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Two mechanisms that determine the Barber-Pole Illusion

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ABSTRACT

In the Barber-Pole Illusion (BPI), a diagonally moving grating is perceived as moving vertically because of the narrow, vertical, rectangular shape of the aperture window through which it is viewed. This strong shape–motion interaction persists through a wide range of parametric variations in the shape of the window, the spatial and temporal frequencies of the moving grating, the contrast of the moving grating, complex variations in the composition of the grating and window shape, and the duration of viewing. It is widely believed that end-stop-feature (third-order) motion computations determine the BPI, and that Fourier motion-energy (first-order) computations determine failures of the BPI. Here we show that the BPI is more complex: (1) In a wide variety of conditions, weak-feature stimuli (extremely fast, low contrast gratings, 21.5 Hz, 4% contrast) that stimulate only the Fourier (first-order) motion system actually produce a slightly better BPI illusion than classical strong-feature gratings (2.75 Hz, 32% contrast). (2) Reverse-phi barber-pole stimuli are seen exclusively in the feature (third-order) BPI direction when presented at 2.75 Hz and exclusively in the opposite (Fourier, first-order) BPI direction at 21.5 Hz, indicating that both the first- and the third-order systems can produce the BPI. (3) The BPI in barber poles with scalloped aperture boundaries is much weaker than in normal straight-edge barber poles for 2.75 Hz stimuli but not in 21.5 Hz stimuli. Conclusions: Both first-order and third-order stimuli produce strong BPIs. In some stimuli, local Fourier motion-energy (first-order) produces the BPI via a subsequent motion-path-integration computation `(Journal of Vision (2014) 14, 1–27)`; in other stimuli, the BPI is determined by various feature (third-order) motion inputs; in most stimuli, the BPI involves combinations of both. High temporal frequency, low-contrast stimuli favor the first-order motion-path-integration computation; low temporal frequency, high-contrast stimuli favor third-order motion computations.

1. Introduction

1.1. The Barber-Pole Illusion

Three classic theories of motion perception (Adelson & Bergen, 1985; Van Santen & Sperling, 1984, 1985; Watson & Ahumada, 1985) assert that, at an early stage of visual processing, motion signals are extracted by neural mechanisms that essentially compute the Fourier energy of the spatiotemporal luminance patterns within their local neighborhoods. For a translating sinusoidal grating, such Fourier-energy based mechanisms signify a direction of motion that is perpendicular to the orientation of the grating. However, in a Barber-Pole Illusion (BPI) such as the one shown in Fig. 1, a diagonally moving grating appears to move vertically when viewed through a vertically-orientated rectangular window (Wallach, 1935).

The BPI suggests that the perceived direction of a motion stimulus is determined not just by local motion energy but also by the shape of the aperture within which the motion signal is visible. To account for such form-motion interaction, requires further elaboration of the existing motion theories that are concerned only with local Fourier energy. Here we revisit previous demonstrations of shape–motion interactions in barber-pole stimuli and present new demonstrations that better define the visual computations involved in producing the BPI.

1.1.1. The Fourier components in barber-pole stimuli

The sensitivity of the lower-level, first-order motion system is well-described by its responses to the Fourier components of the motion stimulus (Chubb & Sperling, 1988; Emerson, Bergen, & Adelson, 1992; Lu & Sperling, 1995b, 1999, 2001; Van Santen & Sperling, 1984, 1985). The barber-pole stimulus is the product $W(x,y)G(x,y,t)$ of a spatial aperture $W(x,y)$ times a drifting

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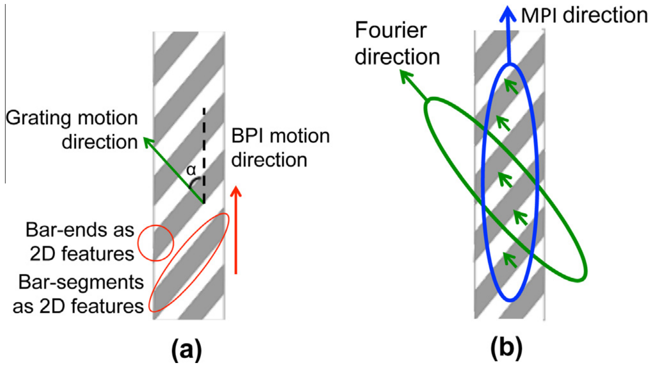

Fig. 1. Illustration of a classical barber-pole display. (a) A classic barber-pole. The physical direction α of grating motion is the direction of the dominant Fourier component(s) of the moving grating; this direction is perpendicular to the grating stripes. However, when viewed through a vertical aperture (e.g., an aperture with the 4:1 vertical:horizontal aspect ratio illustrated here), a grating consisting of diagonally translating bars appears to move vertically, the Barber-Pole Illusion (BPI). Indeed, the barber-pole display does contain unambiguous vertical motion signals carried by the vertical movement of 2D spatial features such as bar-segments and bar-ends. (b) Simplified illustration of the Motion-Path-Integration (MPI) theory (Sun, Chubb, & Sperling, 2014). Ovals in blue and green represent two of many different spatial paths along which local motion energy (short arrows) that has a component in the direction of the path is integrated. Only spatial (and not temporal) integration components of the MPI theory are illustrated here. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sinusoidal grating $G(x, y, t)$. Therefore the Fourier transform of the barber-pole stimulus is simply the convolution of the spatial Fourier transform of W with spatiotemporal Fourier transform of G. The Fourier spectrum of a barber-pole stimulus such as Fig. 1 contains the Fourier components of the aperture $W(x, y)$ splattered symmetrically around each of the Fourier components of the grating $G(x, y, t)$. If the barber pole were simply a single pixel wide, then the barber-pole stimulus would consist of spots moving vertically, and the Fourier analysis would, of course, confirm this. What is not so obvious, however, is that as soon as the barber-pole aperture is wide enough to include just two pixels, the visually important Fourier components signify motion in the diagonal direction, i.e., perpendicular to the grating stripes (see Appendix A).

For practical purposes, the dominant Fourier component, or a pool of the responses of all the visible Fourier components of a barber-pole stimulus, always signifies the direction perpendicular to the orientation of the grating. This means that neurons in visual area V1 that respond to sinewave motion – and nearly all the motion-sensitive neurons do – will signal the diagonal direction, and not the BPI direction. Therefore, accounting for the BPI requires either different kinds of basic motion detectors, e.g., feature detectors or, as we show below, higher-level mechanisms that combine the outputs of the local Fourier motion detectors. The role of feature detectors in the BPI is well established, e.g., (Lorenceau, 2010). Here we present a further characterization of the feature detectors involved in the BPI, new evidence for a higher-order motion-path-integration mechanism, and a road map to show the conditions under which these mechanisms are active.

1.1.2. BPI: the unambiguous motion of 2D spatial features

1.1.2.1. Moving bars. A motion generated by a spatially 1D moving pattern (e.g. a drifting sinusoidal grating) is intrinsically ambiguous because the component of velocity in the spatially invariant pattern dimension cannot be detected. By contrast, the motion direction and speed (velocity) of a 2D moving feature (e.g. a spot, a corner, or a line end) moving in a 2D plane is absolutely unambiguous. A classic barber-pole stimulus contains 2D spatial features that move unambiguously parallel to the boundary of the aperture window. In the barber-pole stimulus illustrated in Fig. 1, all the bar segments inside the aperture move veridically upward along the vertical boundary of the aperture window. Therefore a theory based on a mechanism that tracks the movements of the bar segments could explain the BPI (e.g. Marshall, 1990).

1.1.2.2. Moving end-stops. An alternative explanation of the BPI attributes it to the computation of the bar-ends. This theory is known as the "end-stop" theory (see Lorenceau (2010) for a review). The "end-stop" theory is consistent with many factors known to affect the strength of the BPI. For example, when the relative angle α (see Fig. 1a) is made smaller so that the number of the bar terminators on the vertical boundary decreases, the BPI becomes weaker (Fisher & Zanker, 2001).

The BPI also is weaker when the boundary on the longer side of the aperture is made to appear in a different depth plane than the moving grating, due to various kinds of depth cues (Castet, Charton, & Dufour, 1999; Lidén & Mingolla, 1998; Shimojo, Silverman, & Nakayama, 1989). Bars and the off-plane aperture boundary form "extrinsic end-stops" that are not classified as genuine features, thus cannot generate a strong feature motion.

Less direct support comes from the similarity between the BPI's temporal dynamics and the temporal dynamics of the perceived motion direction of moving line segments. Moving line segments initially appear to move perpendicularly to the line segments' orientation, and the perceived motion direction shifts towards their actual motion direction as exposure duration increases (Lorenceau et al., 1993). Similarly, the perceived motion direction of a classic barber-pole display is initially perpendicular to the grating's orientation, and gradually shifts towards the BPI motion direction (Masson et al., 2000). This pattern of dynamics has been explained in terms of the slower processing time of the "end-stop" mechanism relative to the Fourier motion-energy computation (Pack et al., 2003).

However, some BPI results are inconsistent with the end-stop explanation. When the line grating within an elongated aperture window contains gaps so that interior line-ends also carry unambiguous diagonal motion signals, perceived motion is not in the diagonal motion direction of the interior line-ends. Instead, the complex pattern appears as dashed lines moving along the longer side of the aperture (Castet & Wuerger, 1997). Furthermore, when a plaid pattern (two superimposed gratings) moves inside an elongated aperture, the perceived motion direction of the plaid is biased in the aperture's orientation (Beutter, Mulligan, & Stone, 1996) even though the plaid is moving unambiguously in a different direction.

Recently, Sun, Chubb, and Sperling (2014) introduced a novel moving barber-pole display in which the apertures (the barber poles) and the gratings (the movements within the barber poles) move independently. Because of the movement of the aperture, the 2D motion of the spatial features in the moving-barber-pole stimulus is no longer in the aperture's elongated orientation. In a moving barber-pole display with vertical barber-poles, the movement of features such as bar segments and bar ends is consistent with a specific, rigid direction of diagonal motion. Nevertheless, in peripheral viewing, stimuli of this sort evoke purely vertical motion for a wide range, but not all, of tested conditions. Perceiving vertical motion while all barber-pole features move diagonally implies that, at least in the moving-barber-pole stimulus, other factors than feature motion determine the BPI.

1.1.3. The motion streak theory of the BPI

Badcock, McKendrick, and Ma-Wyatt (2003) found that the BPI was weakened substantially when the barber-pole aperture's