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Moving objects appear to slow down at low contrasts

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Abstract

Moving cars give the illusion of slowing down in foggy conditions, because low contrast reduces perceived speed. A grey square that drifts horizontally across a surround of black and white vertical stripes appears to stop and start as it crosses each stripe, because its contrast keeps changing. A moving square whose vertical and horizontal edges have different contrasts will show illusory distortions in perceived direction. Contrast also affects the apparent amplitude and salience of back-and-forth apparent motion. Finally, a line of black and white dots on a grey surround moves in illusory directions, because of a mismatch in the contrasts along and across the dotted line. Thus, motion signals in the early parts of the visual system are profoundly altered by stimulus luminance and contrast. This suggests that motion is coded by the relative firing rates of neural channels tuned to fast and slow motion, with contrast-dependence being a motion analog of the Bezold–Brucke hue shift.

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1. Introduction

Motion perception allows us to keep track not only of moving objects, but also of our own movements through space (Gibson, 1950; Nakayama, 1985). It also provides valuable raw material for neural modelers. One might guess that motion is a recent evolutionary development, but in fact, as Walls (1942) pointed out, motion perception is one of the most ancient and primitive forms of vision. A hungry frog will starve to death on a heap of plump dead flies, but if one of these flies is jerked around on a fishing line in front of the frog, it will immediately snap up the insect and eat it up. Motion plays a crucial part in the constant arms race between predators and prey. Lions and gazelles have excellent vision for motion, gazelles so that they can see the big cats creeping up on them and predators so that they can track the hasty flight of their prey. Lions will stalk their prey stealthily making minimal movements, and young gazelles will often freeze as a defensive measure, in an effort to outfox the motion perception of the other species.

The range of speeds that we can see is an impressive 1000:1. The moon's slow sail across the sky is too slow, but only just too slow, for us to see. It moves through 360° of visual angle in 24 h, or 0.25 min arc per second of time. Stated differently, it moves through its own diameter in a time of 2 min. The fastest speed we can resolve is about a thousand times faster, depending on illumination and adaptation.

We can run no faster than about 10 mph. Modern cars have increased this speed 10-fold, to a maximum of 100 mph. Nowadays we could hardly live without cars—but it is easy to die in them, since the stopping distance of a vehicle goes up with the square of the velocity, from 4 ft at 10 mph to a frightening 400 ft at 100 mph. And that is on a good dry road in ideal conditions! No wonder that car accidents are the leading cause of death for people between the ages of 5 and 44. One cause of accidents that can be avoided is driving too fast in the fog. For example, on November 4th, 2002, nearly 200 cars and big-rig trucks collided in heavy fog on the Long Beach Freeway, injuring dozens of people, including nine critically. A mangled mess of cars, vans and big-rig trucks shutdown the freeway, about 25 miles south of Los Angeles, for nearly 11 h. Authorities said some motorists were driving too fast for the foggy conditions. Estimates are that cars were moving at 25–35 mph. In the state of Wisconsin alone, about 1200 vehicle accidents occur each year when dense fog is a factor. This results in about 16 deaths and 700 injuries. Nationally, an average of 950 people die in winter-related road accidents each year. Many of these could be avoided.

What can be done? Often fog simply makes other cars invisible. Motorists do not see them and crash into them, and visual science can do nothing about this, although IQ testing

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might help. But at other times fog makes other cars somewhat less visible without hiding them completely, and other motorists misjudge them. Here visual science can perhaps make a useful contribution. Many anecdotes suggest that during a fog, other cars and also one's own car appear to move more slowly than their actual speeds. My recent findings attribute both phenomena to the fact that objects *appear to move more slowly when they are low in contrast*, as they are in a fog. (Note: 'Contrast' refers throughout this paper to the measurable stimulus property of differences in luminance. It does not refer to the 'simultaneous contrast', or illusory brightness induction, that is caused by lateral inhibition.) In a fog, other cars are reduced in contrast so they appear to be going more slowly than they really are. Also, a driver judges his own speed largely by visual cues from the landscape as it slides past him, often viewed through the side windows of the car in peripheral vision (Anstis, 1998). Fog reduces the contrast of the passing landscape, so it appears to slip by him more slowly and he believes that he himself is driving slowly.

2. Results

It is known that apparent speed varies with contrast (Stone & Thompson, 1992; Thompson, 1982; Thompson & Stone, 1997; Thompson, Stone, & Swash, 1996). I have found some novel and direct demonstrations of these illusory changes in apparent speed. Two squares, one of them light grey and the other one dark grey, moved horizontally at constant speed across a stationary surround of vertical stripes (Fig. 1). Each square was exactly two stripe widths in diameter, so that its front and back edges always lay on the same color (black or white). I found that the two squares appeared to stop and start in alternation, depending upon their local contrast. When the dark grey square lay on white stripes it had high contrast (dark versus white) and appeared to speed up momentarily. When it lay on black stripes it had low contrast (dark versus black) and appeared to slow down. The opposite was true for the light grey square. Consequently the two squares appeared to speed up and slow down in alternation, like a pair of walking feet. So I called this the 'footsteps illusion' (Anstis, 2001, 2003). In this display you see the contrast altering the apparent speed in real time. The illusion is very strong, particularly in peripheral vision, where the squares can appear to stop dead and re-start, about once every second or so.

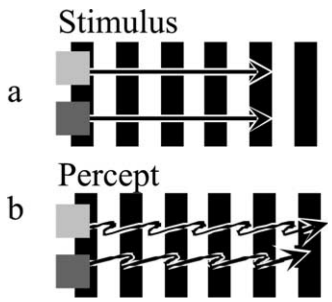

Fig. 1. The footsteps illusion. A light and a dark grey square move together at constant speed across stationary stripes. As they alternately change from high to low contrast, they seem to alternate between high and low speeds.

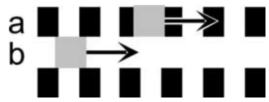

Fig. 2. The upper square shows the footsteps illusion because its leading and trailing edges change contrast as it traverses the stripes. The lower square shows no illusion because only its irrelevant top and bottom edges change in contrast.

I examined which parts of the stimulus cause the footsteps illusion. I moved the squares along a narrow horizontal 'railway track', so that only the front and back edges of the squares contacted the stripes. The illusion was still present in full force (Fig. 2a). Then I moved the squares along a narrow 'clear track' cut through the stripes, so that only the top and bottom edges of the squares contacted the stripes. The illusion vanished (Fig. 2b). Thus, motion computations are local to the moving edges (Fig. 3).

Contrast affects not only smooth real movement, but also stroboscopic apparent movement. A black square and a white square, one above the other, jumped back and forth horizontally through a distance of one-quarter of the square's width. On a dark surround, the white square appeared to jump through a greater distance, because it had a higher contrast. On a light surround, the black square appeared to jump through a greater distance, because now it was the square with higher contrast. This was particularly true in peripheral vision. Here the contrast affects the apparent amplitude of motion, not its apparent speed. This was a true motion illusion; it was not simply a misperception of the position of the two end-points of the motion, because separate experiments showed that the judged positions of stationary squares were not affected by contrast.

Here is another case of contrast affecting stroboscopic as well as real motion. In Fig. 4, two vertical bars, one black and one white, lie side by side but not touching on a grey

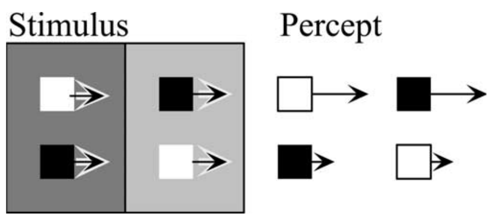

Fig. 3. All squares jump back and forth through exactly the same distance. However, the top squares have higher contrasts against their surrounds, so they appear to move further than the bottom squares.

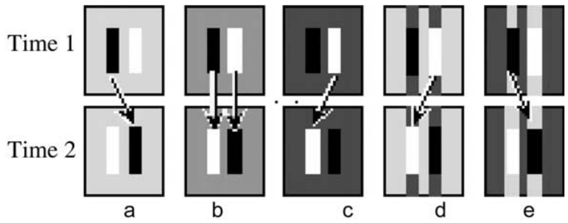

Fig. 4. A black and a white bar abruptly exchange luminances. On a light grey surround (a), the black bar appears to jump, but on a dark grey surround (c), the white bar appears to jump. A mid-grey surround (b) gives little motion. Embedding bars (d) and (e) influence motion more than the rest of the surround does. Thus the bar with the higher contrast against the surround appears to jump.

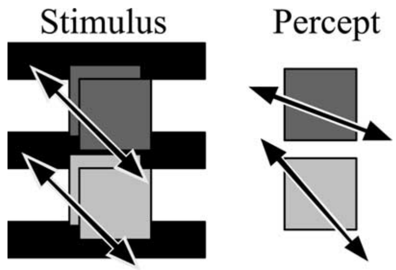

Fig. 5. Squares jumping obliquely. On left, the positions of the squares at times $T1$, $T2$ are shown overlapping. Actual jumps were oblique at 45°, but different contrasts on vertical and horizontal edges altered the perceived motion paths (right).

surround. Suddenly the black bar becomes white and at the same instant the white bar becomes black. What will this look like? Will an observer see the two bars simply exchanging luminances? Or will the black bar appear to jump to the right? Or the white bar to the left? Or will both bars appear to jump past each other in opposite directions? It turns out that the result depends upon the luminance of the surround (Anstis & Mather, 1985; Anstis, Smith, & Mather, 2000; Mather & Anstis, 1995). On a light grey surround, the black bar appears to jump, but on a dark grey surround, the white bar appears to jump. In other words the bar with the higher contrast against the surround appears to jump. I showed, in experiments that I shall not detail here, that the two bars generated motion signals in opposite directions, but the stronger signal predominated in a winner-take-all outcome. An analogous case would be two overlapping, superimposed gratings of vertical bars drifting in opposite directions. Both gratings have the same speed and spatial frequency. If they also have the same contrast, an observer sees a counterphase grating that flickers in place. However, if (say) the rightward grating has a higher contrast, one sees next motion to the right. Once again the two opposed motion signals compete and the stronger one wins.

When the black and white bars in Fig. 4 exchanged luminances, the perceived motion vanished when the surround was mid-grey, at the arithmetic mean of black and white. This mid-grey gave the black and white bars equal Michelson contrasts, defined as $(\text{Max} - \text{Min})/(\text{Max} + \text{Min})$. In the footsteps illusion described earlier, the illusory accelerations also disappeared when the moving square was mid-grey, at the arithmetic mean of the black and white stripes. This meant that its Michelson contrast stayed the same as it crossed the stripes. Interestingly, only the amount of contrast mattered, not its polarity.

Contrast-based motion illusions can be applied to different parts of a single moving object. Two squares, one light grey and the other dark grey, jumped back and forth obliquely, at 45° from the vertical, across a horizontally striped surround (Fig. 5).

The squares were placed so that their top and bottom edges contacted black stripes, whereas their left and right edges contacted white stripes. So the dark grey square's top and bottom edges contacted a black surround and had low contrast. This reduced the effective vertical component of the dark square's oblique motion. Its left and right edges contacted a white surround and had high contrast. This enhanced the horizontal component of its motion. The result was that the dark square appeared to move back and forth between 10 o'clock and 4 o'clock. The opposite was true for the light square, which appeared to move back and forth between 11 o'clock and 5 o'clock. So contrast could alter the perceived direction of motion, as well as its perceived speed. Fortunately this does not usually happen on the road. It would be as if painting one fender of a car black and the other fender white made the whole car appear to move obliquely.

Ends of lines. I found two extreme cases in which different parts of an object move differently: the ends of a moving line are far more important in determining its seen motion than the middle part.

(1) In the well-known *aperture problem*, a long straight line moves behind a circular aperture. The motion of the middle of the line is ambiguous; usually the ends of the line reveal its true motion, but when the aperture hides the end-points the motion remains ambiguous (Adelson & Movshon, 1982). I have found that an aperture problem can arise even without an aperture! A new *peripheral-oblique* phenomenon shows that motion perception is more contrast-dependent in the periphery than in central vision. An oblique grey line oscillated up and down vertically on a black surround, at a rate of 1 Hz and at a retinal eccentricity of 15°, during strict fixation. Since the ends and the middle of the line were all equally visible, the line was correctly seen as moving vertically. However, if the line was made really dim its trajectory appeared to veer round toward the oblique, and by the time it was just above threshold it appears to move at 45°, at right angles to its own orientation. What mattered was the stimulus contrast of the line, not its luminance. This was shown with the photographic negative of the previous setup. A grey line on a white surround was seen correctly, but as it was made lighter and less clearly visible, it also changed its perceived direction of motion

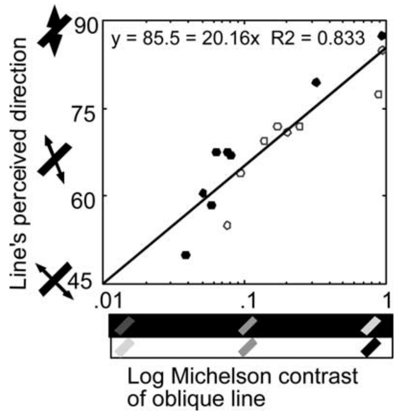

Fig. 6. An oblique peripheral line moving up and down was seen correctly at high contrasts. At low contrasts its ends became invisible and it seemed to move at 45°, at right angles to it own length. Results were the same for a white surround (filled symbols) and a black surround (open symbols).

towards 45°. So a dark line on a black surround, and a light line on a white surround, both showed the same illusory motion (Fig. 6). The reason is that at low contrast and in peripheral vision the terminators start to lose visibility, and with it their ability to influence the perceived direction of motion. The aperture problem can be solved only if the terminators reach some criterion level of contrast—otherwise they are ignored. Eccentricity makes the terminators less visible than the line center; perhaps they are under sampled and stimulate only one receptive field whilst the central portion of the line stimulates a whole row of receptive fields.

(2) Conversely, I pitted the contrast of the ends and of the middle of a line against each other by combining crossover motion with *White's effect* (1979, 1981). We saw in Fig. 4a and c that when a light and a dark bar exchanged luminances on a spatially uniform surround, motion was assigned to the bar that differed most from the surround. I now applied different surrounds to different parts of the bars, by embedding each bar in a long vertical dark line on a light surround, or vice versa (Fig. 4d and e). A titration method showed that the embedding lines were three times as important as the surround in driving apparent motion. For example, lightening (or darkening) the embedding lines by 0.1 log units shifted the motion balance in favour of the darker (lighter) test bar, and the surround had to be darkened (lightened) by as much as 0.3 log units to redress the balance. I conclude that motion strength is determined by contrast of the test bars against the embedding lines, not against the rest of the surround.

Here is another example of contrast affecting perceived direction (Cavanagh & Anstis, 2002; Ito & Anstis, 2002 and unpublished). Fig. 7a shows two lines forming a shallow V. Put a pen tip at the tail of the arrow and move the pen to the left, toward the tip of the arrow. Or simply hold the pen tip stationary and move the page to the right under the pen. Gaze at the pen tip but attend to the two lines. They will

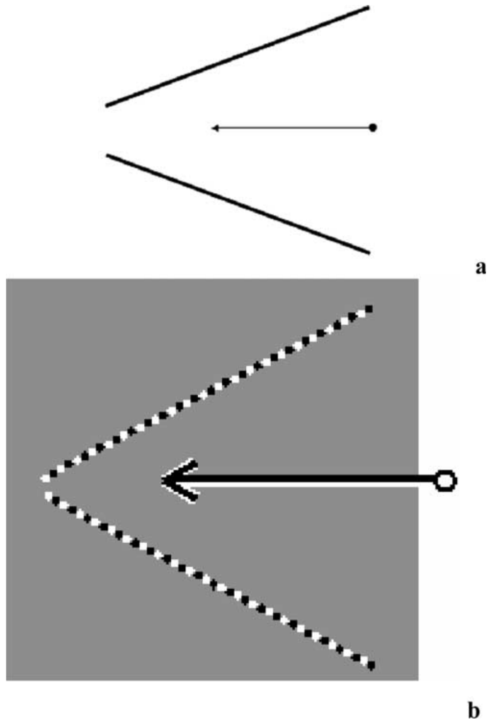

Fig. 7. (a) Move a pen tip to the left along the arrows; black lines appear to converge inwards, but (b) dotted lines appear to move outwards.

appear to move closer together. This is not surprising because the lines really are closer to the fovea when the pen is shifted to the left. But now do the same for the two dotted lines in Fig. 7b. These lines appear to move *outwards*.

Fig. 8 shows the reason. When a long, straight line moves, its motion is ambiguous because the component of

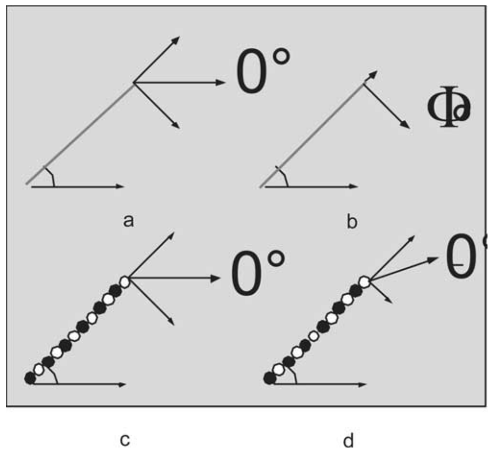

Fig. 8. (a) When an oblique black line moves horizontally to the right (top arrow), its motion can be decomposed into one vector along the line and another at right angles to the line (oblique arrows). (b) Since a straight line is invariant under motion along its axis, the vector along its axis is not perceived. Only the orthogonal vector is seen, and the line appears to move at right angles to its own length in direction Ø. (c) A moving dotted line can be similarly decomposed into two vectors. (d) Now the vector along the axis is seen, or even overestimated, whilst the orthogonal vector is underestimated. Motion is perceived in a direction *O*, closer to the line's orientation.

motion along its length produces no changes at the retina. Thus a straight line is invariant under motion along its own length. If a 45° oblique black line moves horizontally to the right, its motion can be decomposed into a component along its length, which is not seen, and a component at right angles to its own length. Result: The line is perceived as moving obliquely down, at right angles to its own length (Fig. 8a and b). But when a 45° oblique dotted line moves to the right, its motion can again be decomposed into two components, one along its length and the other at right angles to its own length. For the dotted line, however, the contrast along its own length (between black dots and white dots) is about twice as high as the contrast at right angles to its own length (between black dots and the mid-grey surround, or between white dots and the mid-grey surround). So the motion along the line's length, instead of being invisible, is highly visible and high in contrast, so that it predominates over the motion across the line (Fig. 8c and d). The resulting perceived motion is the vector sum of these two components, and the line is perceived as moving almost parallel to its own length.

3. Discussion

All these contrast-based illusions of motion are compatible with models of motion coding that use velocity-tuned neural units, each tuned to a different range of speeds. Such units have been found in primate MT (Allman, Miezin, & McGuinness, 1985; Maunsell & Van Essen, 1983; Mikami, Newsome, & Wurtz, 1986; Zeki, 1974). Let us briefly compare motion coding to color coding. The retina contains three types of cones, namely R, G and B, sensitive, respectively, to long, medium and short wavelengths. The cones have broad, overlapping spectral sensitivity curves, so that a given wavelength stimulates more than one cone type, and each wavelength is coded neurally as the ratio of firing in different cones. For instance, a particular yellow might stimulate the R and G cones equally. If the luminance of the yellow increased, then so would the firing rate of the R and the G cone—in theory by an equal amount, so that the firing ratio R/G would successfully encode a particular yellow despite changes in luminance. However, this compensation for luminance changes is not perfect, and in fact hues do tend to change their appearance, moving toward yellow and blue, and away from green and purple, as the luminance is increased (Fry, 1983). This is the Bezold–Brucke illusion (Pridmore, 1999) and probably reflects a nonlinearity in which the firing rate in one cone, or more likely in one opponent-color pathway, increases more rapidly with luminance than another. The contrast illusions described in the present paper may simply be motion analogs of the Bezold–Brucke effect, in which a medium velocity might stimulate a slow and a fast detector equally. In a perfect system, changes in stimulus contrast would increase the firing of a slow and a fast detector by exactly the same amount, so that the firing ratio Fast/Slow would successfully encode a particular medium speed despite changes in contrast. However, this compensation for changes in contrast may not be perfect. I suggest that the apparent increases in speed with contrast arise because responses of fast detectors grow more rapidly with contrast than do slow detectors. Note that colors show small illusory changes with luminance, whereas in our displays motion shows large illusory changes with contrast.

A series of papers by Grossberg and his colleagues (Chey, Grossberg, & Mingolla, 1997, 1998; Grossberg & Rudd, 1992) offer a far more sophisticated approach along these lines. Their neural network model represents visual velocity as a distributed population code of speed-tuned units, in which the size of a unit's receptive field is correlated with its preferred speed. A key aspect of their model is that larger cells need to have higher thresholds, and that they compete in specific, albeit simple, ways. Their multiple broadly speed-tuned detectors explain a great deal of data about speed estimation and discrimination, and in particular the relationship between contrast and perceived speed. The authors successfully simulated data from Thompson et al. showing that higher contrast increases perceived speed. Moreover, their model can be extended to cover motion grouping and vector coding of motion (Grossberg, Mingolla, & Viswanathan, 2001).

Drive carefully in the fog.

Acknowledgements

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