PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Vision Research 43 (2003) 1879–1893

Vision Research

www.elsevier.com/locate/visres

Geometric and induced effects in binocular stereopsis and motion parallax

Robert S. Allison [a,*], Brian J. Rogers [b], Mark F. Bradshaw [c]

[a] Department of Computer Science, Centre for Vision Research, York University, Toronto, Ont., Canada M3J 1P3
[b] Department of Experimental Psychology, University of Oxford, Oxford, OX1 3UD, UK
[c] Department of Psychology, University of Surrey, Guildford, Surrey, GU2 5XH, UK

Received 4 September 2001; received in revised form 25 April 2003

Abstract

This paper examines and contrasts motion-parallax analogues of the induced-size and induced-shear effects with the equivalent induced effects from binocular disparity. During lateral head motion or with binocular stereopsis, vertical-shear and vertical-size transformations produced 'induced effects' of apparent inclination and slant that are not predicted geometrically. With vertical head motion, horizontal-shear and horizontal-size transformations produced similar analogues of the disparity induced effects. Typically, the induced effects were opposite in direction and slightly smaller in size than the geometric effects. Local induced-shear and induced-size effects could be elicited from motion parallax, but not from disparity, and were most pronounced when the stimulus contained discontinuities in velocity gradient. The implications of these results are discussed in the context of models of depth perception from disparity and structure from motion.

1. Introduction

Human beings rely on a variety of cues to help determine the spatial layout of their surroundings. One of the best known of these is binocular stereopsis, which relies on the processing of differences, or disparities, between the two-dimensional images in the two eyes to recover three-dimensional structure. However, observers without stereopsis can make precise depth judgements even when pictorial cues to depth are uninformative. Since the time of Helmholtz (1909), it has been realised that mobile observers can use motion parallax to obtain monocular depth percepts. From a computational viewpoint, the information provided by motion parallax is very similar to the information provided by binocular parallax (Howard & Rogers, 1995; Rogers & Graham, 1983). [1] In both cases, the observer uses information obtained from two or more spatially separate views of the scene obtained either simultaneously for stereopsis or over time for motion parallax. Several investigators have looked at the equivalence of the depth percepts arising from these two cues and the extent to which the two systems share a common underlying mechanism or interact (e.g. Bradshaw & Rogers, 1996; Cornilleau-Pérès & Droulez, 1993; Johnston, Cumming, & Landy, 1994; Rogers & Collett, 1989; Rogers & Graham, 1982; Tittle, Todd, Perotti, & Norman, 1995).

In this paper, we are mainly concerned with comparing the perception of slant and inclination produced by binocular parallax- and motion parallax-defined stimuli. One of the key features of a surface is its local orientation in depth. We refer rotation in depth about a vertical axis (i.e. from frontal toward a 'wall-plane' surface) as slant. We refer to the rotation of a surface in depth about a horizontal axis (i.e. from frontal toward a 'sky-plane' or 'ground-plane' surface) as inclination. [2] For both stereopsis and motion parallax, surface slant and inclination are associated with parallax gradients. There is some evidence of similarities between stereopsis

* Corresponding author. Fax: +1-416-736-5857.
E-mail addresses: allison@cs.yorku.ca, allison@hpl.crestech.ca (R.S. Allison), bjr@psy.ox.ac.uk (B.J. Rogers).

[1] In this paper we use the term binocular parallax as a synonym for binocular disparity when convenient. This will help to simplify and emphasise the common features of binocular stereopsis and motion parallax.

[2] In Stevens's (1983) nomenclature, inclination is slant with a slant-tilt angle of 90°.

0042-6989/03/$ - see front matter
doi:10.1016/S0042-6989(03)00298-0

and motion parallax in the perceptual processing of these gradients. For example, Rogers and Graham (1983) found that the perceptual anisotropy between stereoscopically defined inclination and slant is paralleled in the motion-parallax domain. Specifically, they reported that subjects are more sensitive to horizontal-shear than to horizontal-size transformations for both binocular parallax- and motion parallax-defined surfaces. In this paper, we consider another aspect of slant perception and look for the existence of motion-parallax analogues of the so-called induced effects previously reported for stereoscopic slant and inclination perception.

1.1. Slant perception from disparity and lateral head motion

Consider an observer fixating a frontal surface in the median plane. For disparity, Ogle (1964) showed that magnification of the horizontal size of the image in one eye with respect to the other produces the impression of a 'wall-plane' surface *slanted* in depth about a vertical axis. Such a horizontal-size transformation introduces a horizontal gradient of horizontal disparity. To first order, this horizontal disparity gradient generates a gradient of relative depth and hence the perceived slant. The magnitude of the resulting slant varies with the horizontal size ratio of the images in the two eyes. For stimuli near the median plane of the head a reasonable approximation for the degree of slant is:

$$\tan^{-1}\left(\frac{2D}{I}\frac{\mathrm{HSR}-1}{\mathrm{HSR}+1}\right)$$

where HSR is the horizontal size ratio, D is the viewing distance and I is the interocular distance (Howard & Rogers, 2002; Kaneko & Howard, 1996; Ogle, 1964; see Backus, Banks, van Ee, & Crowell, 1999 for more general expressions). Many investigators have confirmed that horizontal size parallax gives rise to precepts of slant for stereopsis (e.g. Gillam, Chambers, & Russo, 1988; Mitchison & McKee, 1990; van Ee & Erkelens, 1998). Ogle (1938) referred to this percept of slant from horizontal size disparity as the geometric-size effect since the percept is predicted by the geometry of the situation.

For motion parallax generated by lateral head motion the situation is similar in many respects. If one views a static surface monocularly and moves the vantage point between the station points of the left and right eyes then, at the end points of the travel, one obviously obtains equivalent views to the left and right half-images in the stereoscopic case. Intuitively, one expects a continuous change in aspect ratio of the surface as the head moves laterally with respect to a slanted surface as the eye sees more and less oblique views of the surface. Once again, consider a surface centred on the median plane of the head and that the slant is not too extreme. In this case, for a given head velocity the instantaneous rate of horizontal expansion or compression (a horizontal gradient of horizontal velocity) increases with increasing slant. Thus, when the head moves relative to a slanted surface, velocity gradients are generated in the optical flow field.

However, the horizontal gradient of horizontal velocity does not specify slant uniquely during lateral head motion. For example, a surface generating an instantaneous horizontal gradient of horizontal velocity (horizontal size transformation) during lateral head motion could be a slanted surface placed directly in front of the observer, a surface with different slant located eccentrically (or rotating), or a frontal surface moving in depth relative to observer. Eccentricity and motion in depth generate horizontal velocity gradients in the flow field because the retinal image of the surface shrinks with increased distance due to perspective scaling. Similarly, with binocular viewing of an eccentric surface, the surface is nearer to one eye than the other and hence subtends a larger visual angle in the nearer eye. Thus, horizontal size disparity can arise from surface eccentricity as well as from surface slant.

This essential ambiguity must be resolved before depth can be estimated from horizontal gradients of horizontal parallax. For both motion parallax and stereopsis, one needs to account for the head-centric eccentricity of the surface (and for the possibility that the object moves in the motion parallax case). One possibility is to use extraretinal eye position signals to convert the oculo-centric position of the surface to head-centric coordinates (Backus & Banks, 1999). However, it is also possible to use retinally available signals to correct for the effects of surface eccentricity. When the surface is placed eccentrically (or the head moves to make it so) then both the horizontal and vertical size of the image of surface elements are affected. The horizontal size ratio of the image at two spatially separated vantage points (i.e. at the left and right eye or at two positions during lateral head motion) depends on both the surface's slant and its eccentricity. On the other hand, it has been shown that the vertical size ratio is a function of the surface eccentricity but is affected little by surface slant (Gillam & Lawergren, 1983). Thus, vertical gradients of vertical disparity and vertical velocity could be used to disambiguate slant perception in stereopsis and motion parallax, respectively.

Support for this idea comes from the finding that surface slant can be induced by a gradient of vertical disparities in the so-called induced-size effect (Ogle, 1938). In the induced-size effect, a vertical gradient of vertical disparity (vertical-size parallax transformation) between the half images of an isolated surface creates an impression of a surface slanted in depth. Ogle (1938) called it the induced-size effect because it is as though the vertical magnification of the image in one eye induces an equivalent horizontal magnification of the image in the other eye. According to this interpretation, the vertical-size disparity is 'converted' into an equivalent horizontal-size disparity of opposite sign. For lateral motion parallax, Rogers and Koenderink (1986) demonstrated that modulation of the vertical size of an image during lateral head motion produces an analogous motion-parallax induced-size effect. Further evidence that these orthogonal gradients of vertical parallax are processed during slant perception comes from Meese and his colleagues (Meese & Harris, 1997; Meese, Harris, & Freeman, 1995), who have shown that surface slant can be produced by gradients of vertical velocity during simulated lateral object motion (object-produced parallax).

1.2. Inclination perception with stereopsis and lateral head motion

A vertical gradient of horizontal disparity (horizontal-shear parallax transformation) produces the impression of a surface inclined in depth about a horizontal axis (Ogle, 1964). To first order, this horizontal disparity gradient generates a gradient of relative depth and hence a percept of inclination. The magnitude of the resulting slant varies with the horizontal shear disparity. For stimuli near the median plane of the head, a good approximation for the magnitude of slant is easy to derive:

$$\tan^{-1}\left(\frac{D}{I}\tan(\psi)\right)$$

where ψ is the horizontal shear disparity expressed as a relative shear angle, D is the viewing distance and I is the interocular distance (Ogle, 1964; see Banks, Hooge, & Backus, 2001 for alternative expressions). Analogously, vertical gradients of horizontal velocity (horizontal-shear parallax transformations) are created by inclined surfaces during lateral motion of the head. Braunstein (1968) demonstrated that these velocity gradients are sufficient to support the percept of surface inclination in a motion-parallax display. Since in both cases, the percepts are predicted by the geometry of the situation, we refer to them as geometric-shear effects (after Ogle, 1938).

As in the slant case, these gradients of horizontal parallax do not specify the inclination of a surface unambiguously. Banks et al. (2001) have recently confirmed Mitchison and McKee's (1990) claim that horizontal shear disparity is affected little by surface eccentricity. However, estimation of inclination from horizontal shear parallax relies on torsional alignment of the eyes at the spatially separate vantage points. In stereopsis, for example, cyclovergence of the eyes (torsion of one eye relative to the other) gives rise to horizontal shearing in the disparity field unrelated to surface inclination. Similarly, cyclotorsional head or eye movements during lateral motion parallax give rise to horizontal shearing in the optic-flow field unrelated to surface inclination. Once again we could rely on extraretinal eye and head position signals to compensate for torsional misalignment. However, it is often assumed that this information is unreliable and recent evidence suggests that these signals are not used for stereoscopic perception of inclination (Banks et al., 2001; Kaneko & Howard, 1997). In many situations there is a signal available in the retinal images. When the torsional state of the eyes differs between two views then the retinal positions of the images of objects in the two images differ vertically as well as horizontally. Specifically, torsional misalignment between the views gives rise to horizontal gradients of vertical disparity or vertical velocity in the disparity and optic-flow fields. Thus, horizontal gradients of vertical disparity or vertical velocity could be used to compensate for torsional misalignment during stereopsis and lateral motion parallax, respectively.

In agreement with this proposal, investigators have demonstrated that a horizontal gradient of vertical disparity (vertical-shear parallax transformation) in a large, isolated, textured surface creates the impression of inclination about a horizontal axis (Banks et al., 2001; Cagenello & Rogers, 1990; Gillam & Rogers, 1991; Howard & Kaneko, 1994; Rogers, 1992). We refer to this as the induced-shear effect since, like the induced-size effect, it is not predicted geometrically from the horizontal disparity field alone.

1.3. The induced effects

Recent models of stereoscopic vision have sought to explain the induced-size and induced-shear effects (for review see Howard & Rogers, 2002). The stereoscopic induced-size effect is believed to result from mechanisms designed to account for gaze or target eccentricity in estimating depth (or slant) from disparity. In Koenderink and van Doorn's deformation theory (1976), the gradient of vertical disparity is used to correct the horizontal disparity directly; in other theories (e.g. Gillam & Lawergren, 1983; Mayhew & Longuet-Higgins, 1982) the vertical disparity affects slant indirectly by being used to estimate viewing parameters such as gaze or surface eccentricity that are in turn used to interpret the horizontal disparity. Similarly, the stereoscopic shear induced effect is believed to result from neural and oculomotor mechanisms designed to compensate for cyclotorsional misalignment of the eyes. Thus, vertical shear disparity is used to correct inclination from horizontal shear disparity directly in the theory of Koenderink and van Doorn (1976) or indirectly by using it to estimate or minimize the torsional state of the eyes (Banks et al., 2001; Howard & Kaneko, 1994; Rogers, 1992; Rogers & Bradshaw, 1999).

The analogy with motion parallax is rather direct. For example, a slanted surface located directly in front of the observer will produce an instantaneous horizontal gradients of horizontal velocity during lateral head motion but so will an unslanted but eccentrically located surface (which will expand/contract as the observer moves laterally towards/away from it). Thus, the estimation of surface slant from horizontal size parallax needs to take into account target eccentricity. In the eccentric viewing case, the image also expands/contracts *vertically* as the observer moves laterally towards/away from it and this vertical expansion gives an indication of eccentricity. Similarly, a horizontal shearing in the flow field can be generated by surface inclination but also by relative torsional motion between the eye and the surface during the translation (due to head tilt or ocular torsion relative to the object). Note that in the case of torsion, a *vertical* shearing will also be present in the flow field.

Some theories of structure from motion incorporate information in these orthogonal velocity gradients. The theory of Koenderink and van Doorn (1975) is based upon a first-order analysis of the disparity or flow field, in which the local field is decomposed into differential components of dilation or divergence (Div), rotation or curl (Curl) and two components of deformation, referred to here as Def1 and Def2 (see Howard & Rogers, 1995 for a review). According to the theory, the deformation components of the flow or disparity field, Def1 and Def2, are responsible for determining surface slant and inclination respectively. Longuet-Higgins and Prazdny (1980) also favoured processing the differential structure of the optical flow field using estimates of the deformation (or shear) in the flow-field. They also showed that, in principle, by using the second-order properties (the 'acceleration component') of the optic-flow field, the effects of observer translation and rotation relative to a static scene could be separated and thus metric depth could be recovered. An isolated planar surface was a degenerate stimulus condition for their equations, which could be easily detected but did not allow for unique estimates of observer translation and rotation. During observer-generated motion parallax, this ambiguity may be alleviated by use of efferent or afferent information about the head movement.

Since the calculation of differential invariants is essentially a local operation, it could be performed by local mechanisms (Koenderink, 1986). The experimental evidence, however, suggests that we are insensitive to local variations in deformation disparity when it involves a vertical disparity component (Howard & Kaneko, 1994; Kaneko & Howard, 1996; Rogers, 1992; van Ee & Erkelens, 1998). In stereopsis, vertical shear and size disparity appear to signal viewing system parameters such as gaze angle and cyclotorsional misalignment of the eyes that affect the entire image or large portions of it. Hence, there is no requirement to estimate vertical size and shear disparity locally and it is not surprising that the visual system does not do so.

In contrast to the binocular parallax case, there are several good reasons to expect that the orthogonal velocity gradients would be analysed locally in motion parallax. First, motion-parallax information is acquired over time rather than simultaneously as in the binocular-parallax case. During this time, objects can approach or rotate resulting in local variations in the divergence and curl components that are not possible in binocular stereopsis. Second, whilst vertical-size and vertical-shear transformations in stereopsis can only arise because of 'artefacts' of eccentric gaze or cyclotorsional misalignment, they can occur 'naturally' in motion parallax when the head movements that create the parallax are vertical rather than horizontal. For example, viewing a slanted surface while moving the head up and down creates a vertical-shear component in the optical flow field and an inclined surface will create a vertical-size component.

1.4. Predictions

The demonstrations of the stereoscopic induced-shear effect were subsequent to Rogers and Koenderink's (1986) demonstration of an analogue to the induced-size effect in motion parallax. The present study follows from the work of Rogers and Koenderink (1986) and, in particular, we describe an observer-generated motion-parallax analogue of the induced-shear effect and investigate the motion-parallax induced-size effect in greater detail. We predict the following motion parallax analogues to the geometric and induced effects whilst viewing a display monocularly with lateral head motion:

1. Continuous horizontal-size transformations in the flow field, which are linked to the lateral head motion, should produce a geometric-size effect (slant).
2. Continuous vertical-size transformations in the flow field should produce an induced-size effect (slant).
3. Continuous horizontal-shear transformations in the flow field should produce a geometric-shear effect (inclination).
4. Continuous vertical-shear transformations should produce an induced-shear effect (inclination).

We make the following predictions for the parallax created by vertical head motion:

5. Continuous vertical-shear transformations in the flow field, which are linked to the vertical head motion, should produce a geometric-shear effect (slant).
6. By symmetry, continuous horizontal-shear transformations should produce an induced-shear effect (slant).

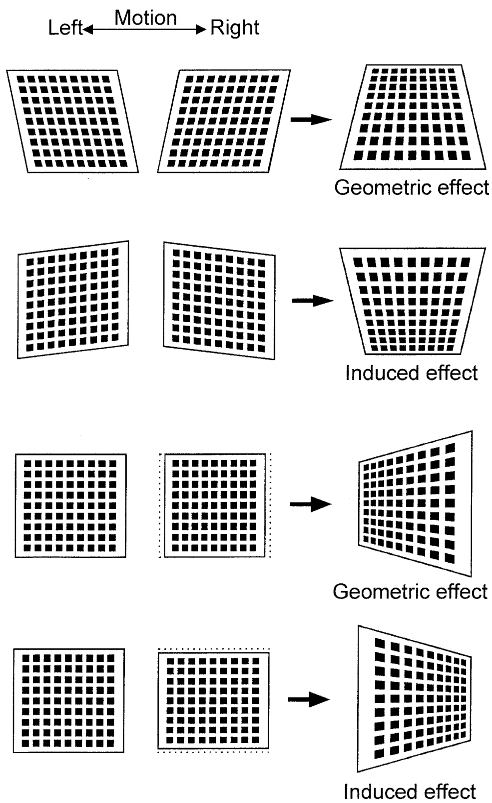

Fig. 1. Predicted geometric-effect and induced-effect percepts from lateral motion-parallax transformations. Left-hand side of the figure shows the transformation of the image for rightward and leftward head motion; the right-hand side shows a cartoon depicting the predicted depth percept (shown in perspective for illustration only; all depth in the experimental displays was from parallax). Note the sign of the induced effects are opposite those of the corresponding geometric effects.

7. Continuous vertical-size transformations should produce a geometric-size effect (inclination).
8. Continuous horizontal-size transformations should produce an induced-size effect (inclination).

In agreement with the main theories of the induced effect (Backus et al., 1999; Banks et al., 2001; Gillam & Lawergren, 1983; Howard & Kaneko, 1994; Koenderink & van Doorn, 1975, 1976; Mayhew & Longuet-Higgins, 1982; Ogle, 1964) the induced effects are expected to be opposite in sign to the equivalent geometric effects for the equivalent transformation (Fig. 1). For example, when viewing a slanted 'left-wall plane' surface centred on the median plane, the horizontal extent of the surface in the optic array decreases with leftward head movement and increases with rightward head movement (while the front of the surface is visible). If the image expands *vertically* with rightward head motion then a 'right-wall plane' surface would be predicted. Similarly, for a 'ground-plane' surface, the projection of the surface onto the optic array undergoes horizontal shear in a clockwise direction for head movements to the right. Once again the induced-shear effect is predicted to be in the opposite direction—if the image shears *vertically* in a clock-wise direction with rightward head motion then a 'sky-plane' surface should be perceived.

Several theories predict that the induced effects for motion parallax should be 'local'. To test this prediction, we presented parallax flow fields in both whole field and side-by-side, 'dumbbell' configurations. If processing is local, we predict that the separate and different slants and inclinations will be seen in each half of a side-by-side display and the boundary between the two halves will be reasonably sharp. These predictions are summarised in Table 1.

We describe three experiments. Experiment 1 measured geometric and induced effects in isolated surfaces; Experiment 2 investigated whether geometric and induced effects are local phenomena using the dumbbell stimuli. Experiment 3 used a nulling technique to investigate more directly the relative strength of the induced and geometric effects under stereoscopic or lateral motion-parallax conditions.

2. Methods

2.1. Participants

Five unpaid volunteers participated in these studies. All had normal vision (one subject, JA, was corrected to normal with her habitual correction) and stereopsis. Two of the authors participated (RA and BJR); the other three subjects were naive to the purposes of the experiment.

2.2. General methods

Random-dot raster images were computer generated and presented on HP1304A large screen oscilloscopes. The displays subtended to 26.7 by 20 degrees at the

Table 1
Predictions for motion-parallax analogues of the geometric and induced effects

Parallax generator	Parallax transformation			
	Horizontal shear	Vertical shear	Horizontal size	Vertical size
Binocular separation	Geometric inclination	Induced inclination[a]	Geometric slant	Induced slant[a]
Lateral head motion	Geometric inclination	Induced inclination	Geometric slant	Induced slant
Vertical head motion	Induced slant	Geometric slant	Induced inclination	Geometric inclination

[a] Global or regional phenomenon.

viewing distance of 57 cm. Ramp generator circuits triggered by the horizontal and vertical synchronisation signals were used to generate the horizontal and vertical raster scan lines and image intensity was controlled by the video output signal. Additional horizontal and vertical signals to the scopes could be used to introduce horizontal and/or vertical parallax signals that were generated by a Wavetek 175 arbitrary function generator synchronised with the video signal.

For the stereoscopic displays, two oscilloscopes were arranged in a modified Wheatstone stereoscope arrangement. The subject viewed the displays from 57 cm with head supported by a chin rest. The displays were viewed in a darkened room and apertures were located close to the eyes to occlude the edges of the displays in order to minimise frame effects. Identical images were presented on both displays and equal but opposite analogue signals from the function generator were used to introduce disparities (binocular parallax) into the half images.

For the motion-parallax displays, a single HP1304A was located at a distance of 57 cm from the observer. The observers placed their head in a chin rest and made lateral head movements at a rate of 1.5 Hz in synchrony with the tones of an electronic metronome. The extent of the head movement was twice the nominal interocular distance or 13 cm. A potentiometer attached to the chin rest sensed the subject's head position, and this signal was used to modulate the signal from the arbitrary function generator. The modulation was such that, when the chin rest was moved 3.25 cm to the left or right of the middle of its travel (i.e. to the nominal vantage points of the left and right eyes during stereoscopic viewing), the images corresponded to the half images for the left or right eye in the stereoscopic displays. In other words, we could express the motion parallax in terms of an equivalent binocular parallax (Rogers & Graham, 1982).

For sessions studying parallax from vertical head motion, the subjects wore a helmet connected to a linear potentiometer suspended from the ceiling and generated vertical head movements in time with the metronome by rhythmically bending and extending their knees. The potentiometer was fastened to the head with a u-joint coupling and constrained to move up and down in piece of plastic pipe. This constrained the head to move up and down with only slight lateral movement. After practice, subjects could make the up and down movements easily without significant lateral motion.

In Experiments 1 and 2, subjects were instructed to attend to the perceived slant or inclination of the displayed surfaces and to make verbal judgements of the direction and degree of surface slant or inclination relative to a fronto-parallel norm. Subjects were trained in making these judgements prior to each experiment. In the training procedure, subjects were required to estimate the magnitude of acute angles drawn on white card and were provided with feedback on their performance. When subjects reached a reliable level of performance the experiments commenced. Experiment 3 used a different nulling technique described below.

2.3. Experiment 1a—single disc

The display consisted of a disc subtending a 240-pixel radius (10 degrees) on a black background. The disc was textured with a 50 percent density random pixel texture. By introducing an additional sawtooth waveform to the X or Y inputs of the oscilloscopes, a linear gradient of either horizontal or vertical parallax could be created across the disc. Thus, horizontal- and vertical-shear or horizontal- and vertical-size transformations were generated. Note that vertical-shear or vertical-size parallax refers to vertical displacement of the image dots—lateral head motion was always used to generate the parallax transformations in Experiment 1a. Slant and inclination were specified solely by these velocity or disparity gradients. We were specifically interested in first-order effects and wanted to eliminate the contributions of the higher-order components due to differential perspective. The second-order effects might be expected to enhance the perception of slant for the geometric-effect stimuli but have no direct counterpart in the induced-effect displays. Note also that most of the acceleration or perspective component was present since the head actually translated with respect to the display. This display was, of course, a real frontal surface and thus the flow fields for (static) images on the display were appropriate for such a surface during head translation. Thus only the acceleration (and higher order) terms related to the *difference* in slant between the simulated surface and the frontal plane were missing.

The amplitude of the sawtooth waveform was varied to create theoretical slants and inclinations of −30°, −15°, 0°, 15° and 30° with respect to the frontal plane (equivalent disparity gradients of −3.50, −1.75, 0, +1.75 and +3.50 arcmin per degree at 57 cm). Positive slants and inclinations were defined to be in the direction of left-wall plane (right side of the surface away, left side near) and ground-plane (top away, bottom near) surfaces, respectively. Positive size parallax was defined as expansion in the right eye or for rightward movement and contraction in the left eye or for leftward movement. Positive shear disparity was defined as clockwise shearing in the right eye or for rightward movement and counter-clockwise shearing in the left eye or for leftward movement.

Separate blocks were run for (i) horizontal motion parallax, (ii) vertical motion parallax, (iii) horizontal binocular parallax and (iv) vertical binocular parallax. Each block consisted of 30 trials in randomised order and block order was counter-balanced. These blocks were composed of trials for each of the five levels of both slant and inclination with three repetitions. Each block was repeated twice for each subject giving six replications of each condition. Following each trial, subjects were required to report, verbally, the perceived inclination or slant of the disc. Four subjects with normal binocular vision participated.

2.4. Experiment 1b

The methods were basically the same as those in Experiment 1a except that the motion parallax was generated by vertical rather than lateral head motion. Separate blocks were run for horizontal and vertical motion parallax. Each block consisted of 30 trials in randomised order; block order was counter-balanced. Trials were presented for each of the five levels of slant and inclination with three repetitions. Each block was repeated twice for each subject giving six replications of each condition. Following each trial subjects were required to report the perceived inclination or slant of the disc. Three of the four subjects from Experiment 1a participated in Experiment 1b.

2.5. Experiment 2—double disc

The display consisted of two abutting discs each subtending 220 pixels (9.2 degrees) located either to the left and right or above and below the centre of the screen. For all trials, equal but opposite parallax transformations were imposed on the two discs in order to cause them to have equal but opposite theoretical slants or inclinations. For discs arranged in a left–right configuration, the superimposed shear parallax theoretically specifies a pair of inclined surfaces in a 'twist' configuration and the size parallax specifies a pair of slanted surfaces in a 'hinge' configuration (Gillam et al., 1988). For discs arranged in a top–bottom configuration, the superimposed shear parallax specifies a pair of inclined surfaces in a 'hinge' configuration and size parallax specifies a pair of slanted surfaces in a 'twist' configuration.

On each trial, subjects were asked to make separate verbal judgements of the direction and magnitude of the perceived slant or inclination of each disc with respect to the frontal plane. Responses to shear and size parallax were studied in separate sessions. Horizontal motion parallax, vertical motion parallax (vertical motion of the image elements), horizontal binocular parallax and vertical binocular parallax were run in four separate blocks. The amplitude of the sawtooth waveforms was varied so as to create theoretical slant and inclination differences between the surfaces of −30°, −15°, 0°, 15° and 30°. Ordering of the blocks for the four subjects was done according to a randomised Latin square design and ordering of trials within each block randomised. Four subjects with normal binocular vision were participants.

2.6. Experiment 3—Nulling

In this experiment subjects were presented with single or double surfaces undergoing vertical-shear or vertical-size parallax transformations (induced effects) generated in response to lateral observer head motion. Equivalent disparity gradients were ±0.875, ±1.75, ±2.63 or ±3.50 arcmin per degree at 57 cm. Double-disc displays were configured in a hinge arrangement. The subjects were required to null the perceived slant or inclination of the surfaces by introducing horizontal-shear or horizontal-size parallax (geometric effect) transformations. The amount of horizontal-shear or horizontal-size parallax could be increased or decreased by the subject in steps of 0.03 arcmin per degree by means of button presses registered by the computer. Two subjects participated in the experiment.

3. Results

3.1. Experiment 1a: Single disc stimuli

When the stimulus was a single disc-shaped random-dot pattern, gradients of horizontal and vertical disparity produced reliable geometric and induced effects, respectively. The results for the four subjects are summarised in Fig. 2a. The magnitude of the geometric-shear and geometric-size effects tended to be larger than the predicted effects (slopes were greater than one). These over-estimations probably reflect a tendency to make scaling over-estimations that we noted in the magnitude estimation training procedure. These errors were minimised with feedback during the training but the over-estimates may be a remnant of this tendency. The induced effects were slightly smaller than the geometric effects for all subjects, but were robust and repeatable.

Horizontal and vertical motion parallax during lateral head motion also produced geometric and induced effects in the four subjects (Fig. 2b). The subjects reported that slant and inclination for the geometric-shear and geometric-size effects were typically accompanied by the percept of the disc being rigid although (in some cases) the surface was seen to counter-rotate about its vertical axis as the head moved side to side. The motion-parallax versions of the geometric-shear and geometric-size effects tended to produce larger perceived inclinations and slants than the equivalent binocular-parallax geometric effects (Fig. 2). The motion-parallax analogues of the induced-shear and induced-size effects were slightly smaller than the corresponding motion-parallax geometric effects but were reliably reported by all subjects. Subjects typically reported that expansion and contraction or motion-in-depth of the disc accompanied the motion-parallax induced-size effect (Rogers & Koenderink, 1986). The motion-parallax induced-shear

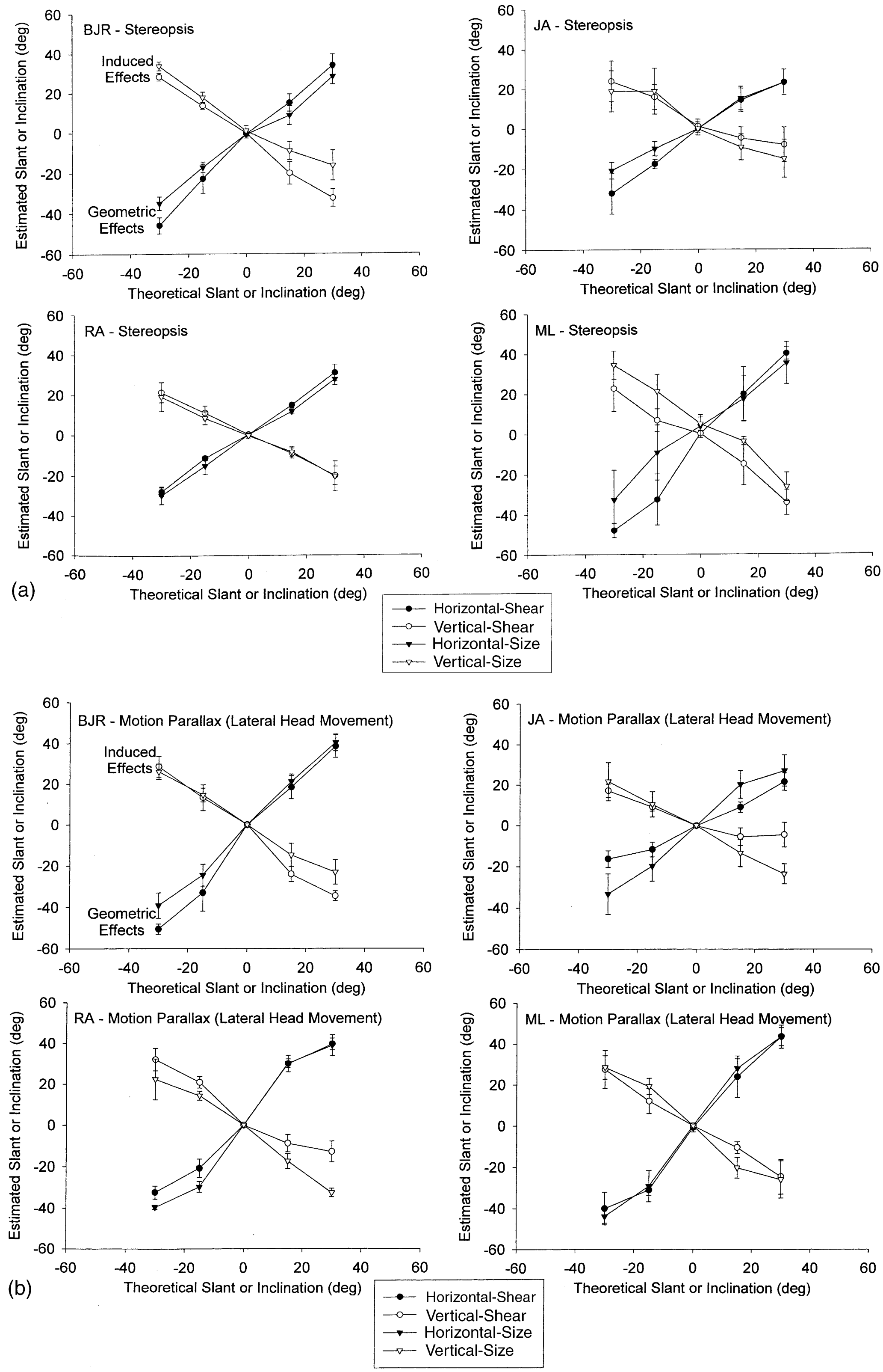

Fig. 2. Results from Experiment 1a, which measured slant and inclination percepts generated by size and shear parallax in isolated random-dot surfaces. (a) Slant and inclination matches for four subjects when viewing stereoscopic displays. (b) Slant and inclination matches for four subjects when viewing motion-parallax displays generated by lateral head motion. Error bars indicate 95% confidence intervals for the mean.

effect was typically accompanied by apparent rotation of the disc about its centre.

Subjects rarely reported anomalous percepts such as depth reversal, slant for shear disparity stimuli or in-

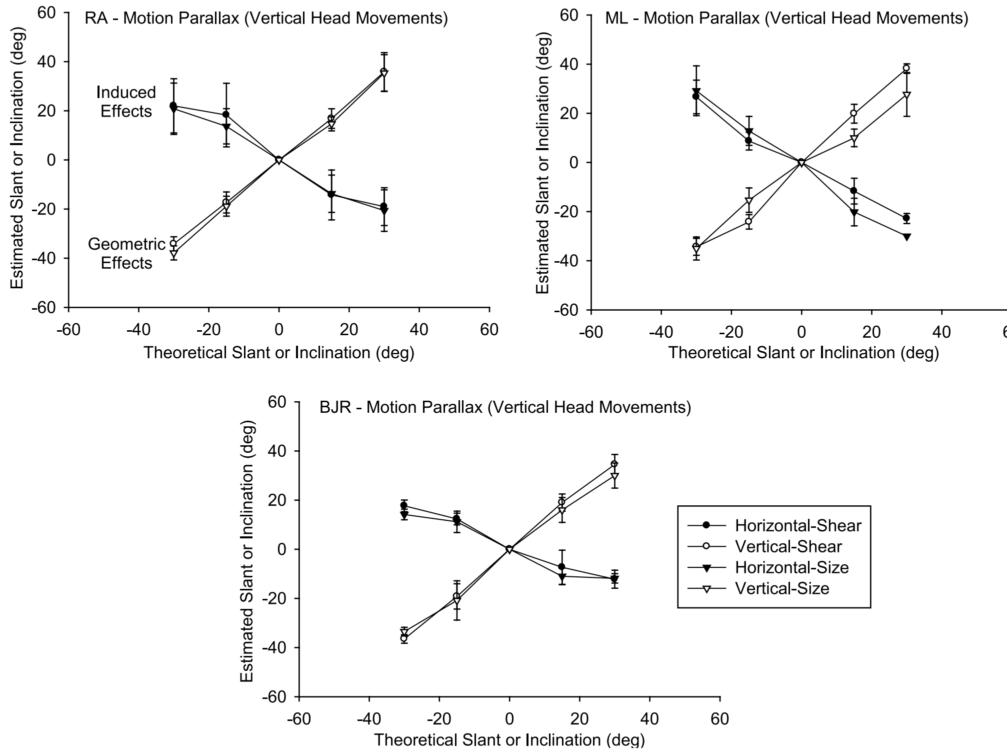

Fig. 3. Slant and inclination matches for three subjects viewing motion-parallax displays generated by vertical head motion. Slant and inclination percepts were generated by size and shear parallax in isolated random-dot surfaces. Error bars indicate 95% confidence intervals for the mean.

clination for size disparity stimuli. These reports constituted approximately one percent of the data and these data have been excluded from the above analyses.

3.2. Experiment 1b—Vertical head motion

When the motion-parallax display was driven by vertical head motion a similar but mirror symmetrical set of results to the lateral motion parallax case was obtained (Fig. 3). During vertical head motion, the slant and inclination of real surfaces create vertical-shear and vertical-size transformations in the flow field, respectively. Vertical-shear and vertical-size parallax generated appropriate geometric effects in the three subjects. Horizontal-shear and horizontal-size parallax are not produced during vertical head motion by real slanted and inclined surfaces. Nevertheless, horizontal-shear and horizontal-size parallax during vertical head motion generated induced effects of surface slant and inclination as predicted. The induced effects were slightly smaller than the geometric effects for the same magnitude of velocity gradient.

3.3. Experiment 2: Double disc stimuli

With stereoscopic presentation, equal but opposite horizontal-size or horizontal-shear disparity in the two adjacent discs generated a strong percept of relative slant or inclination (Fig. 4). As in Experiment 1, depth tended to be overestimated relative to the theoretically predicted slants and inclinations but increased systematically and monotonically with disparity gradient. Twist arrangements (triangular symbols) tended to result in slightly more reported slant than hinge arrangements (circular symbols) although the difference was not significant for all observers. Reported inclination from horizontal-shear disparity in hinge and twist configurations did not differ significantly.

Vertical-size disparity resulted in apparent relative slant between the two discs that increased with increases in relative disparity gradient. However, the boundary between the discs typically appeared gradual rather than sharply defined, as reported by Kaneko and Howard (1996). For both hinge and twist arrangements, vertical-shear disparity resulted in weak reports of relative surface inclination that was opposite to the predicted direction for vertical-shear disparity [3] as reported by Rogers (1992) (Lower Graph, Fig. 4).

[3] This result can be explained if we consider the orientation disparity in the stimulus (see also Cagenello & Rogers, 1990). The random-dot stimulus has signal energy at all orientations. Vertical-shear disparity causes the energy in oblique components to be rotated in the image of one eye relative to the other—an orientation disparity. For side-by-side discs this orientation disparity can generate a percept of inclination in each disc since the sign of the orientation disparity is opposite in the top and bottom halves of each disc. Relative inclination arises since the vertical shear is opposite in the two discs.

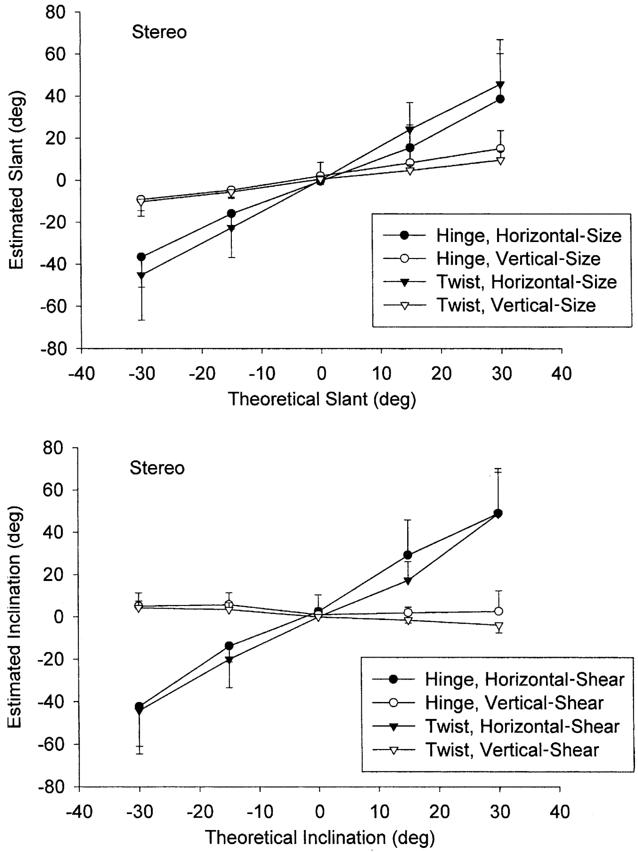

Fig. 4. Difference in slant and inclination matches between the adjacent random-dot discs in stereoscopic displays in Experiment 2. Top shows relative slant percepts generated by relative size disparity between the pair of surfaces, averaged across four subjects. Bottom shows relative inclination percepts generated by relative shear disparity between the pair of surfaces, averaged across four subjects. Positive slope indicates results in the predicted direction. Error bars indicate 95% confidence intervals for the mean.

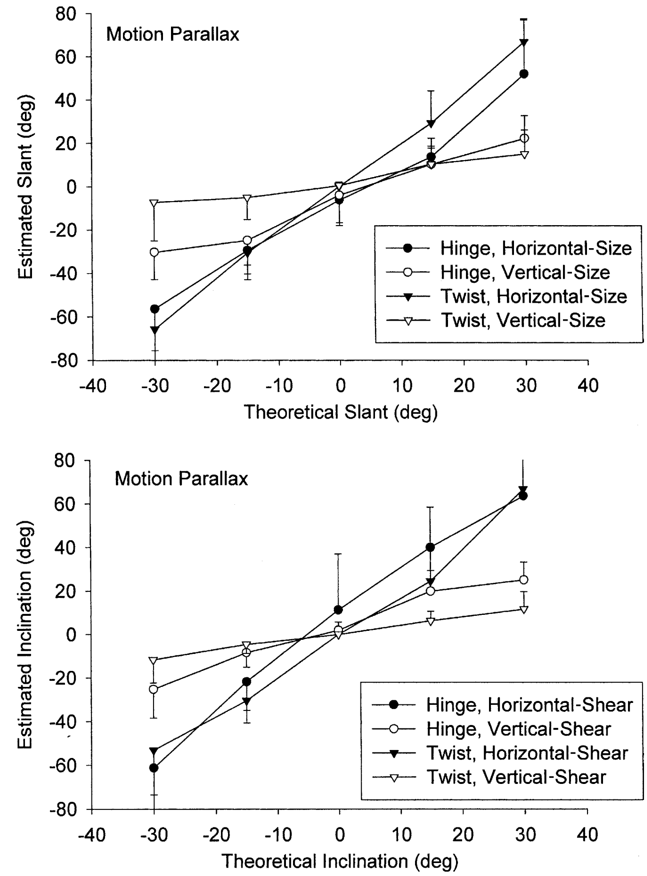

Fig. 5. Difference in slant and inclination matches between the adjacent random-dot discs in motion-parallax displays in Experiment 2. Top shows relative slant percepts generated by relative size parallax between the pair of surfaces, averaged across four subjects. Bottom shows relative inclination percepts generated by relative shear parallax between the pair of surfaces, averaged across four subjects. Positive slope indicates results in the predicted direction. Error bars indicate 95% confidence intervals for the mean.

For lateral head motion, relative horizontal-shear and horizontal-size parallax gave rise to percepts of relative surface inclination and slant respectively (Fig. 5). Reported depth increased monotonically with velocity gradient but tended to exceed the theoretically predicted slants and inclinations. Twist arrangements resulted in slightly more slant than equivalent hinge arrangements.

With lateral head motion, opposite induced-shear and induced-size effects could be elicited in the two discs in the predicted directions and with a sharply defined transition. Relative slants and inclinations were significantly greater for hinge arrangements than for twist arrangements. Furthermore, when opposite vertical-size parallax was presented in the upper and lower discs in a slant-twist configuration (Upper graph, Fig. 5), subjects often reported that they did not see relative slant at all but instead saw relative inclination between the two discs. Thus, the two discs appeared as a inclination-hinge configuration rocking about a vertical axis. In this condition, the percept of relative slant often coexisted with that of relative surface inclination. When oppositely directed vertical-shear parallax transformations were presented in the side-by-side discs of a inclination-twist arrangement (Lower graph, Fig. 5), subjects sometimes saw perceived relative slant rather than perceived relative inclination although this was less frequent than in the slant-twist configuration. These alternative interpretations of the motion parallax are considered in the Discussion. Vertical head motion with double discs was studied in one subject. The subject could see opposite horizontal-shear and horizontal-size induced effects in the two discs, especially when they were arranged in hinge configurations.

3.4. Experiment 3: Nulling

Koenderink and van Doorn's (1975, 1976) differential invariant theory predicts that depth should arise solely

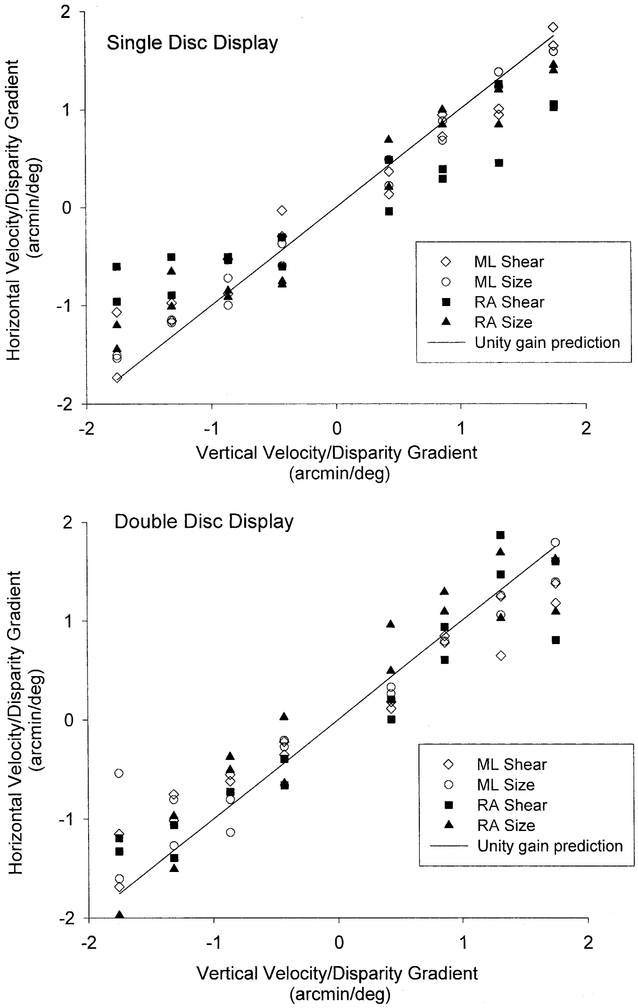

Fig. 6. Results of the nulling experiment (Experiment 3). The scatter plots shows the horizontal gradient that the subject introduced in order to compensate for slant/inclination induced by a vertical disparity gradient. Individual bias was removed to allow for easier comparison of slopes.

from the deformation in the flow or disparity fields—pure rotations or dilations should not result in perceived inclination or slant. Informally, we found that pure deformation parallax transformations (equal and opposite vertical and horizontal-shear or -size parallax) resulted in larger slants or inclinations than from horizontal-shear or horizontal-size transformations alone. Conversely, pure dilation or rotation transformations resulted in small slants and inclinations. To examine the deformation hypothesis more quantitatively we used a nulling technique. Deformation theory predicts that perceived slant or inclination would be nulled when the horizontal and vertical parallax transformations are equal. Under these conditions the stimulus would contain pure rotation (Curl) or dilation (Div) parallax and deformation parallax would have been eliminated.

Regression analysis was used to determine the effect of vertical-size or vertical-shear parallax on the horizontal-size or horizontal-shear parallax setting that caused the surface to appear frontal. The results are summarised in Fig. 6 and in Table 2, which shows proportional change in horizontal velocity gradient required to null out a change in vertical velocity gradient (i.e. the regression slopes).

With single surfaces the two subjects introduced horizontal-velocity gradients that were approximately 55–92% (mean 78%) of the vertical-velocity gradients. For subject RA a horizontal-velocity gradient that was only 55% of the vertical-velocity gradient was sufficient to null out apparent induced-effect inclination. Subjects found the task relatively easy but reported that the percepts of image looming and rotation, which persisted after nulling the slant or inclination, to be somewhat distracting. These percepts are to be expected since, at the theoretically predicted null point, the stimulus should have pure a Div or Curl component. With the double disc stimuli, subjects reported that the slant and inclination appeared to be nulled when a relative horizontal-velocity gradient approximately 88% of the vertical-velocity gradient was introduced.

4. Discussion

The results of the experiments described in this paper reveal the existence of robust analogues of both the induced-shear and induced-size effects for active head-movement-produced motion parallax. Furthermore, the analogues of these effects were found with both lateral and vertical head motion. In a comparable series of experiments, Meese and his colleagues (Meese & Harris, 1997; Meese et al., 1995) have shown that surface slant and inclination can also be produced by gradients of vertical velocity during simulated lateral object motion (object-produced parallax). Seen together, these results suggest that similar underlying mechanisms may be used to determine depth from observer- and object-produced

Table 2
Results of the nulling experiment

Subject	Single surface vertical shear	Single surface vertical size	Hinged surfaces vertical shear	Hinged surfaces vertical size
ML	0.85 ± 0.05	0.92 ± 0.02	0.74 ± 0.04	0.88 ± 0.04
RA	0.55 ± 0.05	0.82 ± 0.05	0.85 ± 0.07	1.05 ± 0.11

Regression co-efficient corresponding to the proportional change in required vertical-velocity gradient for a change in horizontal-velocity gradient is shown (±s.e.).

motion parallax (Rogers & Graham, 1979). In stereopsis, the induced effects have been explained in terms of processes that calibrate and insulate slant perception from the imprecision in determining oculomotor position (Backus & Banks, 1999; Gillam & Lawergren, 1983; Howard & Kaneko, 1994; Mayhew & Longuet-Higgins, 1982; Ogle, 1964; Rogers, 1992). In motion parallax, these effects may reflect similar mechanisms to insulate depth perception from imprecision in the estimation of gaze eccentricity and in the monitoring of cyclotorsional eye and head movements. Given the similarity between the depth percepts arising from stereopsis and motion parallax it is tempting to look for a common substrate. However, as we have indicated previously, the parsing and separate processing of deformation in different local regions may be a consequence of the need to cope with separate object motions rather than evidence of a common substrate with stereopsis.

Koenderink and van Doorn's (1976) theory of binocular space perception predicts that stereopsis should be sensitive to local variations in deformation disparity. The use of Def1 to code surface slant offers immunity to aniseikonia. In particular, it makes stereopsis immune to the isotropic inter-ocular size variation associated with viewing surfaces that are eccentric with respect to the head. The use of Def2 to code surface inclination offers immunity to cyclotorsional misalignment. Our results confirm earlier findings (Gillam & Rogers, 1991; Howard & Kaneko, 1994; Kaneko & Howard, 1996; Rogers, 1992) that deformation disparity is not coded locally. Howard and Kaneko (1994) and Kaneko and Howard (1996) have proposed a modified deformation disparity theory. Instead of a local computation of Def, vertical disparity gradients are pooled over large portions of the binocular visual field to obtain regional or whole field estimates of vertical-size or vertical-shear disparity. Local horizontal-disparity gradient measures are then used to compute the local Def1 and Def2 using a more global estimate of the vertical-disparity gradient.

Other computational models have proposed that vertical disparities are used to estimate viewing system parameters such as the gaze and convergence angles, which are in turn used to recalibrate horizontal disparities (Gillam & Lawergren, 1983; Mayhew & Longuet-Higgins, 1982). The induced-size effect is seen as a consequence of this recalibration process; the induced-shear effect is not modelled but could be if the models were extended to include an estimate of cyclo-torsional fixation disparity. Note that the estimated parameters are oculomotor or viewing system parameters that affect the entire image (Howard & Rogers, 1995). As a result, it would be expected that the visual system obtain a global estimate of these parameters, presumably by pooling local information to increase robustness to noise. The fact that opposite induced-size effects can be seen in two spatially separated regions of the visual field (Rogers & Koenderink, 1986 and Experiment 2) clearly shows that a single viewing system parameter is not used to recalibrate horizontal disparities, as originally proposed by Mayhew and Longuet–Higgins. If, on the other hand, the theory is modified so that separate (and possibly incompatible) parameters are computed on a regional basis, the modified theory will also predict the pattern of results reported here. Thus, the regional estimation of vertical-size and vertical-shear disparity is also compatible with other computational models of stereopsis.

The interpretation of the differential structure of the flow field during lateral head motion is more complicated than the interpretation of the disparity field. In stereopsis, the parallax arises from simultaneous views from spatially separated vantage points. Vertical-shear and vertical-size disparity arise from dilation and rotation associated with global viewing system parameters rather than from the local surface structure. Thus, global vertical-disparity estimates can be used to 'correct' the horizontal disparity field. In contrast, the multiple views used to extract motion parallax are accumulated as a sequence of single views distributed over time and space. As a result, the properties of the flow field can signal object motion during the head movements. Thus, vertical-size parallax can arise from local divergence of the flow field, which signals an approaching or expanding object. Similarly vertical-shear parallax can arise from local rotation, which indicates a rotating object. Clearly, a global correction strategy is not a sensible strategy in the case of motion parallax transformations.

We have shown that vertical-shear and vertical-size motion parallax can be processed locally—at least at the scale of the half-field displays (9° diameter). During vertical head motion, vertical-shear and vertical-size transformations generate geometric rather than induced effects and give rise to local slant and inclination respectively. We have also demonstrated that, during lateral head motion, opposite motion-parallax induced effects can be elicited in the two halves of a double disc display from vertical-shear or vertical-size parallax. The boundary between the two discs was sharp which indicates the operation of local processes. Estimating the precise scale of this process remains to be done. Eliciting independent motion-parallax induced effects seems to depend on phenomenological separation of the surfaces, which allows for interpretation of the looming and rotation percepts that accompany the Div and Curl components.

With our double-disc stimuli, twist configurations produced stronger effects than hinge configurations for horizontal-size binocular or motion-parallax displays although the effect was not as pronounced or consistent as in earlier studies (Gillam et al., 1988). For vertical-size and vertical-shear parallax transformations however, the hinge configurations resulted in larger effects than twist configurations. Gillam et al. (1988) explained the larger slant estimates for twist than for hinge configurations in terms of a discontinuity of horizontal

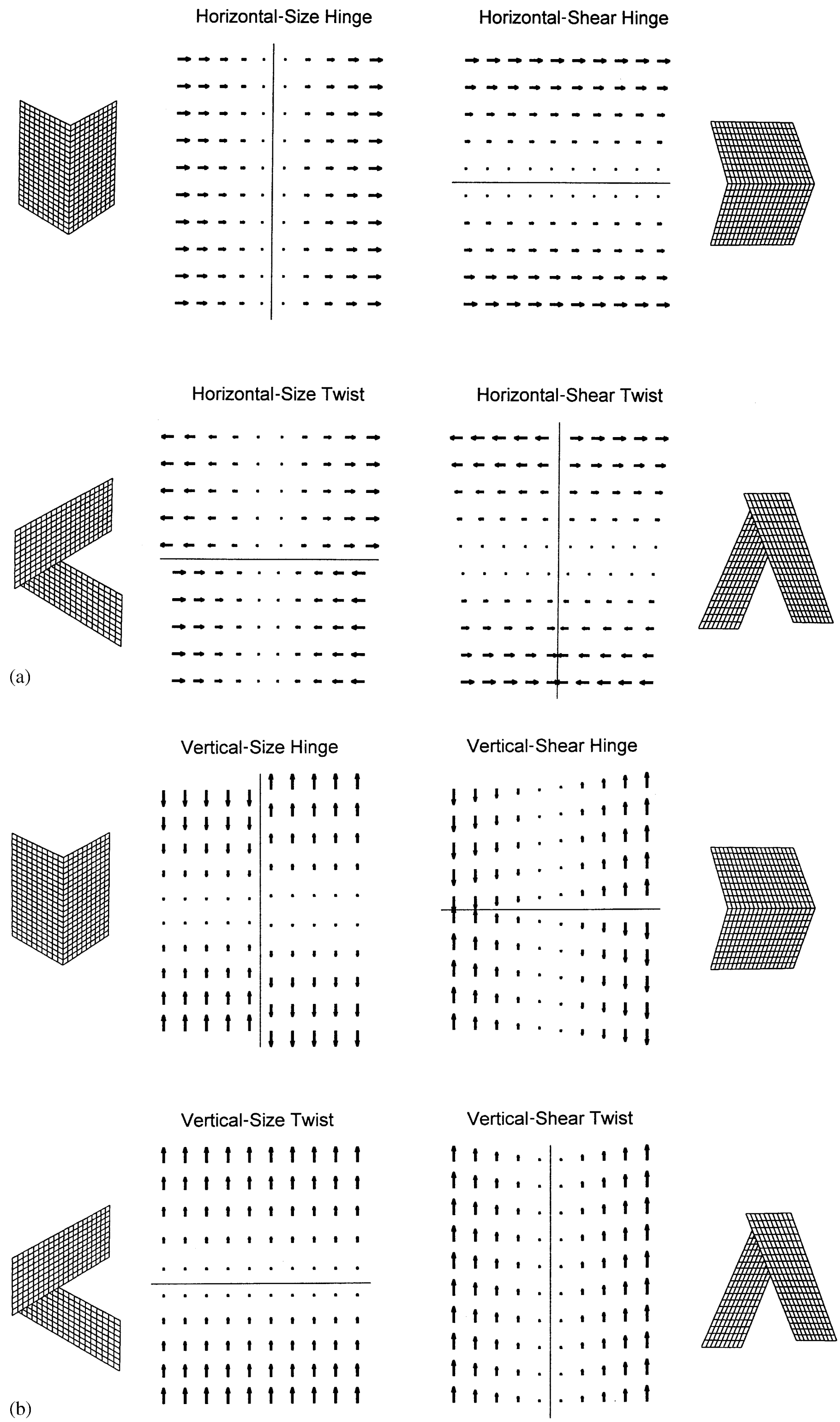

Fig. 7. Schematic representation of flow/disparity fields generated by the various conditions in Experiment 2. Horizontal parallax transformations are shown in (a), vertical transformations in (b). The icons beside the flow/disparity fields represent the theoretically predicted percepts. Discontinuities of velocity (or disparity) gradient are evident in twist arrangements for horizontal-shear and horizontal-size parallax and in hinge arrangements for vertical-shear and vertical-size parallax.

disparity acting as a primitive for stereopsis. Our results can also be explained if vertical parallax discontinuities have a similar saliency. Fig. 7 shows that twist configurations for horizontal-shear and horizontal-size parallax and hinge configurations for vertical-shear and vertical-size parallax both create a discontinuous flow field. Along the boundary between the surfaces there is a gradient of velocity or disparity differences that seems to be a particularly potent stimulus for the visual system.

Due to the sequential rather than simultaneous nature of the motion parallax transformation, alternative interpretations of the flow field are possible. If head motion is sensed perfectly and the object is stationary this ambiguity is constrained. Recently, it has been reported that the visual system favours interpretations of the optic flow that maximize rigidity of the entire scene or 'stationarity' (Wexler, Panerai, Lamouret, & Droulez, 2001). Thus, the visual system seems to preferentially attribute optic flow during observer motion to be due to self-motion and static scene structure rather than to the movement of the observer and of objects in the scene. The presence of continuous stimulus motion phase-locked to head motion is a strong indication that the flow resulted from self-motion and the static structure of the scene (Cornilleau-Pérès & Droulez, 1994; Ono & Steinbach, 1990; Rogers & Rogers, 1992). Thus, stimuli with gradients of vertical velocity that produced surface inclination (slant) with vertical head motion or without head motion were seen as stimuli with induced effect slant (inclination) when the transformation was coupled to lateral head motion.

However, if the object is free to move there is always a family of solutions to the optic-flow problem. The interpretation of motion parallax depends on the partitioning of the flow field into (i) the flow generated by self motion and (ii) the flow generated by object motion. For example, a sinusoidal modulation of a flow field during head motion can be interpreted as a stationary and relatively deeply corrugated surface or as a shallower corrugation, which counter rotates as the subject moves his/her head (Ono, Rivest, & Ono, 1986; Rogers & Collett, 1989). In Experiment 2, the twist arrangements of vertical-size and, to a lesser extent, the vertical-shear parallax tended to be seen as counter-rotating inclination-hinge and slant-hinge arrangements, respectively, during lateral head motion. This interpretation is consistent with the flow field if the object (or subject) were translating up and down. This was also the preferred interpretation of the parallax in the absence of head motion when the same vertical velocity gradients were presented with the head fixed. In the absence of parallax discontinuities, it appears that differential induced effects were too weak to overcome this alternative interpretation. Other examples of alternative interpretations include the apparent looming and rotation of the discs during vertical parallax with lateral head motion. These are due to the dilation and rotation components of the flow field. Lateral head motion cannot sustain these components and hence they are attributed to object motion.

It would be of interest to study other aspects of the analogy between stereoscopic and motion-parallax induced effects beyond the question of whether the computations are performed locally or regionally. For example, there has been considerable debate in recent years as to (a) whether the stereoscopic induced-size effect scales with distance (Backus & Banks, 1999; Rogers, Bradshaw, & Gillam, 1995) and (b) why the induced effect is limited in its linear range (Banks & Backus, 1998). The theoretical arguments have focused on vertical-size disparity's role as an indicator of eccentricity and distance. It would be instructive to study these questions in the motion-parallax domain. We might expect that the results would be different since the Div and Curl components in the flow field can arise from object motion as well as from eccentricity and rotational misalignment and hence are not constrained by the same ecological considerations.

Acknowledgement

This work was undertaken while the first author was supported by a McDonnell–Pew visiting fellowship at the University of Oxford.

References

Backus, B. T., & Banks, M. S. (1999). Estimator reliability and distance scaling in stereoscopic slant perception. *Perception, 28*, 217–242.

Backus, B. T., Banks, M. S., van Ee, R., & Crowell, J. C. (1999). Horizontal and vertical disparity, eye position, and stereoscopic slant perception. *Vision Research, 39*, 1143–1170.

Banks, M. S., & Backus, B. T. (1998). Extra-retinal and perspective cues cause the small range of the induced effect. *Vision Research, 38*, 187–194.

Banks, M. S., Hooge, I. T., & Backus, B. T. (2001). Perceiving slant about a horizontal axis from stereopsis. *Journal of Vision, 1*, 55–79.

Bradshaw, M. F., & Rogers, B. J. (1996). The interaction of binocular disparity and motion parallax in the computation of depth. *Vision Research, 36*, 3457–3468.

Braunstein, M. L. (1968). Motion and texture as sources of slant information. *Journal of Experimental Psychology, 78*, 247–253.

Cagenello, R., & Rogers, B. J. (1990). Orientation disparity, cyclotorsion, and the perception of surface slant. *Investigative Ophthalmology and Visual Science, 31*(Abstracts), 97.

Cornilleau-Pérès, V., & Droulez, F. (1993). Stereo-motion cooperation and the use of motion disparity in the visual perception of 3-D structure. *Perception and Psychophysic, 54*, 223–239.

Cornilleau-Pérès, V., & Droulez, F. (1994). The visual perception of three-dimensional shape from self-motion and object-motion. *Vision Research, 34*, 2331–2336.

Gillam, B., & Lawergren, B. (1983). The induced effect, vertical disparity, and stereoscopic theory. *Perception and Psychophysics, 34*, 121–130.

Gillam, B., & Rogers, B. (1991). Orientation disparity, deformation, and stereoscopic slant perception. *Perception, 20*, 441–448.

Gillam, B., Chambers, D., & Russo, T. (1988). Postfusional latency in slant perception and the primitives of stereopsis. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 163–175.

Helmholtz, H. V. (1909). *Physiological optics. English translation 1962 by J.P.C. Southall from the 3rd German edition of Handbuch der Physiologischen Optik. Vos, Hamburg*. Dover: New York.

Howard, I. P., & Kaneko, H. (1994). Relative shear disparities and the perception of surface inclination. *Vision Research, 34*, 2505–2517.

Howard, I. P., & Rogers, B. J. (1995). *Binocular vision and stereopsis*. New York: Oxford University Press.

Howard, I. P., & Rogers, B. J. (2002). *Seeing in depth: Depth perception*. Toronto: I Porteous.

Johnston, E. B., Cumming, B. G., & Landy, M. S. (1994). Integration of stereopsis and motion shape cues. *Vision Research, 34*, 2259–2275.

Kaneko, H., & Howard, I. P. (1996). Relative size disparities and the perception of surface slant. *Vision Research, 36*, 1919–1930.

Kaneko, H., & Howard, I. P. (1997). Spatial properties of shear disparity processing. *Vision Research, 37*, 315–323.

Koenderink, J. J., & van Doorn, A. J. (1975). Invariant properties of the motion parallax field due to movement of rigid bodies relative to an observer. *Opt Acta, 22*, 773–791.

Koenderink, J. J., & van Doorn, A. J. (1976). Geometry of binocular vision and a model for stereopsis. *Biological Cybernetics, 21*, 29–35.

Koenderink, J. J. (1986). Optic flow. *Vision Research, 26*, 161–179.

Longuet-Higgins, H. C., & Prazdny, K. (1980). The interpretation of a moving retinal image. *Proceedings of the Royal Society, Series B, Biological Sciences* 208, 385–397.

Mayhew, J. E. W., & Longuet-Higgins, H. C. (1982). A computational model of binocular depth perception. *Nature, 297*, 376–378.

Meese, T. S., & Harris, M. G. (1997). Computation of surface slant from optic flow: orthogonal components of speed gradient can be combined. *Vision Research, 37*, 2369–2379.

Meese, T. S., Harris, M. G., & Freeman, T. C. (1995). Speed gradients and the perception of surface slant: analysis is two-dimensional not one-dimensional. *Vision Research, 35*, 2879–2888.

Mitchison, G. J., & McKee, S. P. (1990). Mechanisms underlying the anisotropy of stereoscopic tilt perception. *Vision Research, 30*, 1781–1791.

Ogle, K. N. (1938). Induced size effect. I. A new phenomenon in binocular space-perception associated with the relative sizes of the images of the two eyes. *Archives of Ophthalmology, 20*, 604–623.

Ogle, K. N. (1964). *Researches in binocular vision*. New York: Hafner.

Ono, H., & Steinbach, M. J. (1990). Monocular stereopsis with and without head movement. *Perception and Psychophysics, 48*, 179–187.

Ono, M. E., Rivest, J., & Ono, H. (1986). Depth perception as a function of motion parallax and absolute-distance information. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 331–337.

Rogers, B. J. (1992). The perception and representation of depth and slant in stereoscopic surfaces. In G. A. Orban, & H.-H. Nagel (Eds.), *Artificial and biological vision systems* (pp. 241–266). Berlin: Springer-Verlag.

Rogers, B. J., & Collett, T. S. (1989). The appearance of surfaces specified by motion parallax and binocular disparity. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 41*, 697–717.

Rogers, B. J., & Graham, M. E. (1979). Motion parallax as an independent cue for depth perception. *Perception, 8*, 125–134.

Rogers, B. J., & Graham, M. E. (1982). Similarities between motion parallax and stereopsis in human depth perception. *Vision Research, 22*, 216–270.

Rogers, B. J., & Graham, M. E. (1983). Anisotropies in the perception of three-dimensional surfaces. *Science, 221*, 1409–1411.

Rogers, B. J., & Bradshaw, M. F. (1999). Disparity minimisation, cyclovergence, and the validity of nonius lines as a technique for measuring torsional alignment. *Perception, 28*, 127–141.

Rogers, B. J., Bradshaw, M. F., & Gillam, B. (1995). The induced effect does not scale with viewing distance. *Perception, 24*(Supplement), 33.

Rogers, B. J., & Koenderink, J. (1986). Monocular aniseikonia: a motion parallax analogue of the disparity-induced effect. *Nature, 322*, 62–63.

Rogers, S., & Rogers, B. J. (1992). Visual and nonvisual information disambiguate surfaces specified by motion parallax. *Perception and Psychophysics, 52*, 446–452.

Stevens, K. A. (1983). Slant-tilt: the visual encoding of surface orientation. *Biological Cybernetics, 46*, 183–195.

Tittle, J. S., Todd, J. T., Perotti, V. J., & Norman, J. F. (1995). Systematic distortion of perceived three-dimensional structure from motion and binocular stereopsis. *Journal of Experimental Psychology—Human Perception Performance, 21*, 663–678.

van Ee, R., & Erkelens, C. J. (1998). Temporal aspects of stereoscopic slant estimation: an evaluation and extension of Howard and Kaneko's theory. *Vision Research, 38*, 3871–3882.

Wexler, M., Panerai, F., Lamouret, I., & Droulez, J. (2001). Self-motion and the perception of stationary objects. *Nature, 409*, 85–88.