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Footsteps and inchworms: Illusions show that contrast affects apparent speed

Stuart Anstis
Department of Psychology, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0109, USA; e-mail: sanstis@ucsd.edu
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Abstract. A horizontal grey bar that drifts horizontally across a surround of black and white vertical stripes appears to stop and start as it crosses each stripe. A dark bar appears to slow down on a black stripe, where its edges have low contrast, and to accelerate on a white stripe, where its edges have high contrast. A light-grey bar appears to slow down on a white stripe and to accelerate on a black stripe. If the background luminances at the leading and trailing edges of the moving bar are the same, the bar appears to change speed, and if they are different the bar appears to change in length. A plaid surround can induce 2-D illusions that modulate the apparent direction, not just the speed, of moving squares. Thus, the motion salience of a moving edge depends critically on its instantaneous contrast against the background.

1 Introduction

A stationary surround can profoundly affect our perception of moving objects. The motion of a slowly moving single point of light is difficult to see in a completely dark room. But add a single stationary point of light, and the threshold for seeing motion falls by a factor of five or ten (Tyler and Torres 1972). In other words, relative motion is far easier to see than absolute motion (at least in foveal vision: see McKee et al 1990), and as well as being easier to see it also looks faster. For instance, it is said that when a horseman rides at constant speed across a field and into the trees, he seems to be moving much faster when he is among the trees, which act as stationary landmarks. In general, landmarks decrease the motion detection threshold (Aubert 1886; Leibowitz 1955; Mates 1969; Tyler and Torres 1972; Legge and Campbell 1981; Johnson and Scobey 1982; Bonnet 1984). In addition, objects moving at above-threshold speeds appear to move faster when the stationary background is textured rather than featureless (Gogel and McNulty 1983; McKee and Smallman 1998; Blakemore and Snowden 2000). In this paper I show that nonuniform surrounds can cause the instantaneous apparent speed to vary from moment to moment. Specifically, an object that moves across a striped surround can appear to stop and start as it crosses each stripe. I shall show that these local interactions between object and surround depend critically upon their relative luminances.

I noticed that when a horizontal grey rectangle moved at constant speed across a stationary vertical grating of black and white stripes the rectangle appeared to vary in speed, apparently hesitating or even stopping as it traversed each spatial cycle of the grating. The effect was moderate in foveal vision, but was robust and unmistakable if the pattern was optically blurred, or if it was viewed in peripheral vision. An artist's impression of this illusion is shown in figure 1. A light-grey rectangle and a dark-grey rectangle drift to the right at the same speed across a grating of vertical bars (figure 1a). Both move at the same uniform speed, but each appears to hesitate, or even stop and start, on every spatial cycle. As illustrated in figure 1b, the light rectangle appears to slow down on the white stripes and speed up on the black stripes. Conversely the dark rectangle appears to speed up on the white stripes and slow down on the black stripes. Their apparent speeds vary in counterphase, so they look

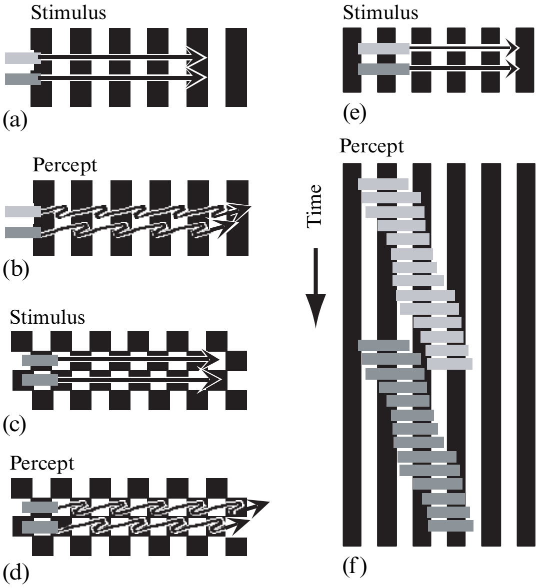


Figure 1. (a) A light-grey and a dark-grey horizontal bar moving exactly in step across a vertically striped surround. This was the stimulus for experiment 1. (b) Subjective appearance of this stimulus. The edges of the light bar appear to speed up on the black stripes and to slow down on the white stripes. The edges of the dark bar appear to speed up on the white stripes and to slow down on the black stripes. Consequently the two bars appear to stop and start in alternation, like the two feet of a walker. (c, d) The contrast of the bars matters, not their luminance. On a checkerboard, two identical dark-grey bars each appear to speed up on the white squares and slow down on the black squares. Thus they appear to stop and start in alternation, since they lie on squares of opposite polarity. (e, f) Shows the 'inchworm' effect using a different convention. Time runs down the page. When the bars are three stripes wide, their leading and trailing edges have different contrasts: when the leading edge is on a black surround the trailing edge is on white, and vice versa. This was the stimulus for experiment 2. Result: the bars appear to change in length as they move along, like inchworms.

like the two feet of a walking man, one speeding up as the other slows down. I call this the 'footsteps' illusion.

1.1 *Contrast, not luminance*

The relative luminance between bar and surround, rather than the absolute luminances, causes this effect. Figure 1c shows that when two *identical* dark-grey bars drifted over a black/white checkerboard, they appeared to stop and start in counterphase, like a pair of footsteps (figure 1d), because their local backgrounds differed—when one bar lay on black squares the other bar lay on white squares. So although the two bars had the same luminance they differed in contrast against the surround, and this sufficed to give the footsteps effect.

1.2 *Contrast, not polarity*

When grey bars move across black and white stripes they change their polarity as well as their contrast. Polarity might conceivably be relevant, since in some circumstances it can alter or even reverse perceived velocity (Anstis 1970; Anstis and Rogers 1975). However, polarity reversal is not necessary for the footsteps effect. I noted informally that when a black and a white horizontal bar moved across light-grey and dark-grey vertical stripes the footsteps illusion was still present, even though the bars never changed their polarity. This shows that a change of figure–ground contrast is sufficient to modulate perceived speed.

2 Experiment 1: The 'footsteps' illusion

2.1 *Method*

In all the experiments the observers fixated on a point on a computer-controlled monitor screen from a distance of 57 cm in a dimly lit room (Anstis 1986; Anstis and Paradiso 1989), and the stimuli moved along a horizontal path that lay 5° above the fixation spot. The display, which was similar to figure 1a, comprised a stationary black and white grating of vertical stripes, with a square-wave luminance profile. The spatial frequency was 0.79 cycle $\deg^{-1}$ (1 cycle = 1.26 deg of visual angle). A horizontal grey bar of height 0.63 deg and horizontal width 1.26 deg moved smoothly and repetitively to the right across this striped background at a velocity of 2.25 deg s^{-1}. Note that the moving bar was exactly two stripe widths (one grating period) in horizontal extent. Thus its left and right hand edges both lay on the same background luminance at all times. Five observers were run.

Luminance values were as follows. The maximum screen luminance was 68.5 cd m^{-2}, which I designate as 100% or 'white'. All luminances are expressed as percentages of this white. The drifting bar was set to one of ten different luminances on different trials, namely 4.3%, 8.4%, 13.5%, 19.6%, 28.4%, 35.9%, 46.8%, 58.6%, 71.4%, 85.0%, and 100%. These grey levels, which ranged from 'black' to 'white', were presented three times each in random order. The observer's task was to rate the apparent smoothness of the bar's motion. If it appeared to move at constant velocity at all times it was to be given a rating of 10. If it appeared repetitively to come to a complete halt it was to be given a rating of 0. If it appeared to fall to half speed its rating was 5, and so on. Thus a rating of 10 represented no illusion (smooth movement), and a rating of 0 represented a maximum illusion of strongly intermittent movement.

The point of interest was the contrast of the moving grey bar, or more specifically the ratio of its contrast when it lay on a white stripe to its contrast when it lay on a black stripe. The greater this contrast ratio, the greater the expected illusion. Contrast is typically measured either as a Weber fraction [$\mathrm{d}I/I$, which is equivalent to $(L_{\max} - L_{\min})/L_{\min}$] or else as a Michelson contrast [$(L_{\max} - L_{\min})/(L_{\max} + L_{\min})$]. For reasons that will become apparent in section 6, I used Weber fractions to derive the contrast ratio, as follows.

The Weber contrast $\mathrm{d}I/I$ of a white stripe against a grey bar is equal to $(L_\mathrm{w} - L_\mathrm{g})/L_\mathrm{g}$, where L_b, L_w, and L_g refer to the luminance of the black stripes, white stripes, and grey bar, respectively. The white stripe is a spatial increment compared with the grey bar, so this expression is positive. The Weber contrast $\mathrm{d}I/I$ of a black stripe against a grey bar is equal to $(L_\mathrm{b} - L_\mathrm{g})/L_\mathrm{g}$. The black stripe is a spatial decrement compared with the grey bar, so this expression is negative.

Consider the change in the contrast of the bar as the bar moves from black stripes to white stripes, in other words the contrast ratio (CR):

$$\mathrm{CR} = \mathrm{abs}\frac{(L_\mathrm{b} - L_\mathrm{g})/L_\mathrm{g}}{(L_\mathrm{w} - L_\mathrm{g})/L_\mathrm{g}} = \mathrm{abs}\frac{L_\mathrm{b} - L_\mathrm{g}}{L_\mathrm{w} - L_\mathrm{g}}\,,$$

where 'abs' ensures that the expression is positive. The contrast ratio is simply the ratio between 'difference between black stripe and grey bar' and 'difference between white stripe and grey bar'. For a mid-grey bar with a luminance that is that is halfway between black and white, the contrast ratio approaches unity. The contrast of such a bar will not change as it moves over the stripes and one would expect no footsteps illusion. When the ratio is shifted away from unity in either direction (dark-grey or light-grey bar), the contrast of the bar will change more as it moves over the stripes and the illusion should increase. As the bar becomes black, or white, it is trivially true that the contrast ratio becomes very large and the illusion should reach a maximum.

This must be so because with zero contrast of the bar relative to the ground one would not expect to see any movement.

2.2 *Results*

Results are shown in figure 2. The Weber contrast ratio of the grey bars is plotted along the abscissa of figures 2 and 3. The ratings have been multiplied by minus one in order to plot increasing strength of the illusion upward in the graph. Figure 2 shows that the illusion was maximal, with the bar slowing to an almost complete standstill, when the bar was almost black or almost white. At mid greys the illusion was reduced but still present. In other words, the bars that changed most in luminance contrast showed the greatest changes in apparent speed.

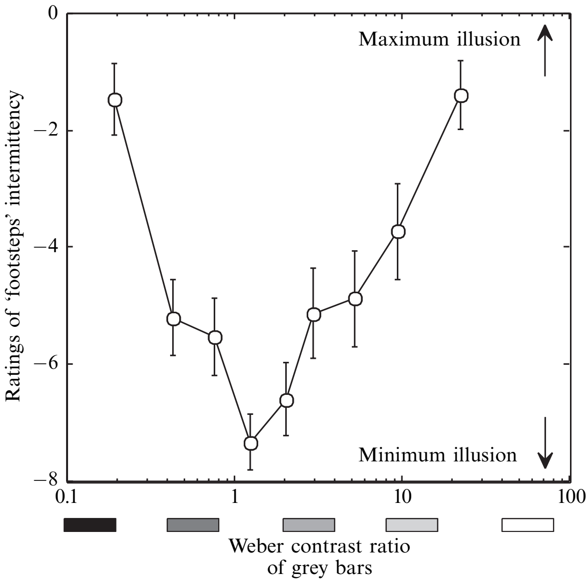


Figure 2. Results for experiment 1 on the 'footsteps' illusion. Ratings of intermittent motion of a horizontally drifting bar as a function of its luminance (mean ±1 SE for five observers). Data are plotted so that maximum illusion is at the top of the graph. Lines are fitted by eye. The bar was 1 spatial period in horizontal extent. The surround was a stationary black and white grating. Apparent intermittency was greatest for black and for white drifting bars, and minimal (though still present) for mid-grey bars that lay close to the arithmetic (not geometric) mean of the black and white stripes.

3 Experiment 2: The 'inchworm' illusion

In experiment 1 the horizontal width of the drifting bars was equal to one spatial period, that is, the width of two vertical stripes, so that the leading and trailing edge of a bar always lay on the same background luminance. The bars were now made three stripes wide (figures 1e and 1f). Consequently the leading and trailing edges appeared to speed up and slow down in alternation, and the whole bar appeared to change in length and to inch its way along in fits and starts like a caterpillar or inchworm. I call this the 'inchworm' illusion. For a light-grey bar, when the leading edge was on a white stripe it had a low contrast and appeared to slow down, while at the same time its trailing edge was on a black stripe, so this had a high contrast and appeared to speed up. Consequently the rear edge tended to partially catch up with the front edge and the bar appeared to contract. Conversely, when the leading edge was on a black stripe it appeared to speed up, while the trailing edge was on a white stripe and appeared to slow down, causing the bar to expand in apparent length. Corresponding arguments apply to a dark-grey bar (figure 1f).

3.1 *Method*

The display and procedure were much the same as before except that the grey bars were now three stripes wide, instead of two. A standard dark-grey bar, fixed in luminance at 13.5% of white, moved from left to right at a speed of 2.25 deg s^{-1}, along a horizontal path 7.25 deg long and positioned 5 deg above the fixation point. A comparison bar moved along a similar horizontal path 5 deg below the fixation point, but this bar moved from right to left; this was to prevent the bars from perceptually locking together, as they might have done if they were vertically aligned. The luminance of this comparison bar was set to each of the same ten luminances as before, and each luminance was presented three times in random order. The observer's task was to rate the perceived expansion and contraction of the lower, variable-grey bar, using the upper fixed-luminance bar as a standard of comparison. The observer was instructed that the upper bar's degree of expansion and contraction was to be assigned a rating of 10, and his or her task was to assign a rating to the expansion and contraction of the lower, variable-luminance bar.

3.2 *Results*

Results are plotted in figure 3 (mean of four observers). Increasing illusions are plotted upward on the graph. (In retrospect, it would have been better to use the same rating scales in experiments 1 and 2.) Figure 3 shows that the inchworm effect was strongest for the very lightest and darkest bars, often exceeding the ratings of the standard bar, and reached a maximum rating of 13 for a white bar. The illusion was reduced, although still present, for mid-grey bars. Although the curves for the inchworm and the footsteps illusions may differ in detail, they are similar in general appearance. Illusions were greatest for extreme values of the contrast ratio, namely for black bars and white bars, and both illusions were minimal for a mid-grey bar with a contrast ratio of unity, whose contrast did not change as it moved over the black and white stripes.

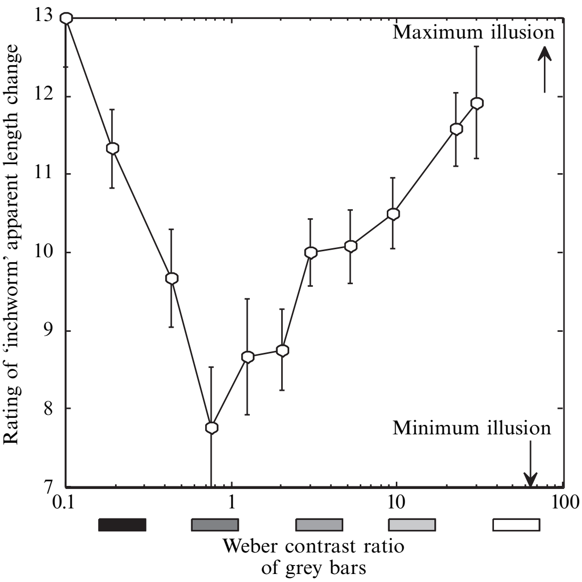


Figure 3. Results for experiment 2 on the 'inchworm' illusion. Ratings of apparent size change of a horizontally drifting bar as a function of its luminance (mean ± 1 SE for four observers). Lines are fitted by eye. The bar was 1.5 spatial periods in horizontal extent. The surround was a stationary black and white grating. Apparent size changes were greatest for black and for white drifting bars, and minimal (though still present) for mid-grey bars that lay close to the arithmetic (not geometric) mean of the black and white stripes.

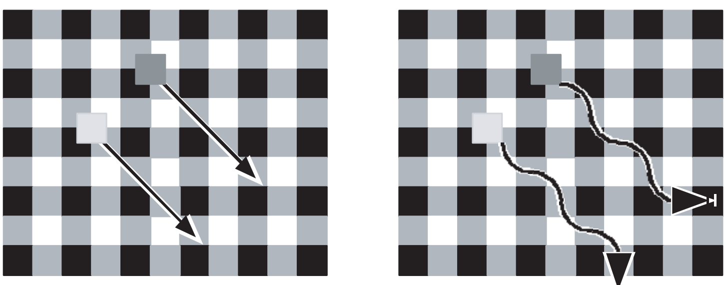
4 Experiment 3: Illusion not caused by brightness induction

Several observers spontaneously remarked that the grey bars appeared to change in brightness as they moved over the stationary stripes, looking apparently lighter when they passed over a black stripe and apparently darker when they passed over a white stripe. These changes, caused by simultaneous brightness induction, led me to wonder whether the conditions responsible for the illusions might be generating phantom spots of the type familiar from the Hermann grid (Spillmann 1994) and from McCourt's induced gratings (McCourt 1982; McCourt and Blakeslee 1994). To test this possibility, I adopted an idea from Cormack et al (1992) and informally tested whether the footsteps illusion was still present under scotopic viewing conditions. The Hermann grid disappears at scotopic levels (Patel 1966; Wist 1976; Trościanko 1982), and so does the induced grating (McCourt 1990). So if the footsteps illusion were somehow caused by brightness induction, the illusion should disappear in scotopic vision.

Five observers dark-adapted for 10 min with a 3.3 log unit neutral density filter over the eyes and then viewed the footsteps stimulus. The result was that the footsteps illusion was just as strong with the 3.3 log unit filter as without; the mean rated illusion was 10.0 when light adapted and 10.2 ($SE = 1.71$) when dark adapted. I conclude that the changes in perceived brightness of the moving bars were ancillary to the illusion, not a critical determinant of it.

5 Experiment 4: 2-D plaids modulate perceived direction of motion

Two orthogonal square-wave gratings were superimposed to make a stationary background plaid, composed of black, white, and mid-grey squares. The moving bars were now two squares, each of the same dimensions as any square constituting the plaid. One moving square was light grey and the other was dark grey, and they moved in synchrony along parallel oblique paths at 45° to the orientation of the plaid (figure 4a). In other respects the stimuli resembled those used before. Five naïve observers viewed this display, while fixating on a point 5 deg eccentric to the motion paths. The result was that all of them spontaneously reported that the two spots seemed to wiggle in and out toward each other, changing their directions repetitively as they pursued their common oblique path (figure 4b). To understand why, consider the upper, dark square as it moved down to the right, at the instant when it crossed over a 'corner' of the plaid. When its leading right-hand edge moved on to a darker vertical stripe, the rightward motion of the square appeared to slow down, since the dark vertical edge moving over a dark surround had a low contrast. At the same instant its leading edge at the bottom moved on to a lighter horizontal stripe, and the downward motion of the square appeared to speed up, since the dark horizontal edge moving over a light surround had a high contrast. Consequently the square seemed to veer toward the vertical.



(a) (b)

Figure 4. 2-D inchworm illusions. (a) A light and a dark square moved in step along parallel oblique paths across a stationary plaid. (b) Artist's impression of the percept: the squares appeared to change direction, apparently wiggling in and out as they moved. For explanation, see text.

We attribute this to vector averaging in the visual system. When the dark square moved across the next 'corner' of the plaid, which had opposite luminance polarities, it seemed to veer toward the horizontal. Corresponding arguments apply to the light square. As a result the two squares appeared to move along counterphasing wiggly paths. Thus the surround plaid differentially affected the contrasts of the moving horizontal and vertical edges and thereby modulated the apparent *directions* of the moving squares, not just their apparent speeds. In other words two orthogonal inchworm illusions could occur simultaneously.

6 Discussion

The footsteps and inchworm illusions depended on contrast. Careful inspection of my stimuli showed that the apparent accelerations and decelerations of the drifting bar were correlated with changes in its luminance contrast. For a dark-grey drifting bar, contrast was low on the black stripes of the surround grating and the bar appeared to move slowly. On the white stripes of the grating the contrast of the drifting bar was high and the bar appeared to move rapidly. For a light-grey drifting bar the opposite was true, and it appeared to speed up on the black stripes and slow down on the white stripes. I regard the footsteps illusion and the inchworm illusion as two examples of this correlation between contrast and apparent speed. In experiment 1 the drifting grey bars were two stripes (one grating period) in horizontal extent, so both ends of the bar always lay on the same luminance. At all times both ends lay on black, or both ends lay on white. Consequently the two ends of the bar varied in apparent speed together, causing the bar to appear to change speed as a whole. In experiment 2 the drifting grey bars were three stripes wide (1.5 spatial periods of the grating), so the two ends of the bar always lay on different luminances. Whenever one end of the bar lay on white, the other end lay on black. Consequently when one end of the bar apparently slowed down, the other end apparently speeded up, leading to apparent changes in the length of the moving bar.

These results are consistent with results in a large number of publications that have shown that perceived speed depends on contrast (Thompson 1976, 1982; Campbell and Maffei 1979, 1981; Kooi et al 1992; Stone and Thompson 1992; Hawken et al 1994; Gegenfurtner and Hawken 1996; Smith and Derrington 1996; Thompson et al 1996; Thompson and Stone 1997; Blakemore and Snowden 1999). Thompson (1976, 1982) showed that slowly moving gratings appeared to slow down when their contrast was reduced, although rapidly moving gratings could appear to move even faster. This effect appears to hold across a wide range of contrasts (Stone and Thompson 1992). Contrast can even affect the perceived speed of texture-based second-order motion stimuli (Ledgeway and Smith 1995; Gegenfurtner and Hawken 1996). Blakemore and Snowden (1999) reviewed these studies, and found that contrast did affect perceived speed for a very wide range of moving stimuli that differed upon such aspects as one versus two dimensions, periodic versus nonperiodic, and whether the stimuli occurred within a static window. They examined a range of stimulus speeds, different types of motion including moving gratings, random-dot patterns, and a single moving disk. They found contrast-induced changes in perceived speed in all these stimuli, which suggests that none of the stimulus factors listed was critical in producing the effect. In general they found that slowly moving patterns presented simultaneously side by side showed the greatest decrease in perceived speed with decreasing contrast. On the other hand, fast speed and successive presentations produced more veridical matches or even an increase in perceived speed with decreasing contrast. These studies showed that contrast reduction tends to reduce the perceived steady-state speed of a stimulus that is viewed for some seconds. Our experiments add to this by showing that the contrast modulation of speed can be rapid. The bars appeared to vary in speed at the temporal frequency with which the bars traversed the stripes, namely 1.8 Hz. Thus the effects of contrast on speed are local in both space and time.

Our illusions tended to be stronger in peripheral than in foveal vision. Cormack et al (1992) also discovered a powerful new motion illusion that occurs only in peripheral vision. A thin vertical bar was moved to the right (toward 3 o'clock) across a stationary grating of oblique lines that was inclined 45° counterclockwise from vertical. When viewed foveally, the true direction of motion was seen. However, at progressively greater eccentricities, the perceived direction of motion became more downwards until, at 15 deg eccentricity, the bar appeared to move towards halfway between 4 o'clock and 5 o'clock, ie parallel to the orientation of the static lines. In some conditions the perceived direction of motion of the bar could deviate from veridical by as much as 90°. Cormack et al attributed this illusion to the motion of the *intersections* (moire fringes) between the moving bar and oblique lines across which it moved. Although their illusion, like mine, involves a grey bar moving peripherally across stationary stripes, the two illusions do not seem to be closely related.

Returning to the effects of contrast, the greatest illusory variations in speed were found when the drifting bar was almost black or almost white. Such bars showed maximum change in contrast—a pure white bar would have zero contrast on a white background stripe, and a contrast of unity on a black stripe. For a black bar the opposite would be true. A mid-grey bar would be expected to show minimum changes in contrast as it moved from a black to a white surround, and indeed our results showed that mid-grey bars gave minimum changes in apparent speed.

In fact, at some mid-grey level the grey bars should have the same contrast on black stripes as on white, so there should be no illusory changes in speed and the inchworm and footsteps illusions should vanish. What would this mid-grey luminance be? The most likely candidate is when the greyness of the bars lies halfway between the black stripes (4.3%) and white stripes (100%). But would this halfway point lie at the arithmetic or the geometric mean of the light and dark stripes? [The arithmetic mean of two luminances L_1 and L_2 is $(L_1 + L_2)/2 = 52\%$, and the geometric mean is $\sqrt{(L_1 L_2)} = 20\%$. As it happens, I had no stimuli with a luminance of 52%, but figures 2 and 3 show that the footsteps and inchworm illusions reached a minimum at luminances near this, at 46.8% and 58.6%, respectively. So the minimum illusions were found near the arithmetic mean of 52%, and were nowhere near the geometric mean of 20%. This might seem inconsistent with the wealth of evidence that early stages of the visual system, perhaps in the retina, apply a logarithmic transform to all input luminances (Whittle 1992a, 1992b). However, it is consistent with our earlier work with rather different motion stimuli. In this earlier study (Anstis et al 2000), we used a motion stimulus in which a dark and a light bar exchanged luminances repetitively on a grey surround. The result was that motion was attributed to the bar that differed more from the surround, that is, on a dark surround the light bar appeared to jump, and on a light surround the dark bar appeared to jump. As in our present experiments, the apparent motion disappeared when the luminance of the surround lay halfway between that of the bars—on a linear, not a logarithmic scale. The reason is simply that at this arithmetic mean point, the black and the white stripe would have equal and opposite Weber contrasts with respect to the grey bar. For instance if the mid-grey bar, white stripes, and black stripes had respective luminances of 52%, 100%, and 4%, then the Weber fraction $\mathrm{d}I/I$ for the black stripe would be

$$\frac{L_\mathrm{b} - L_\mathrm{g}}{L_\mathrm{g}} = \frac{4 - 52}{52} = -\frac{48}{52} = -0.923\,,$$

and for the white stripe would be

$$\frac{L_{\mathrm{w}} - L_{\mathrm{g}}}{L_{\mathrm{g}}} = \frac{100 - 52}{52} = +\frac{48}{52} = +0.923\,.$$

The two Weber contrasts are of opposite sign, since the black stripe constitutes a spatial decrement and the white stripe an increment, but they do have the same magnitude. So as the grey bar moves across from a black stripe to a white stripe, it reverses its polarity but it does not change its contrast. Hence there is no change in contrast to trigger a footsteps illusion, and we saw earlier that polarity change is not necessary for the illusion.

Thus the results reported here are consistent with our earlier results (Anstis et al 2000), in which crossover motion was assigned to the bar with the higher contrast, and vanished when the two bars had the same Weber contrast. In the present study, the differences in perceived instantaneous velocity—the footsteps and inchworm illusions—also vanished when the two bars had the same Weber contrast.

What could be the neural substrate of this dependence of perceived speed upon contrast? It would be instructive to compare the present psychophysical data with the neuronal discharge of motion-sensitive cells when stimulated by targets with different contrasts to the background. It seems intuitively likely that motion-sensitive neurons would signal less vigorously when the contrast is low and respond more briskly to higher-contrast moving patterns, and Thiele et al (2000) have recently discovered just such responses in single neurons in macaque visual area MT (see their figure 4). These neural findings could go a long way to explaining the present illusions.

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