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Temporal aspects of slant and inclination perception

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Abstract. Linear transformations (shear or scale transformations) of either horizontal or vertical disparity give rise to the percept of slant or inclination. It has been proposed that the percept of slant induced by vertical size disparity, known as Ogle's induced-size effect, and the analogous induced-shear effect, compensate for scale and shear distortions arising from aniseikonia, eccentric viewing, and cyclodisparity. We hypothesised that these linear transformations of vertical disparity are processed more slowly than equivalent transformations of horizontal disparity (horizontal shear and size disparity). We studied the temporal properties of the stereoscopic slant and inclination percepts that arose when subjects viewed stereograms with various combinations of horizontal and vertical size or shear disparities. We found no evidence to support our hypothesis. There were no clear differences in the build-up of percepts of slant or inclination induced by step changes in horizontal size or shear disparity and those induced by step changes in vertical size or shear disparity. Perceived slant and inclination decreased in a similar manner with increasing temporal frequency for modulations of transformations of both horizontal and vertical disparity. Considerable individual differences were found and several subjects experienced slant reversal, particularly with oscillating stimuli. An interesting finding was that perceived slant induced by modulations of dilation disparity was in the direction of the vertical component. This suggests the vertical size disparity mechanism has a higher temporal bandwidth than the horizontal size disparity mechanism. However, conflicting perspective information may play a dominant role in determining the temporal properties of perceived slant and inclination.

1 Introduction

A horizontal gradient of horizontal disparity produces the impression of a surface slanted in depth about a vertical axis (a right-wall or left-wall plane). A vertically oriented gradient of horizontal disparity produces the impression of a surface inclined in depth about a horizontal axis (a sky or ground plane).(1) Since these effects are predicted from the geometry of binocular vision, we call them geometric effects (after Ogle 1938). A vertical gradient of vertical disparity (a vertical size disparity) in an isolated textured surface also creates an impression of a surface slanted in depth. This effect is not predicted from the projective geometry of real slanted surfaces. 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. Thus, the vertical size disparity is converted into an equivalent horizontal size disparity of opposite sign. A horizontal gradient of vertical disparity (vertical shear disparity) in a large isolated

(1) Stevens (1983) has suggested alternative terminology for the description of the orientation of surfaces. In this scheme, the slant angle describes the degree of rotation of the surface out of the frontal plane and tilt angle describes the orientation of the axis of this rotation in the frontal plane. Thus, slant and inclination would be referred to as slant with tilt angles of 0° and 90° respectively. Traditionally tilt angle refers to the rotation of an element in the frontal plane. Stevens's scheme could be considered a generalisation of this definition. We prefer to reserve tilt to describe the orientation of stimulus features rather than of reference frames.

textured surface creates the impression of inclination about a horizontal axis (Howard and Kaneko 1994). This is the shear-disparity analogue of the induced-size effect and will be referred to as the induced-shear effect. It has been proposed that these vertical disparity mechanisms protect against aniseikonia, differences in size due to eccentricity, and cyclodisparity (Ogle 1964; Howard and Kaneko 1994). Because the proposed mechanisms are sensitive to parameters that change gradually over space or affect the entire binocular visual field, one would expect vertical disparities to be averaged over wide areas of the visual field. This should reduce the effects of local noise in arriving at a single estimate of the viewing system parameters. Stenton et al (1984) and Kaneko and Howard (1996, 1997) demonstrated that vertical shear and size disparities are averaged over large portions of the visual field. Similarly, we may suppose that temporal averaging is employed to arrive at a stable estimate of parameters that change slowly over time.

Whole-field vertical shear disparity results from cyclotorsional misalignment of the eyes. Rogers (1992) proposed that the inclination perceived in a display with vertical shear disparity could be due to cyclovergence transforming the vertical shear disparity into a horizontal shear disparity. Van Rijn et al (1994) and Rogers (1992; see also Howard and Rogers 1995) have shown that vertical shear disparity is a strong stimulus for cyclovergence eye movements. Although this is an attractive explanation, subsequent evidence has shown that cyclovergence does not provide a complete explanation for the induced-shear effect (Howard and Kaneko 1994). If cyclovergence plays a role in determining the percept of surface inclination in the induced-shear effect, we may expect the temporal characteristics of the induced-shear effect to be determined by the temporal properties of cyclovergence. Cyclovergence is a slow eye-movement system with little response at high temporal frequencies or short durations (Howard and Zacher 1991). Thus, we would expect the induced-shear effect to be limited at high temporal frequencies and at short durations. Even if cyclovergence does not play a major role, we might expect the sensory mechanism that mediates the induced-shear effect to be relatively slow-acting if its role is to deal with the slowly changing parameter of cyclodisparity. Similarly, if the induced-size effect results from mechanisms designed to deal with aniseikonia—a slowly changing parameter of the optical system—we would expect its response to be sluggish. Mayhew and Longuet-Higgins (1982) and others have proposed that vertical disparity patterns are used to obtain estimates of viewing system parameters such as gaze direction and vergence angle (or, alternatively, eccentricity and viewing distance). Averaging over time may allow for more robust estimates of these parameters. The integration time for this averaging process could not be unlimited since these parameters change with motion of the target or of the observer.

Thus, we hypothesised that vertical disparities are processed more slowly than horizontal disparities. According to this hypothesis, the contribution of vertical disparity to perceived slant and inclination should be weakened relative to that of horizontal disparity as temporal frequency is increased or presentation time shortened. These experiments were designed to investigate the percept of inclination and slant in depth induced by vertical and horizontal shear and size disparities as a function of temporal frequency and exposure time.

2 General methods

Computer-generated images were presented dichoptically in a large Wheatstone stereoscope in a darkened room by means of two Electrohome EDP-58 projection monitors. All surfaces were covered with matte black cloth or paint. Care was taken to mask the monocular half-images from being directly viewed, so that only the fused stimulus was visible through the mirrors. The image for most of the experiments was an irregularly textured black-and-white circular pattern subtending 60 deg of visual angle (see figure 1) at the viewing distance of 93 cm.

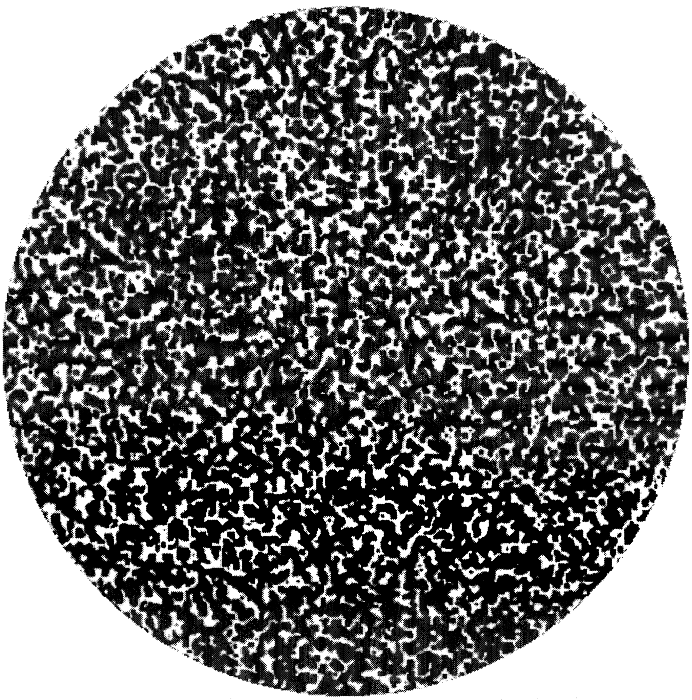

Figure 1. Scaled version of the irregularly textured display used for the experiments.

An irregular pattern was used to minimise perspective – disparity cue conflict. Gibson (1950) reported that subjects consistently underestimate the slant of surfaces defined by a texture gradient in the absence of other cues. He noted that this regression to the frontal plane was much stronger for irregular textures than for regular textures. One effect of texture irregularity is to add noise to estimates of texture gradient. Young et al (1993) have provided evidence that, under cue conflict, percepts shift to the more reliable cue when noise degrades information from the other.

The image pairs were pre-computed and the base image transformed to produce various combinations of vertical and horizontal shear and size disparities. Sub-pixel interpolation was employed to reduce the aliasing effects of a finite pixel count. The percept was of a flat textured plane rotated out of the frontal plane. Size disparity produced a plane slanted about a vertical axis, and shear disparities produced a surface inclined about a horizontal axis. In experiment 1, the images were presented statically for various durations. In experiment 2, a sequence of frames (frame rate 15 Hz) produced a sinusoidal modulation of shear or size disparities.

Shear disparities were of four types: horizontal shear, vertical shear, rotation, and deformation (see Gillam and Rogers 1991; Howard and Kaneko 1994). Note that rotation can be interpreted as horizontal and vertical shear in the same direction[(2)] and deformation can be interpreted as horizontal and vertical shear in opposite directions. Four types of scale, or size, disparity were used: vertical magnification, horizontal magnification, deformation, and dilation (overall magnification). Dilation can be interpreted as horizontal

[(2)] Strictly speaking this is true only at small angles—a horizontal shear cannot be applied following a vertical shear to result in a rotation. However, rotation disparity can be considered to be composed of gradients of horizontal and vertical disparity like those arising from horizontal and vertical shears. Furthermore, the work of Koenderink and van Doorn (1976) suggests that their deformation theory may be implemented by detectors detecting the amount of horizontal shear in vertically oriented elements relative to the amount of vertical shear in horizontally oriented elements. We feel that this type of decomposition is a physiologically plausible means of detecting deformation disparity.

and vertical size disparity in the same direction, and deformation can be interpreted as horizontal and vertical size disparity in opposite directions. Since induced effects and geometric effects produce opposite depth, deformation disparities should produce a larger effect than either component alone. The component effects should tend to cancel in the rotation and dilation conditions.

The predictions of the hypothesis that vertical disparity is processed more slowly than horizontal disparity are as follows. Vertical shear and size disparities are predicted to result in reduced slant at high temporal frequency. Consequently, with increasing temporal frequency, the percept evoked by the vertical disparity component should decrease relative to that evoked by the horizontal disparity component. This should reduce perceived depth in deformation disparity conditions but increase perceived depth in rotation and dilation disparity conditions.

Subjects matched the perceived slant or inclination of the disparity surface with that of a subsequently presented real surface. The comparison surface was centrally located in front of the subject and when illuminated it was visible through the semi-silvered mirrors forming the stereoscope. This real surface was textured with the same pattern as that of the test surface and subtended 32 deg. The comparison surface contained a variety of depth cues to its true orientation. The surface was supported on a gimbal mounting and could be rotated about either a horizontal or vertical axis by the subject, by means of a long steel rod. After each presentation of a test surface, the real surface was illuminated and subjects adjusted its slant or inclination to match the perceived slant or inclination of the test surface. After the subject indicated the surface was appropriately adjusted, calibrated voltages from potentiometers attached to the slant and inclination axes of the comparison (real) surface were read into a computer.

3 Experiment 1

The purpose of this experiment was to measure the time course of the build-up of the percept of surface slant and inclination. The relative contributions of vertical and horizontal size-disparity and shear-disparity mechanisms were evaluated by studying the response to combinations of horizontal and vertical gradients of disparity. According to the hypothesis outlined above, the effects of the horizontal disparity component should become evident sooner than those of the vertical disparity component.

3.1 *Method*

The irregularly textured display described above was presented initially with zero disparity (it appeared as a flat, frontal surface). A constant disparity gradient was then added to the display to cause it to rotate in depth out of the frontal plane. Horizontal shear, vertical shear, rotation, and deformation disparities were used to induce inclination. Vertical magnification, horizontal magnification, deformation, and dilation disparities were used to induce slant. Two levels (0.73° and 1.46° of shear disparity, or 1.28% and 2.56% of size disparity) and both directions of disparity were used for each of the transformations. These levels were used for both the horizontal and vertical components of the rotation, dilation, and deformation disparity transformations. The test stimulus was presented for 0.1, 1, 10, or 30 s, after which the comparison surface was illuminated. The subject matched the slant or inclination of the comparison display to the final perceived slant or inclination of the test surface. Four subjects with normal binocular vision were studied. Each stimulus, level, and duration combination ($8 \times 4 \times 4$) was presented eight times over four sessions in randomised order.

3.2 *Results*

Figures 2 and 4 show perceived inclination and slant, respectively, as a function of disparity for various exposure durations averaged across the four subjects. For each subject, responses were normalised by dividing the judged slant or inclination by the

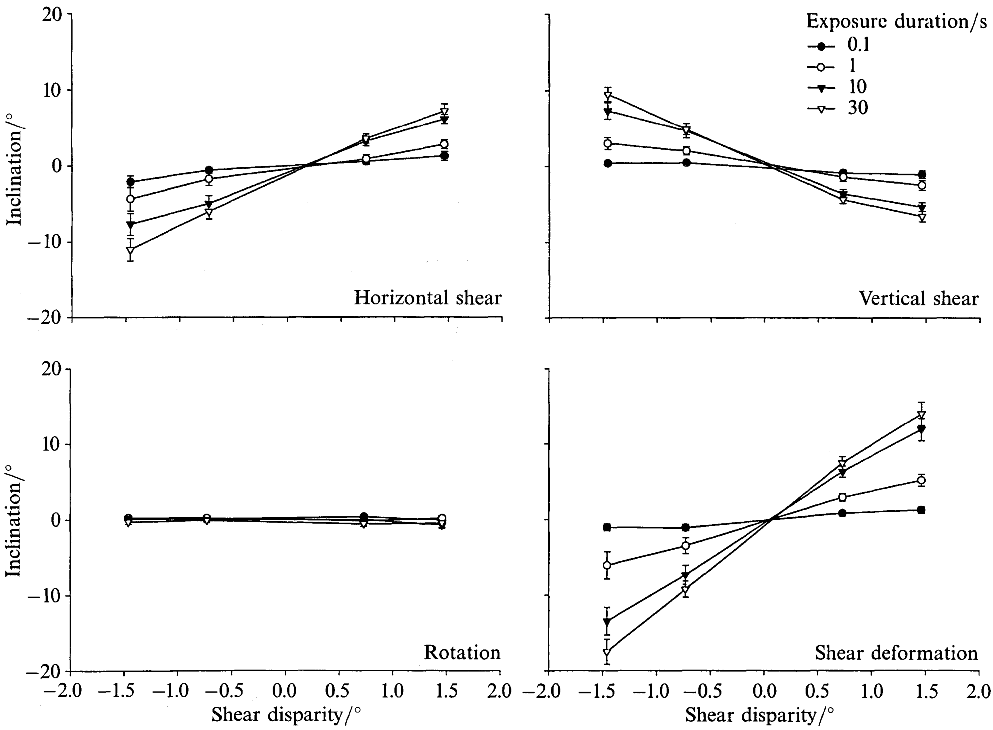

Figure 2. Inclination matches as a function of disparity for various exposure durations averaged over the four subjects (±SEM) for combinations of vertical and horizontal shear disparity.

theoretical slant or inclination predicted from the horizontal size or shear disparity component (10° and 20° for shear or size disparity of 0.73° or 1.28%, and 1.46° or 2.56%, respectively). Figures 3 and 5 show these normalised responses collapsed across disparity level and plotted as a function of duration for each subject. Note that this procedure introduces some additional variability. This is because it ignores idiosyncratic differences between sky and ground responses and the differences in response gain between the two stimulus levels. For example, for inclined surfaces the subjects tended to respond more strongly when disparity specified a ground plane than when it specified a sky plane, leading to a somewhat asymmetric response. Results for slant and inclination are discussed separately below.

3.2.1 *Inclination.* For each horizontal shear disparity, perceived inclination increased significantly with exposure duration (figure 2). Inclination was underestimated at all exposure durations, but more so at short durations. Perceived inclination increased with increased horizontal shear disparity as expected. Figure 3 shows that subjects HJ and XF typically saw some inclination even at the shortest 0.1 s duration. Subject JZ perceived no inclination and subject RA perceived inclination opposite to the predicted direction for 0.1 or 1 s presentations of horizontal shear disparity. At longer durations, all subjects saw inclination in the predicted direction. At 30 s exposure time, inclination was typically underestimated for horizontal shear disparity and was less than the predicted values of 10° and 20° for the 0.73° and 1.46° shear conditions.

For vertical shear disparity, only subject XF perceived any depth in the shortest 0.1 s presentation. The other three subjects perceived no inclination at the 0.1 s presentation, and JZ reported no inclination at the 1 s presentation. Perceived depth increased with exposure time and disparity level as in the horizontal shear disparity conditions. In subject HJ, there was little difference between the 10 and 30 s presentation durations

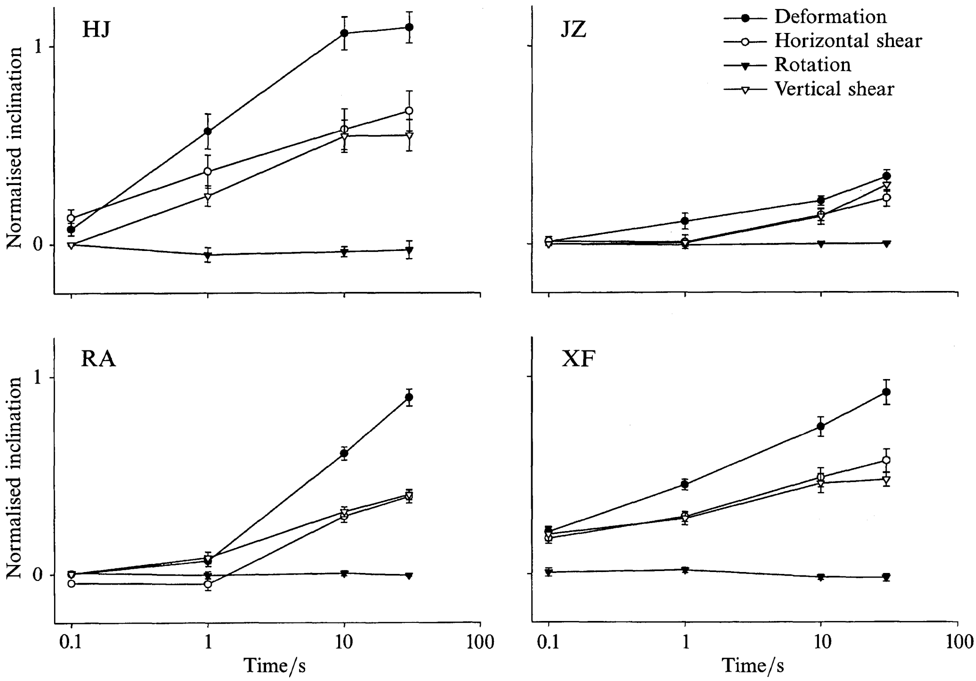

Figure 3. Normalised inclination matches for various combinations of shear disparities as a function of exposure duration in the four subjects (±SEM). For rotation, positive inclination indicates response in the direction predicted from the horizontal shear disparity component.

which suggests that responses saturate. In the other three subjects, however, depth continued to build over the 30 s exposure. There is little suggestion in the slopes of the duration functions that the response to vertical shear is appreciably slower than the response to horizontal shear (except perhaps for subject HJ). At the shortest durations, however, subjects were more apt to report inclination for horizontal shear than for vertical shear. This perhaps indicates a shorter latency for horizontal shear disparity. For rotation disparity, all subjects reported little depth, regardless of exposure time or stimulus level. The predicted transient response in the direction of the horizontal shear component was not observed. For shear deformation, perceived inclination was typically larger than for either horizontal or vertical shear disparity. At exposures of 10 and 30 s, the response to deformation was close to the sum of responses to the horizontal and vertical disparity components. At the shortest duration, the response to deformation disparity was similar in size to the response to horizontal shear disparity.

Occasionally, subjects responded with a depth match in the opposite direction to that predicted by disparity—a so-called slant reversal (Gillam 1967; see also Stevens and Brookes 1988). We counted a response as a slant or inclination reversal if the normalised response exceeded 0.05 and was opposite to the predicted direction. We excluded rotations since the predicted inclination is zero. Across the other three conditions, reversals occurred significantly more often for short durations (0.1 and 1 s) than for long durations (10 and 30 s), occurring in 41 of 384 trials and in 6 of 384 trials, respectively ($\chi_1^2 = 27.76$, $p < 0.001$). Specifically, reversals occurred significantly more often for the two short durations for horizontal shear ($\chi_1^2 = 20.571$, $p < 0.001$) and shear deformation ($\chi_1^2 = 8.258$, $p < 0.01$) cases but not for vertical shear. However, the low frequency of reversals for deformation (8 of 256 trials) makes frequency analysis problematic. Reversals were also significantly more common for horizontal shear disparity than for vertical shear and deformation disparity, occurring in 32 of 256 trials for horizontal shear disparity compared with 7 and 8 of 256 trials for vertical shear ($\chi_1^2 = 17.347$, $p < 0.001$) and deformation ($\chi_1^2 = 15.62$, $p < 0.001$) shear disparities.

In summary, for the four subjects, the percept of inclination built up slowly over durations up to 30 s for horizontal, vertical, and deformation shear disparities. Analysis of variance indicated a significant effect of exposure duration, disparity magnitude, and their interaction on the response for horizontal, vertical, and deformation shear disparity conditions ($p < 0.01$). The nature of the interaction was that perceived depth built up more slowly with larger disparities even after normalisation by disparity magnitude. None of these parameters had a significant effect on the response to rotation disparity. Regression analysis did not demonstrate a significant difference in the effect of exposure duration for horizontal versus vertical shear disparities. Little depth was reported at 0.1 s presentation time for any condition. For rotation, little depth was seen even at 30 s duration.

3.2.2 *Slant.* The trends for slanted surfaces were generally similar to those for inclined surfaces. On average (figure 4) subjects perceived more slant for each horizontal size disparity as exposure duration increased. As expected, perceived slant increased with increased horizontal size disparity especially for longer durations. Figure 5 shows that three subjects tended to see slant in the correct direction although greatly underestimated even at 30 s durations. One subject (RA) tended to perceive the slant in the wrong direction for these very short durations. All subjects saw slant in the correct direction for longer presentations. For 30 s exposure time, slant matches were the largest but still fell short of theoretical values. We did not find the well-known anisotropy between slant about a vertical axis and inclination about a horizontal axis—perhaps because of the small sample size.

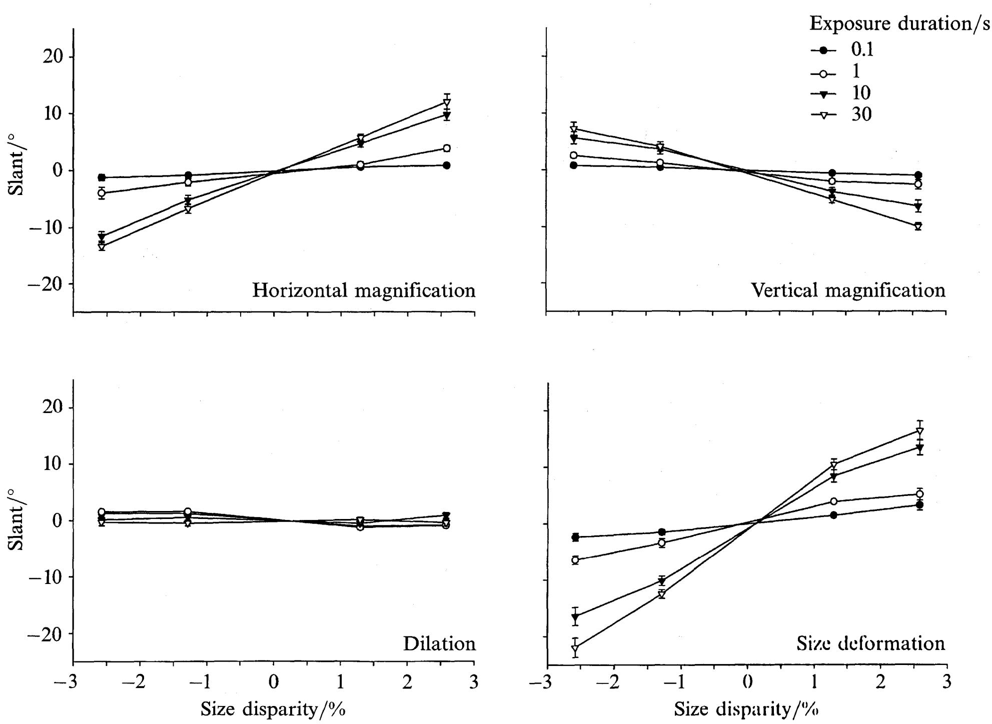

Figure 4. Slant matches as a function of disparity for various exposure durations averaged over the four subjects (±SEM) for combinations of vertical and horizontal size disparity.

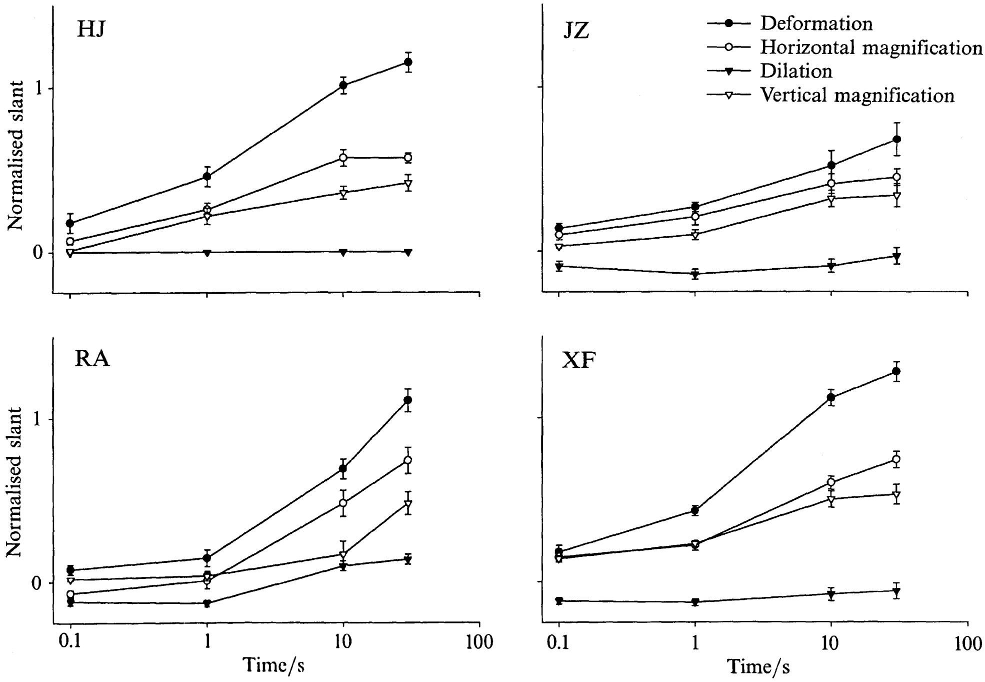

Figure 5. Normalised slant matches for various combinations of size disparities as a function of exposure duration in the four subjects (±SEM). For dilation, positive slant indicates response in the direction predicted from the horizontal size disparity component.

For vertical size disparity, perceived slant increased with exposure time and disparity level as in the horizontal size disparity data. Only subject XF perceived depth in the shortest 0.1 s presentation. Slant built up over the 30 s exposure of the vertical size disparity stimulus for all four subjects. The slopes of the horizontal and vertical size disparity versus duration curves do not suggest a difference in the temporal properties of the two responses. There was some evidence that the latency for vertical disparity is somewhat longer since subjects were more apt to report slant at short durations when the stimulus contained horizontal rather than vertical size disparity. However, there is also a suggestion in the data that the vertical size disparity mechanism is faster since the curves for dilation disparity go in the direction of the vertical component for brief durations in three of the four subjects. Otherwise the dilation disparity results are generally flat and show little depth for all exposure times and disparity levels. The predicted transient response in the direction of the horizontal size component was not observed. For size deformation, the response was typically larger than that for either the horizontal or vertical size disparities and was close to their sum at 10 and 30 s exposure durations.

Excluding dilations, where predicted slant is zero, depth reversals occurred more often in the 0.1 and 1 s durations than in the 10 and 30 s durations, occurring in 26 and 7 of 384 trials, respectively ($\chi_1^2 = 11.38$, $p < 0.001$). Specifically, the frequency of depth reversals was significantly higher for the two short durations than for the longer durations for horizontal size transformation ($\chi_1^2 = 16.43$, $p < 0.001$) but not for vertical and deformation size disparities. In the size deformation disparity case, the low frequency of reversals makes frequency analysis have little statistical power. Slant reversals were rarest for size deformation, occurring in only 2 of 256 trials, significantly less than for horizontal size disparity ($\chi_1^2 = 14.35$, $p < 0.001$). Reversals were slightly more common in horizontal size disparity trials than in the vertical size disparity trials, occurring in 19 versus 12 of 256 trials, respectively but this difference was not significant ($\chi_1^2 = 1.654$, $p > 0.1$). Most of the reversals for slant were reported by one subject (RA). As we reported above, dilation disparity tended to result in matched depth corresponding to the vertical component for short durations and to the horizontal component for long durations if slant was perceived. Frequency analysis confirmed that depth in the vertical direction was reported more often for short durations than for long durations ($\chi_1^2 = 31.352$, $p < 0.001$).

In summary, for all subjects, the percept of slant built up over durations up to 30 s for horizontal, vertical, and deformation size disparities. Analysis of variance indicated a significant effect of exposure duration, disparity magnitude, and their interaction on the perceived slant produced by horizontal, vertical, and deformation size disparity ($p < 0.01$). When the responses were normalised, a significant magnitude by duration interaction still existed, indicating a somewhat slower build-up of perceived slant for larger disparities ($p < 0.05$). Regression analysis did not demonstrate a significant difference in the effect of exposure duration for horizontal versus vertical shear disparities. For dilation, little depth was seen at long durations. A small transient response in the vertical direction was found in three subjects. This was reflected in a significant effect of exposure duration on the response to dilation disparity ($p < 0.01$).

3.3 *Discussion*

Gillam et al (1984) measured the latency of slant perception for horizontal size disparity using a monocular matching task. Their operational definition of latency was the time at which the matched slant exceeded 50% of the final value. Latencies were 15 and 25 s for their two observers for 5% horizontal magnification. This result suggests a relatively slow development of the slant percept. Van Ee and Erkelens (1996a) measured the time course of slant and inclination perception using methods similar to those used here for horizontal shear and size disparities in large isolated displays. We have confirmed their findings that weak slant and inclination are perceived for presentation durations of less than 1 s, with the percepts eventually developing over a period of up to 30 s. We have extended these observations for various combinations of vertical and horizontal size and shear disparity. We have found a similar slow development of the percepts of slant and inclination for stimuli with vertical size or shear disparity. When horizontal and vertical disparity gradients are combined and specify the same direction of slant or inclination the build-up of the percept is similarly slow.

Experiment 1 failed to support the hypothesis that gradients of vertical disparity are processed more slowly than gradients of horizontal disparity. The build-up of the percept for vertical shear and size disparity was not appreciably slower than the build-up for horizontal shear and size disparity. Dilation disparity tended to evoke slant responses in the direction of the vertical component for short exposure durations. This provides some evidence that the response to vertical size disparity is faster than the response to horizontal size disparity. Alternatively, the vertical size disparity may potentiate the slant reversal effect for horizontal size disparity.

Gillam et al (1988) have shown that the post-fusional latency for identification of one of seven slant or inclination configurations was longest when the horizontal shear or size disparity transformation was applied to the entire stimulus, particularly for slant. Latencies were reduced and perceived slant and inclination were larger when the test surface was presented along with a reference stimulus containing a different gradient of horizontal disparity. Presence of a reference surface is not expected to aid in the processing of vertical disparity since vertical shear and vertical size disparities are averaged over large portions of the visual field (Kaneko and Howard 1996, 1997).

Somewhat surprising is the slow build-up of depth for horizontal shear and size disparity. Several studies have demonstrated that the percept of slant or inclination is weak for horizontal size and shear disparity in the absence of a visual reference (Gillam et al 1988; Brookes and Stevens 1989; van Ee and Erkelens 1995). This has been interpreted as an insensitivity of the visual system to low spatial frequency changes in disparity. This interpretation is supported by the existence of an analogue of the Craik – O'Brien – Cornsweet illusion in the disparity domain (Anstis et al 1978). In contrast, in these studies discontinuities in disparity were well perceived. The visual system appears to be especially sensitive to abrupt changes in relative horizontal disparity and relatively insensitive to absolute disparities or constant gradients of absolute disparity. Gillam et al (1988) reported that depth builds up slowly for horizontal shear and especially slowly for horizontal size disparities. These investigators found that an abrupt spatial change or discontinuity in horizontal size disparity greatly reduces the latency for perceiving surface slant. In this experiment, we have shown that an abrupt temporal change in horizontal size or shear disparity does not result in a rapid percept of surface slant or inclination. Thus, it appears that a temporal disparity change cannot substitute for spatial change in disparity gradient in enhancing the slant response at short exposure durations. One caveat is that the disparity cue in our experiments, as well as those of Gillam et al (1988), was in conflict with other depth cues, especially perspective, which were consistent with a frontal surface regardless of disparity. Stevens et al (1991) have provided anecdotal evidence that, under conditions of cue conflict, gradients of disparity are relied on more as viewing time increases. The possible effects of disparity – perspective conflict are discussed further below.

The response to deformation disparity is ideally the sum of the response to horizontal and vertical disparity components. This additive relationship holds approximately at long exposure durations but fails at short durations where the response is close to the values found for horizontal disparities. This could be the result of longer time being required to process larger slants or inclinations. In agreement with this interpretation, we found that the build-up of perceived slant and inclination was slower with larger disparity although the effect was not large.

4 Experiment 2

In this experiment suprathreshold matching was used to map the relative temporal frequency sensitivity of visual mechanisms responding to vertical and horizontal size and shear disparities. We also studied the response to combinations of horizontal and vertical size disparities (size deformation and dilation disparity) and to combinations of shear disparities (shear deformation and rotation disparity). This allowed for evaluation of the relative potency of the horizontal and vertical components as temporal frequency was varied.

4.1 *Method*

For these measurements, five cycles of sinusoidal oscillation were presented at each of five frequencies in random order (0.112, 0.225, 0.45, 0.90, 1.8 Hz). Subjects perceived a flat textured plane which sinusoidally changed its inclination or slant with respect to the frontal plane. The same eight size and shear disparity transformations were used as in experiment 1. The magnitude of the disparity oscillation was 1.46° peak shear disparity or 2.58% peak size disparity. Subjects indicated the sign of inclination (or slant) by verbally reporting when the surface was a sky or ground plane (or right-wall/left-wall plane), a task which could be performed only for the lowest three frequencies. At the highest frequencies, subjects could only indicate when peaks of one sign occurred or which sign peak came first. After the presentation of each frequency, the subject matched the slant or inclination of a visible comparison display (not seen during the test display) to the furthest and nearest extent of the depth oscillation of the test surface. The subjects saw each stimulus combination twice over two sessions. The perceived surface slant or inclination as a function of temporal frequency of disparity gradient modulation was obtained. Eleven subjects with normal binocular vision were studied.

In three subjects, an extended frequency range was studied with stimuli presented at lower temporal frequencies of 0.0187, 0.037, and 0.075 Hz. In these three subjects, we also looked at the response to stimulus oscillation of horizontal size and shear disparity in the presence or absence of a zero-disparity surround. In this stimulus, the irregularly textured disk was divided to consist of a central disk subtending 32 deg visual angle and an annular surround separated by a 5 deg black region. The central disk was subject to the disparity oscillation while the outer annulus had a constant zero disparity.

4.2 *Results*

The results required treating the subjects as two separate groups. Eight of the eleven subjects comprised the first group. They perceived the surface oscillating in phase with the horizontal and vertical disparity transformations. Since there were no significant differences between the two directions of slant or inclination estimates, the data were collapsed across direction. Repeated-measures analysis of variance found a significant interaction between frequency and transformation type for the pooled inclination data ($F_{12,84} = 8.46, p < 0.01$) as well as the main effects of frequency ($F_{4,28} = 14.40, p < 0.01$) and transformation type ($F_{3,21} = 15.64$, $p < 0.01$). Regression analysis showed that in these subjects perceived inclination declined significantly ($p < 0.01$) with increased frequency for horizontal, vertical, and deformation shear disparity transformations (see figure 6a). There was no discernible difference between the sensitivity to temporal frequency for the horizontal and vertical shear transformations either in the ensemble or individual data sets (ie the slopes were not significantly different). Perceived inclination for rotation disparity was small and tended to peak slightly at mid-frequencies. The sign of the inclination for rotation disparity was consistent with that predicted for the horizontal shear disparity component. Individuals in this group also showed trends consistent with the group averaged data. Regression analysis on individual data indicated a negative slope versus frequency for horizontal, vertical, and deformation shear disparities although the trends did not reach significance in some individual data sets.

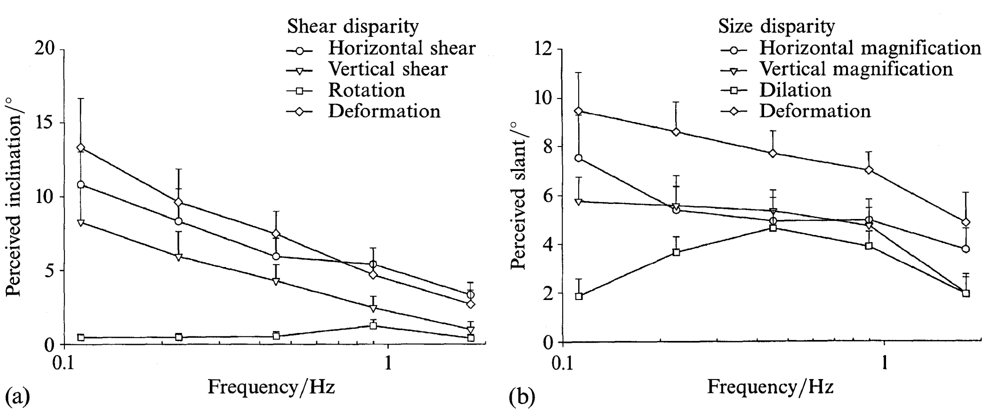

Figure 6. (a) Inclination matches as a function of temporal frequency for horizontal shear disparity, vertical shear disparity, shear deformation disparity, and rotation disparity. (b) Slant matches as a function of temporal frequency for horizontal size disparity, vertical size disparity, size deformation disparity, and dilation disparity. The curves represent the averaged response (±SEM) of eight observers.

Results for slant in these eight subjects were similar but the effects were not as strong. Since there was no significant difference between the right-wall and left-wall estimates, the data were collapsed across direction. Repeated-measures analysis of variance revealed a significant interaction between frequency and transform type for the ensemble slant data ($F_{12,84} = 3.33$, $p < 0.01$) as well as main effects of frequency ($F_{4,28} = 4.70$, $p < 0.01$) and transformation type ($F_{3,21} = 8.24$, $p < 0.01$). Regression analysis showed that, in these subjects, perceived slant declined significantly ($p < 0.05$) with increased frequency for horizontal, vertical, and deformation size disparities (see figure 6b). There was no discernible difference between the sensitivity to temporal frequency for the horizontal and vertical size components (the slopes were not significantly different). Perceived slant for dilation disparity was small at high and low frequencies and tended to peak at mid-frequencies and was in the direction of the vertical size disparity component. Individuals in this group also showed trends consistent with the pooled data. Regression analysis on individual data typically indicated a negative slope versus frequency for horizontal, vertical, and deformation shear disparities. However, the weaker effects for the slant case resulted in many of these trends not being significant in the individual data.

The three subjects comprising the second group perceived the inclination or slant of the surface opposite to the predicted direction (slant-reversal effects) for oscillating horizontal gradients of disparity. Thus, when the horizontal size disparity corresponded to a surface slanted right side nearer, they reported that it appeared left side nearer. Similarly, they reversed the sign of the perceived inclination in oscillating horizontal shear disparity patterns. These subjects had a response that differed markedly from that of the subjects who saw the slant direction veridically. They did not tend to see slant or inclination falling with frequency; instead they saw very little depth at the lowest frequency, which stayed the same or increased slightly with frequency. We tested one of these subjects (along with two of the other group) over an extended low-frequency range. This subject was not prone to depth reversals at very low frequencies of oscillation (less than 0.1 Hz) and saw depth at these very low frequencies which declined with increased frequency (figure 7). Thus, this subject appeared to show a similar response to the other subjects but shifted to a much lower frequency range. None of the three subjects saw depth reversals for oscillations of horizontal size or shear disparity in a central stimulus in the presence of a zero-disparity annular visual surround. The matched depth for the subject prone to depth reversals (as well as for the two individuals from the other group) was higher than observed for the isolated stimulus in the main experiment and declined with increased temporal frequency in the presence of the surround. Note that the central disk in this stimulus was considerably smaller than that used in the main

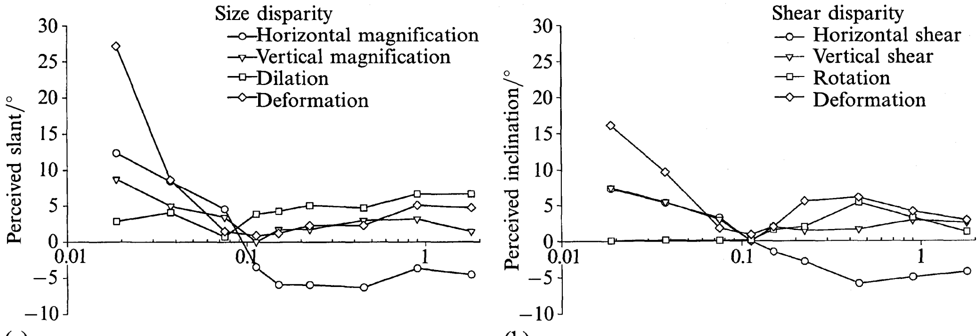

Figure 7. Slant (a) and inclination (b) matches in subject who was prone to perceiving slant in the opposite direction to that predicted by disparity (slant or inclination reversals). Reversed slant is represented in the figure by negative slant or inclination.

experiment. With this smaller disk presented in isolation this subject still experienced depth reversals and did not have a strong impression of depth.

With oscillating dilation disparity, all subjects in both groups saw slant in the direction corresponding to the *vertical size disparity* component. Note that this is opposite to the typically small slant seen with static dilation disparity and opposite to the direction predicted in the Introduction. With static or oscillating rotation disparity, all subjects who saw inclination saw it in the direction of the horizontal component. Inclination or slant seen in the oscillating displays with horizontal, vertical, or deformation shear or size disparity was smaller than that seen in static presentations and less than the theoretical values (20° for horizontal disparity). Average levels of slant and inclination for static presentations were typically larger than the slants and inclinations observed in the dynamic displays.

4.3 *Discussion*

Amplitudes of temporally oscillating inclination and slant were underestimated at the frequencies used. In addition, perceived slant and inclination declined with increased temporal frequency for horizontal, vertical, and deformation disparities in eight of eleven subjects. This suggests that stereoscopic processing is limited at high temporal frequencies. Richards (1972) found that the apparent depth of a test bar oscillating in depth, as measured with a depth probe, declined with increasing temporal frequency of disparity oscillation over a range similar to that studied here, for disparities less than 0.5°. For larger disparities apparent depth was maximal for frequencies of approximately 1 Hz. Regan and Beverley (1973) measured the amplitude of disparity oscillation required to match the depth of a simultaneously presented static disparity. They found that, for frequencies up to 2 – 3 Hz, the depth produced by a given amplitude of sinusoidal oscillation of disparity was nearly equal to that produced by static disparity of the same amplitude. Above these frequencies, perceived depth fell steeply with increasing frequency. This suggests that attenuation of depth in stereopsis occurs at much lower frequencies than temporal limits for luminance flicker. However, Regan and Beverley's results predict that slant perception is relatively unaffected by temporal frequency over the low range used in our experiment. A possible explanation may be that a constant gradient of disparity is treated much like an absolute disparity (absolute disparity gradient) to which the visual system is comparatively insensitive (Gillam et al 1984; Mitchison and Westheimer 1984, 1990). In the two studies discussed above, targets were presented against a textured background (Regan and Beverley 1973) or in the presence of fixation targets (Richards 1972). Our results support the proposal that point disparity between two targets or a target and the background is well perceived, while a constant gradient of disparity is not. However, as we shall see, it is not clear to what extent the high-frequency roll-off can be attributed to cue conflict rather than intrinsic limits in stereoscopic processes.

According to our hypothesis, one would predict a larger fall-off with temporal frequency for vertical shear and size disparity than for horizontal shear and size disparity. We could find no evidence of a difference in sensitivity to temporal frequency in direct comparisons of the vertical and horizontal frequency responses. A potentially more sensitive method of comparing the sensitivity of horizontal and vertical disparity gradient mechanisms is to study the response to stimuli which contain combinations of the two components. Our hypothesis predicts that the response should become dominated more by the horizontal component as temporal frequency increases. The most straightforward test is the dilation or rotation case in which the horizontal and vertical components indicate opposite directions of slant or inclination. We predicted that perceived depth for rotation and dilation disparity would be in the direction of the horizontal disparity component and would increase with temporal frequency. Over the lowest part of the frequency range studied, the depth response to dilation or rotation disparity tended to increase with increased temporal frequency, typically peaking at mid-frequencies. However, perceived slant for modulations of dilation disparity was in the direction of the vertical rather than the horizontal component. This does not support the proposal that the horizontal size disparity mechanism has a higher temporal bandwidth than the vertical size disparity mechanism. Rather it suggests that the vertical size disparity mechanism has a higher temporal bandwidth. The small increase in response in the direction of the horizontal component for rotation disparity suggests that the vertical mechanism may be slower in the shear disparity case, although the effect is weak.

Considerable individual differences exist both in the qualitative and quantitative results. The variability in the data and the presence of subjects who consistently saw slant reversals suggest that conflicts between perspective and stereopsis may play a role. As Gillam (1967, 1993) has pointed out, a possible explanation for the slant-reversal effect is that it is an example of a size – distance paradox (or more descriptively a shape – slant paradox) resulting from size constancy effects (this point is expanded on in the next section).

The findings that at least one subject prone to reversals was able to resolve this conflict with extremely low temporal frequencies and that all subjects showed an appropriate stereoscopic response with 30 s static presentations suggest that the conflict has a motion or temporal component. A zero-disparity reference enhanced the perception of disparity gradients with more slant or inclination reported. Furthermore, a reference stimulus seemed to help disambiguate perspective – disparity conflict.

5 General discussion

The hypothesis put forward in the Introduction proposed that vertical disparity patterns are processed more slowly than horizontal disparity patterns. In studying the effects of both viewing time (experiment 1) and temporal frequency (experiment 2) we found no clear difference between the percepts evoked by horizontal and vertical disparity. However, perceived slant for modulations of dilation disparity was in the direction of the vertical component. This suggests that, contrary to the hypothesis, the vertical size disparity mechanism has a higher temporal bandwidth. Aniseikonia due to changing optical conditions in the eye tends to change slowly with ageing and growth. Thus, we predicted that vertical size disparity would be processed relatively slowly if used as an indicator of aniseikonia. However, a type of aniseikonia arises when viewing eccentrically located objects. The interpretation of optical slant from horizontal size disparity is ambiguous owing to this aniseikonia. To resolve this ambiguity, an estimate of headcentric eccentricity is required before the horizontal size disparity is interpreted. The pattern of vertical disparity is a potential cue for eccentricity (Mayhew and Longuet-Higgins 1982). When the subject or target is mobile, the headcentric eccentricity can change (van Ee and Erkelens 1996b). Thus, a mobile observer requires that vertical size disparity be processed in order to estimate the current headcentric direction of a target prior to the interpretation of slant from horizontal disparity. Therefore, if one assumes that vertical size disparity is used to estimate the eccentricity of a surface, it is not unreasonable that vertical size disparity be processed more rapidly than horizontal size disparity.

An alternative explanation for the response to dilation disparity may be that cue conflict is a significant factor that is more potent for horizontal size disparity than for vertical size disparity. If this is the case, the effects of cue conflict may have interfered with our ability to compare the dynamics of horizontal and vertical disparity processing. Gillam (1968), Gillam and Ryan (1992), and Ryan and Gillam (1994) studied disparity – perspective cue conflict in slant perception. They found that conflicting linear perspective produced strong depth attenuation when horizontal disparity specified surface slant. Little is known about the mechanisms of size constancy and cue conflict under the induced effects. It has been proposed that perspective cue conflict may play a role in limiting the linear range of the induced-size effect. Banks and Backus (1998) have recently looked at this issue experimentally. They found, when both perspective cue conflict was eliminated and when the eye position was consistent for the observed disparity (according to theories that attribute the induced effect to localising the stimulus eccentrically), that the induced-size effect no longer had a saturation at larger magnifications. This suggests that perspective cue conflict plays a role in limiting the range of the induced-size effect.

The fact that we used a large display may have contributed to strong perspective cue conflict. Blake et al (1993) have recently shown, using an ideal observer model, that texture cues to surface inclination (compression and density) become more reliable with larger stimuli. Buckley et al (1996) found that four of six observers experienced increased surface inclination as field of view increased from 10 to 30 deg when texture specified an inclined surface and disparity specified a frontal surface. When both texture and disparity specified an inclined surface, increase in stimulus size also resulted in an increase in perceived inclination. In the present study, we required large displays to achieve robust size and shear-induced effects (Kaneko and Howard 1996, 1997).

Subjects occasionally reported slant or inclination in the opposite direction to that predicted by disparity. Gillam (1967, 1993) has investigated this phenomenon most thoroughly. She has proposed two explanations. One is based upon size-constancy effects. Several subjects experienced the percept of slant in the reversed direction for brief presentations of horizontal and vertical shear and size disparity. This suggests that perspective – disparity conflict resolution has a temporal component. Normally if a textured disk is inclined or slanted in depth, there is a gradient of image size from near to far. In these experiments, objective average texture size, density, and overall pattern shape were constant over the pattern and the same for all disparities. Size constancy predicts that if the visual subtense of an object on a retina (or with respect to the cyclopean eye) is constant, apparent size will be scaled by apparent distance. If size-constancy mechanisms operate, texture elements and the pattern as a whole should appear smaller in the near part of the disk and larger in the far part. Thus, the apparent texture gradient and disparity give conflicting information about the direction, or sign, of slant or inclination. Some subjects see the surface according to disparity with the shape distorted. Others seem to use the apparent perspective and see the surface sloping in the opposite direction (Gillam 1967, 1993).

This size-constancy explanation is apparently paradoxical. The texture gradient is only a consequence of the stereoscopic relation between depth and disparity but the depth predicted by disparity is not perceived by the subject. That the disparity produced apparent size changes can be perceived in the absence of corresponding changes in perceived depth suggests that depth and size judgments are both driven by registered disparity but are not causally linked. Similar explanations have been proposed for the moon illusion (Kaufman and Rock 1962) and the paradoxical size – distance effects seen with convergence micropsia (Ono et al 1974). Erkelens and Regan (1986) have shown that subjects shown open loop absolute disparity changes over the whole field do not perceive changes in egocentric distance of the target surface. However, subjects do perceive the target becoming apparently smaller for increased crossed disparity and larger for uncrossed disparity. Regan et al (1986) have reported that these size changes do not tend to cause the surface to oscillate in depth in the opposite direction to that predicted by disparity. However, the conflict with apparent size changes may inhibit the percept of motion in depth caused by changing disparity. These size – distance paradox effects result from zero-order (constant) size – disparity conflicts. Our data and those of Gillam (1967) suggest that similar slant – shape paradox effects can occur for first-order (gradient) size – disparity conflicts.

Gillam proposed a second explanation of slant reversals based on the idea that the horizontal size disparity of eccentric displays is calibrated by perspective (Gillam 1993; see also Frisby et al 1995). This theory of slant reversal is quite appealing although it relies on the somewhat unconventional use of slant relative to the frontal plane rather than optical slant as the percept. However, whatever the merit of this theory for static slant reversals it cannot explain our dynamic results. We have noted reversal effects for both horizontally and vertically oriented gradients of horizontal disparity. The Gillam (1993) theory is incapable of explaining reversed depth for inclination. Gillam found that in static conditions reversals were more common for slant than inclination which led her to reject the slant – shape paradox explanation for the static case (Gillam 1993). However, our results show that reversals can occur for inclination as well, especially under dynamic conditions. While this theory may help to explain the anisotropy found in the incidence of slant reversals under static conditions, an analogous argument cannot account for inclination reversals under dynamic conditions.

Cue conflict may also be significant in interpreting some of our other findings. We found that amplitudes of temporally oscillating inclination and slant are underestimated at the frequencies used and for short presentations. Perceived slant and inclination declined with increased temporal frequency for horizontal, vertical, and deformation disparities in the majority of our subjects. However, considerable individual differences existed. The most striking of these differences is the tendency for some subjects to report slant and inclination in the opposite direction to that predicted by disparity. Recent work in our laboratories suggests that much of the variability and apparently paradoxical results in the present experiments may be explained by cue conflict. Our stimulus had only weak static perspective cues from texture gradients in the irregular texture. However, we have found that perspective cue conflict is enhanced with moving stimuli and short durations. In the present experiments, apparent texture gradient induced by disparity indicated slant or inclination opposite that arising from the direct effect of the size or shear disparity. Thus, at higher frequencies and for brief exposures, the indirect effect of the apparent texture gradient (or even of the zero texture gradient in the absence of size constancy) may cancel the direct effect of disparity. This may account for the weak percepts of depth from disparity at high frequencies.

This cue conflict may also account for the fact that Gillam's (1968) subjects had great difficulty in nulling the slant introduced by aniseikonic lenses by adjusting the actual physical slant of the stimulus. The results were unreliable because of "the odd appearance of the moving contours viewed through the lens". This forced her to choose an alternative matching measure. The lenses introduced apparent size distortion appropriate for the disparity (Gillam 1967) that caused the apparent perspective changes to conflict with the disparity. If kinetic perspective dominates kinetic disparity, as we have found, it is little wonder that Gillam's subjects had difficulty performing the nulling task. When the stimulus moves, the velocity gradients of changing perspective provide sufficient information to allow for determination of the surface slant given the assumption of rigidity (Braunstein 1968). Thus we expect that the conflicting perspective has the strongest modulating effect on perceived depth at higher temporal frequencies or for shorter presentations. The dependence of stereoscopic slant and inclination perception on temporal frequency and viewing time found in this study may reflect this temporal sensitivity to perspective at least in part. We are currently investigating to what extent the temporal sensitivity of slant perception can be attributed to cue conflict.

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References

Anstis S M, Howard I P, Rogers B, 1978 "A Craik–Cornsweet illusion for visual depth" *Vision Research* **18** 213–217

Banks M, Backus B, 1998 "Extra-retinal and perspective cues cause the small range of the induced effect" *Vision Research* **38** 187–194

Blake A, Bülthoff H, Sheinberg D, 1993 "Shape from texture: ideal observers and human psychophysics" *Vision Research* **33** 1723–1737

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

Brookes A, Stevens K A, 1989 "The analogy between stereo depth and brightness" *Perception* **18** 601–614

Buckley D, Frisby J P, Blake A, 1996 "Does the human visual system implement an ideal observer theory of slant from texture" *Vision Research* **36** 1163–1176

Ee R van, Erkelens C J, 1995 "Binocular perception of slant about oblique axes relative to a visual frame of reference" *Perception* **24** 299–314

Ee R van, Erkelens C J, 1996a "Temporal aspects of binocular slant perception" *Vision Research* **36** 45–51

Ee R van, Erkelens C J, 1996b "Stability of binocular depth perception with moving head and eyes" *Vision Research* **36** 3827–3842

Erkelens C J, Regan D, 1986 "Human ocular vergence movements induced by changing size and disparity" *Journal of Physiology* **379** 145–169

Frisby J P, Buckley D, Wishart K A, Porril J, Gårding J, Mayhew J E W, 1995 "Interaction of stereo and texture cues in the perception of three-dimensional steps" *Vision Research* **35** 1463–1472

Gibson J, 1950 "The perception of visual surfaces" *American Journal of Psychology* **63** 367–384

Gillam B, 1967 "Changes in the direction of induced aniseikonic slant as a function of distance" *Vision Research* **7** 777–783

Gillam B, 1968 "Perception of slant when perspective and stereopsis conflict: experiments with aniseikonic lenses" *Journal of Experimental Psychology* **78** 299–305

Gillam B, 1993 "Stereoscopic slant reversals: a new kind of 'induced' effect" *Perception* **22** 1025–1036

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

Gillam B, Flagg T, Finlay D, 1984 "Evidence for disparity change as the primary stimulus for stereoscopic processing" *Perception & Psychophysics* **36** 559–564

Gillam B, Rogers B, 1991 "Orientation disparity, deformation, and stereoscopic slant perception" *Perception* **20** 441–448

Gillam B, Ryan C, 1992 "Perspective, orientation disparity, and anisotropy in stereoscopic slant perception" *Perception* **21** 427–439

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, Zacher J E, 1991 "Human cyclovergence as a function of stimulus frequency and amplitude" *Experimental Brain Research* **85** 445–450

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

Kaufman L, Rock I, 1962 "The moon illusion" *Science* **136** 953–961

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

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

Mitchison G J, Westheimer G, 1984 "The perception of depth in simple figures" *Vision Research* **24** 1063–1073

Mitchison G J, Westheimer G, 1990 "Viewing geometry and gradients of horizontal disparity", in *Vision: Coding and Efficiency* Ed. C Blakemore (Cambridge: Cambridge University Press) pp 302–309

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" *AMA Archives of Ophthalmology* **20** 604 – 623

Ogle K N, 1964 *Researches in Binocular Vision* (New York: Hafner)

Ono H, Muter P, Mitson L, 1974 "Size – distance paradox with accommodative convergence" *Perception & Psychophysics* **15** 301 – 307

Regan D, Beverley K I, 1973 "Some dynamic features of depth perception" *Vision Research* **13** 2369 – 2379

Regan D, Erkelens C J, Collewijn H, 1986 "Necessary conditions for the perception of motion in depth" *Investigative Ophthalmology & Visual Science* **27** 584 – 597

Richards W, 1972 "Response functions for sine- and square-wave modulations of disparity" *Journal of the Optical Society of America* **62** 907 – 911

Rijn L J van, Steen J van der, Collewijn H, 1994 "Eye torsion elicited by oscillating gratings: effects of orientation, wavelength and stationary contours" *Vision Research* **34** 533 – 540

Rogers B J, 1992 "The perception and representation of depth and slant in stereoscopic surfaces", in *Artificial and Biological Vision Systems* Eds G A Orban, H Nagel (Berlin: Springer) pp 241 – 266

Ryan C, Gillam B, 1994 "Cue conflict and stereoscopic surface slant about horizontal and vertical axes" *Perception* **23** 645 – 658

Stenton S P, Frisby J P, Mayhew J E W, 1984 "Vertical disparity pooling and the induced effect" *Nature (London)* **309** 622 – 624

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

Stevens K A, Brookes A, 1988 "Integrating stereopsis with monocular interpretations of planar surfaces" *Vision Research* **28** 371 – 386

Stevens K A, Lees M, Brookes A, 1991 "Combining binocular and monocular curvature features" *Perception* **20** 425 – 440

Young M J, Landy M S, Maloney L T, 1993 "A perturbation analysis of depth perception from combinations of texture and motion cues" *Vision Research* **33** 2685 – 2696