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Background stripes affect apparent speed of rotation

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Abstract. A gray line that rotated about its own center against a stationary background of vertical stripes appeared to double in perceptual speed as it rotated through the vertical position and thus momentarily aligned with the background. Four factors may contribute to this speed-up: (i) landmarks, in which the tip of the moving vertical line moves horizontally across the maximum number of stationary stripes; (ii) orientation repulsion of the moving line by the vertical stripes, which may distort the line's perceived position and hence its perceived speed; (iii) the orientation of an induced brightness pattern along the line; and (iv) the motion of the induced brightness pattern, which moves physically most rapidly along the line when the line is near vertical. To test these possibilities, an annulus display provided landmarks but no intersections, and this almost abolished the effect. A rotating-slit display provided an oriented, moving pattern that mimicked the induced brightness but had no landmarks, and this increased the effect. We conclude that the motion, but not the orientation, of the intersections [option (iv)] was responsible for the illusion. 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.

1 Introduction

We have found that, when a line rotates at constant speed about its own center against a background of stationary vertical stripes, it appears to vary in speed during each revolution, looking markedly faster when it passes through the vertical (figure 1a).


(a) (b) (c)

Figure 1. The stimuli. (a) In the basic illusion, the line seems to rotate faster when it passes through the vertical. (b) Annular display. Although striped background landmarks are still present, the illusion is abolished. (c) Slit display. A periodic pattern (real rather than induced) slides along the line as in (a), but landmarks are hidden. The illusory modulation of rotary motion is the same as in (a), or even enhanced. (For technical reasons, rotation rates were lower in the slit condition. See text.)

We speculated that four possible factors might be at work:

(i) Landmarks, in which the tip of the moving vertical line moves horizontally across the maximum number of stationary stripes at '12 o'clock'. An example of a landmark effect is a horseman who rides across a field and through the trees. He appears to move faster when among the trees because they provide stationary landmarks against which his speed relative to the trees can be judged.

(ii) Orientational repulsion of the moving line by the vertical stripes, such as one finds in the Zöllner (1862) illusion. This is probably caused by lateral inhibition between neural orientation detectors (Blakemore et al 1970). Hypothetically, the vertical stripes might repel the rotating line, first delaying its apparent approach and then speeding up its apparent departure from the vertical.

Our two other hypotheses are based upon the induced brightness patterns seen in the moving line. This brightness pattern is induced into the gray moving line by the surrounding grating (McCourt 1982; Foley and McCourt 1985; Blakeslee and McCourt 1999). The pattern matches the intersections of the grating and the line like a moiré. These 'moirés' have two interesting properties:

(iii) Oriented moirés: when the gray line moved over the stripes, oriented induced brightness patterns appeared at the intersections (McCourt 1982; Foley and McCourt 1985; Blakeslee and McCourt 1999). These moiré-like effects appeared to have an orientation midway between that of the stripes and the gray line. When the stationary stripes were seen through a rotating slit (see below), the little stripe lengths were vertical.

(iv) Moving moirés: the pattern of induced brightness at the intersections moved most rapidly along the rotating line when the line was near vertical, following a tangent of θ, where θ is the angle between the moving line and the vertical stripes. Spillmann's useful review (1993) gives general examples of moiré intersections and also deals with brightness induction in occluded gratings.

To anticipate, our experiments will show that moving moirés [option (iv)] can account for the speed illusion. Before we give details, we shall describe two earlier publications that share some properties in common with our illusion.

Cormack et al (1992) reported an illusion somewhat like 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 this to the vertical motion of the moiré intersections between the moving line and the surround, and commented that this illusion dramatizes differences in motion processing between the fovea and the periphery. Our illusion, however, occurs in central vision.

Wade et al (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. Moiré patterns were visible in the stimuli of Wade et al as well as in Cormack et al, and this will be taken up again in section 4.

In both these cases as well as for our line that rotated over a grating, the grating produces an induced brightness pattern that has two important properties: it has local orientations within the gray line (McCourt 1982; Foley and McCourt 1985; Blakeslee and McCourt 1999), especially if viewed in peripheral vision, and it also runs along the lines as the line moves relative to the gratings.

2 Experiment 1

2.1 *Procedure*

We measured our illusory variation in rotation rate with a null method. A mid-gray line, 9 deg long and 12.5 min of arc wide, rotated at various speeds on a background of square-wave black-and-white stripes of spatial frequency 1.2 cycles deg^{-1}.

To evaluate the illusory rotary motion, we modulated the line's rotation rate, moving the line most slowly when it was vertical and most rapidly when it was horizontal. The amplitude of this sinusoidal modulation of the real rate was adjusted to null out the perceptual increase in speed that occurred when the line and the background stripes were aligned. For example, at a minimum amplitude of zero, the line would rotate at constant speed; at an amplitude of 50%, the speed at vertical would be 3 times the speed at horizontal; and at a maximum amplitude setting of 100%, its rotation rate would vary between a maximum of twice the mean speed and minimum, briefly, of zero. The observer adjusted the amplitude using a mouse, until satisfied that the line was rotating at an apparently constant rate, and then clicked the mouse button. This automatically recorded the observer's setting for later analysis and randomly selected a new mean rotation rate and direction for the next trial. In practice, to avoid long-term adaptation to the stripe orientation, the whole display was tuned through a right angle on half the trials, selected at random, so that the stripes were horizontal (and the speed adjustments were correspondingly matched to the horizontal).

The mean rotation rate of the line was pre-set randomly on each trial to a value between 0.24 and 1.22 revolutions s^{-1} (88° to 440° s^{-1}), and was equally often clockwise as counterclockwise. The observer viewed a computer-controlled monitor screen from a distance of 57 cm in a dimly lit room, and controlled the speed variations of the line by means of a mouse. The programs were run on a Macintosh G4 computer under Mac OS X and were written in Macromedia Director CX.

Three conditions were run in separate blocks of trials. These three conditions are shown in figure 1. In figure 1a, the line rotated against the striped background. Together with two other conditions (figures 1b and 1c), we tested three of our hypothetical explanations: landmarks, orientation repulsion, and oriented moirés.

We tested the landmark theory with the annular display shown in figure 1b. Instead of a full-length line, two line tips swept along a clear annular path that was denuded of stripes. This was intended to provide landmarks, inside and outside the annulus, against which the speed of the line tips could be judged, but no moiré intersections, since the line was never directly superimposed on the stripes. To test for the role of the periodic induced pattern, in figure 1c a rotating slit cut in a black virtual occluder provided a partial view of the underlying stationary stripes. This display mimicked the induced moirés but with very high contrast and salience. Most important, there were no landmarks, since no stripes were visible anywhere outside the moving slit. It also ruled out any orientation repulsion from the striped regions surrounding the moving line.

In practice, the slit stimuli shown in figure 1c took longer for the computer to plot, so the range of rotation rates in this condition was slower, namely up to 0.55 revolution s^{-1}.

2.2 *Results*

Results are shown in figure 2. In figure 2, although there were 20 conditions (two stripe orientations, and ten speeds ranging either from -1.22 to $+1.22$ revolutions s^{-1} or from -0.55 to $+0.55$ revolution s^{-1}), the results for clockwise and counterclockwise rotations, and for the vertical and horizontal stripe orientations, have been pooled for analysis, yielding five conditions, namely rotation rates of 0.24, 0.49, 0.73, 0.98, and 1.22 revolutions s^{-1} for the stimuli shown in figures 1a and 1b, and rotation rates of 0.11, 0.22, 0.33, 0.44, and 0.55 revolution s^{-1} for the stimulus shown in figure 1c. Results are expressed as the ratio of the maximum to the minimum physical rotation rate during each revolution that was needed to make the rotation rate appear constant. This provides a nulling measure of the illusion. Note how large this rotary motion illusion really is. By way of comparison, a strong static illusion such as the Müller-Lyer can be nulled by setting the two arrow lengths to a ratio of $1:1.2$ at most. In the illusion presented here, the speed nulling ratio could easily be two to one or higher.

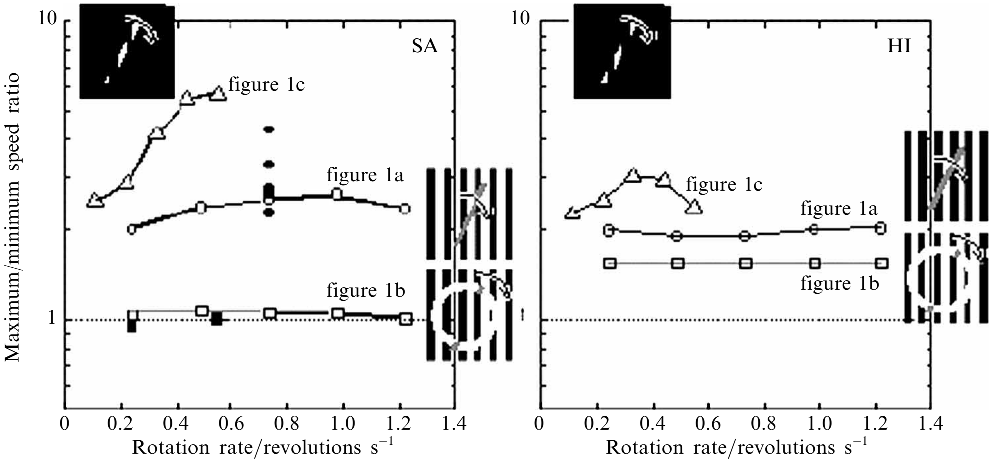

Figure 2. Results for observers HI and SA (two of the authors). A gray line rotating against stationary vertical stripes (figure 1a) appeared to rotate at a constant speed when its speed at the horizontal was set to approximately twice its speed at the vertical (open circles). Results at the median speed for five additional naive observers are shown as filled circles. Moving the line tips along a white, unstriped annulus (figure 1b) greatly reduced the illusion for HI or abolished the illusion completely for SA (squares). A rotating slit through which parts of the stripes could be seen (figure 1c) gave a very large illusion (triangles). Conclusion: the apparent changes in speed are caused by the induced brightness patterns running along the rotating line.

Results were relatively constant across rotation rates. The two main observers were among the authors, so to rule out any suggestion of bias we also collected data from five naive observers for the stimulus shown in figure 1a at the median speed of 0.73 revolution s^{-1}. These results are superimposed as solid circles on SA's data in figure 2a. Figure 2a shows that the data for our two authors lay well within the range for naive observers. In fact, four out of five naive observers showed stronger illusions than SA and HI, with maximum/minimum ratios ranging from 2.61 to a remarkable 4.3.

The annular display in figure 1b gave little or no illusion, whilst the slit display in figure 1c gave a very strong illusion. This is of theoretical importance; our results offer no support to the 'landmark' effect, in which the tip of the moving vertical line moves horizontally across the maximum number of stationary stripes, since the annular display in figure 1b, which provided landmarks but no intersections, virtually abolished the illusion. On the other hand, our results strongly support the 'intersection' hypothesis, in which oriented induced brightness patterns in the line move most rapidly when the line is near vertical, since the rotating-slit display in figure 1c that provided an equivalent moving pattern but no landmarks, gave a similar or increased effect.

3 Experiment 2. Spatial frequency of the background stripes

We varied the number and fineness of the moving moirés by varying the spatial frequency of the background stripes over a three-octave range from 0.625 to 5 cycles deg^{-1}. The stimulus was as in figure 1a and the line always rotated at 0.73 revolution s^{-1}. The spatial frequency and orientation of the stripes (horizontal or vertical), and the direction of rotation of the gray line, were randomly selected on each trial.

Results for two observers are shown in figure 3. Figure 3 shows that the illusion was strong across the entire range of spatial frequencies tested, and was not systematically affected by spatial frequency. The ratio of maximum to minimum speed that appeared to give a constant rotation rate, averaged across all spatial frequencies, was 2.14 for SA and 2.5 for ES. Veridical perception would have given a ratio of 1.

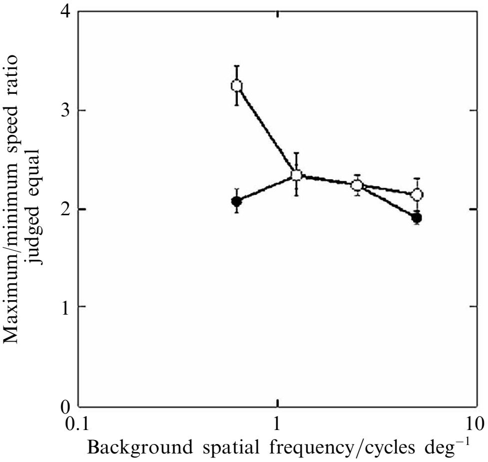

Figure 3. Illusion is strong (>2) for all spatial frequencies of the background stripes tested.

4 Discussion

To summarize the results of the two experiments, a background of stationary stripes strongly influenced the apparent rotation rate of a line. The line appeared to move most rapidly when it was nearly parallel with the background stripes, and to null this effect the speed had to be *doubled* when the line was orthogonal to the stripes. The effect was robust across a wide range of rotation rates for the line and across a wide range of spatial frequencies for the background stripes.

Our results reveal that the critical component of the stimulus is the pattern of brightness variations induced in the rotating gray bar by the background stripes of the stationary grating (McCourt 1982). Like a real moiré pattern, the spatial scale of this induced moiré changes with the angle between the gray bar and the grating, having the same spatial frequency as the grating when the bar is orthogonal to the grating but then dropping to zero spatial frequency when the bar is aligned with the grating. As a result, individual light and dark spots on the induced pattern move outward along the bar as it rotates from orthogonal to parallel and then reverse direction moving inward along the bar as the bar returns to the orthogonal orientation. We claim that this pattern motion along the bar is the cause of the apparent speed increase of the bar. Clearly, neither the landmarks nor the orientation repulsion from the surround grating were a factor: the version of a line in an annulus had landmarks but no illusion and the rotating slit over a grating showed the illusion in the absence of landmarks and orientation repulsion, nor did the moving pattern have to be induced as it was in the original display. The illusion was also seen on real brightness patterns in the rotating-slit case. The motion of the brightness patterns along the lines is therefore the source of the illusory modulation of the rotation. In principle, the speed with which the patterns move along the rotating line approaches zero when the line is horizontal and approaches infinity when the line is vertical. This huge variation in the pattern speed induces a large (twofold) variation in the perceived rate of rotation. The visual system seems to confound the pattern motion along the line with the rotation of the line itself, and this failure to partial out the two orthogonal motions suggests the presence of some visual mechanisms that are tuned for velocity but not for direction.

We conclude that the background grating causes the modulation of the rotation speed only because of the motion of the induced moiré that it creates. We have recently tested this more directly by removing the grating and replacing the rotating bar with a rotating line of dots (Anstis et al 2005). When the dots are given an inward or outward motion of their own, toward or away from the center, the apparent speed of the rotating line-dots increases by a factor comparable to the strength of the effects seen here. In further studies, we shall examine possible factors underlying the misattribution of radial motion to rotational speed.

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