Monocular aniseikonia: a motion parallax analogue of the disparity-induced effect

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Mayhew and Longuet-Higgins have recently outlined a computational model of binocular depth perception[1] in which the small vertical disparities between the two eyes' views of a three-dimensional scene are used to determine the 'viewing parameters' of fixation distance (d) and the angle of asymmetric convergence of the eyes (g) (refs 2, 3). The d/g hypothesis, as it has been called[4], correctly predicts that a fronto-parallel surface, viewed with a vertically magnifying lens over one eye, should appear to be rotated in depth about a vertical axis[1,3-5]. We report here a comparable illusion for surfaces specified by monocular motion parallax information, which can be explained more simply by considering the differential invariants of the optic flow field. In addition, our observations suggest that the disparity-induced effect is not a 'whole field' phenomenon nor one limited to small magnification differences between the eyes[1,4].

The vertical magnification of one eye's image of a binocularly-viewed surface produces the impression of a surface rotated about a vertical axis through the fixation point. This effect was called the 'induced effect' by Ogle[6] because he believed that horizontal disparities were 'induced' into the neural representations by a compensatory isotropic scaling mechanism acting to minimize the vertical size differences caused by eccentric fixation. Since horizontal disparities are affected by both the magnitude of any depth differences and the degree of eccentric fixation (g), the zero horizontal disparities in an induced effect stimulus have to be 'corrected' so that the relative distance and the slant of a surface can be perceived correctly. However, it appears that Ogle did not appreciate the more general significance that vertical disparities at other retinal locations apart from the vertical meridian provide a potential source of information about distance to the fixation point, as well as the angle of eccentric convergence. The mathematical proof for this has been independently provided by Gillam and Lawergren[7] and Mayhew and Longuet-Higgins[1-3]. In both cases, the induced effect is seen as a necessary consequence of a stereoscopic system which uses vertical disparities to determine the viewing system parameters.

As yet, there is little evidence that presence of vertical disparities in a stereogram actually gives a subjective impression of eccentric convergence but, as several authors have pointed out, this might be due to the presence of conflicting oculomotor information[1,7]. However, the magnitude and the direction of the induced effect are both consistent with the d/g hypothesis[3]. Mayhew and Longuet-Higgins also argue the case for the induced effect being a global or 'whole field' phenomenon, since there could only be a single estimate of eccentric fixation angle and therefore only a single 'correction' would be applied to the horizontal disparities in the surrounding area[1,4]. As additional evidence for their theory, they note that the magnitude of the induced effect does not increase when the vertical size difference is greater than about 4-6%[1,6]. This would be predicted by their hypothesis since larger differences in size would imply impossibly large angles of asymmetric convergence[1,7]. Both claims are examined in this paper.

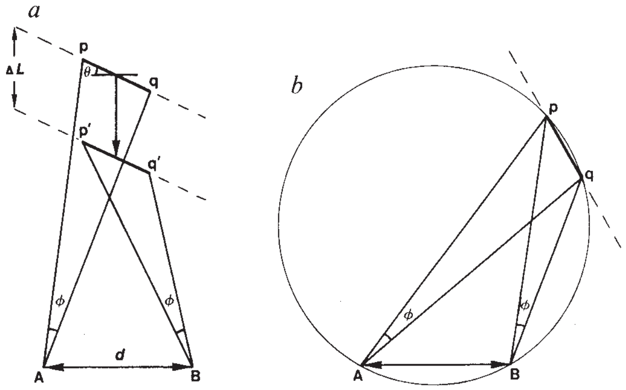

Fig. 1 In a, pq represents part of a surface slanting at an angle θ to the frontoparallel plane, which moves forward to p'q' at the same time as a monocular observer moves from A to B. It can be shown that the horizontal angle subtended at the eye ϕ will remain constant when $\tan\theta = \Delta L/d$. In contrast, since the surface is closer at B than A, the vertical angle subtended will increase. In b, the horizontal angle subtended again remains constant and the vertical angle subtended increases when the monocular observer moves from A to B towards an eccentrically placed slanting surface pq. The two situations differ only by an eccentric rotation of the lines of sight.

The disparity-induced effect can be perceived when one eye's image of a binocularly-viewed scene is magnified vertically. The motion parallax analogue of this illusion—monocular aniseikonia—was created by continuously magnifying and minifying the image projected to a single viewing eye during side-to-side movements of the observer's head[8]. The instantaneous monocular images of the scene at the end points of the lateral head movement necessarily correspond to the two simultaneous binocular views of the same scene when a meridional magnifying lens is placed over one eye. For all the observations reported in this paper, the image transformations for both the parallax and disparity-induced effects were effected electronically, rather than by optical means. The images consisted of either a single random dot pattern, or a pair of random dot patterns viewed independently by the two eyes, each subtending a 20° × 20° visual angle. The disparity-induced effect was produced by increasing the vertical gain slightly on one oscilloscope and decreasing it slightly on the other. The horizontal widths of the patterns remained identical. To produce the parallax-induced effect, the vertical gain of a single, monocularly-viewed oscilloscope was modulated according to the position of the observer's head. Thus the vertical size of the dot pattern was maximal at one end of travel and minimal at the opposite end of travel. Observers were asked to report the perceived orientation and shape of the random dot surfaces in the different experimental conditions.

With binocular viewing of the disparity-induced surface, our results replicate those of previous studies[3,6,7]. Observers reported that the surface appeared to be slanting in depth with the right-hand side apparently closer than the left, when the right eye's image was vertically magnified, and vice versa for magnification of the left eye's image. Increasing the difference in vertical magnification between the two eyes increased the angle of perceived slant, as found previously.

With monocular viewing of the parallax-induced surface, a similar pattern of results was obtained. Observers reported that the surface appeared to be slanting in depth with the right-hand side closer than the left when the monocular image was progressively magnified with head movement to the right and vice versa. Again, the angle of perceived slant increased with an increase in the extent of vertical magnification/minification (for a constant head movement). In both the disparity-induced effect and its parallax analogue, the apparently slanting surfaces were

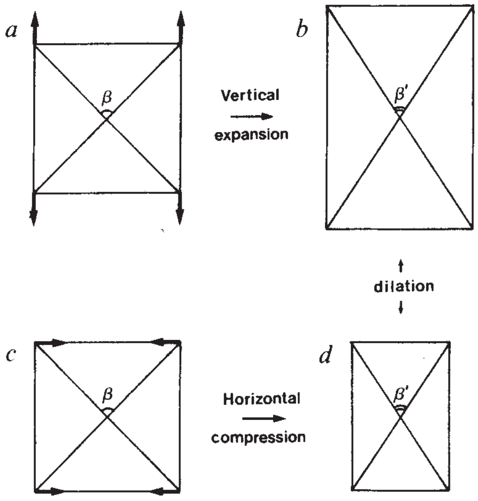

Fig. 2 The vertical expansion of the square pattern segment from *a* to *b* will produce the same amount of local and global deformation (as indicated by the change in the orientation difference between the diagonals $\beta \rightarrow \beta'$) as the horizontal compression of the same pattern segment from *c* to *d*. The transformed patterns, *b* and *d*, are related by a uniform or isotropic expansion.

always perceived as lying directly in front of the observer, rather than eccentrically to one side. In the case of the parallax-induced effect, the slanting surface was also perceived to approach and recede along a median path as the image expanded and contracted. This percept is entirely consistent with the geometry of the transformation, since the image of a slanting surface which approached an observer as he moved laterally towards the "closer" side, would indeed expand vertically, but remain of constant width (Fig. 1*a*).

The interpretation chosen by the visual system is, however, not the only one consistent with the image transformation. In fact, there are an infinite number of possible solutions (unlike the disparity-induced effect which has only one solution). For example, a surface positioned eccentrically and slanting with respect to the direction of gaze, would also generate an image whose vertical size increased and decreased with head movements whilst its horizontal size remained constant (Fig. 1*b*). This particular solution lies behind the explanation proposed by Mayhew and Longuet-Higgins to account for the disparity-induced effect[1]. The fact that observers do not experience this perceptual outcome suggests that, for the parallax system, a vertical size change which accompanies a horizontal head movement is interpreted as a motion in depth rather than resulting from eccentric fixation.

Two additional sets of observations were made for the disparity- and parallax-induced effects. First, as mentioned above, the d/g hypothesis predicts that the induced effect should be a 'whole field' phenomenon, since it seems unlikely that the visual system could entertain different, and therefore contradictory, estimates of the angle of eccentric convergence at the same time. Empirical evidence for the 'whole field' characteristic of the effect comes from the observation that an embedded region which is magnified in one eye's view does not appear to be slanted with respect to the surround[1,5,9]. However, the perception of opposite induced effects in neighbouring spatial regions is possible in both the classical induced effect and the parallax analogue reported here. For example, if the images of the left and right halves of the random dot pattern seen by the right eye are minified and magnified respectively (with respect to the images seen by the left eye), subjects report that the left half of the pattern appears to be slanting closer to the left and the right half slanting closer to the right. According to the d/g hypothesis this could only be possible if the vertical disparities in the *left* half field were interpreted as indicating asymmetric convergence to the right, and in the right half field as indicating asymmetric convergence to the left. A comparable 'double' induced effect was also obtained for surfaces specified by motion parallax information.

The second piece of evidence cited in favour of the d/g hypothesis is that the induced effect does not increase with vertical magnifications greater than 4-6%[3,6]. Indeed, this prediction was used by Frisby[4] to discount Westheimer's finding that sensitivity to vertical disparities is much poorer than for horizontal disparities[10]. However, we have found that the apparent slant of induced effect surfaces does still increase monotonically right up to a 50% magnification difference, when induced effects specifying opposite slants are alternated every few seconds. At the 57-cm viewing distance used in the present experiments, the maximum possible magnification difference which could result from asymmetric convergence would be less than 7%.

Our proposed explanation of the parallax-induced effect is based on the use of differential invariants to describe the optic flow field[11-13]. As Koenderink has shown, the slant of a surface is uniquely specified by the amount of deformation or shear in the flow field, if the extent of observer motion is known. Clearly, the vertical expansion of a monocular image, which underlies the parallax-induced effect, will produce the same degree of deformation in the flow field as a horizontal contraction of the same image (Fig. 2). Hence, the same surface slant is specified. What remains after the deformation component has been extracted is a simple divergence term which is positive in the first case and negative in the second. In the parallax-induced effect, the divergence term is clearly not ignored but instead is responsible for the apparent approach and recession of the slanted surface noted earlier.

Could the proposed explanation also account for the disparity-induced effect? Given that both the mathematical analyses of disparity and parallax transformations[14] and their perceptual characteristics are so similar[15,16], it is tempting to speculate that the perceived surface slants seen in the disparity-induced effect are the result of having a visual system which uses the amount of deformation between the two binocular images as an indicator of surface slant[17]. If this were the case, then the visual system would be left to account for the isotropic size difference between the eyes (the divergence component). The human visual system may have evolved to use this as an indicator of eccentric fixation or it may simply be ignored. Hence, our explanation of the induced effect also allows for the angle of eccentric fixation to be recovered from the disparity field, but differs from the Mayhew and Longuet-Higgins interpretation in that this does not have to be done, even implicitly. According to the d/g hypothesis, vertical disparities are used to signal the angle of asymmetric convergence which is then used to scale horizontal disparities. The fact that vertical disparities do not appear to give the impression of asymmetric convergence, together with the other characteristics of the induced effects reported here, suggests that our proposed explanation may be more parsimonious.

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