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Matching perceived depth from disparity and from velocity: Modeling and psychophysics

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ABSTRACT

We asked observers to match in depth a disparity-only stimulus with a velocity-only stimulus. The observers' responses revealed systematic biases: the two stimuli appeared to be matched in depth when they were produced by the projection of different distal depth extents. We discuss two alternative models of depth recovery that could account for these results. (1) Depth matches could be obtained by scaling the image signals by constants not specified by optical information, and (2) depth matches could be obtained by equating the stimuli in terms of their signal-to-noise ratios (see Domini & Caudek, 2009). We show that the systematic failures of shape constancy revealed by observers' judgments are well accounted for by the hypothesis that the apparent depth of a stimulus is determined by the magnitude of the retinal signals relative to the uncertainty (i.e., internal noise) arising from the measurement of those signals.

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1. Introduction

When a stationary object is viewed binocularly, the horizontal disparities created by the relief of the object can be used by the visual system to recover information about the three-dimensional (3D) shape. Likewise, when the same object is viewed monocularly, information about 3D shape can be gathered from the pattern of projected velocities generated by the relative motion between an observer and the object. In the present investigation, we will try to understand in which conditions these two different sources of depth information support the perception of an equivalent amount of depth.

1.1. Perceptual depth estimation from retinal images

It has long been recognized that disparity and velocity signals by themselves are insufficient to specify the distal depth map that has generated the two-dimensional (2D) image. For a local analysis of the visual field, in fact, the depth difference (z) with respect to the fixation point is related to the disparity (d) and velocity (v) signals through parameters which are not specified by optical information (see Fig. 1). For small visual angles, the equations become:

$$d \approx \mathrm{IOD}\frac{z}{z_f^2} + \varepsilon_d, \tag{1}$$

$$v \approx \left(\frac{T_x}{z_f} + \omega\right)\frac{z}{z_f} + \varepsilon_v, \tag{2}$$

where z is the depth-difference with respect to the fixation point, z_f is the fixation distance, IOD is the inter-ocular distance, T_x is the x-axis translation of the observer and ω is the rotation of the object. ε_d and ε_v specify additive Gaussian noise with zero mean and standard deviations σ_d and σ_v

In order to compute the absolute amount of depth, the horizontal disparities must be scaled inversely with the square of the viewing distance, z_f^2 (by assuming that the IOD is known). Likewise, the velocity signals must be scaled so as to take into account the observer's translational component T_x, the object's rotation ω and the inverse of the viewing distance. To simplify the following discussion, we will denote with:

$$k_{d_0} = \frac{\mathrm{IOD}}{z_f^2}, \tag{3}$$

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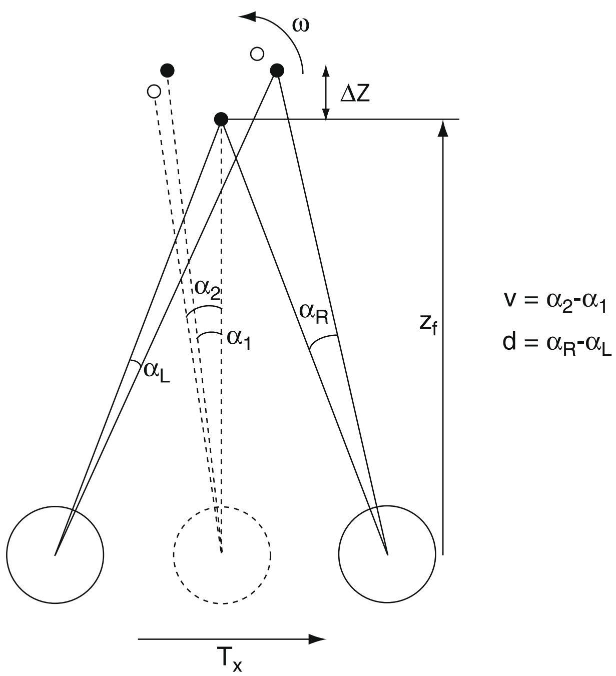

Fig. 1. Schematic illustration of the viewing geometry. z_f is the viewing distance; α_L and α_R are the angles formed by the visual lines connecting a flanking point to the left and right eyes and the two visual axes; Δz is the front-to-back depth of the stimulus configuration along the line of sight. ω represents the angular rotation about a vertical axis centered at the fixation point. The open circles represent the position of the flanking points after the rotation. α_1 and α_2 are the angles between the visual line connecting a flanking point to the cyclopean eye and the visual axis of the cyclopean eye before and after the rotation, respectively.

the scaling factor for veridical recovery of Euclidean depth from disparity information. Likewise, we will denote with:

$$k_{v_0} = \frac{1}{z_f}\left(\frac{T_x}{z_f} + \omega\right), \tag{4}$$

the scaling factor for veridical recovery of Euclidean depth from velocity information.

In summary, the disparity and velocity signals are related to the depth of the projected object through parameters not specified by optical information. Disparity signals are related to depth through the squared reciprocal fixation distance z_f; the velocity signals are related to depth through the reciprocal of the fixation distance, the angle of rotation ω, and the translation velocity T_x. How can the "missing parameters" z_f, ω, and T_x be recovered?

1.2. Perceived depth from disparity signals

The parameter z_f may be specified by not-retinal information, such as the vergence angle of the eyes and the state of the accommodation (e.g., Proffitt & Caudek, 2002). Some investigations have provided evidence that observers can estimate fixation distance from vergence (Frisby, Buckley, & Duke, 1996; Tresilian & Mon-Williams, 2000; Tresilian, Mon-Williams, & Kelly, 1999) and accommodation (Fisher & Ciuffreda, 1988). In general, however, extra-retinal information does not guarantee a veridical recovery of viewing distance. The vast majority of experiments on the perception of depth from binocular disparity, in fact, has shown systematic distortions of depth-from-stereo. In the context of the inverse-geometry models of depth perception, these distortions of depth have been attributed to a mis-estimation of the viewing distance (e.g., Johnston, 1991; for a discussion, see Todd & Norman, 2003).

Some of these experiments have been conducted in the laboratory with computer-generated displays (Bradshaw, Glennerster, & Rogers, 1996; Brenner & Landy, 1999; Brenner & van Damme, 1999; Collett, Schwarz, & Sobel, 1991; Glennerster, Rogers, & Bradshaw, 1996, 1998; Johnston, 1991; Johnston, Cumming, & Landy, 1994; Norman & Todd, 1998; Todd, Oomes, Koenderink, & Kappers, 2001; Tittle, Todd, Perotti, & Norman, 1995), whereas other studies have been carried out by using real objects in fully illuminated natural environments (Baird & Biersdorf, 1967; Battro, Netto, & Rozestraten, 1976; Bradshaw, Parton, & Glennerster, 2000; Cuijpers, Kappers, & Koenderink, 2000a, Cuijpers, Kappers, & Koenderink, 2000b; Gilinsky, 1951; Harway, 1963; Koenderink, van Doorn, Kappers, & Todd, 2002; Koenderink, van Doorn, & Lappin, 2000; Loomis, Da Silva, Fujita, & Fukusima, 1992; Loomis & Philbeck, 1999; Norman, Crabtree, Clayton, & Norman, 2005; Norman, Lappin, & Norman, 2000; Norman, Todd, Perotti, & Tittle, 1996 – see their Experiment 4). In most of the cases, however, the psychophysical literature suggests that human observers do not estimate the viewing distance correctly.

1.3. Perceived depth from velocity signals

The recovery of depth from velocity information, besides being undermined by the indeterminacy of z_f, also suffers from the indeterminacy of the parameters ω and T_x. A veridical description of the Euclidean structure of an object can be derived from second-order optic flow, if appropriate assumptions are introduced in the interpretation process (Longuet-Higgins & Prazdny, 1980; Ullman, 1979). It has been shown, however, that human observers have a very limited sensitivity for the second-order temporal properties of the optic flow and thus rely mainly on velocities to recover 3D information (Hogervorst & Eagle, 2000; Todd & Bressan, 1990). If only the first-order information is used, however, it is not possible, in principle, to derive a veridical estimate of depth.

In our own research, we have showed that observers recover metric information from the optic flow in a heuristic and patchway fashion. We provided evidence that this is achieved by a probabilistic process which assigns the most likely 3D interpretation to (ambiguous) local first-order properties of the optic flow. As a consequence, the perceptual interpretation of velocity information is, in general, neither veridical nor internally consistent (Caudek & Domini, 1998; Caudek & Proffitt, 1993; Caudek & Rubin, 2001; Di Luca, Domini, & Caudek, 2004, 2007; Domini & Braunstein, 1998; Domini & Caudek, 1999, 2003a, 2003b; Domini, Caudek, & Proffitt, 1997; Domini, Caudek, & Richman, 1998; Domini, Caudek, & Skirko, 2003; Domini, Caudek, & Tassinari, 2006; Domini, Caudek, Turner, & Favretto, 1998; Domini, Vuong, & Caudek, 2002; Tassinari, Domini, & Caudek, 2008).

2. Perceptual depth-matching of single-cue stimuli

If the visual system were able to veridically estimate the "missing parameters" z_f, ω and T_x, then two single-cue displays would elicit the perception of the same depth extent when they correspond to the projection of the same distal depth extent z. The literature on the perceptual interpretation of disparity and velocity signals, however, reveals systematic failures of shape constancy (see the previous section). As a consequence, a disparity-only stimulus can be perceived as deeper or shallower than a velocity-only stimulus, even if the two stimuli are generated by the projection of the same distal depth extent, $z_d = z_v$. Likewise, a disparity-only stimulus can be perceived as having the same depth extent of a velocity-only stimulus, even if the two stimuli are generated by the projections of two different depth extents, $z_d \neq z_v$.

The goal of the present investigation is to explain these "depth mis-matches". Two different hypotheses will be contrasted.

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