twenty readings). The apparent static displacement of the kinetic windows was 26 min arc with grey surround dots, 20.5 min arc with white surround dots, and 7.5 min arc with no surround dots. Since these are the perceived offsets between two kinetic windows moving in opposite directions, a single window compared to a stationary landmark would show half these values.

Thus the apparent displacement was greatest when the surround dots were grey, the same as the drifting dots, so that the kinetic edges were defined only by motion. The apparent displacement was less for white or black surround dots, against which the kinetic windows stood out as darker or brighter so that their positions could be seen independently of motion information.

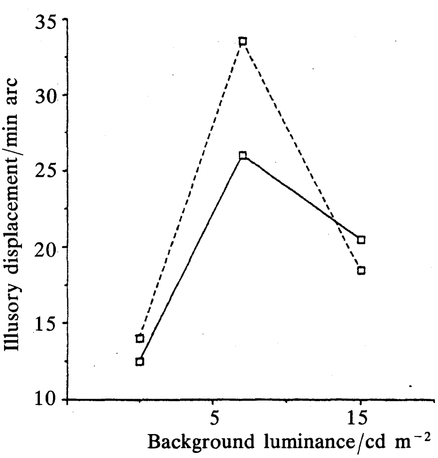

Figure 2. Illusory displacement between upper and lower squares plotted against background luminance. The square luminance was always held constant at 7 cd m^{-2}. The solid line represents the graph for experiment 1 in which the background dots were stationary, whereas the dotted line represents the graph for experiment 3 (twinkling background). Notice that illusory displacement is greatest at equiluminace. Each datum point on the solid line graph represents the mean of two hundred and forty readings (twelve subjects, twenty readings each). For the dotted line graph each datum point represents the mean of one hundred and twenty readings (six subjects, twenty readings each).

3 Experiment 2: Drifting dots affect perceived size

To rule out eye movements as a possible explanation, we created a display consisting of two annular windows containing radially drifting dots. The annuli were side by side with their centers 5.6 deg to the left and right of a fixation spot. The inner diameter of each annulus was 3.9 deg and the outer diameter was 7 deg. The dots in the left annulus drifted out radially from the center of the annulus in an expanding pattern, and the dots in the right annulus drifted inward toward the center in a contracting pattern. As a result it was found that the contracting annulus looked subjectively smaller than the expanding annulus, even though both annuli were the same size. Five subjects (three of whom were naive) were asked to null out this apparent size difference by adjusting the actual size of one annulus using a hand operated mouse until both annuli looked the same size. Subjects adjusted the expanding annulus in half the trials and the contracting annulus in the others. When the expanding annulus was adjusted its diameter was 7.8% smaller than the contracting one. When the contracting annulus was adjusted its diameter was 8.1% larger than the expanding one. Since the eyeballs cannot contract or expand (Nakayama 1988, personal communication) we conclude that the illusory displacement of kinetic edges cannot be explained by eye movements.

4 Experiment 3: Background of twinkling dynamic noise

This experiment was identical to experiment 1 except that we replaced the stationary dots in the background with twinkling dynamic noise. The number of dots per unit area was identical inside and outside the windows in any one movie frame. Again, the frame alternation rate was identical inside and outside the windows, so that if the 'movie' was stopped no windows were seen. We measured the perceived displacement of the windows in six additional naive subjects and found that the degree of mislocalization was even greater than in experiment 1 (see figure 2, dotted lines).

Why is the illusory displacement slightly less in experiment 1 (stationary dots background) than in experiment 3 (twinkling dots background)? One possibility is that stationary dots generate strong position signals which provide a frame of reference for the visual system when judging the location of the illusory edges. The position signals are removed by using dynamic noise background, and this enhances the illusory displacement.

5 Experiment 4: Titchener circles

Titchener (1902) showed that a test circle looks apparently smaller when it is surrounded by large inducing circles than when it is surrounded by small circles. We produced a Titchener illusion by manipulating only the *subjective* size of the inducing circles as described in experiment 2.

Two identical test annuli were filled with twinkling random noise against a sparse random-dot background. The left test annulus was surrounded by six inducing annuli which contained expanding drifting dots, and which therefore appeared larger than they really were. The right test annulus was surrounded by six inducing annuli which contained contracting drifting dots, and therefore appeared smaller than they really were. In fact, all fourteen annuli had the same physical diameter. Result: The left test annulus looked slightly *smaller* than the right test annulus. Thus the illusory size change produced by the dot drift was able in its turn to induce a secondary illusory size change in the test annuli. More formal experiments are needed to determine the magnitude of the effect.

6 Discussion

The observations described here are closely related to a class of effects that we call motion capture (Ramachandran 1987; Ramachandran and Inada 1985; Ramachandran and Anstis 1986). In a recent study of motion capture (Ramachandran 1987), a stationary yellow square was superimposed on an *equiluminous* grey surround, and viewed in peripheral vision. A sparse pattern of coarse black dots was optically superimposed on this yellow square and moved back and forth across it at about 0.5 Hz. The square appeared to move vividly along with the dots even though it was always stationary. Since equiluminous chromatic borders excite the motion system only weakly (Ramachandran and Gregory 1978; Cavanagh et al 1985; Livingstone and Hubel 1987; Ramachandran 1987; Schiller et al 1990) the visual system has no way of 'knowing' that the yellow square has not moved. Consequently the square is 'assumed' to have moved in the same direction as the dots (Ramachandran 1987). If the yellow square is given a different luminance from the grey background the motion capture collapses.

So, equiluminous chromatic edges can undergo motion capture from nearby (non-equiluminous) moving objects. We believe that the illusory motion of the kinetic edges is caused by a similar sequence of events, in which strong motion signals derived from moving dots get misapplied to the kinetic edge so that it appears to move as well (figure 1). But what causes the *position* of these kinetic edges to be displaced in the direction of the drifting dots? One possibility is that the location attributed to an edge that stimulates a direction selective cell is offset in its preferred direction. This offset would help to anticipate the location of the edge and would compensate for the actual displacement of the object that would occur during the inevitable neural delays of visual processing. Thus the perceived position is not the position of the stimulus when it actually triggers the unit but its *anticipated* position when the signal must interact with other sensory or motor processes. This offset would have played a role in our experiments to the extent that signals from directionally selective units are used to localize an edge. In the case of kinetic edges, for example, about half the units involved in identifying the edge are direction selective and the edge would therefore appear substantially displaced. When there is also a luminance contrast across the kinetic edge, nondirectional units with no offset can also be used to localize the edge and so it appears less displaced.

Finally, although the illusions described here may be mediated, at least in part, by early physiological mechanisms (as outlined above) we found that they could be strongly modulated by higher perceptual effects such as stereoscopic figure-ground reversal. The margins of a kinetic window appeared to drift much more when the texture enclosed by it was perceived as a patch in front of the static surround than when it was perceived as a hole through which a moving texture was visible. The moving patch could be made to appear in front of or behind the static surround either by voluntary figure-ground reversal or else by introducing appropriate retinal disparities between the eyes. In either case both motion-capture and positional misalignment were especially striking when the patch was in front. This implies that the assignment of motion to a contour depends strongly on whether that contour is seen as belonging to the figure or to the stationary ground.

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