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Illusory depth induced by binocular torsional misalignment

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Abstract

This study reports a new depth illusion in which a static flat pattern appears stratified stereoscopically when viewed binocularly with an elevated gaze. Three psychophysical experiments measured perceived relative depth and fixational cyclodisparity (a rotation of one eye's view relative to the other eye's view about the line of sight) when flat patterns drawn with solid or dashed curved lines were fixated at various levels of gaze elevation. Experiments 1 and 2 showed that the patterns drawn with solid lines produced illusory depth only at large gaze elevations (downward and upward). Experiment 3 showed that the magnitude of the illusory depth was correlated with that of fixational cyclodisparity. These results suggest that the illusory depth originates in the binocular torsional misalignment generated by gaze elevation.

Keywords: Stereo matching; Binocular torsional alignment; Gaze elevation; Listing's law

1. Introduction

Stereo matching refers to the visual system's ability to compare and analyze the retinal images of the two eyes (e.g., Howard & Rogers, 1995; Wheatstone, 1852). To determine the direction of stereo matching for three-dimensional (3D) perception, the visual system is assumed to use epipolar lines—a set of the retinal projection of the planes defined by the interocular axis and points in 3D space (e.g., Frisby & Pollard, 1991). When the eyes' retinal images are superimposed with respect to the horizontal meridian, the epipolar lines are approximately horizontal and parallel to each other (unless the eyes converge extremely). Therefore, the disparity measured along the epipolar lines is called horizontal disparity, which provides quantitative depth information for a given gaze direction when combined with viewing-distance information. To calculate horizontal disparity accurately, the epipolar lines should be parallel to the horizontal meridian with respect to the head, rather than to the retinal horizontal meridian. Note that the epipolar lines used or assumed by the visual system are not directly observable and therefore should be inferred from perceived 3D shapes. (Although the concept of "epipolar lines" is originally based on projective geometry, here I use this term to refer to the direction in which the human visual system calculates binocular disparity for depth perception.)

One aspect that needs to be considered in human stereo matching is binocular torsional misalignment,[1] defined as a rotation of one eye relative to the other eye about the line of sight in Helmholtz coordinates.[2] In the present paper, misalignment refers to a deviation from the torsional state

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[1] This can be called "cyclovergence." In this paper, I use the term cyclovergence to refer to the torsional eye movements in opposite directions when it is explicitly induced by a retinal cyclodisparity (i.e., visually induced cyclovergence).

[2] Throughout this paper, I use the Helmholtz coordinate system (Each eye's 3D position is represented by sequential rotations about the horizontal, vertical, and torsional axes of the eye in that order. See Howard & Rogers, 1995). This coordinate system is useful in representing binocular torsional misalignment when gaze direction changes (Schreiber, Crawford, Fetter, & Tweed, 2001; Somani, DeSouza, Tweed, & Vilis, 1998). That is, if torsion is constant, gaze elevation does not change cyclodisparity.

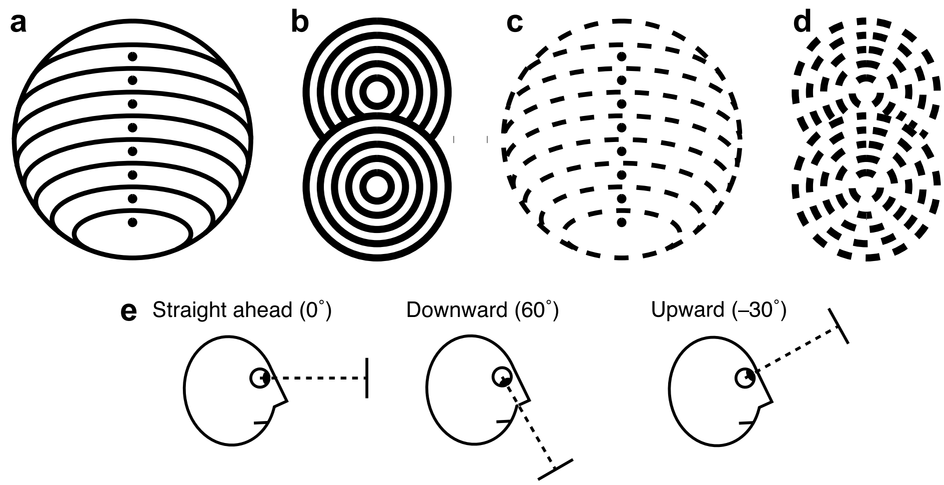

Fig. 1. Depth illusions that depend on gaze elevation. (a and b) To perceive the illusory depth quickly, (1) place a printed copy of this figure on a desk; (2) fixate the center of each pattern (a) or (b) with a downward gaze as eccentric as possible at a short viewing distance (approximately 30 cm); (3) keep the line of sight almost perpendicular to the figure (just as it is illustrated in the middle panel in e). The curved lines will appear as a convex "dome" that contains the vertical dot array in (a), and the lower disk will appear in front of the upper one in (b). Viewing the patterns at a shorter distance (a larger convergence angle) will produce a stronger illusory effect; this is qualitatively consistent with Schreiber et al.'s (2001) model. (c and d) A dashed-line version of (a and b) does not produce the illusory depth. (e) A schematic description of gaze angles to perceive the illusory depth. No relative depth is observed with a straight-ahead gaze.

of a straight-ahead gaze. An intuitive consequence of binocular torsional misalignment is retinal cyclodisparity, a torsional rotation of one eye's view relative to the other eye's view (cf. The cyclodisparity presented with a stereoscope is called cyclorotation in this paper). There are two theoretical possibilities for the accurate coding of headcentric horizontal disparity.[3] (Schreiber et al., 2001; van Ee & van Dam, 2003). One possibility is that the visual system adjusts the orientation of epipolar lines depending on the torsional state of the eyes by using retinal or extraretinal information. The other possibility is that the oculomotor system maintains binocular torsional misalignment to be minimal in all situations, and then the visual system uses the epipolar lines whose orientation is parallel to the retinal horizontal meridian.

Schreiber et al. (2001) examined this issue in situations where binocular torsional misalignment is introduced by the elevation of gaze (a vertical rotation of the eyes). They measured cyclorotation thresholds for perceiving a shape defined by the horizontal disparity of random dots at various levels of gaze elevation. Gaze elevation is known to introduce binocular torsional misalignment when the eyes converge (Minken & Van Gisbergen, 1994; Mok, Ro, Cadera, Crawford, & Vilis, 1992; Porrill, Ivins, & Frisby, 1999; Schreiber, Tweed, & Schor, 2006; Tweed, 1997). Schreiber et al. found: (a) that cyclorotation thresholds for perceiving a disparity-defined 3D shape are correlated with the torsional misalignment at each gaze elevation and (b) that the range of cyclofusion (*torsional* stereo matching: Ogle & Ellerbrock, 1946) is approximately ±5° of cyclodisparity from its center (Similar results were reported by Kertesz & Sullivan, 1978, who used random-line stimuli). The first result suggests that the epipolar lines are fixed with respect to the retina; the second result, however, suggests that the visual system adjusts the orientation of epipolar lines within the range of cyclofusion (approximately ±5°) [or searches a limited range of two-dimensional (2D) retinal regions] when the stimuli are random dots.

The primary purpose of this study is to report a new depth illusion that provides insights into the issue of whether or not the visual system adjusts the orientation of epipolar lines relative to the retinal horizontal meridian. Instead of spatially distributed elements such as random dots, the patterns I devised here (Fig. 1a and b) are flat patterns that comprise solid curved lines. (Each pattern comprises arcs that are aligned vertically and connected to each other by T-shaped junctions.) Geometrically speaking, the matching direction of solid lines presented with a binocular disparity is locally ambiguous (similar to the case of the aperture problem for motion: van Ee & Schor, 2000). Therefore, measuring the perceived depth of solid lines where binocular torsional misalignment must be induced would be one way to examine whether the visual system adjusts the orientation of epipolar lines. If the orientation of epipolar lines is appropriately maintained with respect to the head, any flat pattern would appear flat as a consequence of cyclofusion.[4] The basic effect I report here, however, is that a flat pattern (Fig. 1a and b) appears stratified

[3] Accurate stereo matching, however, is not sufficient to produce a veridical percept of 3D scenes. For example, perceived 3D shape quantitatively distorts depending on the inappropriate scaling of viewing distance (e.g., Johnston, 1991).

[4] In this paper, I regard cyclofusion as the appropriate rotation of epipolar lines with respect to the retinal horizontal meridian, whereas it is known to induce cyclovergence with a small gain (Howard, Sun, & Shen, 1994; Kertesz & Sullivan, 1978).