Kinetic Edges Become Displaced, Segregated, and Invisible

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A square can be segmented if it differs from its background in texture, in depth or especially in motion, even when it has the same mean luminance as the background. We displayed stationary windows filled with coherently drifting random dots, against a background of random dots that were either static or else twinkling incoherently. The edges of the windows were defined by motion. The apparent drift velocity was slower against a twinkling background, presumably owing to lateral inhibition between velocity-sensitive channels in the window and in the background. During steady fixation a peripherally viewed window of drifting dots soon disappeared into its twinkling background, becoming invisible within 4 to 8 seconds, presumably owing to adaptation of directional information. The stationary window appeared to be displaced by up to 0.3° in the direction of the drifting dots that it contained. This did not occur if the dots in the window were made to differ in mean luminance from the surrounding dots.

We also displayed stationary windows filled with a grating that drifted to the left or right, against a spatially uniform gray background. We used a special flicker technique to remove luminance edges from the edges of the window. The stationary window appeared to be displaced in the direction of the grating's drift. This did not occur if there were luminance edges at the edges of the window. If the left and right eye each saw a separate stationary window in which a grating drifted to the left and right respectively, the binocularly fused window appeared to be displaced in stereoscopic depth.

In a display of multiple stationary windows, the grating drifted to the left in half of the windows chosen at random, and to the right in the other half. Motion segregation into a leftward and a rightward group was achieved effortlessly, but only if there were no luminance edges. We conclude that in the absence of luminance cues the positions of motion-defined edges are inferred by integration of velocity signals. When edges are defined jointly by motion and by luminance, the luminance cues heavily outweigh the motion cues in determining perceived position and segregation by motion.

Introduction

A solid white square on a black surround is visible because it is more luminous than its surround (Figure 1a). But even if it has the same mean luminance, it can be segmented by virtue of other visual properties,[1] such as color,[2]

texture[3] (Figure 1b, c), depth[4] (Figure 1d), and motion[4-6] (Figure 1e, f). The random-dot kinematogram,[4] or motion-defined square window, shown in Figure 1f, is the main stimulus used in this paper and was displayed on a monitor controlled by a microcomputer.[7]

In Figure 1e, a central square of dense random dots drifts to the right over a surround of static random dots. The edges of the square move with the dots, so the display resembles a square of sandpaper moving over a large stationary sheet of sandpaper. In Figure 1f, a central window with stationary edges contains dense random dots that drift to the right. The edges of the window do not move with the dots. This is like a square hole cut in a large stationary sheet of sandpaper, through which a second sheet can be seen moving to the right. Perceptually the moving central square or window stands out strongly, owing to the visual ability known as motion segregation,[8] which perceptually groups together all objects which move along the same motion path ("common fate"). (A car driver sometimes makes use of motion segregation by moving his head sideways to make all the dirt on the windshield shear visually in the opposite direction. This perceptually disentangles the dirt on the nearby screen from the distant scene that he wants to see.)

Notice that the central window does not exist in any single glance or snapshot: it exists only as a temporal relationship between successive movie frames.[6] The edges of the window were made visible only by motion, not by luminance since the dots in the window and the surround had the same mean luminance. Such motion-defined edges are called "kinetic edges."[6] If the mean luminance of the dots in the window is higher or lower than in the surround dots, this adds a "luminance edge" to the kinetic edge.

All the stimuli described in the first part of this paper were stationary windows filled with motion (Figure 1f), not the drifting square shown in Figure 1e. The surround was filled with dense random dots, which in some cases were static, like sandpaper, and in other cases were dynamic, twinkling in random incoherent motion like the "snow" on a detuned TV receiver. Later we shall describe stationary windows filled with drifting gratings.

Results

We have found four new illusions with kinetic edges:

1. Drifting dots appear to slow down when they are surrounded by twinkling dots.

2. A stationary window filled with drifting dots, surrounded by twinkling dots, and falling on the peripheral retina, vanishes after only 4 to 8 seconds of steady fixation.

3. A stationary window filled with drifting dots appears to be displaced by up to 24 minutes arc in the direction of the dot drift.

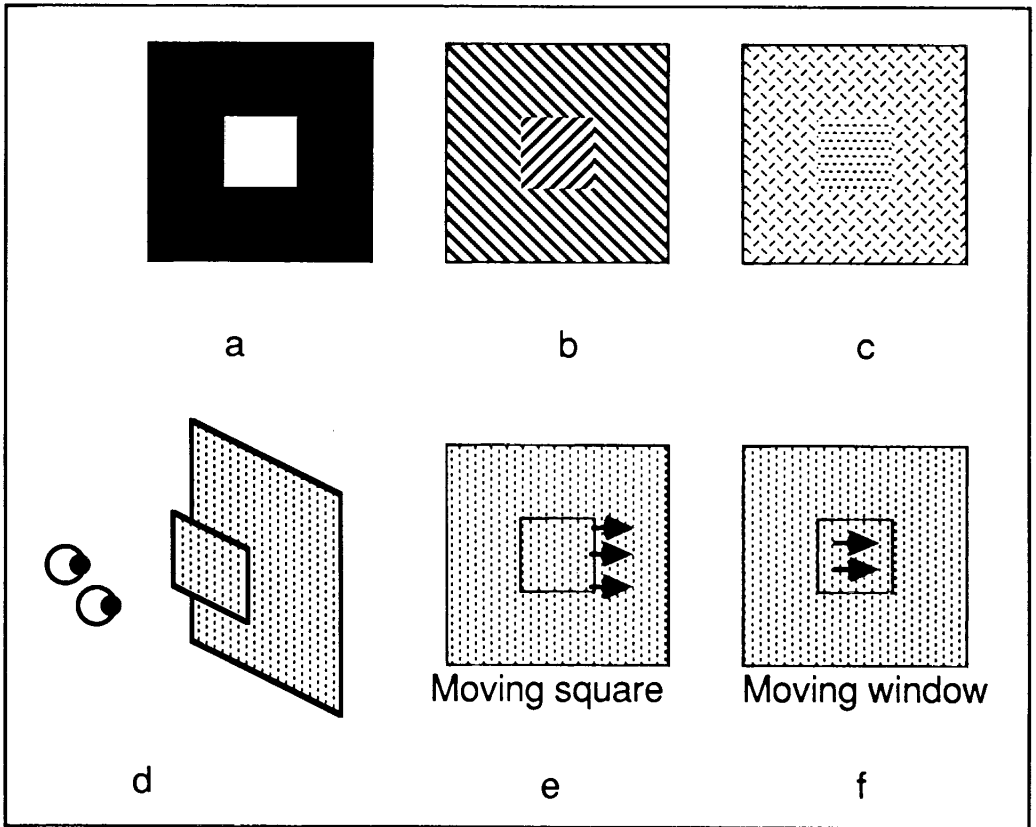4. A multiple array of stationary windows filled with drifting gratings show effortless motion segregation into

Figure 1. Ways to see a square. **a.** luminance. **b and c.** texture. **d.** stereoscopic depth. **e and f.** motion. In **e** the whole square drifted to the right (arrows), including the edges. In **f** the dot texture drifted to the right behind a window with stationary edges. All the stimuli we used were windows like **f.**

gratings that drift to the left versus gratings that drift to the right, but only if luminance edges are removed from the window edges in a way that will be described below.

Apparent slowdown. Figure 2 shows two stationary rectangular windows, oriented horizontally and filled with random dots that drifted in opposite directions. The actual stimuli were not round black disks as diagrammed, but were dense random dots, 50 percent black and 50 percent white. Result: on a twinkling random-dot surround (Figure 2b), the dots appeared to drift no-ticeably more slowly than they did on a static surround (Figure 2a). It might be imagined that the static dots provided landmarks that increased the apparent drift velocity, but this was not so because the apparent speed against the twinkling random-dot surround was still slower than against a uniform gray surround (Figure 2c), which provides no landmarks. We presume that horizontal components of the incoherent noisy motion in the surround are stimulating velocity-sensitive channels, which then apply lateral inhibition to channels that sense the drifting dots.

Figure 2. Upper and lower strips were stationary windows containing texture that drifted to left and right (arrows). Subject fixated midway between them. Apparent drift rate was slower on twinkling surround (a) than on static dots (b) or on uniform gray surround (c).
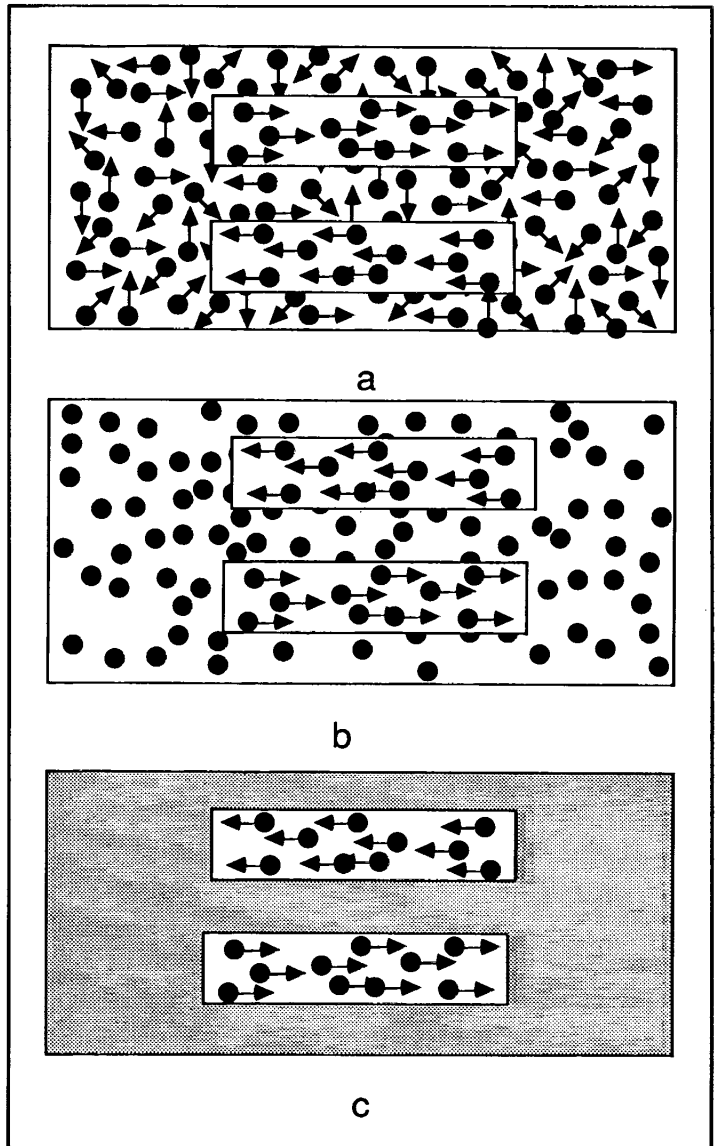
Sudden disappearance. The observer fixated a point 5° to 10° away from the window of drifting dots embedded in a dynamic surround (Figure 3a). (This phenomenon was not found with a static surround.) Result: the peripherally viewed window completely vanished after an inspection time of only 4 to 8 seconds (Figure 3b). It can be unnerving to have such an arti-ficial "blind spot" develop so rapidly, and the window remained invisible until a chance eye movement brought it on to a fresh patch of retina. There seems to be very rapid adaptation of the directional motion signal that distinguishes coherent drifting motion from the incoherent random motion of the noise. (Even after it has disappeared from view, the drifting window continues to
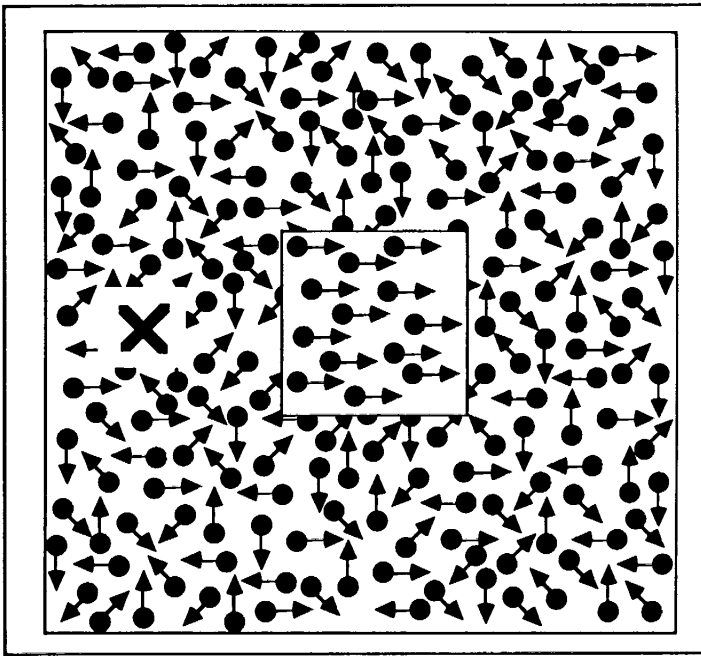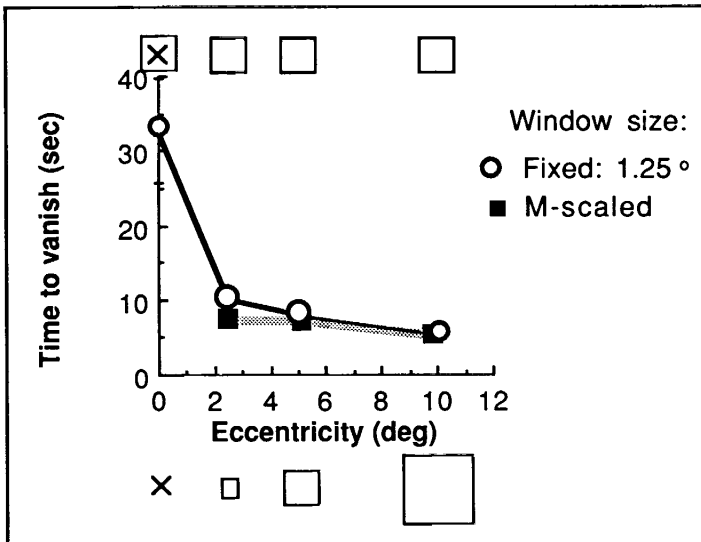
Figure 3. a. A window filled with dots that drift to the right was centered in a surround filled with randomly twinkling dots. The window appeared subjectively displaced to the right (illusory displacement).

If the subject fixated the cross then, **b.** the whole window could disappear within 4 to 8 sec. Circles: Eccentricity of the window was varied while size was held constant. Squares: Size and eccentricity were varied together, keeping the window "M-scaled" (see text).

selectively adapt motion sensors, because stopping the motion reveals a strong negative aftereffect of motion.)

A window that was foveated never disappeared. This suggest a hitherto unnoticed difference between motion processing within the fovea and outside it. The greater the eccentricity, the more rapidly the windows disappeared. It made little difference whether window sizes were held constant as eccentricity was varied or were M-scaled, that is, made linearly larger with eccentricity (Figure 3b). This scaling holds constant the cortical region stimulated by the window.[9]

Illusory displacement.[10] The stationary window appears to be displaced from its true position, in the direction of the drifting dots that it contains. With a static surround, this illusion was seen in peripheral but not in foveal vision. With a dynamic surround, the illusion was seen in both foveal and peripheral vision. Illusory displacement was measured by subjectively aligning the drift-filled window with stationary landmarks. Four small square windows, each of side 1.5°, were arranged at the corners of a larger square of side 6° which was centered on the fixation point. Each square window was stationary but contained a field of sparse random white dots that continually appeared at one edge of the window, drifted horizontally across it at a speed of 2.3°/sec, and disappeared. 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 4). As a result it was found that the square array looked trapezoidal because the static positions of the windows appeared to be displaced in the direction of the dot drifts. This displacement, measured by a nulling method, was 24.2 minutes arc (Figure 4b). (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.) If the surround dots were made lighter or darker than the dots in the window the resulting luminance edge greatly reduced or abolished this apparent displacement.

When long strip-like windows were used, as in Figure 2, the apparent displacement was greater when the dots drifted across the strips, than when they drifted along the strips. Therefore, misalignment is promoted by long borders along which dots appear or disappear, and not by long trajectories as the dots traverse the central portion of the window. So apparent shifts are probably produced by dots moving at edges, not dots traveling across the central region of a window, and long trajectories produce little apparent shift. This is analogous to a white square whose apparent brightness depends more on the luminance at edges discontinuities than in the center of the square.

Drifting dots could also affect apparent size. Two identical annuli were set up side by side, one filled with "expanding" and the other "contracting" dots (not illustrated). A null method of adjustment showed that the "expanding" annulus looked seven to eight percent bigger than the "contracting" one.

This result suggests that when the visual system has to judge the position of a moving edge at any given instant, it uses two rather different strategies. The first strategy is simply to read off the location of an edge on the retinal mosaic (local sign). The second strategy depends upon successive integration of velocity signals to estimate position. For edges defined by luminance the first strategy is simple, direct and available. Equiluminous kinetic edges, on the other hand, generate only
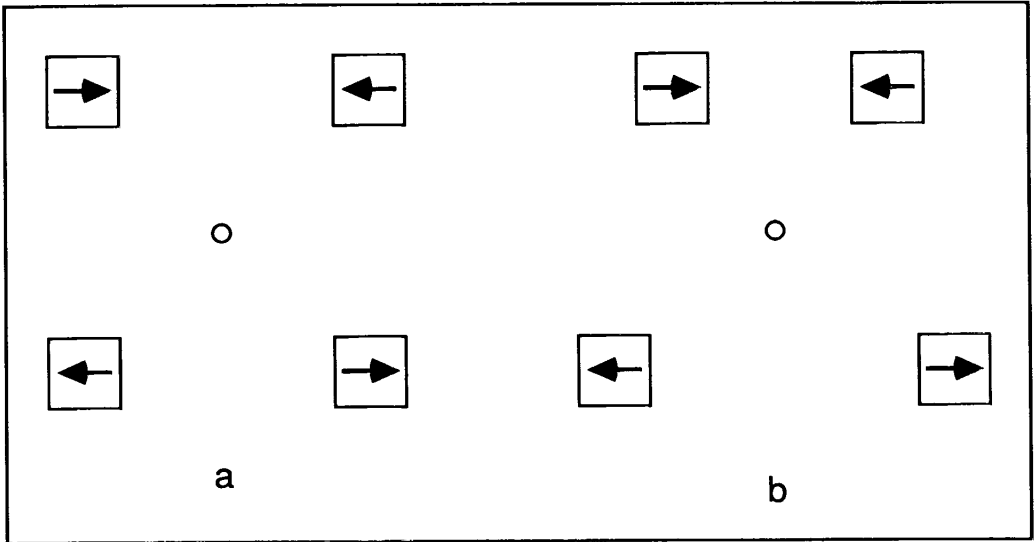
Figure 4. Four stationary windows were arranged in a square, around a central fixation point. Each window contained random dots drifting in the direction of the arrows. Result: upper windows looked closer together than lower ones (not to scale).

weak positional signals and consequently the system may have be forced to estimate the position of the kinetic windows by integrating the velocity information. This displaces the perceived position in the direction of the dot drift. It is as though the position of a car on the road were being measured in two ways: directly from the odometer, luminance signals, and indirectly by integrating the speedometer readings over time, integration of velocity. The direct method is simpler and more reliable, but fails at equiluminance, permitting the indirect method to serve as a backup.

Why did luminance edges reduce or abolish the illusory displacement and rapid disappearance phenomena? Do they operate by keeping the window visible? They could do this wherever they lay inside the window. Or must they specifically mark the edges of the window? We investigated this by put-

ting luminance-defined features, namely grating bars, inside the windows. The bar-filled windows could always be seen, even when they were not moving. At the same time we found a way to avoid luminance edges, described below.

Windows filled with drifting gratings. Stationary windows were filled with drifting gratings and set into a spatially uniform gray surround. The bars of the grating inside the window were always visible, whether they were moving or stationary. Notice that if the surround was a constant gray at all times, then it always generated a visible luminance edge because it contrasted with the temporally varying luminance of the bars where they appeared at one edge of the window and disappeared at the other.

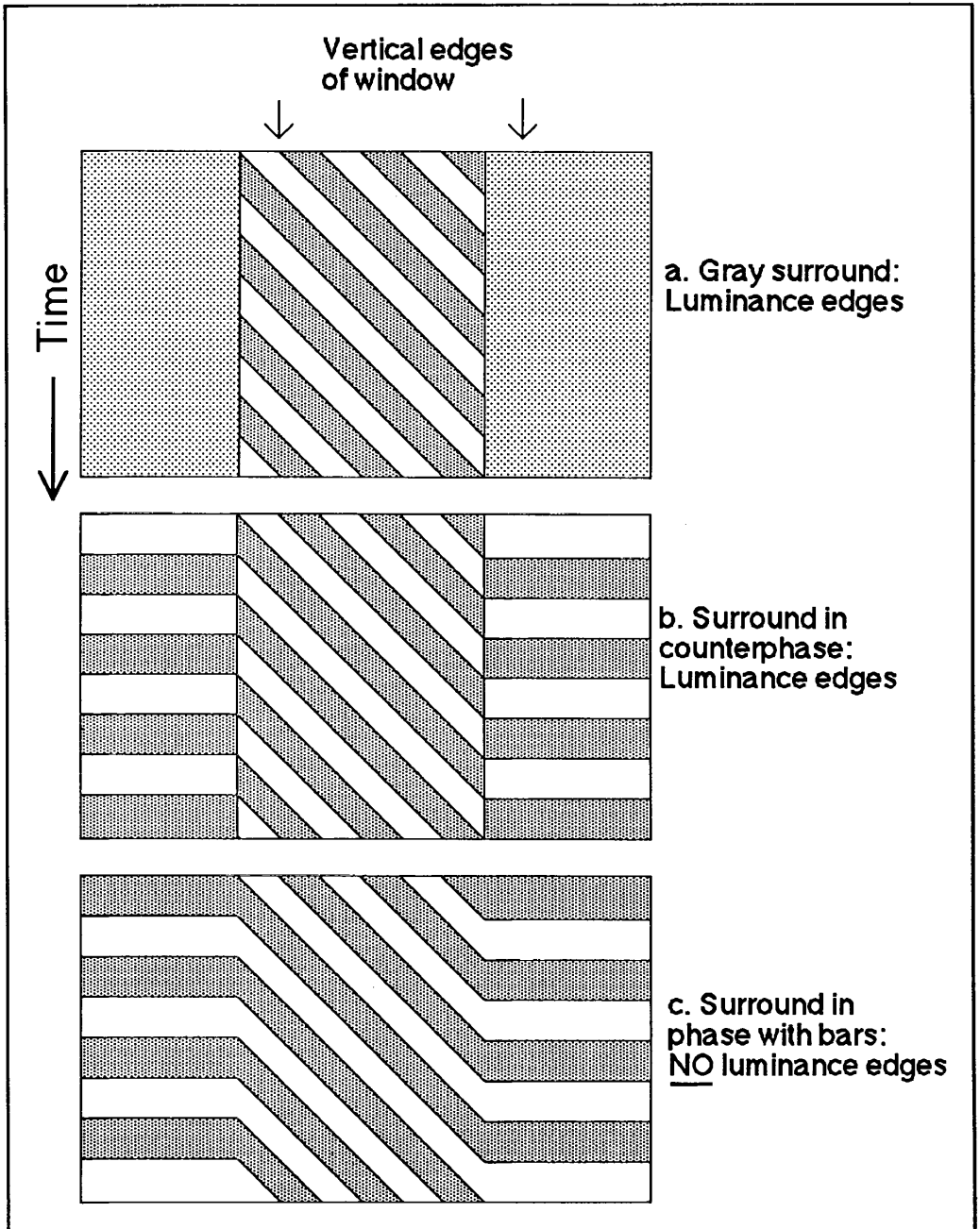In Figure 5, time runs down the page so that any horizontal line drawn across the figure would represent the

Figure 5. Flicker method for removing luminance edges from stationary windows filled with drifting gratings. Time runs down the page. Central diagonal stripes symbolize not a diagonal grating but a vertical grating drifting to the right. Horizontal stripes in **b** and **c** symbolize not a striped surround but a uniform surround flickering in step with the bars of the grating as they appeared at the left side of the window and disappeared at the right side. **a.** Steady, uniform gray surround differed from luminance of bars at the sides of the window, so there were always luminance edges. **b.** Surround flickered in counterphase with the bars at the sides of the window, so there were always luminance edges. **c.** Surround flickered in phase with the bars at the sides of the window, so there were no luminance edges. Result: **c** showed apparent displacement phenomenon and good motion segregation, but **a** and **b** did not.

stimulus at a given moment in time. Imagine viewing the figure through a narrow horizontal slit in a card which you scan down over the stimulus; the central stripes will then appear to drift to the right, and in Figure 5b and c, the regions on either side will appear to darken and lighten repetitively. Thus the central diagonally striped region represents a stationary window that contains not a diagonal grating but a vertical grating which is drifting to the right. The grey side regions in Figure 5a represent a steady grey surround, and in Figure 5b and c, the horizontally striped regions at the side represent a surround which is not striped but is a spatially uniform grey, with the luminance varying sinusoidally in time in step with the bars as they appear at the left edge and disappear at the right edge of the window. In Figure 5b the surround is always in phase with the bars at the window edges, so that there is no luminance edge at the edge of the window. Figure 5c shows a control condition with the surround always in counterphase with the bars at the window edges, so that there is a strong luminance edge at the edge of the window. Notice that the vertical sides of the window, which have crisp sharp luminance edges in Figure 5c, provide only fuzzy subjective edges in Figure 5b. Of course these arise from orientation differences in the printed Figure but arose from velocity differences in the actual experimental stimulus. Result: with a gray surround (Figure 5a) we found no illusory displacement or rapid disappearance.

The luminance edges were now removed by causing the whole spatially uniform surround to vary sinusoidally in luminance over time, in phase with the grating bars as they reached the edges of the window (Figure 5b). Result: removing the luminance edges restored the illusory displacement phenomenon (Figure 6a), but not the rapid disappearance.

In a control condition the luminance edges were restored by making the whole spatially uniform surround vary sinusoidally in luminance over time, in counterphase with the grating bars at the edges of the window (Figure 5c). Result: the illusory displacement phenomenon disappeared again. Yet both the drifting window and the surround were each exactly as before, the only difference lay in their relative temporal phase.

Stereoscopic disparity. Opposite illusory displacement presented to each eye yields disparity-based subjective depth. The stimulus of Figure 6a was presented to the left eye and its left-right mirror image was presented to the right eye (Figure 6b). Viewed by each eye in turn, the middle grating appeared to be displaced to the right in the left eye, and to the left in the right eye. When the two pictures were fused binocularly, the middle window appeared to be nearer in depth than the top and bottom windows, as one would expect from crossed disparity. This was only true when the gray surround ramped in phase with the window edges to eliminate luminance edges. If luminance edges were introduced (not shown) all three windows appeared to lie in the same depth plane.

In summary, windows filled with drifting gratings show illusory displacement despite that fact that the bars are
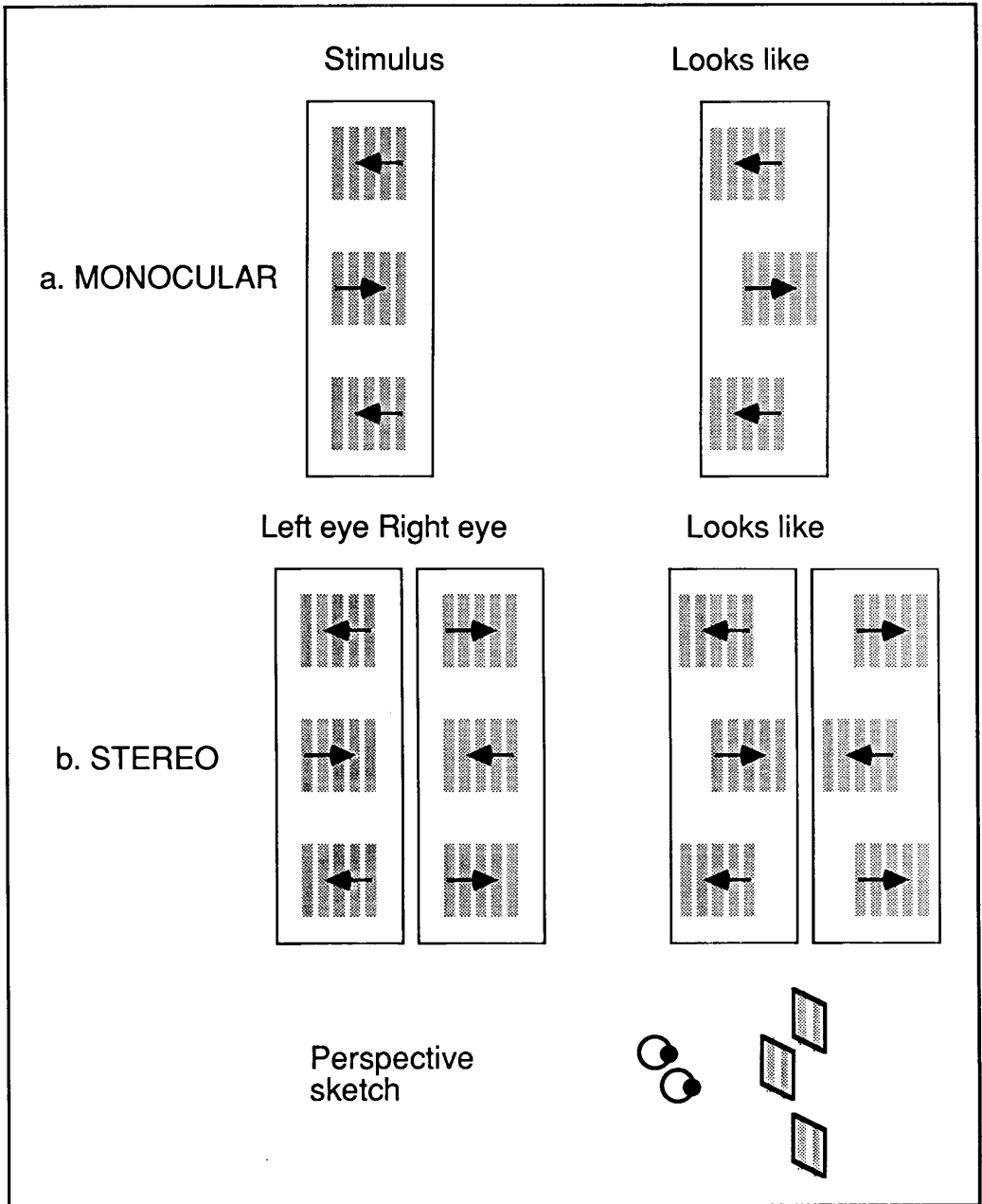
Figure 6. a. Three stationary windows, aligned vertically, contained drifting gratings. Top and bottom gratings drifted to the left, middle grating drifted to the right. There were no luminance edges, because the background luminance varied in phase with the window edges (not shown). Result: middle window appeared to be displaced to the right. **b.** Left eye saw same as a, right eye saw its mirror image. Result: in the binocularly fused image the central window appeared nearer than the others.

always visible, but only if there are no luminance edges. Thus the illusory displacement depends upon edges being defined by motion and not by luminance, but are unaffected by visible feature within the windows. On the

other hand, the windows filled with gratings never disappear in peripheral vision.

Motion segregation. Points that move together in "common fate" are immediately grouped together into a single perceptual unit. This rapid grouping process is called motion segregation. It is an effortless, pre-attentive process that operates in parallel because the time taken to achieve segregation does not increase with the number of dots, the moving dots "pop out" as a group straight away.[11] Contrast this with "serial" perceptual processes which take longer for more dots.[12]

An example of motion segregation is shown in Figure 7 in which a subset of dots, arranged in the shape of a letter T, move to the left and are immediately recognized as a T against the background of dots moving to the right. (In Figure 7 the dots have been drawn in different shades of gray for clarity, but the actual dots were all black.)

Little striped squares can be used instead of spots. An array of multiple stationary windows (Figure 7c) contained gratings that drifted to the left in a T-shaped subset of the windows and to the right in the others. On a black surround that gave strong luminance edges at the window edges, little or no motion segregation was reported. Also, if the surround luminance ramped in antiphase to the window edges, which also maintained strong luminance edges as in Figure 5b, there was little or no motion segregation. However, if luminance differences were removed from the window edges by ramping the sur-round luminance in phase with the window edges as in Figure 5c, there was dramatic motion segregation. The letter T "popped out" and appeared to sail along to the left.

Discussion

We do not yet really understand these new motion phenomena, but here are our speculations, which await further research.

1. We suggest that the apparent slowdown of drifting dots in a window when they are surrounded by dynamic random noise is a form of simultaneous motion contrast, or lateral inhibition from the horizontal components of the incoherent twinkle to the horizontal drift.

2. We suggest that the rapid disappearance of a peripherally viewed window of drifting dots in a dynamic surround is a form of successive motion contrast, in which directional information adapts out rapidly outside the fovea.

3. We suggest that the apparent displacement of a window of drifting dots arises because the visual system estimates the position of the kinetic edge by integrating velocity signals from the drifting dots. Adding a luminance edge gives a veridical estimate of position and the illusion vanishes.

4. We interpret our motion segregation results as follows (Figure 8):

    a. Motion processing applies the labels "left" and "right" to the subsets of windows that contain motion respectively to the
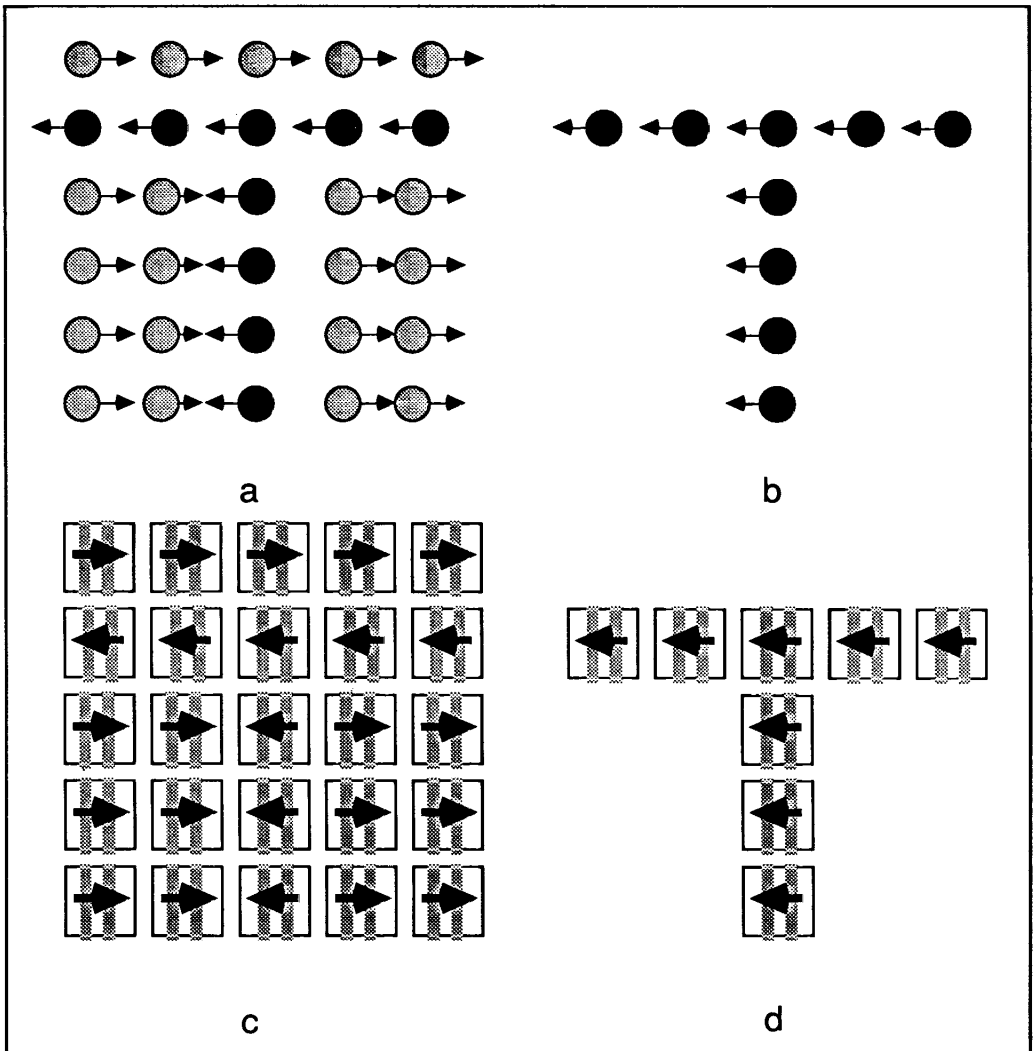
Figure 7. Motion segregation. **a.** Gray dots moved to the right, black dots to the left. Actually all dots were black; some are made gray here for exposition only. Result: the T-shaped region of leftward dots detached itself from the background **b.** in immediate, pre-attentive motion segregation. **c.** Stationary windows were filled with gratings that drifted to the left in a T-shaped subset of windows, and to the right in the remainder. Result depended on the background, which is not shown. If background luminance varied in phase with the window edges, giving no luminance edges, there was strong pre-attentive motion segregation, as in **d.** If background varied in antiphase with the window edges, giving luminance edges, there was little or no motion segregation.

left and to the right, and this selective labeling enables segregation.

b. Luminance edges apply the same luminance label to all the windows. (Leftward and rightward windows have the same luminance attributes.)

c. The labels compete, and luminance labels are stronger than motion labels, so they disable the segregation.

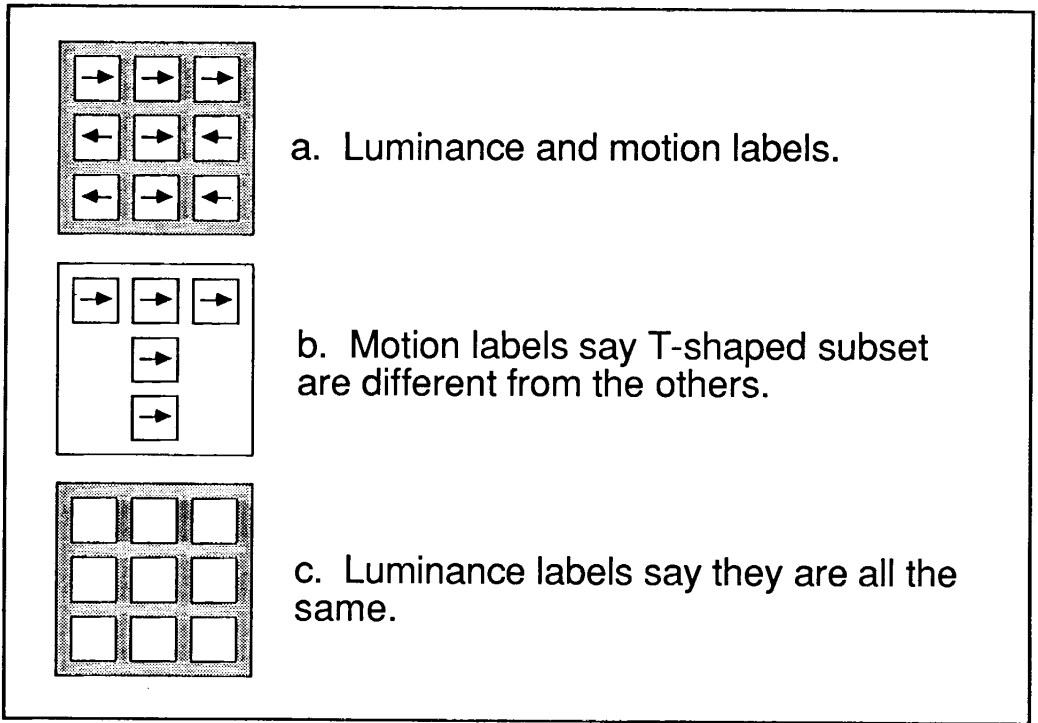This leaves unanswered the question of why luminance edges inhibit motion segregation, since it seems as

Figure 8. Model of motion segregation.

though the visual system is throwing away useful information. Why is one unable to ignore the luminance labels, isolate the motion signals, and use these alone to form a separate neural map to achieve motion segregation? Are the luminance and motion labels indissolubly pooled before segregation takes place?

Looking ahead, it is known that perceptual segregation can be supported by many other visual dimensions such as color, texture, disparity (depth), orientation, spatial frequency, etc. Perhaps each of these properties could be used to label different subsets of the same visual scene, so that competitive segregations could be set up experimentally, pitting color against depth and so on to determine the relative dominance of these visual properties.

Acknowledgments

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