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Perceived depth in non-transitive stereo displays

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ABSTRACT

The separation between the eyes shapes the distribution of binocular disparities and gives a special role to horizontal disparities. However, for one-dimensional stimuli, disparity direction, like motion direction, is linked to stimulus orientation. This makes the perceived depth of one-dimensional stimuli orientation dependent and generally non-veridical. It also allows perceived depth to violate transitivity. Three stimuli, *A*, *B*, and *C*, can be arranged such that $A > B$ (stimulus *A* is seen as farther than stimulus *B* when they are presented together) and $B > C$, yet $A \leqslant C$. This study examines how the visual system handles the depth of *A*, *B*, and *C* when they are presented together, forming a pairwise inconsistent stereo display. Observers' depth judgments of displays containing a grating and two plaids resolved transitivity violations among the component stimulus pairs. However, these judgments were inconsistent with judgments of the same stimuli within depth-consistent displays containing no transitivity violations. To understand the contribution of individual disparity signals, observers were instructed in subsequent experiments to judge the depth of a subset of display stimuli. This attentional instruction was ineffective; relevant and irrelevant stimuli contributed equally to depth judgments. Thus, the perceived depth separating a pair of stimuli depended on the disparities of the other stimuli presented concurrently. This context dependence of stereo depth can be approximated by an obligatory pooling and comparison of the disparities of one- and two-dimensional stimuli along an axis defined locally by the stimuli.

1. Introduction

Binocularly viewed one-dimensional (1-D) patterns such as gratings, lines, and edges are subject to the stereo 'aperture problem', which makes their disparity directions and magnitudes ambiguous (Farell, 1998; Morgan & Castet, 1997). The result is that stereoacuity and perceived depth for 1-D patterns vary with stimulus orientation, a fact known for many years but open to diverse interpretations (Blake, Camisa, & Antoinetti, 1976; Ebenholtz & Walchli, 1965; Farell & Ahuja, 1996; Friedman, Kaye, & Richards, 1978; Morgan & Castet, 1997; Ogle, 1955; see Howard & Rogers, 2002). In general, the psychophysical effects of 1-D stimulus orientation are consistent with an effective disparity that has a direction perpendicular to the orientation (Chai & Farell, 2009; Farell, 1998, 2006; Morgan & Castet, 1997; Patel, Bedell, & Sampat, 2006; Patel et al., 2003; Quaia et al., 2013), though the physiological evidence is mixed (e.g., Cumming, 2002; Durand, Celebrini, & Trotter, 2007; Maske, Yamane, & Bishop, 1986).

The perceived depth between a 1-D stimulus and a 2-D stimulus is a case in which horizontal disparities do not predict stereo depth perception (Chai & Farell, 2009; Farell, Chai, & Fernandez, 2009). The depth between a grating and a plaid, for example, is predicted instead by a version of the intersection-of-constraints rule (Fennema & Thompson, 1979; Adelson & Movshon, 1982) applied to the two-dimensional disparity vectors. This calculation orthogonally projects the plaid's disparity vector onto the grating's disparity axis; examples are shown in Fig. 1. The perceived depth separating the stimuli varies with the relative magnitude of disparity components along this axis (Farell, Chai, & Fernandez, 2009). Equivalently, the disparities can be compared in the direction of the plaid's disparity; the grating's disparity in this case is given by the intersection of its constraint line with the plaid's disparity axis. We call the results of either version of this calculation the *projected disparity* value. Because relative but not absolute disparity directions enter into the computation, it is possible for two simultaneously presented stimuli, one 1-D and the other 2-D, to appear at the same depth even though the horizontal disparity of one is negative and that of the other is positive (Farell, Chai, & Fernandez, 2009). This allows us to create sets of stimuli that have contradictory depth relations. We study the perception of such stimuli here.

1.1. Violations of transitivity

Transitivity asserts that if *A* is further than *B*, and *B* is further than *C*, then *A* should be further than *C*. A transitive series has a

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consistent ordering, so its consistency is quantitative, not merely qualitative. Considering the discussion above, however, it would not be surprising to find violations of transitivity in depth when *A*, *B*, and *C* include both 1-D and 2-D stimuli. For example, given the proper choice of stimulus dimensionality and disparity, stimuli *A* and *B* are seen at the same depth when they are viewed together; *B* and *C* are seen at the same depth when they are viewed together; but *A* and *C* are seen at different depths when they are viewed together (see Figs. 1 and 2). Bringing all three stimuli together into a single display would show whether these pairwise depth relations determine the depth structure of the display as a whole. We ask here whether humans can see stable depth relations among *A*, *B*, and *C* when they are presented all at once, creating a display with internal pairwise inconsistency. How does stereo processing of such displays differ from those in which *A*, *B* and *C* have consistent pairwise disparities? Are there alternatives to pairwise depth comparisons that can resolve the incompatible disparities? Or are the incompatibilities not resolved but seen?

Our interest here is in characterizing how the depth seen in displays made up of pairwise inconsistent stimuli differs from the depth seen in displays whose stimulus pairs have consistent relative depths. We describe three experiments, with a grating and two plaids playing the roles of stimuli *A*, *B*, and *C*. The first experiment assessed the perceived depth order of the three stimuli directly. The second and third experiments examined depth-order judgments to a relevant subset of stimuli within the displays. The data show a stimulus-dependent recalibration of the effective disparity direction. The disparities of all the stimuli in the display, whether relevant to the task or not, contribute to the resulting depth judgments. This resolves the perceptual inconsistencies between the stimuli within the display and reveals a global disparity computation of depth judgments of 1-D stimuli.

2. General methods

The displays contained three stimuli in Experiment 1 and five (two of which were redundant) in Experiments 2 and 3. One stimulus was a sinusoidal grating patch and the others were plaid patches formed by summing two orthogonal gratings. Gaussian contrast envelopes (with zero disparity) defined the location of these stimuli. Individual stimuli were characterized by three parameters: Dimensionality (1-D or 2-D), disparity magnitude (fixed for plaids, varying in magnitude across trials for gratings), and disparity direction (between +45° and −45°, plus one case of 135° and −135°, where the positive and negative horizontal directions are 0° and ±180°, respectively). The orientation of the grating was either 45° or 135° in all three experiments. Because a grating's disparity direction can be regarded as normal to its orientation, a grating with a 45° orientation has an associated disparity axis running along the +135°/−45° direction, and a grating with a 135° orientation has one running along the +45°/−135° direction.

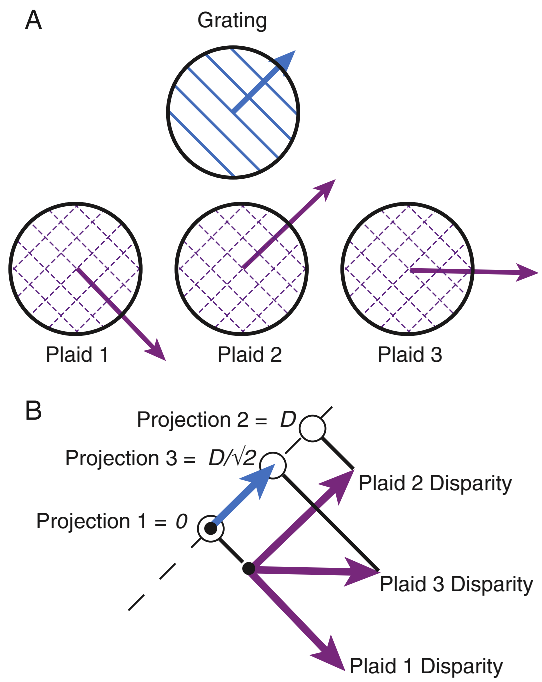

Fig. 1. Perceived depth predicted from projected disparities. (A) Arrows showing disparity vectors of sample grating (top) and three plaids (with disparity magnitudes exaggerated relative to the pattern wavelength). Disparity directions are 0° (horizontal) and ±45°. (B) Plaid disparities projected onto the grating's disparity axis. This axis is indicated by the dashed line. For clarity, the origins of the plaid disparity vectors are displaced from the origin of the grating disparity vector. The solid oblique lines intersect the grating's disparity axis perpendicularly, giving the projections of the plaids' disparities. The projected values assume a disparity magnitude is D for all three plaids. The relative sizes of the components along the grating's disparity predict that a grating with the disparity depicted here will appear farther in depth than one plaid, nearer than another, and at the same depth as the third, despite two of the plaids having equal horizontal disparities and therefore appearing in the same depth plane.

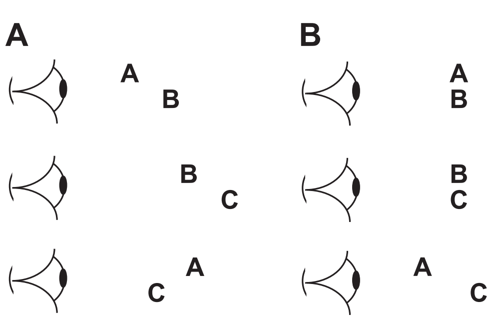

Fig. 2. Two examples of non-transitive depth, with stimuli *A*, *B*, and *C*. (A) The standard example of non-transitivity: $B > A$, $C > B$, $A > C$. (B) Alternative arrangement: $A = B$, $B = C$, $A \neq C$.

The plaids had two sinusoidal components, one oriented at 45° and the other at 135°. In the case of a plaid with a disparity in the +45° direction, the right retinal image differed from the left solely by a phase shift of the 1-D component with the 135° orientation. The component oriented at 45° had the same phase in the two retinal images, a disparity of zero. When superimposed, these sinusoidal components perceptually cohere in depth, resulting in a unified 2-D stimulus seen in a single depth plane—a plaid rather than two distinct gratings (Adelson & Movshon, 1984; Calabro & Vaina, 2006; Delicato & Qian, 2005; Farell, 1998; Farell & Li, 2004). With the component disparities just described, the 2-D pattern features (for example, the 'blobs' formed at the intersections of the component gratings) have a disparity that is oblique, in the +45° direction. The horizontal component of this disparity is positive, corresponding to the 'far' depth at which the plaid is seen relative to a stimulus with zero disparity.[1]

All procedures carried out in the studies reported here followed the tenets of the World Medical Association Declaration of Helsinki and were approved by the Institutional Review Board of Syracuse University. All participants in the experiments participated with their informed consent.

[1] Direction is defined here by a vector from a location of a 2-D feature in the retinal image of the left eye to the nearest identical feature in the retinal image of the right eye after the two retinas have been overlaid in anatomical correspondence (where 'identical' discounts differences in contrast due to the Gaussian envelope).