Chapter 63

Low-Level Motion Illusions

Stuart Anstis

Introduction

Motion is simply the changes in an object's position over time, so in theory we could perceive motion by sensing the different positions adopted by a moving object over time and dividing the shift by the time taken. But this is not what happens. Instead, motion is a fundamental perceptual dimension, with its own specialized neural mechanisms. Detecting rapidly moving prey or predators in real time is crucial to survival, which is presumably why we have evolved specialized motion detectors; in fact Walls (1942) described motion perception as the most ancient and primitive form of vision. Reichardt (1986) has described a possible "delay-and-multiply" structure for neural motion detectors.

In apparent or stroboscopic motion, an object is flashed up successively in two (or more) different positions. A Reichardt detector will respond to such intermittent stimuli, which can also look convincingly like real movement to human observers. This is the basis of TV and movies. Watson and Ahumada (1985) have modeled human sensitivity to apparent motion. It makes sense in evolutionary terms that we should respond to intermittent, or otherwise poor-quality, stimuli and perceive them as motion, because a false positive, in which we believe we see motion although none is there, is far better than a false negative, in which we fail to notice that a predator is creeping or sprinting toward us. R. L. Gregory has compared motion perception to a lock, which must be designed to accept even ill-fitting keys such as apparent motion (otherwise it would lock out homeowners as well as burglars). Apparent motion has attracted much experimental attention, partly because the stimuli are so tractable and easy to manipulate. This chapter presents various illusions of apparent motion.

Crossover Motion

In Video IV.63-1, two parallel bars side by side, one dark and one light, switch luminances repetitively over time. (Only the luminances matter; the colors are immaterial.) This generates a stimulus that is consistent with two potential competing bar motions, one dark and the other light. The result is the bar that is seen as moving is whichever bar has the higher contrast, and this depends on the relative luminances of the bars and their surround. On a light surround, the dark bar is seen as moving (Video IV.63-1, Panel 1). On a dark surround, the light bar is seen as moving (Panel 2).

[insert Video IV.63-1]

Thus the bar differing more from the surround luminance dominates the motion percept (Anstis, 2003; Anstis & Mather, 1985; Anstis, Smith, & Mather, 2000). This is consistent with the notion of "motion energy," which depends on luminance contrast (Adelson & Bergen, 1985). But this is not the whole story. Although Panels 1 and 4 are the same except for the dark, vertical embedding bars in Panel 4, these are enough to make the light bar move in Panel 4. In other words, motion is computed in the brain after the filtering processes that are responsible for White's effect (Blakeslee, Pasieka, & McCourt, 2005; White, 1981).

Reverse Phi

Anstis (1970) and Anstis and Rogers (1975) showed that a two-frame movie of apparent motion appears to go in the reverse direction if the two frames are of opposite contrast. We termed this “reverse phi.” Video IV.63-2, kindly supplied by Patrick Cavanagh, shows reverse phi. On fixation of the central spot, the outer ring of radii appear to rotate counterclockwise and the inner ring clockwise. However, inspecting and tracking an individual radius reveals that the outer ring actually rotates clockwise and the inner ring counterclockwise. Reverse phi is consistent with Adelson and Bergen’s (1985) motion-energy model.

[insert Video IV.63-2]

Wehrhahn (2006) measured the spatiotemporal range over which reverse phi could be seen. He presented pairs of lines on a gray background. Either both were bright or both were dark (equal contrast polarity: normal phi), or one line was bright and the other was dark (opposite contrast polarity: reverse phi). Observers were instructed to indicate the perceived direction of motion. With foveal viewing, reverse phi was seen for small spatial separations (0 to 12 arcmin) and small temporal offsets (8 to 33 ms).

Bours, Kroes, and Lankheet (2009) noted that low-level contrast information in the primary visual pathway is represented in two different channels. On-center cells signal positive contrasts (light spots) and off-center cells signal negative contrasts (dark spots). They quantitatively compared motion coherence detection for regular and for reverse-phi motion stimuli. In reverse-phi motion, the contrast of a pattern flips during displacements, so sensitivity is therefore based on correlating positive and negative contrasts, whereas for regular motion it is based on correlating similar contrasts. They concluded that reverse phi is perceived through an efficient combination of signals from on and off cells. The same authors (Bours, Kroes, & Lankheet, 2007) compared reverse phi to the motion aftereffect, arguing that motion adaptation causes reduced activity during a stationary test stimulus, which by means of directional opponency leads to motion perceived in the opposite direction. Their results led them to suggest that reverse-phi motion similarly reduces the activity of low-level motion detectors.

Livingstone and Conway (2002) examined responses to phi and reverse-phi apparent motion stimuli in 118 V1 cells in alert macaques. *All* of the cells showed direction-selective responses to two-bar apparent-motion stimuli, and all of them showed reversed direction preference when the two bars were of opposite contrast. Similarly, Krekelberg and Albright (2005) found that macaques—just like humans—perceived a reversed direction of motion when a stimulus reversed contrast with every displacement (reverse-phi). This reversal of perceived direction had a clear correlate in the neural responses of MT cells, which were predictive of the monkey's behavioral decisions.

Reverse-phi recently found an unexpected real-world application that may benefit some paralyzed people. Spillmann, Anstis, Kurtenbach, and Howard (1997) noted that a random-dot field undergoing counterphase flicker paradoxically appears to move in the same direction as head and eye movements (i.e., opposite to the optic-flow field) due to reverse-phi motion caused by apparent pixel movement between successive retinal images. The reversed motion provides a positive feedback control of the display, whereas under normal conditions retinal signals provide a negative feedback. This altered polarity can invoke self-sustaining eye movements akin to involuntary optokinetic nystagmus. Lorenceau (2012) used this display because, although static, it can sustain smooth eye movements in arbitrary directions. After brief training, participants gained volitional control over smooth pursuit eye movements and could generate digits, letters, words, or drawings at will. For persons deprived of limb movement, this offers a fast, creative, and personal means of linguistic and emotional expression.

Bicycle Spokes Illusion

Video IV.63-3 shows a sectored disk that rotates clockwise. The thin spokes between the sectors appear to rotate counterclockwise, but in fact the spokes themselves never change their brightness or position. If we gaze at the center of the disk for 20 s and then stop the motion, we see a strong motion aftereffect, whose direction is clockwise, appropriate to the apparent movement of the spokes, not to the physical jumps of the sectored disk. The spokes must be thin, must lie along the edges of the sectors, and their brightness must be similar to the sectors that they abut. In Video IV.63-3 the spokes have different brightness levels, matched to the sectors they abut, and the disk rocks back and forth through one sector width. Result: All the spokes move in unison, opposite to the direction in which the sectors move.

[insert Video IV.63-3]

If one examines the grey levels of the spokes and sectors, one finds that there is one point per rotation when any given spoke first merges with the preceding sector on one side, then with the succeeding sector on the other side. This gives a motion signal that jumps across the tiny width of each spoke. In addition, the movements of the separate spokes are not simultaneous but step clockwise in time around the disk. Gestalt factors group all these sequential movements together, and the entire spoked wheel is perceived as rotating continuously. The tiny counterclockwise spoke movements are more perceptually compelling than the large clockwise sector movements and dominate in the motion aftereffect, showing that they stimulate neural motion detectors more effectively. Possibly, motion sensors with small receptive fields and tuned to small motions are more numerous or more sensitive than sensors tuned to larger motions.

Footsteps

In the footsteps illusion, a dark blue square and a light yellow square, one above the other, move smoothly together across a pattern of vertical black and white stripes. Although the squares actually move at constant speed, their perceived speed varies dramatically. The blue square alternately appears to speed up and slow down, apparently hesitating or even stopping as it traverses each spatial cycle of the grating. Conversely, the yellow square appears to slow down and speed up in counterphase to the blue square (Anstis, 2001, 2003a, 2003b).

[insert Video IV.63-4]

As illustrated in Video IV.63-4, the light yellow square appears to slow down on the white stripes, where its edges have low contrast, and speed up on the black stripes, where its edges have high contrast. Conversely, the dark blue square appears to speed up on the white stripes and slow down on the black stripes. Their apparent speeds vary in counterphase, so they look like the two feet of a walking man, one speeding up as the other slows down. Thus the apparent speed of a moving edge depends on its instantaneous contrast against the background. The color of the squares is actually irrelevant, since color has little or no input into motion (Cavanagh, Tyler, & Favreau, 1984)—the blue and yellow simply keep the squares visible even at low contrasts. The footsteps illusion is quite strong if one tracks the moving squares, but it is even stronger if one fixates the stationary cross in Video IV.63-4 so that the squares fall on the peripheral retina.

[insert Anstis Video IV.63-5]

One can show that the leading and trailing edges are more important than the lateral (top and bottom) edges of the moving bars by selectively removing parts of the background stripes. In a "railroad track" condition, the bars run along a striped "track" of the same vertical height as the stripes (Video IV.63-5, left) so that the leading and trailing edges move over the surround stripes but the lateral edges at top and bottom of the bars do not. This gives a strong illusion. In a condition that resembles a "clearing in a forest," the squares run along a clear white "track" cut through the surround grating so that the stationary stripes abut only the lateral edges, not the leading and trailing edges, of the squares (Video IV.63-5, right). Now the illusion virtually disappears. I conclude that it is the motion contrast of the leading and trailing edges, not the lateral edges, of the moving bars that produces the footsteps illusion (but see later discussion).

[insert Video IV.63-6]

In Video IV.63-6, two footsteps illusions can be placed at right angles and both applied in combination to a single square (Anstis, 2004). Two diamonds, one yellow and one blue, jump up and down through one-tenth of their own diameter, and by varying the contrast along all four of its edges, one can steer its apparent direction (not its speed). The diamond is positioned on a surround of black and white quadrants in such a way that its top-left and bottom-right edges lie on black quadrants. For the light yellow diamond on the left, these two edges have high contrast, so their motion component is subjectively magnified. The other two edges lie on white quadrants. These edges have low contrast, so their motion component is subjectively diminished. The opposite is true for the dark blue diamond on the right. As a result, the motion path appears to be tilted away from the vertical, counterclockwise for the yellow diamond and clockwise for the blue diamond.

Measurements show that the perceived direction of motion varies with the 0.6 power of the contrast ratio. This implies that if one edge of the diamond had twice the contrast of the other, the observer could cancel it out by choosing an oblique path that made the lower-contrast edge move through 1.52 times the distance of the higher-contrast edge ($2^{0.6} = 1.52$).

The simplest explanation of the footsteps illusion asserts that perceived speed varies with contrast (Thompson, 1982). Blakemore and Snowden (1999) reviewed the effects of contrast on apparent speed and found that contrast did affect perceived speed for a very wide range of moving stimuli. The footsteps illusion shows that the contrast modulation of speed can be rapid. The bars appear to vary in speed at the temporal frequency with which the bars traverse the stripes, namely 1.8 Hz. Thus the effects of contrast on speed are local in both space and time.

Each moving bar has the same width as one period of the background grating, so that its leading and trailing edges always lie on the same luminance. Thus when the front and back edges of the dark blue square lie on black stripes, these edges have lower contrast and are harder to see, so the square appears to slow down. When the blue square lies on white stripes, its edges have higher contrast and are easier to see, so the square appears to speed up. The opposite is true for the light yellow square.

However, Howe, Thompson, Anstis, Sagreiya, and Livingstone (2006) made some further observations that suggest that this explanation is too simple and that the contrast of the lateral (top and bottom) edges also plays a part. The top and bottom edges cannot add any motion information—all they can do is dilute the motion. Howe et al. suggest that the signal from each edge is weighted by its contrast, so the total perceived motion is the weighted average of the signals from each of the four edges. Thus the footsteps illusion is caused by the variations in luminance contrast at the leading and trailing edges of each bar, relative to the variations in luminance contrast at the lateral edges of the bar.

What could be the neural substrate of this dependence of perceived speed on contrast? It seems intuitively likely that motion-sensitive neurons in the brain would signal less vigorously when stimulated by moving targets whose contrast is low and respond more briskly to higher-contrast moving patterns, and Thiele, Dobkins, and Albright (2000) have recently discovered just such responses in single neurons in macaque visual area MT (see their Fig. 4). These neural findings could go a long way in explaining the footsteps illusion.

Similar illusions exist for position as well for motion. Static bars in Figure IV.63-1 show an analogous illusion of position, which is known as the Wenceslas illusion (Thompson & Anstis, 2005: see also Sunaga, Sato, Arikado, & Jomoto, 2008).

[insert Fig, IV.63-1]

The ends of the bars lie along obliques that are actually straight but appear to undulate. This is consistent with the fact that the same visual processing stream that handles motion perception is also responsible for position perception (Livingstone & Hubel, 1987).

Zigzag Motion

If a sparse pattern of randomly scattered dots makes a sequence of small jumps to the right, one naturally sees motion to the right. If it makes a sequence of jumps downward, but the jumps are “too big” for the visual system to take in, one sees not motion downward but dots jumping about randomly. There is a limit to the jump size that the visual system can tolerate.

[insert Video IV.63-7]

Now look at the set of movies embodied in the Video IV.63-7. Each video contains the identical set of moving random dots, which differ only in their relative magnifications. These are accurately labeled as x1, x2, x4, x8, x16, and x32. When they are set in motion, most people see the dots in the bottom row as mostly moving downward and those in the top row as moving to the right, with perhaps doubtful directions of motion for the x8 and x16 dots. In fact, all the dots are moving in exactly the same way (except magnified accordingly to the dot sizes). To verify this, inspect "Ziggy" from different viewing distances, especially doubtful cases such as x8. Viewed from close up, which increases the magnification, the x8 dots appear to move to the right. Viewed from further away, which decreases their magnification, the very same dots appear to move downward.

How is this possible? Each set of random dots moves rigidly, making a small jump to the right followed by a downward jump 10 times larger, in an endless alternation. So the dots are descending a very steep staircase. At small magnifications such as x1 or x2, one sees the alternating jumps, but the sideways jumps are almost too small to notice, and the overall path of the dots is almost vertically downward, toward a direction between 5 o'clock and 6 o'clock. However, for the large magnifications such as x32 or x16, the large jumps are too large for the visual system to respond to adequately, and observers notice only the rightward jumps. The large jumps exceed Dmax (Baker & Braddick 1985), correspondence is lost, and the observer loses track of which dot is which.

We conclude that, for apparent motion, less is more. Small jumps stimulate large numbers of motion-selective neurons that are tuned to small jumps and slow motion, whereas there are very few motion-selective neurons tuned to very large jumps.

The Furrow Illusion: Peripheral Motion

The retinal periphery has far less cortex at its disposal than the fovea, so it is forced to use highly economical coding. This involves poor acuity plus, it seems, an inability to combine local neural signals of motion into the percept of complete moving objects.

[insert Video IV.63-8]

Video IV.63-8 shows a spot moving vertically across an oblique grating. The spot is a “negative lens” because this gives more salient intersections, which seem to bolster the illusion. In foveal vision one sees the vertical motion veridically, but in increasingly peripheral vision the motion path seems to diverge more and more from the vertical until at large eccentricities it appears to move along a 45° trajectory, parallel to the background grating.

[insert Video IV.63-9]

In Video IV.63-9, spots move around in a circle against a background of stripes that periodically change their orientation. In foveal vision the moving spots are seen veridically, but in the periphery they appear to slide around an elliptical path that aligns with the background stripes as these alternate between horizontal and vertical.

[insert Video IV.63-10]

In Video IV.63-10, the moving horizontal bar never changes its length or width, but it appears to change its size and depth dramatically, especially in peripheral vision. In Video IV.63-11, two spots move up and down along vertical paths, kissing two static vertical red lines. Note that these lines appear to bow slightly outward in barrel distortion, owing to the Hering (1861) illusion. But in peripheral vision the paths of the spots appear to bow strongly inward, opposite of the Hering distortion.

[insert Video IV.63-11]

Thus while the Hering illusion is an instance of orientation contrast, this "furrow illusion" (Anstis, 2013) is an instance of orientation assimilation. The furrow illusion is consistent with the idea that the peripheral visual field responds adequately to the moving intersections shown in Video IV.63-8 but is unable to integrate these local intersection signals into the percept of a complete moving object (Braddick, 1993). I conclude that the retinal periphery sacrifices this top-down ability in the interests of economy.

References

Adelson, E. H., & Bergen, J. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America, 2*(2), 284–299.

Anstis, S. M. (1970). Phi movement as a subtraction process. *Vision Research*, *10*, 1411–1430.

Anstis S. (2001). Footsteps and inchworms: Illusions show that contrast affects apparent speed. *Perception*, *30*, 785–794.

Anstis, S. (2003a). Levels of motion perception. In L. Harris & M. Jenkin (Eds.), *Levels of perception.* New York: Springer.

Anstis S. (2003b). Moving objects appear to slow down at low contrasts. *Neural Networks, 16*, 933–938.

Anstis S. (2004). Factors affecting footsteps: Contrast can change the apparent speed, amplitude and direction of motion. *Vision Research, 44*, 2171–2178.

Anstis, S. (2013). Contour adaptation. *Journal of Vision, 13*(2). http://jov.arvojournals.org/article.aspx?articleid=2193818

Anstis, S., & Mather, G. (1985). Effects of luminance and contrast on direction of ambiguous apparent motion. *Perception, 14*(2), 167–179.

Anstis, S. M., & Rogers, B. J. (1975). Illusory reversal of visual depth and movement during changes of contrast. *Vision Research*, *15*, 957–961.

Anstis, S., Smith, D. R., & Mather, G. (2000). Luminance processing in apparent motion, Vernier offset and stereoscopic depth. *Vision Research, 40*(6), 657–675.

Baker, C. L. Jr., & Braddick, O. J. (1985). Eccentricity-dependent scaling of the limits for short-range apparent motion perception. *Vision Research, 25*(6), 803–812.

Blakemore, M. R., & Snowden, R. J. (1999). The effect of contrast upon perceived speed: A general phenomenon? *Perception*, *28*, 33–48.

Blakeslee, B., Pasieka, W., & McCourt, M. E. (2005). Oriented multiscale spatial filtering and contrast normalization: A parsimonious model of brightness induction in a continuum of stimuli including White, Howe and simultaneous brightness contrast. *Vision Research, 45*(5), 607–615.

Bours, R. J. E., Kroes, M. C. W., & Lankheet, M. J. M. (2007). The parallel between reverse-phi and motion aftereffects. *Journal of Vision, 7*(11), 8.

Bours, R. J., Kroes, M. C., & Lankheet, M. J. (2009). Sensitivity for reverse-phi motion. *Vision Research, 49*(1), 1–9.

Braddick, O. (1993). Segmentation versus integration in visual motion processing. *Trends in Neurosciences*, *16*(7), 263–268.

Cavanagh, P., Tyler, C. W., & Favreau, O. E. (1984). Perceived velocity of moving chromatic gratings. *Journal of the Optical Society of America, 1*, 893–899. http://jov.arvojournals.org/article.aspx?articleid=2193004

Hering, E. (1861). *Beiträge zur Physiologie: I. Zur Lehre vom Ortssinne der Netzhaut.* Leipzig, Germany: Engelmann.

Howe, P. D. L., Thompson, P. G., Anstis, S. M., Sagreiya, H., & Livingstone, M. (2006). Explaining the footsteps, belly dancer, Wenceslas and kickback illusions. *Journal of Vision, 6*(12), 1396–1405.

Krekelberg, B., & Albright, T. D. (2005). Motion mechanisms in macaque MT. *Journal of Neurophysiology* 93(5), 2908-21. Epub 2004 Dec 1.

Livingstone, M., & Conway, N. (2002). Responses of V1 neurons to reverse phi stimuli. *Journal of Vision, 2*(7), 127.

Livingstone, M. S., & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience, 7*, 3416–3468.

Lorenceau, J. (2012). Cursive writing with smooth pursuit eye movements. *Current Biology, 22*(16), 1506–1509.

Reichardt, W. (1986). Processing of optical information by the visual system of the fly. *Vision Research, 26*, 113–126.

Spillmann, L., Anstis, S., Kurtenbach, A., & Howard, I. (1997). Reversed visual motion and self-sustaining eye oscillations. *Perception, 26*(7), 823–830.

Sunaga, S., Sato, M., Arikado, N., & Jomoto, H. (2008). A static geometrical illusion contributes largely to the footsteps illusion. *Perception, 37*(6), 902–914.

Thiele, A., Dobkins, K. R., & Albright, T. D., (2000). Neural correlates of contrast detection at threshold. *Neuron, 26*, 715–724.

Thompson, P. (1982). Perceived rate of movement depends on contrast. *Vision Research, 22,* 377–380.

Thompson, P., & Anstis, S. (2005). Retracing our footsteps: A revised theory of the footsteps illusion. *Journal of Vision*, *5*(8), 929.

Walls, G. (1942). *The vertebrate eye and its adaptive radiation.* Bloomfield Hills, MI: Cranbrook Institute of Science.

Watson, A. B., & Ahumada, A. J. Jr. (1985). Model of human visual-motion sensing. *Journal of the Optical Society of America A, 2,* 322–341.

Wehrhahn, C. (2006). Reversed phi revisited. *Journal of Vision, 6*(10), 2.

White, M. (1981). The effect of the nature of the surround on the perceived lightness of grey bars within square-wave test gratings. *Perception, 10*(2), 215–230.

Figure IV.63-1.

The Wenceslas illusion—a static form of the footsteps illusion. The straight oblique row of yellow dashes looks curvy.

Video IV.63-1.

A light and a dark bar exchange places. The bar with the higher contrast against the background is the one that appears to move—the dark blue bar on the light surround in (1), the light yellow bar on the dark surround in (2). When the bars are embedded in stationary stripes, results are consistent with White’s effect—the light yellow bar embedded in a dark stripe appears to move in (3), and the dark blue bar embedded in a light stripe in (4).

Video IV.63-2.

In this video, made by Patrick Cavanagh, the radial spokes reverse their luminance polarity on every frame. This makes them appear to move opposite to their physical displacement. During fixation on the central spot, the outer radii appear to rotate clockwise and the inner radii counterclockwise. If the motion is then stopped, the outer radii show a counterclockwise aftereffect of motion and the inner ones show a clockwise aftereffect. But if we look directly at an outer radius, we can see that it is actually moving around counterclockwise. Reverse phi is consistent with Adelson and Bergen's (1985) model of motion energy.

Video IV.63-3.

The thin grey spokes never change their luminance or position, but when the sectors jump round clockwise in apparent motion, the spokes appear to rotate counterclockwise. If the motion is then stopped, a clockwise aftereffect of motion is seen—appropriate to the movement of the spokes, not of the sectors.

Video IV.63- 4.

The two squares move together at constant speed. But fixate the red cross and the two squares seem to speed up and slow down in alternation, like the two feet of a walker. They appear to move fast when they have high contrast and slowly when they have low contrast.

Video IV.63-5.

The two bars on the left that run along a "railroad track" show the footsteps illusion, while the two bars on the right that run along a "forest clearing" do not.

Video IV.63-6.

Both diamonds move vertically, but look midway between them and their motion axes appear to be inclined outward. The higher-contrast edges dominate over the lower-contrast edges.

Video IV.63-7.

All the moving random-dot stimuli are identical, except that they are shown at magnifications of x1, 2, 4, 8, 15, 32. Yet the smaller magnifications seem to move downward, while the identical stimuli at higher magnifications appear to move to the right. The reason is each random-dot field makes small horizontal jumps, alternating with large downward jumps, as if descending a steep staircase. At small magnifications, these motions are seen veridically. But at large magnifications, the large jumps give only weak signals of motion, and the visual system loses track of which dot is which. The result is only the small rightward jumps are visible at the highest magnifications.

Video IV.63-8.

A striped disk moves vertically up and down across oblique stripes. In foveal vision this is seen veridically. But at increasing retinal eccentricities, the disk's path looks increasingly oblique, until in far peripheral vision the disk appears to move parallel to the stripes.

Video IV.63-9.

A circle of eight disks rotates clockwise against a background of stripes that are alternately vertical and horizontal. In foveal vision this is seen veridically. But in peripheral vision the disks appear to slip and slide around an ellipse that is roughly parallel to the background stripes.

Video IV.63-10.

The moving horizontal bar is always the same size. But it appears to change dramatically in its apparent length and depth, even in foveal vision but particularly in peripheral vision.

Video IV.63-11.

In the Hering (1861) illusion the red vertical lines are parallel but appear to bow slightly outward like the sides of a barrel. But the Furrow illusion is *not* simply a dynamic version of this. When the striped disks move up and down, always kissing the red lines, they appear to bow strongly inward (pincushion distortion), opposite to the direction of the Hering illusion. The Hering illusion shows orientation contrast while the Furrow illusion shows orientation assimilation.