The furrow illusion: Peripheral motion becomes aligned with stationary contours

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A spot moved vertically up and down across a background grating that was tilted at 45°. In foveal vision this was seen accurately, but when viewed peripherally the spot's path was perceptually attracted toward the grating orientation, and at large eccentricities (>20°) the spot appeared to move at 45°, parallel to the grating. The intersections between the grating and the moving spot drive this illusion, revealing profound differences between fovea and periphery in processing visual motion.

Keywords: motion perception, peripheral vision, illusion orientation, assimilation


Introduction

I find that when a spot moves in a straight line across a static background of high-contrast stripes that are tilted or curved, the spot's trajectory appears to be attracted toward these stripes and seems to move along a tilted or curved path. This happens only in peripheral vision. In foveal vision the straight motion paths are seen correctly, but with increasing eccentricity the background induces greater perceptual distortions. I shall offer first qualitative and then quantitative results.

The peripheral retina is by no means simply a coarser version of the fovea. It is true that visual acuity falls off progressively as one goes further into the periphery, as measured by acuity for Snellen letters (Anstis, 1974), gratings, or vernier targets. Anstis (1998) briefly reviews this literature. Correspondingly, retinal receptive fields become progressively larger into the periphery (Curcio & Allen, 1990). But in addition the fovea and periphery differ markedly in their relative responses to position and movement. Acuity for both position and motion fall off from the fovea into the periphery, but motion acuity falls off more slowly, with the result that the peripheral retina tends to be relatively more sensitive than the fovea to moving stimuli (Edwards & Nishida, 2004). Waving at somebody in a crowded airport is likely to stimulate their peripheral motion receptors and provoke a saccade in the correct direction.

Qualitative results

I begin with several demonstrations of the effects, followed by quantitative measurements. In Movie 1, two spots move back and forth along parallel horizontal paths. The upper yellow spot moves across a field of upward-pointing chevrons or inverted V's, and in peripheral vision its path look like an inverted "U." Conversely the lower yellow spot moves across downward-pointing V's and its path looks like a "U." The paths of the two spots appear to bow outward. For the red spots the background chevrons are the other way up and the spot paths appear to bow inward. In peripheral vision it is difficult to believe that the spots actually move along horizontal paths with no up and down motion whatsoever. The illusion was disrupted, however, if the background stripes were flickered in counterphase (not shown).

In Movie 1 the colors of the spots made little difference. But I noticed that the peripheral motion effects were strongest when the spot was a "negative lens" that reversed the polarity of the background seen through it. So I used a negative lens in the remaining movies. In Movie 2 several varieties of spot, including a negative lens, move up and down across background stripes that are tilted at 45°. The result is that in foveal vision the spot is correctly seen as moving vertically, but as one looks further into the periphery the spot's path seems to be more deflected, until it looks virtually parallel with the 45° stripes. This stimulus is further studied in Experiments 1 and 2 later on.

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In Movie 2, at first the moving disk is a negative lens. Both the static background and the drifting disk are filled with stripes; which stripes are more important for the furrow illusion? I selectively removed the stripes from the disk and background in the following conditions, which run sequentially within Movie 2:

1. a striped disk on a striped surround (negative lens),
2. a gray disk on a striped surround,
(3) a striped disk on a gray surround, like a gray screen with a round hole in it moving up and down in front of a static tilted grating.

(4) a thin striped annulus on a gray surround, like Condition 3 except that the moving hole is a thin annulus. This condition gives the minimum conditions for the furrow illusion, with all the stripes removed and leaving only the intersections between circle and grating, which are visible as moving black and white arcs within the annulus. The oblique movements of these intersections are shown in Movie 2.

Conditions 1-4 all show the illusion and the disk or annulus seems to move obliquely in peripheral vision.

(5) the disk stripes are now left-oblique, orthogonal to the right-oblique stripes in the background. The result is that the stripes cancel out and no oblique illusion is seen.

To reduce the file size, only one up-and-down stroke is shown for each condition.

In Movie 3 the background consists of concentric circles, and the spots move along straight parallel chords, horizontal on the left and vertical on the right. However, they appear to move along similar curved circular arcs. This effect is so strong that simply looking midway between the two circular displays usually puts them far enough into the periphery to generate the illusion.

Movie 2. The spot moves vertically, but in peripheral vision it appears to move obliquely, parallel to the background stripes. The spot begins as a negative lens that reverses the polarity of the stripes within it. Then it becomes a gray spot, then a hole.

Movie 4 shows that the illusion is driven by the local background, not the remote background. The left-hand spot runs along a narrow gray horizontal strip that insulates the spot from the background stripes, while the right-hand spot runs along a background of circular arcs. The result is that in foveal vision, the two spots are correctly seen as running along parallel paths, while in peripheral vision the right-hand spot, but not the left-hand spot, shows the illusion of moving along an arc. The conclusion is that the illusion is sharply localized and the spot, as on the right, must touch the oblique stripes, not just be near them.

In Movie 5 a ring of spots rotates clockwise while the background stripes flip occasionally between horizontal and vertical. In foveal vision, the background orientation does not affect the perceived movement. But in peripheral vision, the circular motion is distorted into an elliptical path, parallel to the background stripes. The two halves of the elliptical motion seem to slide past each other. I have found (not shown here) that the illusion persists even when some stripes are selectively deleted, just as they were in Movie 2. In other words the rotating spots can be grey on a striped surround, or striped on a grey surround, and instead of spots one can use even rotating thin annuli that show only the intersections on a gray surround. All these conditions show the illusory sliding and shearing.

Movie 6 shows an illusory size change. The moving horizontal test bar is always the same length, but appears to get longer and shorter, and perhaps also...
nearer and farther away, as it moves up and down. I measured the apparent change in length by matching it with an adjustable moving bar, and I found that the striped bar appeared to change in length by 13% when viewed at an eccentricity of 12°, and by 27% at an eccentricity of 24° (mean of 5 Ss × 3 trials).

I also noted that apparent motion did not provoke the illusion as real motion does. When a spot jumped back and forth vertically against oblique stripes (not shown), the motion path was still correctly seen as vertical when viewed peripherally. Compare this to Movie 2, in which real motion did appear to be tilted toward the orientation of its background.

**Quantitative results**

**Experiment 1: Retinal eccentricity**

I measured the perceived spot path in Movie 2 as a function of retinal eccentricity. A negative lens spot of diameter 1° moved back and forth vertically along a
path 10° long, at a rate of 0.6 cycles/s and at a velocity of 12°/s. It moved across a striped disk of diameter 16°. These stripes formed a black and white square wave grating, of spatial frequency 1 cycle/deg.

To avoid left/right biases, the orientation of the background stripes was randomly set on each trial to be either +45° or −45°. The fixation point was randomly set to one of five eccentricities: 0°, with the fixation point lying in the center of the large striped disk; or 4°; or 8°, lying at the edge of the striped disk; or 16°; or 24° of eccentricity. An adjustable short red line was always centered on the fixation spot, and the observer’s task was to adjust the orientation of this line to match the apparent axis of the spot motion. This was done by striking four keys (n = −10°, j = −1°, i = +1°, o = +10°). When satisfied with the match, the observer struck the space key and the computer recorded the result for later analysis, and automatically presented the next trial. Results for orientations of +45° and −45° were combined and averaged.

Results are shown in Figure 1.

Figure 1 shows that the illusion was absent in central vision but increased linearly with eccentricity, reaching its maximum at 24° eccentricity. At this eccentricity the spot’s path looked almost parallel to the background stripes (45°). This demonstrates clear differences between foveal and peripheral responses to visual motion.
Experiment 2: Contrast of background grating

The setup was the same as Experiment 1, except that now I varied the contrast of the background grating. The retinal eccentricity was fixed at $24^\circ$, and the Michelson contrast of the background grating was randomly set on each trial to one of five values, namely 0.1, 0.2, 0.4, 0.8, and 1.0. As before, to avoid left/right biases, the orientation of the background stripes was randomly set on each trial to be either $+45^\circ$ or $-45^\circ$, and the results for the left and right orientations were combined in analyzing the results.

Results are shown in Figure 2.

Figure 2 shows that the contrast of the grating made no difference to the illusion, which was equally strong for all contrasts ranging from 0.1 to 1.0.

Experiment 3: Background orientation

On different trials the tilt of the stripes was randomly set to 12 orientations all around the clock, spaced $15^\circ$ apart, namely $-90^\circ$ (horizontal), $-75^\circ$, $-60^\circ$, $-45^\circ$, $-30^\circ$, $-15^\circ$, $0^\circ$ (vertical), $+15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, $90^\circ$. The observer fixated a small spot centered on an adjustable short red line, which lay at a fixed eccentricity of $24^\circ$ to the right of the center of the striped disk. On every trial, as before, the observer adjusted the tilt of the red line to match the apparent tilt of the moving spot’s path.

Results are shown in Figure 3. Figure 3 shows that the motion illusion was a sinusoidal function of the background orientation. As the background stripes deviated from $0^\circ$ (vertical), the illusory deflection of motion first increased to a maximum when the stripes were tilted at $45^\circ$, and declined again as the stripe orientation increased from $45^\circ$ to $90^\circ$ (horizontal). Note how strong the illusion was. When the background stripes were tilted at $+45^\circ$ or $-45^\circ$, the spot path was also tilted at $45^\circ$ or $-45^\circ$, so that the spot appeared to move exactly parallel to the stripes, even though the path was actually vertical. This illusory deflection of $45^\circ$ may be the strongest directional illusion known.
Experiment 4: The role of intersections

The furrow illusion can be compared to the barber pole illusion (Fisher & Zanker, 2001; Lalanne & Lorenceau, 2006; Stoner & Albright, 1994). In the barber pole illusion, the inducing grating moves inside a stationary contour, while in the furrow illusion the contour of the inducer moves across the whole image, but there is a close resemblance in the motion direction of intersections between the grating and the contour.

Movie 7 depicts a circle that moves up and down, intersecting as it moves with the stripes of a tilted grating. On the downward stroke most of these intersections move down to the left (small red circles), but a few move up to the right (small blue circles), wherever the right-oblique parts of the moving circle are tilted more steeply than the grating. I thank Dr. Akiyoshi Kitaoka for pointing this out to us. But do these intersections actually influence our percepts? To find out, I moved each part of the circle separately by treating it as a 36-sided polygon and breaking it down into 18 short tangents, each 0.4° long of visual angle wide, and oriented from the vertical at 0°, 10°, 20°, 30°, 40°... 160°, 170°, (180°) of rotation. I viewed each moving dash separately and estimated its perceived direction of motion. Specifically, two experienced observers viewed a vertically moving dash, whose orientation was selected randomly on each trial, and adjusted the orientation of a short red line lying through the fixation point until it appeared to match the direction of the dash’s trajectory. The background grating was oriented at 45° clockwise from vertical and was viewed at an eccentricity of 16° of visual angle. Ten trials were run in random order for each dash orientation. Otherwise the setup was the same as for Experiment 1.

Results for the two observers are shown in Figure 4. The 18 tangential dashes (actually 36, since diametrically opposite tangents have the same orientation) are arranged in a circle, and the direction in which each black dash appeared to move is shown by a colored arrow through it (mean of 10 trials). Since each dash actually moved vertically, then veridical perception would have made all the colored arrows vertical. In most cases, however (red arrows), the motion paths were shifted perceptually toward the orientation of the background grating. The exception is for dashes whose slopes were steeper than the background stripes – in other words, lying between the 45° stripe orientation and the 0° vertical motion. For these, the perceived motion paths (blue arrows) were tilted counterclockwise, away from the orientation of the background stripes. These results show that the intersections drive the perceived motion of the short tilted dashes. The majority motion of these tangential components is also consistent with the results in Experiment 1 for the perceived direction of a whole circle.

Discussion

I will compare the furrow illusion first to three other illusions that look superficially similar but that I believe are unrelated to ours, and then to illusions that look different but may be related to ours.

Unrelated illusions

1. Is the furrow illusion simply a mobile form of Hering’s (1861) illusion? In this classical geometrical illusion, parallel vertical lines lying across a background of radiating lines appear to bow slightly outward, like the red vertical lines in Movie 8.

This apparent convexity may be caused by lateral inhibition between orientation detectors (Carpenter & Blakemore, 1973). Are the spot paths simply following along the parallel lines in Hering’s illusion, producing a similar result? After all, Swanston (1984) and Gogel (1977) have shown that when spots move vertically across a field of radiating lines, their paths appear to bow outwards just as static parallel lines do, while Wenderoth and Johnson (1983) found similar effects for the Poggendorff illusion. And Khuu (2012) has recently reported a kinetic Zollner illusion in which the path of a moving object appears to tilt away from oriented background lines in the same direction as the classic Zollner illusion.
Figure 4. A circle was broken up into 18 differently oriented tangential fragments. Each short black fragment moved up and down vertically across a right-oblique static grating, and two observers (SA, ND) matched its perceived axis of motion. Most of these axes were biased clockwise, toward the background (red arrows), but for steeply right-oblique lines they were biased counter clockwise (blue arrows). Results are consistent with Movie 7.

Movie 8. Vertical lines appear to bow slightly outward (the Hering illusion). The moving spots kiss the lines. Yet in peripheral vision they appear to bow strongly outward. So the furrow illusion is not a kinetic Hering illusion.
However, this cannot be the explanation of the furrow illusion. First, our illusion is far stronger. Swanston (1984) found that the paths of spots moving across a Hering radiating display were deflected by only 1.8°, whereas our illusory deflections in Experiments 1 and 2 could be as large as 45°—a factor 25 times larger. Second, our illusion goes in the opposite direction. Both the static version of the Hering illusion and Swanston’s (1984) kinetic version are instances of orientation contrast or repulsion, in which the test lines appear to be rotated away from the inducing contour. On the other hand, our illusion is an instance of orientation assimilation, in which the motion paths become more parallel to the inducing contours. Thus our effect has nothing in common with the classical geometrical illusions. This can be seen in Movie 8. The two spots move vertically up and down, kissing the (apparently convex) red lines, but in peripheral vision their motion paths appear to be strongly concave, bowing inward. This demonstrates how the furrow illusion is not only far stronger than the Hering illusion, but is also in the opposite direction.

In the past I have studied other illusory percepts from peripherally viewed objects in motion across a striped background. However, I believe that the furrow illusion is quite different from these.

2. In a moiré-related effect, Anstis, Ito, and Cavanagh (2006) found that background stripes affected the apparent speed of a rotating line. When a long line rotated at constant speed against a background of vertical stripes, it seemed to almost double in speed as it moved through the vertical. The effect was robust across a wide range of rotation rates and spatial frequencies. The authors attributed this to the movement of moiré fringes running rapidly along the length of the rotating line when it was close to vertical. The fact that this motion along the length of the line affected the perceived speed of the line orthogonal to its own length indicates a failure on the part of the visual system to fully decouple tangential from radial motion.

3. The furrow illusion is different from the “footsteps illusion” (Anstis, 2001, 2003, 2004). Movie 9 shows four squares smoothly moving in step horizontally. The top two squares, one blue and one yellow, move across vertical stripes and, in peripheral vision, they show the footsteps illusion, which makes the squares seem to stop and start in alternation, changing their perceived speeds like the two feet of a walking person (hence the name “footsteps’). Anstis attributed this illusion to the effects of contrast upon perceived speed (Thompson, 1982). When the front and back edges of the moving squares lay on black stripes, the dark blue square had low contrast so appeared to slow down, while the light yellow square had high contrast so appeared to speed up. The opposite happened when the squares lay on white stripes.

The two bottom squares, both negative lenses, move across oblique stripes and show the furrow illusion in peripheral vision, making them seem to move obliquely. In short, the footsteps illusion changes the apparent speed, while the furrow illusion changes the apparent direction.

Related illusions

I now turn to illusions that may be related to the furrow illusion, and that may offer hints about a common mechanism.

Lines that move across a grating

4. Wade, Swanston, Ono, and Wenderoth (1983) and Wade and Swanston (1984) superimposed an oblique line tilted at 45° on a vertical striped grating. When the grating expanded so that its stripes became wider, the line appeared to rotate and become more vertical. As with Cormack, Blake and Hiris’ (1992) stimulus described in the next paragraph, when the grating expands its intersections with the oblique line move upward on the upper part of the line and downward on its lower part. The “moving beads” impart an apparent rotation to the oblique line.

5. Cormack, Blake and Hiris (1992) reported an illusion that is probably related to ours. They moved a short line, tilted at 45°, horizontally across a field of vertical lines and viewed it in peripheral vision. The line appeared to move up or down vertically. They attributed their effects to the vertical motion of the moiré intersections between the moving line and the surround, which looked like a tiny row of beads; the direction in which these intersections moved accurately predicted the direction of the illusory movement. Their illusion, like ours, dramatizes differences in motion processing between the fovea and the periphery.

Drifting windows and stationary gratings, and vice versa

6. I have already called attention to the barber pole illusion, in which a grating drifts behind a slot. The perceived direction in which the grating moves is jointly determined by the orientation of the grating, and the direction in which the intersections move along the edges of the slot (Fisher & Zanker, 2001; Lalanne & Lorenceau, 2006; Stoner & Albright, 1994). In a similar arrangement that produced a different illusion, Anstis (1989) filled a stationary square window with a grating of sinusoidal bars drifting to the right. The luminance cues at the left and right edges of the window were removed by ramping the background luminance up and down, always matching the stripes as they entered and
exited the window. The result is that without the luminance cues to anchor the edges of the window, the entire window appeared to drift steadily to the right, in the direction of the stripes that it contained. De Valois and De Valois (1991) improved this stimulus by vignetting the edges to produce what they called “stationary moving Gabors,” namely stationary blurry patches through which a grating drifted to the right. This removed the need to vary the background luminance, and it gave strong illusory drift of the entire Gabor patch to the right. It also forms the basis of two illusions: Peter Tse’s “infinite regress” and Art Shapiro’s “break of the curveball.” These can be seen at:

http://www.youtube.com/watch?v=UVLLku3SJk
http://illusioncontest.neuralcorrelate.com/cat/top-10-finalists/2012/

My furrow illusion has also been posted at:
http://www.newscientist.com/blogs/ntsv/2012/05/friday-illusion-bend-an-objects-path-with-your-mind.html#more

I speculate that the furrow illusion is an inside-out version of a stationary moving Gabor. Instead of a stationary Gabor disk with stripes moving inside it, the furrow illusion presents stationary stripes with a disk moving over them. Imagine a vertically striped Gabor patch moving straight downward across a blank

surround. Within the Gabor the stripes are drifting to the right. The Gabor can be seen drifting obliquely down and to the right, as in Shapiro’s (2010) illusion. The furrow illusion is the inverse of this. The disc that moves downward is blank but it is surrounded by a grating oriented at, for example, 45°. The downward moving disc appears to drift obliquely, as if along the furrows of the grating. It is as if the motion of the stationary grating along the contour of the blank disc acts like moving grating within the moving stationary Gabors.

There is a nice symmetry between a blank spot moving over the static grating background, as in the furrow illusion, and a static grating that is only visible through a hole in a moving gray surface, as in one form of a stationary moving Gabor, or as in Shapiro’s curveball. It comes from the Fourier transform of both being the same.

The Fourier transform of the product of two patterns is the convolution of the two transforms. The Fourier transforms of the grating, and of the spot, are the same in both cases. The spot with value 1.0 on a background of 0, shows the background through the spot and nothing around it. The spot of value 0 with background 1 shows that static background but the spot is blank. The only difference between their transforms is the direct current level and some phase term. I suggest that the negative lens spot gives a particularly strong furrow illusion because it combines

Movie 9. Four squares move in parallel. Upper panel shows the footsteps illusion (Anstis, 2001). Spots appear to alternate in speed because of their contrast against the black and white stripes. Lower panel shows the furrow illusion. In peripheral vision, the squares seem to move obliquely. So the furrow illusion (direction) is different from the footsteps illusion (speed).
motion cues both within and outside the travelling spot.

The fovea can analyze local motion signals and use them to segment a scene into different moving objects, but the periphery clearly fails to do this. Why do these furrow stimuli look so dramatically different in peripheral versus foveal vision? The first possibility is a simple loss of resolution—a bottom-up stimulus failure caused by the well-known low acuity of the periphery (Anstis, 1974, 1998; Curcio & Allen, 1990). But this is unlikely, because I was unable to simulate the illusions seen in peripheral vision by simply blurring the furrow stimuli in foveal vision (not shown). Instead, it is more likely that the periphery is unable to segment motion effectively. This is a top-down failure, implying that the expensive computational machinery necessary for motion segmentation is reserved for the fovea. Experiment 4 showed that when a short moving line is viewed peripherally, its perceived direction of motion is a weighted average of (a) its actual movement, and (b) the motion of the intersections as it moves across the background stripes. These intersections perforce run along the background stripes and so will tend to bias the perceived movement toward the stripe orientation. Experiment 1 showed that the weighting given to the intersections increases with increasing eccentricity.

Thus, although the fovea can readily segment a moving target from its moving intersections with the background, the periphery seems to confound the two. Braddick (1993) has pointed out that reliable motion perception requires two conflicting processes: (a) integration of visual motion signals from neighboring locations in the visual field, which will smooth out spatial variations in velocity, and (b) differential processing of local velocity differences, so that moving objects appear sharply distinct from their background. Integrative processes lead to spreading of perceived motion, while differential processes lead to motion contrast and segmentation. Whereas integration and differentiation are kept in balance in the fovea, the furrow illusion might arise from an imbalance in the periphery between integration and differentiation, with motion integration winning out over segmentation.

The periphery may also have a problem with motion parsing. The fovea can readily discriminate between moving targets, which really are objects, and sliding intersections when one moving object overlaps another. These intersections are not themselves objects, and the fovea knows this but the periphery does not. Thus the fovea readily parses intersections as not being objects (Anstis, 1990, 2007), so that smooth pursuit eye movements can track moving objects but not moving intersections (Anstis & Ito, 2010). In the furrow illusion, the distinction between moving targets and sliding intersections breaks down and they are combined into a single illusory motion instead of being segmented into several motions.

In sum, the fovea analyzes the complex neural motion signals in our stimuli, parsing them into, for example, a striped window moving across a stationary striped grating. The moving intersections where the window crosses the grating are never treated as separate objects, but instead help to segregate the window figure from the grating background, and the intersections themselves. It is a different story for the more primitive mechanisms in the periphery, which lacks the top-down ability to make such segregations. Instead, the periphery lumps together the raw neural motion signals coming from the global window and the local intersections into a single weighted average, with the weight assigned to the intersections increasing at greater eccentricities. Thus the furrow illusion has revealed profound differences in the way that the periphery and fovea process visual motion.

Acknowledgments

This work was supported by a grant from the UCSD Psychology Department. I am grateful to Pembroke College, Oxford, for a Visiting Fellowship, and to the Humboldt Foundation for a Fellowship. Thanks to my students Sean Deering, Doreen Hsu, Katherine Hsueh, Alexis Pammit, Esther Strom, and especially Neal Dykmans for their assistance in collecting and analyzing the data, and to Patrick Cavanagh and Akiyoshi Kitaoka for valuable discussions and suggestions. This illusion was presented at the annual Vision Sciences Society illusions contest in Naples, FL in May 2012.

Commercial relationships: none.
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