Motion and stereoscopic tilt perception

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Abstract — Stereoscopic perception of tilt about a vertical or horizontal axis is influenced by size and shear disparities, respectively. Other researchers have reported that, under certain conditions, stereoscopic perception deficits occur when the dots in a random-dot stereogram move at a velocity that produces optokinetic nystagmus. Here we examine how size disparity and shear disparity affect stereoscopic tilt perception under various motion conditions. We hypothesized that visual stimulus motion may interact with these disparities to affect tilt perception. Our results indicate that shear disparity and size disparity effects under static conditions are maintained under motion conditions. A possible explanation for the conflict between the current and previous results is discussed, as are implications for binocular head-mounted display applications.

Keywords — *stereomotion, stereopsis, shear disparity, size disparity, perceived slant, perceived inclination, the induced effect, tilt, depth perception*

1 Introduction

Because the two eyes are separated horizontally, each eye views the world from a slightly different vantage point. This results in a shift or displacement of the images on the two retinas. The brain makes use of these small differences to perceive depth. Designers of binocular head-mounted displays (HMDs) create depth perceptions by using projective geometry to create images appropriate for the viewing positions of the two eyes.

The stereoscopic depth cues of objects in front of or behind the plane of fixation are based on the spatial differences (disparities) between image locations on the left and right retinas. These disparities are analyzed in terms of their horizontal and vertical components.[1,2] In nature, the horizontal components are much larger than the vertical components. Nevertheless, both the vertical and horizontal components are essential for accurate depth perception.

1.1 Horizontal disparities

By convention, horizontal disparities of objects nearer than the fixation point are called *crossed,* while those of objects behind the fixation point are called *uncrossed.* Objects that fall at the fixation point have zero disparity. A planar surface of texture elements that is horizontally magnified in one eye relative to the other will be perceived as tilted about the vertical axis[i].[1,3,4] Imagine that this surface is perceived as tilted right side away from the viewer. By convention this *right-side-away tilt* is called *positive slant.* The points along the vertical axis of rotation have zero horizontal disparity. To the right of the axis the amount of uncrossed disparity increases until it reaches the maximum at the right edge of the plane (likewise for crossed disparities on the left). This *horizontal gradient* of horizontal-size disparities is illustrated in Fig. 1(a). The amount of size disparity (magnification) is specified as a percentage, where by convention, positive disparity indicates that *the magnified image is projected to the right eye.* Perceived slant varies as size-disparity magnitude changes. The theoretical relationship between the disparity magnitude, M, and perceived slant angle in degrees is described by

$$\text{slant} = \arctan[(M-1)/(M+1)(2z_0/I)](180/\pi), \qquad (1)$$

where I is the interpupillary distance (IPD) and z_0 is the viewing distance. Here, if there is a +4% disparity magnitude, then M = 1.04; if there is a –4% disparity magnitude, then M = 0.96.

Whereas horizontal-size disparities produce tilt about a vertical axis, horizontal-shear disparities produce tilt about a horizontal axis. Imagine that a surface is tilted about a central horizontal axis, such that its top is inclined away from the observer. By convention this *top-away tilt* is called *positive inclination.*[ii] Above the horizontal axis, the amount of uncrossed disparity increases until it reaches a maximum at the top of the plane (likewise for crossed disparities below the axis). A vertical[iii] gradient of horizontal disparities can be created by *horizontally* shearing one image of a stereogram pair, as illustrated in Fig. 2(a). The shear-disparity magnitude is specified in terms of angle, where positive

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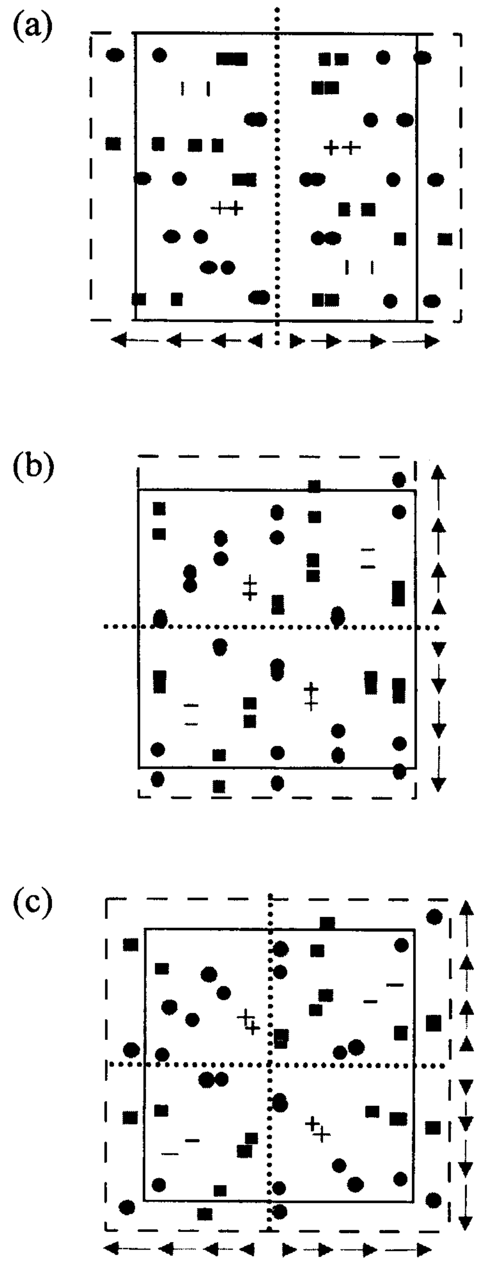

FIGURE 1 — Size disparity schematic: In each figure the black elements represent the image presented to the left eye, and the gray elements represent the linearly transformed image to the right eye. The illustrations are: (a) positive horizontal-size disparity, (b) positive vertical-size disparity, and (c) positive overall-size disparity; *i.e.*, equal components of vertical and horizontal magnification. When the linearly transformed image is presented to the left eye, the disparities are nominally negative. The amount of magnification shown here is exaggerated for illustration.

shear indicates a *clockwise angular change to the right eye.* Perceived inclination varies as shear-disparity magnitude changes. The theoretical relationship between disparity magnitude, β, in degrees and perceived inclination angle in degrees is described by

$$\text{inclination} = \arctan[\tan(\beta\cdot\pi/180)z_0/I](180/\pi), \qquad (2)$$

where I is the IPD and z_0 is the viewing distance.

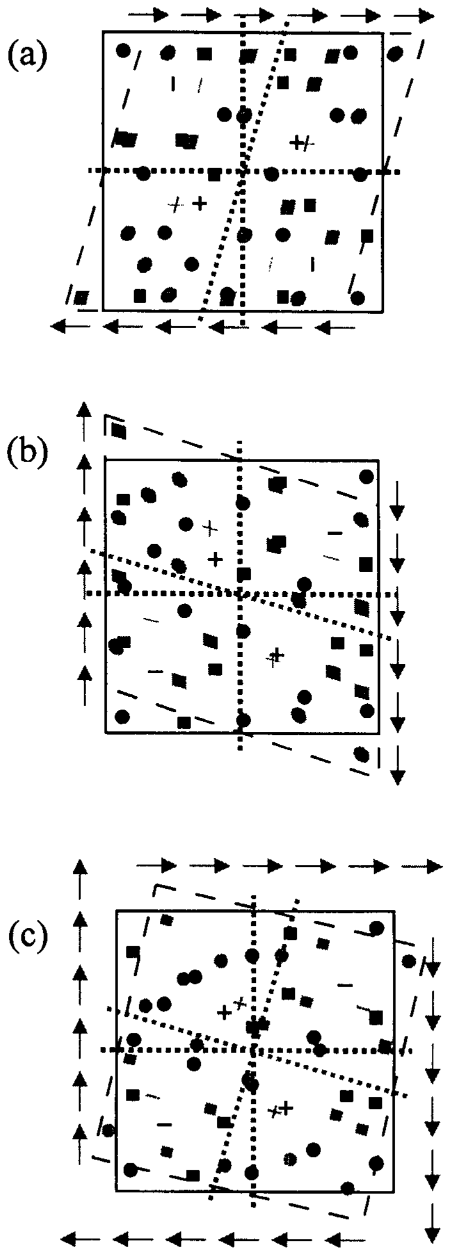

FIGURE 2 — Shear disparity schematic: In each figure the black elements represent the image presented to the left eye, and the gray elements represent the linearly transformed image to the right eye. The illustrations are: (a) positive horizontal-shear disparity, (b) positive vertical-shear disparity, and (c) positive rotation, *i.e.*, equal components of vertical-and horizontal-shear disparity. When the direction of shear in the right eye is counter-clockwise, the disparities are nominally negative. The amount of shearing shown here is exaggerated for illustration. In experimental stimuli the total shearing was equally divided between the eyes.

1.2 Vertical disparity

The geometry of vertical disparity can quickly become complicated when the direction of gaze is other than directly ahead (in the mid-sagittal plane), so we will limit our discussion to this special case, which is sufficient for the purposes here. A stimulus point that lies directly ahead has no vertical disparity. Within the plane of fixation, vertical disparity increases as the product of the vertical and horizontal distance from the fixation point. Vertical disparity can (a) provide relative depth constancy that is invariant to absolute viewing distances,[5,6] (b) be used to compensate for distortions in oblique gaze,[7,8] and (c) provide robustness against ocular torsion by computing depth as the relative difference between horizontal disparities and vertical disparities[iv].[2,7,9]

Gradients of vertical disparity can be manipulated in a manner similar to the horizontal disparity manipulations described in the previous section. *Vertical-size* manipulation is illustrated in Fig. 1(b), and *vertical-shear* manipulation is illustrated in Fig. 2(b). Manipulations of vertical size and vertical shear produce a tilt percept that is opposite to that produced by a horizontal size and horizontal shear of the same direction and is referred to as the induced effect.[1,7,10] Thus, a positive vertical-size manipulation (*i.e.*, a magnification of the vertical components in the right eye) produces a planar surface tilted *left-side* away (*i.e.*, negative slant). A positive vertical-shear manipulation (*i.e.*, a clockwise shearing of the vertical components) in the right eye produces a planar surface tilted *bottom-away* (*i.e.*, *negative inclination*).

1.3 Combinations of horizontal and vertical disparities

In addition to testing the effects of horizontal disparities and vertical disparities independently, researchers have also tested the effects of combined horizontal and vertical disparities. *Overall size disparity* is equivalent to equal proportions of vertical-and horizontal-size disparities, as illustrated in Fig. 1(c). *Rotation disparity* is equivalent to equal proportions of vertical- and horizontal-shear disparities, as illustrated in Fig. 2(c). Images containing overall size or rotation disparities produce little or no tilt when presented alone. While rotation disparity will induce cyclovergence of the eyes, which reduces the disparity, images will appear frontal even in subjects with low gain of cyclovergence.[7,8,11] The reason images with overall size or rotation disparities appear frontal is because the visual system codes tilt in terms of the difference between horizontal and vertical disparities. Since patterns with overallsize or rotation disparities have equal amounts of vertical and horizontal disparities with equal signs, they are seen as lying in the frontal plane. However, these stimuli presented simultaneously with zero-disparity stimuli[v] (superimposed or adjacent) can produce tilt that follows the horizontal component of the manipulation.[4,7,10,12]

1.4 Processing of stereoscopic disparities

Deformation theory[3,9,13] suggests that perceived tilt of a planar surface depends on the difference between the horizontal and vertical components. This would explain why images containing overall size or rotation disparities appear frontal when presented alone. However, the horizontal and vertical components of disparity are assessed differently. The horizontal components are processed locally whereas the vertical components are averaged over large areas. Thus, perceived tilt is assessed in terms of the difference between local horizontal components and global vertical components. Evidence supporting this theory has been presented for perceived tilt about a horizontal axis[7,10] and perceived tilt about a vertical axis.[3,4]

Howard and Pierce[4,10] described the effects of superimposing zero-disparity (natural, see-through) imagery onto an image with synthetic disparities. Their studies used an angle-matching task where participants manually rotated a disk to match the perceived angle of a test image. Their results showed significant interactions between disparity patterns and zero-disparity imagery. The perceived tilt of a horizontal disparity image was greater when presented with a superimposed zero-disparity image, which they referred to as an *enhancement effect*. In addition, a superimposed zero-disparity image was perceived as tilted away from an image containing horizontal-size (but not shear) disparities, which they referred to as a *contrast effect*. As distinguished from images with horizontal disparities, perceived tilt of test images containing vertical disparities was suppressed when a zero-disparity image was superimposed and both images combined to form one surface.

Optic misalignment or display distortion in an HMD can produce unwanted disparities that, in turn, can produce erroneous depth perceptions. For example, a static stereoscopically presented image that is magnified horizontally to one eye will appear slanted in the direction of the magnified eye.[1,3] If magnified vertically it will appear slanted in the opposite direction. The problems associated with erroneous disparities are compounded when synthetic imagery is superimposed on natural imagery, as in see-through type HMDs. For example, enhancement and contrast effects discussed earlier can occur as a result of disparity variations between synthetic and natural imagery. Moreover, under certain conditions, the entire visual system will attempt to re-normalize itself to disparities in synthetic imagery and thereby induce distortions onto the see-through imagery. An example of this is viewing stereoscopic images containing rotation disparities with superimposed simple zero-disparity imagery. Under these conditions, the rotated images appear fronto-parallel and inclination is induced onto the zero-disparity imagery.

1.5 Motion effects

Fox[14] demonstrated that optokinetic nystagmus (OKN) can be induced purely by the motion of stereoscopic contours created with cyclopean random-dot stereograms. In a later series of papers, Hadani and Vardi[15,16] reported that depth perception can be impaired when the dots of a random-dot stereogram move smoothly across the field. Specifically, stereopsis impairment occurs when (a) the angular velocity of the dots is in a range that induces OKN and (b) the cyclopean contours of the random dot stereogram alternate in depth, between two depth planes, across a spatial grating at certain spatial frequencies. Within certain angular-velocity and spatial-frequency ranges participants perceived the dots to move across a smooth plane instead of alternating across a spatial grating. Vardi and Hadani[16] attribute the deficit to a temporal integration averaging of the two depths.

Vardi and Hadani[16] showed that smooth pursuit of dots moving at 7.2 cycles/s impaired the perception of stationary cyclopean stimuli. Patterson[17] and his colleagues examined discrimination thresholds for direction of motion. They reported a loss of cyclopean spatial structure and cyclopean motion detection at 8 cycles/s or greater. The similarity of these velocity limits suggests that both tasks are processed by a common neural mechanism.

Westheimer and McKee[18] presented data indicating that horizontal stereo-disparity acuity in the human fovea remains unimpaired with brief duration retinal image motion up to 2°/s. However, they did not test for impairment to stereoscopic processing involving vertical disparities, nor has anyone examined whether motion affects perceived tilt.

Given the evidence for (a) the interaction between disparity and zero-disparity imagery and (b) the influence of certain motion velocities on stereopsis, the current study examined the interaction of these factors on perceived tilt. Specifically, we tested whether the addition of motion at velocities known to produce OKN may be sufficient to produce an impairment to tilt perception when disparity imagery is mixed with zero-disparity imagery. These effects could have important implications for HMDs under flight-training conditions. Visual anomalies experienced during simulation training could result in either impaired training in the simulator or negative training transfer to the aircraft.

2 Experiment 1: Effect of motion on slant perception

In this experiment we examined the effect of size disparity and stimulus motion together on slant perception.

2.1 Methods

2.1.1 Participants

Three young male adults (ages 22, 24, and 32) with normal non-corrected vision participated in this experiment. All participants were naïve to the purpose of the experiment and all were paid.

2.1.2 Apparatus

Images were displayed on two computer monitors (Radius Model TX-D2151RD, 60 Hz refresh) mounted in a mirror haploscope with two 40% reflective mirrors (60% transmissive). The two mirrors were positioned at a 45° angle with respect to the participant's line of sight. The distance from the vertex of the 90° angle formed by the two glass planes and the center of each monitor was 33.5 cm. The mirrors were mounted such that the line of sight was centered with respect to the center of the monitors.

Participants responded using a response disk, 17.5 cm in diameter and 6 mm thick. The disk was mounted directly in front of the participant at the same distance as the perceived planar surface (33.5 cm) and was centered with respect to the binocularly fused image. The disk rotated about a vertical axis that was centered with respect to the apparent stereoscopic image.

2.1.3 Stimuli

2.1.3.1 Experimental stimuli

Each image was a computer-generated pattern of 98 elements consisting of open squares, crosses, and lines. Individual squares and crosses subtended 0.85° of visual angle in the horizontal and vertical dimensions. The lines were drawn horizontally and vertically and their length also subtended a 0.85° visual angle. The lines used to form each element were 0.083° in width. Each element was drawn in red (which has a higher rate of phosphor decay) to reduce the "comet-tail" effect on individual elements in the motion conditions. The elements were randomly distributed in a 14 column by 10 row matrix. Matched elements were displayed on the two computer monitors in the mirror haploscope setup. The fused zero-disparity images appeared frontoparallel at a distance of 33.5 cm and subtended 46.5° horizontally and 41° vertically. All other monocular perspective cues were eliminated and the surroundings were black.

Each texture element was always presented completely; that is, there was never a texture element that was partially occluded or chopped off at the sides of the display. Elimination of partial elements is important because the "half-occlusion" stimulus situation is a cue for depth in its own right,[19] and cue conflict can occur between occlusion cues and stereoscopic cues to depth.[20] Arrington[21] referred to this condition as segmentation rivalry.

The size disparity was introduced into the image by increasing the size of the image shown to either the right or left eye. Three types of size disparity were presented: horizontal, vertical, and overall, as shown in Fig. 1. In both the horizontal- and vertical-size disparity conditions, the spacing between the elements as well as the size of each element were increased by some percentage along one dimension as shown in Figs. 1(a) and 1(b), respectively. For overall-size disparity, the spacing and size of each element were increased along both dimensions as shown in Fig. 1(c). Four levels of horizontal, vertical, and overall-size disparity were used: 2%, 4%, 6%, and 8% with a control level of 0%. The four levels of size disparity were presented to both the right and the left eye. This manipulation has been previously shown to influence the direction of perceived slant of the planar surface. This manipulation will be referred to as the direction of disparity, positive for right-eye magnification and negative for left-eye magnification.

The disparity pattern was presented either alone or with one of two superimposed zero-disparity images: a horizontal line subtending 15° of visual angle or a randomly distributed pattern of elements. The zero-disparity horizontal line was centered with respect to the disparity image. The zero-disparity pattern was constructed from the same set, and approximately the same number, of texture elements as the disparity pattern. The zero-disparity texture elements were randomly distributed about a 14 column by 11 row matrix. The rows and columns of the zero-disparity pattern alternated with the rows and columns of the disparity pattern. To distinguish the two superimposed patterns, the luminance of the zero-disparity pattern was periodically dimmed slightly. The occasional dimming was verified by preliminary experiments to be sufficient to allow naïve subjects to categorically distinguish the pattern of interest, but was not salient enough to affect the perceived tilt.

The stimuli were shown as static images as well as under two types of motion conditions. Stimulus motion was either downward or leftward (moving across from right to left), both at a rate of 4°/s. In stimulus motion conditions, when a zero-disparity pattern was superimposed on the disparity pattern, both patterns moved in the same direction and at the same rate. However, when a zero-disparity line was superimposed on a disparity pattern, the line remained static while the disparity image moved.

2.1.3.2 Calibration stimuli

A real stimulus was used in a separate procedure to standardize the perceived slant responses across the different participants. The calibration surface was constructed using a black and white laser print of a computer-generated pattern of elements, which was mounted on a stiff board measuring 33.5 × 26.8 cm. This calibration surface was constructed from the same set of texture elements and density of elements as the disparity patterns of the haploscope used in the main experiment. Also, it was presented at the same direction of gaze and at the same viewing distance. The experimenter could adjust the slant of the calibration surface to any angle by mechanically rotating it about the vertical axis through the center of the board.

2.1.4 Procedure

2.1.4.1 Screening and pre-test procedure

Participants were first prescreened for both visual acuity and stereopsis deficits. A Snellen chart was used to test visual acuity and a Randot™ Stereotest was used to detect stereopsis deficiencies. Each participant's interpupillary distance (IPD) was measured using an Essilor™ Instruments digital corneal reflection pupilometer. The average IPD across participants was used in Eq. (1) to compute the theoretically predicted slant.

2.1.4.2 Experimental procedure

Each participant performed three blocks of trials. A block of trials consisted of {[3 disparity types (horizontal size, vertical size, overall size) × 4 disparity levels (2%, 4%, 6%, 8%) × 2 disparity directions (positive, negative)] + [1 control (zero-disparity trial)]} × [3 superimposed zero-disparity stimuli (none, line, pattern) × 3 motion types (no motion, leftward, and downward)] for a total of 225 test trials. Each block was divided into 9 trial sets as defined by motion type and superimposed zero-disparity stimuli. Presentation order of each trial set within a block was determined using a Latin square design. Trials within each set were randomly presented.

Participants were tested over a 9-day period. At the beginning of each session, participants performed 12 practice trials. Participants were instructed to concentrate on the central region of the display while responding. They were first asked to report the number of columns and rows that they could fuse. They were then asked to make a general description of the image and verbally estimate the angle of perceived slant in degrees. Next, they adjusted the unseen response disk to match the perceived slant of the disparity pattern. Finally, they hapticly adjusted the response disk to match the perceived slant of the zero-disparity stimulus when one was presented.

2.1.4.3 Calibration procedure

In a separate calibration procedure, participants set the unseen response disk to match the perceived slant of a surface of texture elements on a physical calibration surface. The surface contained a full range of binocular and monocular depth cues. It was randomly positioned between ±60° slant at 5° intervals. For each angle, participants provided four consecutive responses with the response disk being reset to 0° between each response. For each participant, the response means were plotted and fitted with a third-order polynomial function. The participants' calibration function was then used to adjust their mean responses to the test stimuli.

2.2 Results

2.2.1 Perceived slant for horizontal-size disparity

Figure 3 shows the adjusted slant means for the horizontal-size disparity conditions. Each panel's abscissa indicates the disparity magnitude in the disparity pattern. Positive values along the abscissa indicate that the right-eye image was larger. Negative values indicate that the left-eye image was larger. Mean slants are plotted along the ordinate. Values

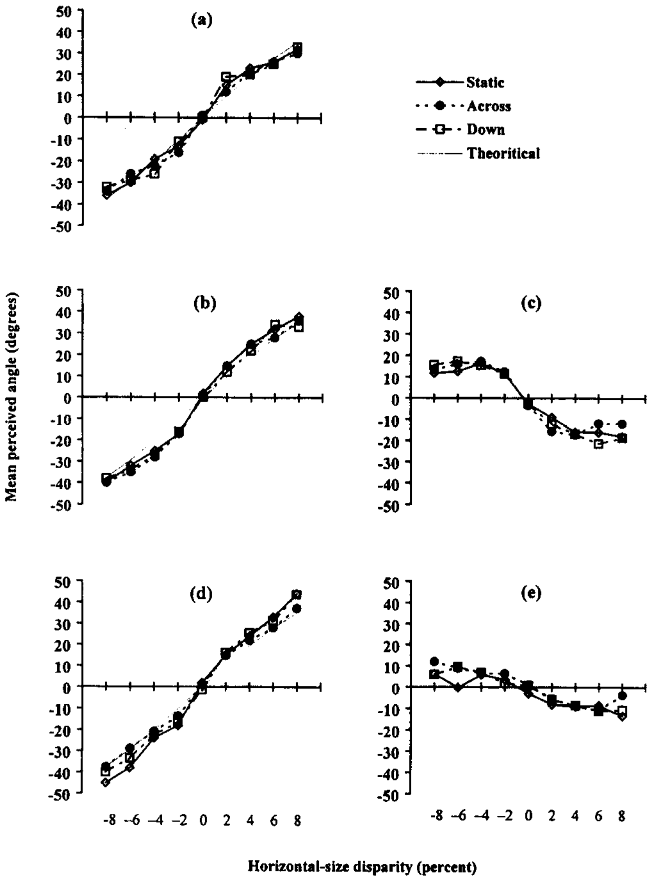

FIGURE 3 — Perceived slant as a function of horizontal-size disparity and motion type for: (a) the size-disparity stimulus alone, (b) the size-disparity stimulus in the presence of a superimposed zero-disparity line, (c) the superimposed zero-disparity line, (d) the size-disparity stimulus in the presence of a superimposed zero-disparity pattern, and (e) the superimposed zero-disparity pattern. Mean results for three participants.

above or below the zero line indicate that the fused image was perceived as right-side away or left-side away, respectively. The thin solid line indicates the theoretically predicted response pattern based on Eq. (1).

Mean slants of disparity stimuli were submitted to a four-way analysis of variance (ANOVA)[vi] with motion type, superimposed stimuli, disparity direction, and disparity magnitude serving as the within-subject variables. Although control trials are shown in Fig. 3, they were excluded from the analysis. The subject-by-factor interactions served as the error term in computing the F-ratios.

Examination of Figs. 3(a), 3(b), and 3(d) shows a significant interaction [$F(6,12) = 3.94$, $p = 0.021$] between superimposed stimuli and disparity magnitude. This is indicated by the larger effect of disparity magnitude when a superimposed zero-disparity pattern was presented than when the disparity pattern was viewed alone or with a zero-disparity line. This is the *slant enhancement* effect described in the introduction. These figures also show that the slant means of the disparity pattern approached theoretical values and increased as the disparity magnitude increased for all three motion conditions. The main effect for disparity magnitude, as predicted by Eq. (1), was significant, $F(3,6) = 17.94, p = 0.002$.

Examination of different motion conditions in Fig. 3 suggests that a pattern of moving elements with horizontal-size disparities produced approximately the same perceived slant as a static pattern of the same disparities. Thus, the main effect of motion type was not significant, as were remaining main effects and interactions.

A four-way ANOVA was computed for zero-disparity slants. None of the main effects or interactions was significant. Figures 3(c) and 3(e) show, however, that the zero-disparity line and, to a lesser extent, the zero-disparity pattern produced negative slants when the disparity pattern was larger in the right eye, and positive slants when the disparity pattern was larger in the left eye. The significance of these contrast effects was examined statistically by testing the constant (grand mean) terms for the zero-disparity line and pattern slants. The slant contrast effect was significant for the superimposed line, $F(1,2) = 20.22, p = 0.046$, but not for the superimposed pattern.

The participants did not report any difficulty in fusing the elements of either the disparity patterns or the zero-disparity stimuli.

2.2.2 Perceived slant for vertical-size disparity

Figure 4 shows the response data for the vertical-size disparity conditions. As shown in Figs. 4(a) and 4(b), slant means varied inversely with disparity magnitude when the disparity image was presented alone or with a zero-disparity line. This differs from the effect of disparity magnitude shown in the horizontal-size conditions. Figs. 4(a) and 4(b) show that when the right-eye image was larger (positive size disparity), a negative slant was perceived. By contrast, when the left-eye image was larger (negative size disparity), a positive slant was perceived. This is characteristic of Ogle's[1] induced effect. Figure 4(d) shows that the induced effect was suppressed when a superimposed zero-disparity pattern was presented. For this latter condition, the angle means of the vertical-disparity pattern remained at 0° as disparity magnitude increased. A four-way ANOVA on disparity slant means revealed that the interaction between superimposed stimuli and disparity magnitude was significant, $F(6,12) = 5.65$, $p = 0.005$. The main effect for superimposed stimuli was significant, $F(2,4) = 10.19$, $p = 0.027$, and the main effect for disparity magnitude approached significance, $F(3,6) = 4.22, p = 0.063$.

In the vertical-size disparity condition, motion was found to interact with superimposed stimuli, $F(4,8) = 7.21$, $p = 0.009$, suggesting that motion mediated the effect of superimposed stimuli. Although statistically significant, differences among slant means[vii] for the three motion conditions (static, downward, and leftward) within each level of the superimposed stimuli conditions (none, with a zero-disparity line, and with a zero-disparity pattern) were 4.0° or less. Relative to the range of slant means across levels of

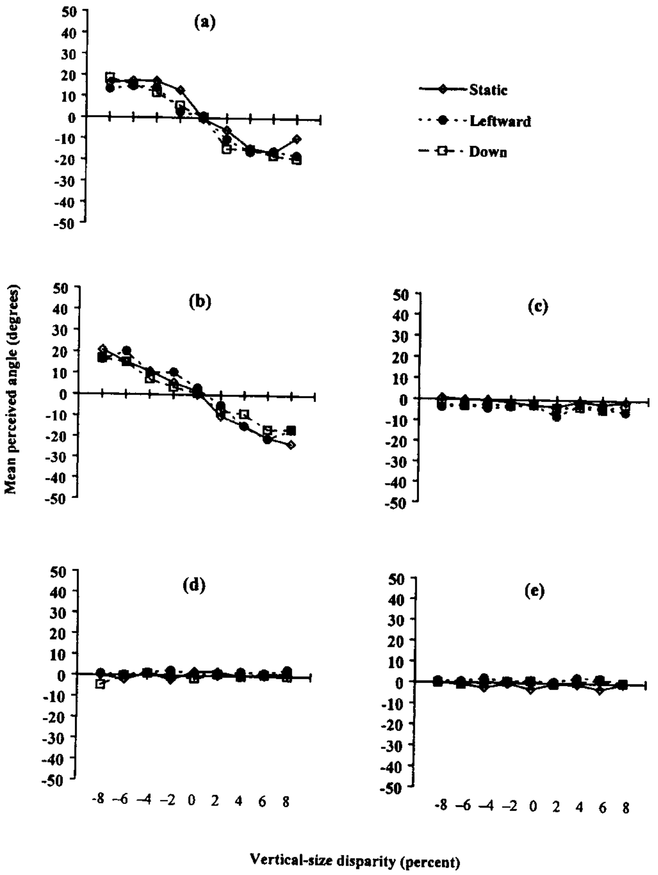

FIGURE 4 — Perceived slant as a function of vertical-size disparity and motion type for: (a) the size-disparity stimulus alone, (b) the size-disparity stimulus in the presence of a superimposed zero-disparity line, (c) the superimposed zero-disparity line, (d) the size-disparity stimulus in the presence of a superimposed zero-disparity pattern, and (e) the superimposed zero-disparity pattern. Mean results for three participants.

disparity magnitude, which exceeded 18° when disparity patterns were presented alone or with a zero-disparity line [see Figs. 4(a) and 4(b)], the magnitude of the effect due to motion was small. None of the remaining main effects or interactions was significant.

The slant means for the zero-disparity line and the zero-disparity pattern, shown in Figs. 4(c) and 4(e), respectively, were analyzed in a four-way ANOVA. The analysis showed no significant interactions or main effects – even the constant terms were not significant.

Two of the three participants reported having difficulty in fusing all rows of the pattern (four out of 11 rows on average) with greater than 4% magnification. The presence of a zero-disparity stimulus adversely influenced the ability to fuse the texture elements (*i.e.*, increased diplopia).

2.2.3 Perceived slant for overall-size disparity

Figure 5 shows the adjusted slant means for the overall-size disparity conditions. In general, the angle means of the disparity pattern increased as the disparity magnitude increased. The slant means followed the predicted slant of the horizontal-size component of disparity. In other words, when the right-eye image was larger (*i.e.*, positive size disparity), positive slant was perceived, whereas negative slant was perceived when the left-eye image was larger. In addition, the angle means for the disparity pattern were largest when a zero-disparity pattern was superimposed. Thus, the effect of the disparity magnitude was enhanced by the presence of a zero-disparity stimulus. This slant enhancement effect is similar to that which was obtained for horizontal-size disparity conditions. A four-way ANOVA on disparity slant means revealed a significant interaction between disparity magnitude and superimposed stimuli, $F(6,12) = 6.01$, $p = 0.004$. Additionally, the analysis showed significant main effects for disparity magnitude and for superimposed stimuli, $F(3,6) = 58.68, p < 0.001$ and $F(2,4) = 10.27, p = 0.027$, respectively.

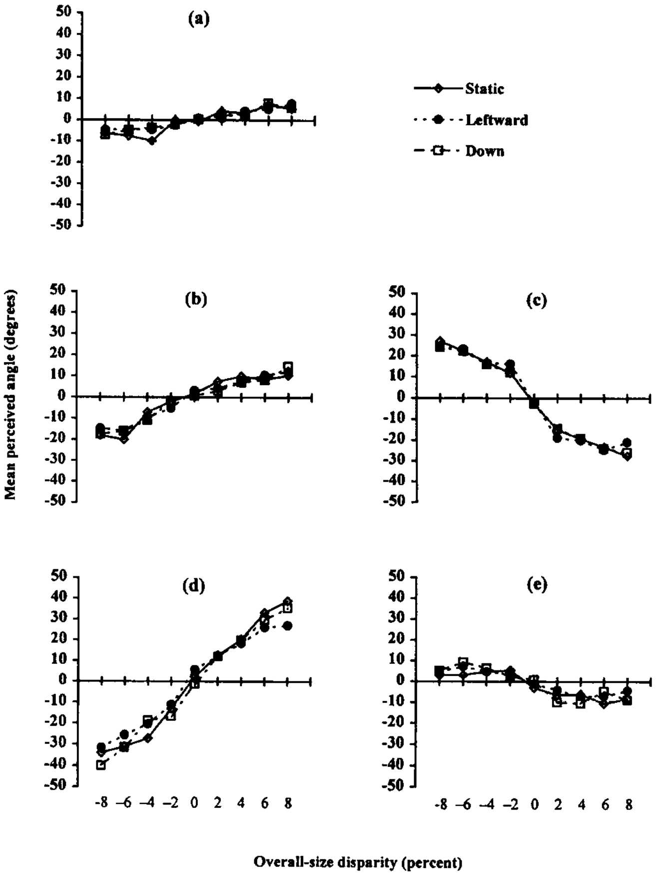

FIGURE 5 — Perceived slant as a function of overall-size disparity and motion type for: (a) the size-disparity stimulus alone, (b) the size-disparity stimulus in the presence of a superimposed zero-disparity line, (c) the superimposed zero-disparity line, (d) the size-disparity stimulus in the presence of a superimposed zero-disparity pattern, and (e) the superimposed zero-disparity pattern. Mean results for three participants.

A pattern of moving elements with overall-size disparities produced the same perceived inclination as a pattern of static elements with the same disparities. Therefore, the depth-enhancement effect was shown to be robust in regards to the different motion conditions. None of the other main effects or interactions was significant.

Figure 5(c) shows that the zero-disparity line was perceived as slanting in the direction opposite to that of the disparity pattern. The slant of the line increased as the magnitude of disparity in the pattern increased. However, Fig. 5e shows that the perceived slant of the zero-disparity pattern remained near 0° as the disparity magnitude in the disparity pattern increased. These contrast effects are similar to results obtained for horizontal-size disparity conditions. A four-way ANOVA on the slant means of superimposed zero-disparity stimuli showed the interaction between the disparity magnitude and superimposed stimuli was significant, $F(3,6) = 14.99$, $p = 0.003$. The analysis also revealed significant main effects for disparity magnitude and for superimposed stimuli, $F(3,6) = 6.87$, $p = 0.023$ and $F(1,2) = 15.95$, $p = 0.057$, respectively. None of the remaining main effects or interactions was significant.

Participants reported more difficulty fusing the peripheral half of the elements of the disparity stimuli when there was a superimposed zero-disparity pattern. In these cases, the elements became increasingly diplopic as they were positioned farther away from the center.

3 Experiment 2: Effect of motion on inclination perception

In this experiment we investigated the effect of shear disparity under motion conditions on the perceived tilt about the horizontal axis (inclination).

3.1 Methods

3.1.1 Participants

Two young male adults (ages 21 and 25) with normal noncorrected vision participated in this experiment. Both participants were naïve to the purpose of the experiment and both were paid.

3.1.2 Apparatus

The images were displayed using the equipment discussed in Experiment 1. In addition, the participants used the same response disk described in Experiment 1, except that the disk was remounted to rotate about a horizontal axis.

3.1.3 Stimuli

Pattern stimuli were generated in a manner similar to that described in Experiment 1. However, in the current experiment each individual element was sheared, as was the planar array of elements, to create the perception of a continuous smooth planar surface. The individual lines of the texture elements were anti-aliased and sub-pixel averaged. This was especially useful in eliminating the perception of a step-like pattern in depth.

The shear disparity was introduced into the image by shearing the images along a horizontal axis, a vertical axis, or a combination of both (rotation), as shown in Fig. 2. A positive shear indicates a clockwise rotation to the right eye of one or both axes about a center point. Negative shear indicates a counterclockwise rotation to the right eye. The amount of shear was equally divided between the left and right eye. For example, consider positive horizontal shear. Monocularly, the disparity images appear as parallelograms. An open-square element located in the upper-right-hand corner of the fused field would remain in the same row, but would be shifted rightward in the right eye from its original zero-disparity position and leftward in the left eye by the same distance. Four levels of horizontal-shear, vertical-shear and rotation disparity were used: 2°, 4°, 6°, and 8° with a control level of 0°. Both positive and negative shear disparities were presented.

The disparity pattern was presented either alone or with one of two superimposed zero-disparity images. The superimposed zero-disparity stimulus was either a vertical line (which extended the length of the field) or a randomly distributed pattern of elements. The zero-disparity line was centered with respect to the disparity image pattern. The zero-disparity pattern contained the same set of texture elements as the disparity pattern. The elements were randomly distributed about a 14 column by 11 row matrix. The rows and columns of the zero-disparity pattern alternated with the rows and columns of the disparity pattern. As in the previous experiment, a regular but subtle change in the light intensity of the zero-disparity pattern elements distinguished them from the disparity pattern elements.

The stimuli were shown as static images or under two types of motion conditions. Both static and motion conditions were identical to those in Experiment 1. In addition, stimuli used for the tilt calibration procedure were the same as those used in Experiment 1, except that they were now mechanically rotated about the horizontal axis.

3.1.4 Procedure

A block of trials consisted of {[3 disparity types (horizontal shear, vertical shear, rotation) × 4 disparity levels (2°, 4°, 6°, and 8°) × 2 disparity directions (positive, negative)] + [1 control (zero-disparity trial)]} × [3 superimposed zero-disparity stimuli (none, line, pattern) × 3 motion types (no motion, leftward, and downward)] for a total of 225 test trials. There was the same number of sessions and blocks as in Experiment 1, and the same procedures and controls were employed. Participants were tested over a 9-day period. At the beginning of each trial, participants reported the number of columns and rows they could fuse. They were then asked to adjust the disk to match the inclination of the disparity and, when present, the zero-disparity stimuli.

Instructions, practice trials, and the calibration procedure using a physical calibration surface were all the same as described in section 2.1.4, except the stimulus surfaces

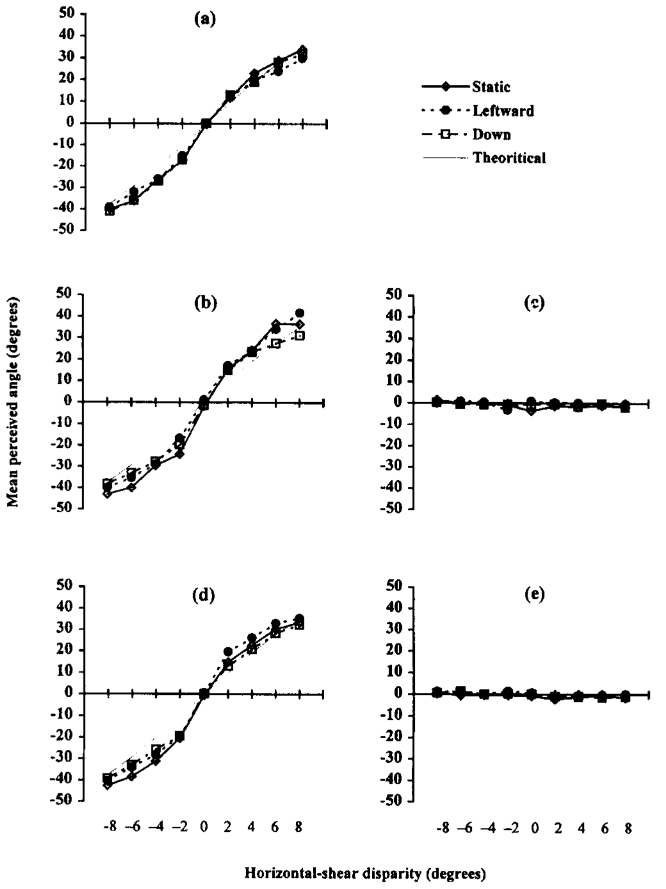

FIGURE 6 — Perceived inclination as a function of horizontal-shear disparity and motion type for: (a) the shear-disparity stimulus alone, (b) the shear-disparity stimulus in the presence of a superimposed zero-disparity line, (c) the superimposed zero-disparity line, (d) the shear-disparity stimulus in the presence of a superimposed zero-disparity pattern, and (e) the superimposed zero-disparity pattern. Mean results for two participants.

and response paddle were set to rotate about the horizontal axis.

3.2 Results

3.2.1 Perceived inclination for horizontal-shear disparity conditions

Figure 6 shows the adjusted inclination means for the horizontal-shear-disparity conditions. Each panel's abscissa indicates the shear disparity magnitude in the disparity pattern. Positive values along the abscissa indicate a clockwise shear to the right eye, whereas negative values indicate a counterclockwise shear to the right eye. The inclination means are plotted along the ordinate. Values above or below the zero line indicate that the fused image was perceived as top-side away or top-side towards, respectively. The thin solid line indicates the theoretically predicted response pattern based on Eq. (2).

As predicted by Eq. (2), the inclination means of the disparity pattern increased as the disparity magnitude increased. Positive horizontal-shear disparities produced positive-inclination perceptions, while negative horizontal disparities produced negative-inclination perceptions. Inclination means for the disparity stimuli of the two participants were submitted to a four-way ANOVA^{viii} with motion type, superimposed stimuli, disparity direction, and disparity magnitude serving as the within-subject variables. The subject-by-factor interactions served as the error terms in computing the F-ratios. The analysis showed a significant main effect of disparity magnitude, $F(3,3) = 803.64$, $p < 0.001$. All other interaction and main effects were not significant. Thus, horizontal-shear disparities produced similar inclination perceptions across all motion conditions. In addition, unlike the results for horizontal-size disparity conditions in Experiment 1, depth enhancement was not evidenced for inclined surfaces in the presence of frontal ones.

Examination of Figs. 6(c) and 6(e) indicates that the superimposed zero-disparity line and pattern appeared to lie in or close to the frontal plane, distinct from the inclined plane in which the disparity pattern appeared to lie. The inclination means for these superimposed zero-disparity stimuli were analyzed in a four-way ANOVA. The analysis showed no significant interactions or main effects. Thus, depth contrast of frontal surfaces in the presence of inclined surfaces was not apparent.

The participants did not report any difficulty in fusing the elements of either the disparity pattern or the zero-disparity stimuli.

3.2.2 Perceived inclination for vertical-shear disparity conditions

Figure 7 shows the response data for the vertical-shear disparity conditions. Figures 7(a) and 7(b) show that, when presented either alone or with a superimposed line, the inclination means of the vertical disparity pattern varied inversely with disparity magnitude. Positive vertical-shear disparities produced negative inclination perceptions, while negative disparities produced positive inclination perceptions. This is the shear-disparity counterpart of Ogle's[1] induced effect with size disparities. A four-way ANOVA on disparity inclination means revealed a significant interaction between superimposed stimuli and disparity magnitude, $F(6,6) = 29.76$, $p < 0.001$. Additionally, the main effects of superimposed stimuli and disparity magnitude were significant, $F(2,2) = 61.15$, $p = 0.016$ and $F(3,3) = 114.72$, $p = 0.001$, respectively. The superimposed-stimuli by disparity-magnitude interaction can be explained by the reduced effect of disparity magnitude when a zero-disparity pattern is superimposed. Figure 7(d) shows that when a zero-disparity pattern was superimposed, the vertical disparity pattern appeared frontal at all levels of disparity magnitude.

The analysis also showed an interaction between motion and superimposed stimuli, $F(4,4) = 53.07, p = 0.001$. Similar to analysis of vertical-size disparity data, this result

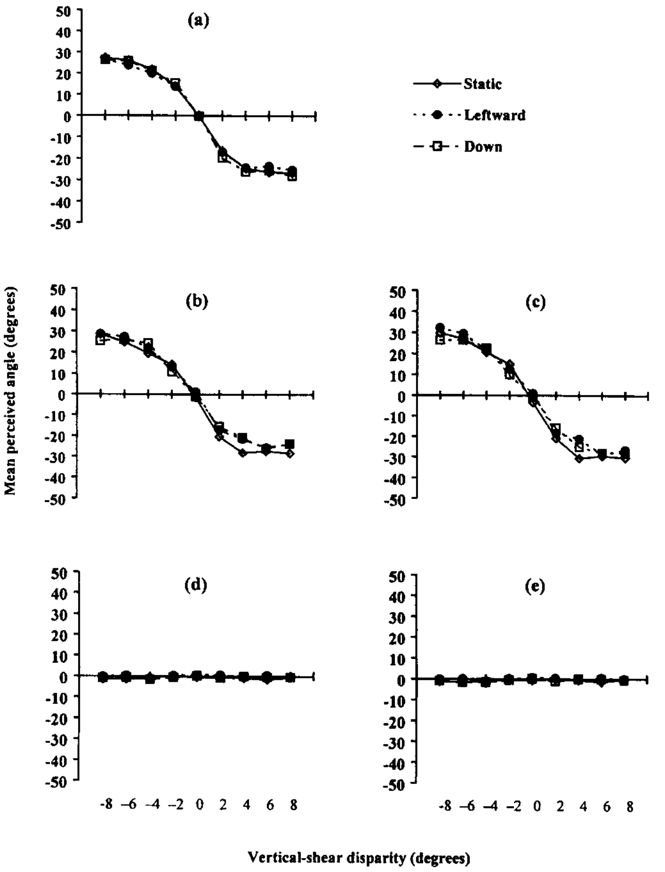

FIGURE 7 — Perceived inclination as a function of vertical-shear disparity and motion type for: (a) the shear-disparity stimulus alone, (b) the shear-disparity stimulus in the presence of a superimposed zero-disparity line, (c) the superimposed zero-disparity line, (d) the shear-disparity stimulus in the presence of a superimposed zero-disparity pattern, and (e) the superimposed zero-disparity pattern. Mean results for two participants.

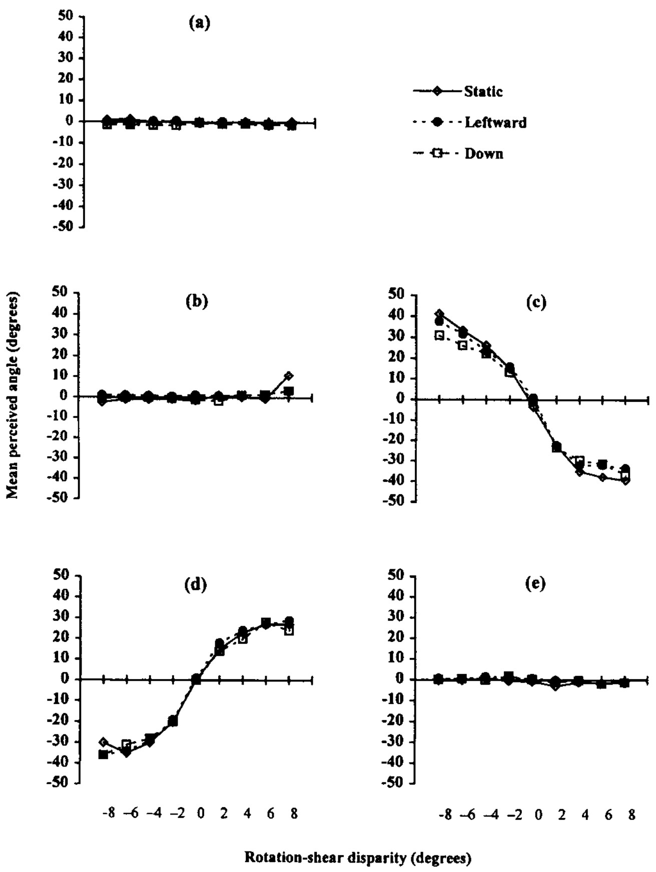

FIGURE 8 — Perceived inclination as a function of rotation disparity and motion type for: (a) the rotation-disparity stimulus alone, (b) the rotation-disparity stimulus in the presence of a superimposed zero-disparity line, (c) the superimposed zero-disparity line, (d) the rotation-disparity stimulus in the presence of a superimposed zero-disparity pattern, and (e) the superimposed zero-disparity pattern. Mean results for two participants.

suggests that motion mediated the effect of the superimposed stimuli. However, differences among inclination means[ix] for the three motion conditions (static, downward, and leftward) within each level of the superimposed stimuli conditions (none, with a zero-disparity line, and with a zero-disparity pattern) were 2.4° or less. Relative to the range of inclination means across levels of disparity magnitude, which exceeded 27° when disparity patterns were presented alone or with a zero-disparity line [see Figs. 7(a) and 7(b)], the magnitude of the effect due to motion was small. All remaining main effects and interactions were not significant.

The effect that disparity magnitude had on the perceived inclination of the zero-disparity stimuli is shown in Figs. 7(c) and 7(e). The inclination means of the zero-disparity line varied inversely with disparity magnitude. The zero-disparity line appeared to lie on the same surface as the disparity pattern with the same inclination. This is not surprising because the line fell along the mid-vertical axis of the disparity pattern where vertical shear was zero. The zero-disparity pattern appeared frontal at all levels of disparity magnitude. This interaction between disparity magnitude and the zero-disparity stimuli conditions was significant, $F(3,3) = 17.02$, $p = 0.022$. The main effects of superimposed stimuli and disparity magnitude were also significant, $F(1,1) = 318.05$, $p = 0.036$ and $F(3,3) = 35.77$, $p = 0.008$, respectively.

The analysis of the zero-disparity stimuli also revealed a significant main effect for motion, $F(2,2) = 23.23$, $p = 0.041$. Although this effect is statistically significant, the actual differences among inclination means for the three motion conditions were 1.4° or less. Relative to the range of inclination means across levels of disparity magnitude, which exceeded 29° degrees for the zero-disparity line [see Fig. 7(c)], the magnitude of the effect of motion again was small. None of the other main effects or interactions was significant.

Participants reported difficulty fusing 15% of the outermost elements in the disparity pattern when there was a superimposed zero-disparity pattern. In these cases, the elements became increasingly diplopic as they were positioned farther away from the center.

4.2.3 Perceived inclination for rotation disparity conditions

Figure 8 shows response data for the rotation disparity conditions. Figures 8(a) and 8(b) show that, when presented either alone or with a zero-disparity line, the rotation disparity pattern was generally perceived as frontal at all levels of disparity magnitude. When a zero-disparity pattern was superimposed [see Fig. 8(d)], the inclination means for the rotation disparity pattern increased in the direction of the horizontal-shear component as the disparity magnitude increased. Similar to the perceived angles of horizontal-shear disparities, positive rotation disparities were perceived as positive inclinations, while negative disparities were perceived as negative inclinations. The four-way ANOVA on disparity-inclination means revealed the interaction between disparity magnitude and superimposed stimuli to be significant, $F(6,6) = 47.95, p < 0.001$. The main effect of superimposed stimuli was also significant, $F(2,2) = 23.33, p = 0.041$.

The analysis also revealed a significant interaction between superimposed stimuli and disparity direction, $F(2,2) = 28.13, p = 0.034$. As seen in Fig. 8(d), with a superimposed zero-disparity pattern, positive disparities produced smaller inclination means than did negative disparities. No other main effects or interactions were significant.

Analysis of inclination means of superimposed zero-disparity stimuli showed a significant three-way interaction between the disparity magnitude, disparity direction, and superimposed stimuli, $F(3,3) = 22.56, p = 0.015$. Additionally, significant interactions were revealed between disparity magnitude and superimposed stimuli, $F(3,3) = 31.11, p = 0.009$, and between disparity magnitude and disparity direction, $F(3,3) = 21.41, p = 0.016$. A significant main effect was obtained for disparity magnitude, $F(3,3) = 59.79, p = 0.004$. The main effect for superimposed stimuli approached significance, $F(1,1) = 98.70, p = 0.064$.

Figure 8(c) shows that the inclination means of the zero-disparity line increased as disparity magnitude increased. The zero-disparity line was negatively inclined when superimposed onto a pattern with positive rotation disparity and positively inclined when combined with a pattern with negative rotation disparity. However, Fig. 8(e) shows that the zero-disparity pattern appeared frontal at all levels of disparity magnitude. This accounts for the interaction between superimposed stimuli and disparity magnitude.

Figure 8(c) shows that for lower disparity magnitudes (*i.e.*, 2° and 4°), inclination means are larger for the zero-disparity line when disparity direction was negative rather than positive. However, this interaction was not indicated for the zero-disparity pattern data [Fig. 8(e)]. This data pattern accounts for the three-way interaction between disparity magnitude, disparity direction, and superimposed stimuli.

A significant main effect was also obtained for motion, $F(2,2) = 500.34, p = 0.002$. Figure 8(c) shows the slightly larger angle responses made to a superimposed zero-disparity line when the disparity pattern were static rather than moving. Downward motion showed less perceived inclination than leftward motion. The actual differences among inclination means for the three motion conditions, however, were 2.3° or less. Compare this to the range of inclination means across levels of disparity magnitude, which exceeded 36° for the zero-disparity line [see Fig. 8(c)]. Thus, as with all previously reported motion effects, the magnitude of this main effect was relatively small.

Participants reported difficulty fusing 79% of the outer elements in the disparity stimuli when there was a superimposed zero-disparity pattern. In these cases, the elements became increasingly diplopic as they were positioned farther away from the center.

4 Discussion

In this study, we investigated the effects of various types of size and shear disparity on stereoscopic tilt perception in order to determine whether previously reported results could be extended to viewing conditions involving moving stimuli. More specifically, we asked "what perceptual anomalies might be expected when moving images are coupled with shear and size disparities in HMDs?" Significant main and interaction effects were indicated for motion under some conditions; however, the relative magnitude of these effects was small. Thus, under these viewing conditions, motion is deemed unlikely to affect the general perception of tilt produced by size and shear disparities for both disparity and zero-disparity stimuli.

4.1 Interactions between disparity and zero-disparity stimuli

As geometrically predicted, tilt perceptions induced by horizontal shear and size disparity are functions of disparity magnitude and direction (Figs. 3 and 6). Statistical analysis of these data showed that for horizontal size but not shear disparities, this tilt perception is enhanced by the presence of a zero-disparity stimulus. This is also shown by the larger effect of disparity magnitude when a superimposed zero-disparity pattern was present for the horizontal-size disparity data (Fig. 3), but not for the horizontal-shear condition (Fig. 6). Similarly, depth contrast effects were found when zero-disparity stimuli were superimposed onto horizontal size, but not shear, disparity stimuli. These results are generally consistent with previous research[4,10,12] on depth contrast and depth enhancement using static displays. These studies reported depth contrast for zero-disparity stimuli in the presence of horizontal-size, but not horizontal-shear, disparity stimuli. They also showed greater depth enhancement for horizontal-size than for horizontal-shear conditions.

For vertical shear and size disparity patterns, tilt perceptions were induced only when presented alone or with a "low-energy" (*i.e.*, line) zero-disparity stimulus (Figs. 4 and 7). Unlike the horizontal disparity image, a large zero-disparity pattern severely reduced the tilt percept for the vertical disparity surface.

Combinations of horizontal and vertical disparities (*i.e.*, overall size and rotation) showed minimal tilt perceptions when presented alone (Figs. 5 and 8). Evidence exists that the minimal tilt perception of rotated images is due in part to ocular torsion,[7] which nulls out much of the horizontal disparity. This nulling process, however, is not complete. For both overall-size and rotation disparity stimuli viewed alone, the minimal tilt perceptions are indicative of the averaging of vertical and horizontal disparities suggested by deformation theory. When a large zero-disparity image is superimposed onto overall-size or rotation disparity patterns, the inclination percept of the disparity surface follows the horizontal component of the disparity. These results are presumably due partly to an inhibition of ocular torsion (for rotation disparity stimuli), as well as to a reduction in the space-averaged vertical disparities of disparity patterns due to the presence of the zero-disparity image (for both overall-size and rotation disparity conditions).

4.2 Relative energy contributions of superimposed imagery

This study also tested the interactions of motion and disparity (shear and size) with various superimposed zero-disparity image conditions (none, line, pattern). The motivation for this manipulation comes from the use of see-through-type HMDs that combine synthetic stereoscopic imagery with natural imagery. Our results show slant contrast and slant enhancement effects when imagery containing horizontal components of size disparity (*i.e.*, horizontal- and overall-size disparity conditions) is combined with zero-disparity imagery, as shown in Figs. 3 and 5.

Besides contrast and enhancement, there can be a transfer of perceived tilt between patterns containing rotation disparity and zero-disparity imagery, depending on their relative energy contributions. This can be seen in Fig. 8 where the relationship between the 8(b) and 8(c) panels is reversed, as shown in the 8(d) and 8(e) panels. When presented alone, a pattern with rotation disparity appears frontal, as does a zero-disparity line. However, when superimposed onto one another, the stronger rotation disparity pattern maintains a frontal appearance and the line appears inclined. Compare this to the case where a zero-disparity pattern is superimposed onto a pattern with rotation disparity. In this latter case, the zero-disparity pattern appears frontal and it is the disparity pattern that appears inclined. Additionally, in this condition subjects reported more difficulty fusing the peripheral elements of the rotation disparity pattern. These results suggest that the zero-disparity pattern provided a stronger cyclofusion guide than the zero-disparity line. That is, it provided more energy to the part of the visual system that is responsible for cyclovergence and central re-normalization of tilt perception.

These results are consistent with the recent results of Arrington, Pierce, and Moreno,[22] in which the inclination percept is shown to be a function of stimulus energy. They varied stimulus energy of a large superimposed zero-disparity image by varying its luminance, while measuring the perceived inclination of a rotation disparity image. They employ the term *energy* to generally include all stimulus features that are salient; that is, produce neural activity. Specifically, with respect to tilt perception, the energy of a pattern includes all components that are salient to the parts of the stereoscopic visual system responsible for tilt perception, including cyclovergence control and central re-normalization. Salience of a particular stimulus element would be some, currently unspecified, function of its luminance contrast, spatial-frequency components, horizontal and vertical components of orientation, retinal eccentricity, retinal motion, flicker, *etc.* For example, it has been shown[7,8] that for cyclovergence, stimuli are more salient when they fill the binocular field than when they are foveal, presumably because the peripheral retina is more sensitive to vertical disparities. As a negative example, Arrington and Pierce[23] have shown that isoluminant color contrast shows little or no salience for the cyclovergence system. The findings here serve to support this relative energy model of tilt perception.

4.3 Implications for HMD systems

The results of the experiments described in this paper have three main implications for HMDs. First, unanticipated shear and size disparities due to optical misalignment or image distortions may result in erroneous tilt perceptions. For example, a mismatch in horizontal display width settings between the right- and left-eye images will produce horizontal-size disparities, which in turn can induce erroneous slant perceptions. Second, erroneous tilt percepts may be compounded in some cases when disparity imagery is combined with zero-disparity imagery. Continuing with the previous example, if presented in a see-through-type HMD, the error could transfer to the see-through imagery producing a contrast effect. Our experiments specifically addressed the case where the disparity and zero-disparity images were at the same location in depth. We believe that these results should apply to an out-the-window visual situation where overlay imagery is collimated at infinity and the real-world imagery is practically at infinity. Moreover, many HMDs can be adjusted to superimpose the overlay image at the same focal and stereo depth as is required for viewing a separate display system seen through the HMD. How the magnitude of these types of interactions varies as the stimuli is separated in depth, however, is an open question.

Finally, our results indicate that the effects of shear and size disparities and their interaction with zero-disparity imagery do not appear to be compounded by motion of the type used in our test conditions. We verified by preliminary experiments that the results are qualitatively robust against variations in velocity until the velocity becomes too fast for the smooth phase of OKN or phosphor smearing substantially changes the stimulus properties. This information suggests that calibrating HMD systems under static conditions will provide the same quality of depth perception under motion conditions. There is no evidence that spurious stereodepth deficits may emerge in HMD systems under motion conditions.

4.4 Motion and stereoscopic limits

Reproducing the stimulus configuration of Hadani and Vardi,[15] we qualitatively confirmed that the effects they reported using a 30-Hz display also occur using a 60-Hz display. They showed a deficit in stereoscopic depth perception when the frequency of depth oscillation across space (cyclopean spatial frequency) was carefully matched to eye-motion velocity (smooth component of induced OKN). With a superimposed normal plane, our stimuli comprised rows and columns of texture elements that similarly alternated in depth. If the compromise of stereoscopic depth perception by motion is to generalize beyond Hadani and Vardi's specific configuration, then we should have observed a deficit with the test stimuli in our main experiment. Our results indicate that this was not the case — we observed no deficit in stereoscopic perception due to motion. The main difference between the two studies is that with our stimuli the texture elements moved on smooth planar surfaces with various gradients of depth. Their stimuli were composed of moving random dots that oscillated in depth as they moved across a stationary corrugated surface.

Finally, our results support those of Patterson[17] and his colleagues. In examining thresholds for discriminating direction of motion in cyclopean random-dot displays, they reported that the thresholds for horizontal (leftward, rightward) versus vertical (upward, downward) motion were similar. We concur with them that sensitivity is isotropic for horizontal and vertical motion.

5 Conclusion

We have studied the effects of size and shear disparity on stereoscopic tilt perception in order to determine whether previously reported results could be extended to viewing conditions approximating those of a real-world application such as flight simulation. Optical misalignments and image distortions in HMD systems are known to produce erroneous depth perceptions. Additionally, depth perceptions are also influenced by motion (*e.g.*, motion parallax, optic flow, looming). Unlike previous efforts that used static images only, we included motion that has been shown in prior studies to impair stereoscopic depth perception. Our results indicate that size and shear disparities affect tilt perception of disparity and zero-disparity stimuli similarly in both static and moving displays. The use of HMD systems in ground-based simulators and in flight has heightened the need to further understand the impact of intended disparities (*e.g.*, stereographic 3-D effects) and unintended disparities (*e.g.*, misalignment of optical elements, distortion of the display device) in such systems. Our studies show a strong effect of size and shear disparities on the perception of tilt for both disparity patterns, as well as superimposed zero-disparity stimuli. Although our results suggest that designers and users of stereoscopic HMDs need to be cognizant of disparity effects on the perception of tilt, they need not be concerned with potentially complex interactions between the perceived tilt of simulated imagery containing disparities and the changing motion of that imagery.

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7 Endnotes

[i] Perceived orientations of *planar surfaces* are related to *linear transformations* between the half images of the stereogram. Perception of *non-planar surfaces* depends on *higher-order spatial differences* between the half images; these will not be considered in this paper.

[ii] In this paper we will use the term *inclination* to indicate rotation about the horizontal axis, and use the term *slant* to indicate rotation about the vertical axis. This usage differs from that of Stevens,[23] formalization in which *slant* is defined as the angle between the surface-normal and the line of sight, and *tilt* is defined as the slant direction (rotational angle) with respect to the frontal plane, namely the angle between the projection of the surface-normal onto the fronto-parallel plane and the horizontal in the frontal plane.

[iii] Note that the axis of the gradient is orthogonal to the axis of rotation.

[iv] Ogle[1] proposed that apparent tilt (slant) is proportional to the difference between vertical and horizontal disparities (a "relative magnification hypothesis"). As a corollary, Cagnello and Rogers[9] proposed a "relative shear hypothesis" that they extended from Koenderink and Van Doorn's[13] deformation theory.

[v] In this paper, the zero-disparity stimuli are stereogram pairs matched to a real fronto-parallel surface, *i.e.*, identical stereogram pairs.

[vi] All ANOVAs in Experiment 1 used both positive and negative perceived slants. Right-side-farther slants were signed positive for right-eye magnified (positive) disparity and were signed negative for left-eye magnified (negative) disparity. Conversely, right-side-nearer slants were signed negative for positive disparity stimuli and were signed positive for negative disparity stimuli. Thus, the dependent variable in these analyses was a measure of slant angle adjusted for the direction of the size disparity. The absolute values of disparity magnitude were used in these analyses. Disparity direction (positive *vs.* negative) was treated as a separate factor.

[vii] The means used in these computations were adjusted for the direction of the size disparity (see endnote vi above). Thus,

they are the same mean values as those used to compute the reported two-way interaction.

[viii] All ANOVAs in Experiment 2 were computed using both positive and negative observed inclination values. *Top farther* inclinations observed for positive shear and rotation disparity angles were given positive values. For negative shear and rotation angles, top farther inclinations were given negative values. *Top nearer* inclinations for positive shear and rotation angles were given negative values, and were given positive values for negative shear and rotation angles. Thus, the dependent variable in these analyses was a measure of inclination angle for shear and rotation direction. The absolute values of shear and rotation angle were used in these analyses. Direction (positive *vs.* negative) was treated as a separate factor.

[ix] The means used in the comparisons reported here and later in this results section were adjusted for the direction of the shear disparity (see endnote viii above). Thus, they are the same mean values as those used to compute the reported ANOVAs.

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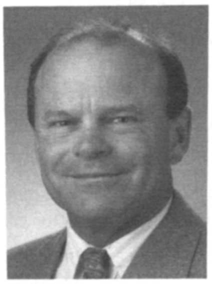

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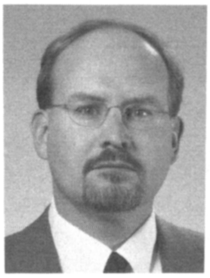

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