PERGAMON

Vision Research 40 (2000) 1869–1886

Vision Research

www.elsevier.com/locate/visres

Temporal dependencies in resolving monocular and binocular cue conflict in slant perception

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Received 6 April 1999; received in revised form 8 November 1999

Abstract

Observers viewed large dichoptic patterns undergoing smooth temporal modulations or step changes in simulated slant or inclination under various conditions of disparity–perspective cue conflict and concordance. After presentation of each test surface, subjects adjusted a comparison surface to match the perceived slant or inclination of the test surface. Addition of conflicting perspective to disparity affected slant and inclination perception more for brief than for long presentations. Perspective had more influence for smooth temporal changes than for step changes in slant or inclination and for surfaces presented in isolation rather than with a zero disparity frame. These results indicate that conflicting perspective information plays a dominant role in determining the temporal properties of perceived slant and inclination.

Keywords: Stereopsis; Perspective; Cue interaction; Temporal; Slant; Inclination

1. Introduction

The spatial layout of objects and surfaces in a scene can be derived from a variety of monocular and binocular cues (Sedgewick, 1986; Howard & Rogers, 1995). For instance, the relative depths can be obtained from the pattern of binocular disparities or from the monocularly visible perspective structure. One of the most elementary characteristics of a surface or surface element is its orientation in depth, or slant. Surface rotation in depth out of the frontal plane about a vertical axis is referred to as slant (a right-wall or left-wall plane); rotation out of the frontal plane about a horizontal axis is called inclination (a sky or ground plane).[1] Any rotation of a surface element in depth can be thought of as a combination of a slant and an inclination.

Perception of surface slant and inclination can be derived from disparity, perspective and other depth cues. Gradients of horizontal disparity produce the impression of surface slant or inclination. For a patterned stimulus, monocular linear perspective and foreshortening could be used to compute surface slant if the shape of the patterned stimulus is known or assumed. Similarly, given assumptions of homogeneity and isotropy, the slant of textured surfaces could be computed from gradients of scaling, compression or density (Gibson, 1950; Cutting & Millard, 1984). Several studies have investigated how perspective and stereopsis interact in the perception of surface slant (Gillam, 1968; Youngs, 1976; Stevens & Brookes, 1988; Ryan & Gillam, 1994; Banks and Backus, 1998) and in the perception of curvature and discontinuities (Brookes & Stevens, 1989; Stevens, Lees & Brookes, 1991; Buckley & Frisby, 1993; Johnston, Cumming & Parker, 1993; Frisby, Buckley, Wishart, Porril, Gårding & Mayhew, 1995).

An interesting characteristic of stereoscopic processing is the slow build-up of perceived depth for horizontal shear (inclination) and size (slant) disparity imposed on isolated stimuli. Gillam, Flagg and Finlay (1984) reported that the 50% rise times of the slant percept

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[1] In an alternative scheme, the slant angle is the angle between the line of sight and the surface normal, and the angle of tilt is the orientation of the axis of this slant rotation in the frontal plane (Stevens, 1983). Thus, slant and inclination would be referred to as slant with tilt angles of 0 and 90°, respectively.

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PII: S0042-6989(00)00034-1

(latency to reach 50% of the final steady state value) produced by a 5% horizontal size disparity were 15 and 25 s for their two observers. This result suggests a relatively slow development of the slant percept. Van Ee and Erkelens (1996a, 1998) and Allison, Howard, Rogers and Bridge (1998) have also reported a long build-up time in measurements of the time course of slant and inclination perception with the percepts eventually developing over a period of up to 30 s. Allison et al. (1998) reported that slant or inclination oscillations were poorly perceived for temporal oscillations of size and shear disparities in an isolated stimulus, particularly as temporal frequency increased. These temporal frequency limitations occurred at much lower temporal frequencies than expected based on experiments using point stimuli (Regan & Beverley, 1973).

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, Chambers & Russo, 1988; Brookes & Stevens, 1989; Van Ee & Erkelens, 1996a). In contrast, discontinuities in disparity were well perceived. The visual system appears to be especially sensitive to spatial changes in relative horizontal disparity and relatively insensitive to absolute disparities or constant gradients of absolute disparity (Anstis, Howard & Rogers, 1978). In all these experiments, the disparity cue 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 than initially. The long latencies for stereoscopic slant perception may be a manifestation of the temporal characteristics of the resolution of perspective–disparity cue conflict.

The way that people resolve cue conflict may be related to the considerable qualitative and quantitative individual differences that have been noted in studies of stereoscopic slant perception. One of the most striking of these differences is the so-called slant-reversal phenomenon in which subjects perceive slant opposite to that specified by disparity (Gillam, 1967). The slant-reversal effect has been found to be more common for brief rather than long exposures and for dynamic rather than static stimuli (Allison et al., 1998). This demonstration of a temporal factor in slant reversal confirmed Gillam's (1967) anecdotal finding. Gillam (1967) has also reported that slant reversals are more common when the stimulus contains strong perspective information. As she has pointed out, a possible explanation for the slant-reversal phenomenon is that it is an instance of a size–distance paradox (or perhaps more descriptively a slant–shape paradox) due to size constancy effects (Gillam 1967, 1993). As one would expect, in the experiments of Allison et al. (1998), subjects typically perceived apparent perspective in the shape and texture of the stereoscopic surface. This apparent perspective is opposite to the perspective observed in a real, homogeneously textured, slanted surface and thus indicates a slant opposite to that indicated by disparity. This could explain slant reversal. This explanation appears paradoxical — the apparent perspective arises only from the size constancy associated with stereoscopic depth. One way out of the paradox is to suppose that stereoscopic slant perception and size constancy are both driven by disparity but are not causally linked (Gillam, 1967; Oyama, 1974). The temporal characteristics of the slant-reversal effect may reflect the temporal characteristics of stereo–perspective cue interaction.

In this study we investigate possible temporal dependencies in the resolution of disparity–perspective conflict. Kinetic and static disparity and perspective cues to slant and inclination were placed in various combinations of consonance and conflict and perceived slant or inclination was measured under a variety of stimulus conditions.

2. General methods

Computer generated images were presented dichoptically in a large Wheatstone stereoscope. Translucent Mylar screens were mounted to the left and right of the subject on the sides of a cubical frame and viewed through mirrors mounted at 90° from a distance of 93 cm. Images were rear projected onto these screens using two Electrohome EDP-58 monochrome projection monitors. The screens subtended 65° height × 75° width at each eye. Stereoscopic stimuli were presented in a dark room and all surfaces were covered with matte black cloth or paint. In order to maintain a clean stimulus, care was taken to mask the monocular half images from being directly viewed, so that only the fused stimulus was visible through the mirrors.

Alignment and geometry correction of the half images was achieved by superimposing a projected grid pattern upon a real grid pattern that could be mounted on the side screens and adjusting the image. Alignment was also verified against a physical grid pattern display located directly in front of the subject at 93 cm and viewed through the semi-silvered mirrors. The mirrors and projected images were aligned with spirit levels and plumb lines. That the half images were coplanar with, and at the same distance as, the alignment surface was verified by the absence of parallax between the comparison surface and either the half images or the fused dichoptic image.

Observers viewed an isolated dichoptic pattern undergoing changes in simulated slant and inclination. Horizontal size and shear disparity were used to induce stereoscopic slant and inclination, respectively. Monocular slant/inclination was portrayed by perspective transformations. The image pairs were pre-computed and the base image transformed to produce various combinations of perspective and disparity cues to surface slant or inclination. The display was composed of 640×480 pixels (width $\times$ height) refreshed at 67 Hz. Sub-pixel interpolation was employed to reduce the aliasing effects of a finite pixel count. The percept was of a flat textured plane slanted in depth about a vertical axis or horizontal axis. In the experiments, the images were either presented statically for various durations, or a sequence of frames (frame rate 33.5 Hz) was displayed which produced a modulation of portrayed slant and inclination.

The perspective projections were computed for the viewing distance and were constructed as projections through the cyclopean eye (midway between the eyes) of a slanted or inclined plane onto the screen. This projection was used to calculate the perspective projection of the simulated surface onto the screens of the stereoscope. Since the projection was made through the cyclopean eye the perspective projections in the displays for both eyes (the distal stimuli) were identical and corresponded to an average of the perspective transformation that would occur in each eye's image for a real slanted surface. Note that proximal stimuli were not identical in the two eyes, even without added disparity, since the images contained the disparities appropriate for a frontal surface at the viewing distance (Rogers & Bradshaw, 1993).

To present a stereoscopic surface slanted or inclined in depth, half images with horizontal disparities were generated and presented in the stereoscope (Howard & Kaneko, 1994; Kaneko & Howard, 1996). A horizontal size disparity produces the impression of surface slant. A horizontal shear disparity produces the impression of surface inclination. These effects are predicted from the geometry of binocular vision and thus after Ogle (1938) we call them geometric effects.

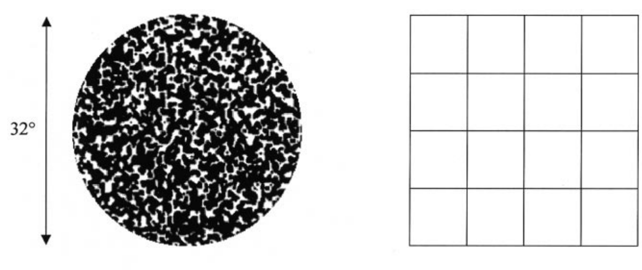

Fig. 1. (a) Scaled version of the irregularly textured display used for these experiments. (b) Grid pattern used in experiment 1. Actual images were white on black rather than black on white and subtended 32°.

Perspective and disparity were combined in four ways:

1. Disparity appropriate for the slant in depth and perspective appropriate for a frontal surface (disparity-alone transformation),
2. Perspective appropriate for the slant and disparity appropriate for a frontal surface (perspective-alone transformation),
3. Disparity and perspective concordant and appropriate for the slant (concordant transformation), and
4. Disparity and perspective in conflict, specifying the same magnitude of slant but in opposite directions (opposite transformation).

Note that under all conditions, except the concordant cues transformation, perspective and disparity were in conflict. Perspective and disparity are in strongest conflict for the opposite condition because they differ in sign as well as magnitude.

Subjects matched the perceived slant or inclination of the test surface with that of a subsequently presented real surface. This real surface was textured with the same pattern as that of the test surface in Fig. 1a and subtended 32°. It was located directly in front of the subject at a distance of 93 cm and was visible through the semi-silvered mirrors when illuminated. The comparison surface contained a variety of depth cues to its true orientation (e.g. absolute and relative disparity, texture gradient, blur and accommodation). The surface was supported on a visible gimbal mounting and could be rotated about either a horizontal or a vertical axis by the subject, using a long steel rod. The rod was attached to the corner of the comparison surface and pushing or pulling on it caused the surface to rotate about the axis of rotation. Following 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 surface were read into a computer.

3. Experiment 1: disparity–perspective conflict

The purpose of this experiment was to investigate temporal dependencies in the resolution of disparity–perspective cue conflict. Our earlier study (Allison et al., 1998) and work of others (Ryan & Gillam, 1994; Backus & Banks, 1999) suggested that conflicts between perspective and stereopsis play an important role in the occurrence of slant and inclination reversal and in the inter-subject variability in slant estimation. Furthermore, these conflicts seemed enhanced for kinetic stimuli that underwent changes in slant. We studied slant and inclination perception with various combinations

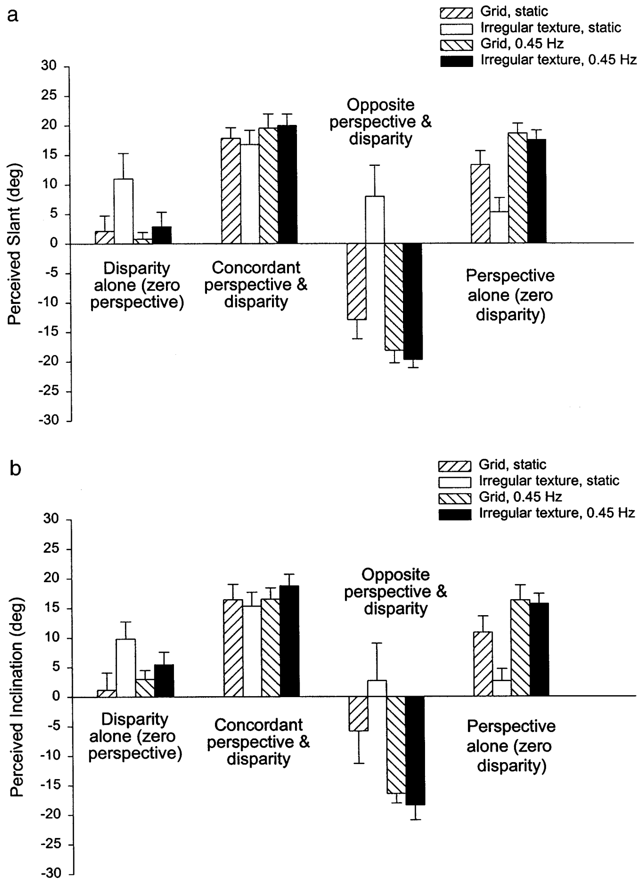

Fig. 2. Perspective and stereo interactions in (a) slant and (b) inclination perception (experiment 1). The chart shows mean slant or inclination estimates for the irregularly textured stimulus or a regular grid stimulus. Perspective was concordant with, or opposite disparity, or specified no slant when disparity specified a slanted surface, or specified slant when disparity was zero. Positive slant indicates perceived slant or inclination in the direction specified by the perspective and/or disparity cues. For the opposite situation positive values of slant or inclination indicate perceived depth in the direction specified by disparity (and opposite to perspective). Error bars indicate 95% confidence intervals.

of disparity and perspective information under static and kinetic conditions.

3.1. Method

Two stimulus patterns were used: an irregularly textured pattern (first used by B. Rogers) and a rectangular grid pattern (Fig. 1). Both patterns subtended 32° of visual angle. These stimuli were chosen to provide different levels of disparity–perspective conflict. The grid was composed of regularly spaced lines and provided strong linear perspective, aspect ratio and foreshortening cues to surface slant. In contrast, the irregular texture provided mainly weak texture gradient information (due to the irregularity) and some overall outline aspect ratio cues. This texture consisted of coarse, blob-like, white features on a black background (approximately 40% density; average blob width of roughly 0.8°).

These stimuli were transformed to present various combinations of perspective and disparity cues to slant or inclination (see Section 2). For these measurements, the patterns were presented initially as static frontal surfaces. Disparity and/or perspective were then introduced after a subject-controlled interval. The stimulus profile was either a given disparity-perspective combination presented statically for 30 s (a step change in portrayed slant) or for five cycles of sinusoidal oscillation at 0.45 Hz (kinetic stimuli). For sinusoidal stimulation, the peak disparity and/or perspective corresponded to a predicted peak slant or inclination of 20°. Disparity or perspective for static presentations, also, corresponded to theoretical slant or inclination of 20°.

For the kinetic stimuli, subjects reported when the surface appeared to be a sky or ground plane (or a right wall/left wall plane) and the timing of these reports was related to the sign of stimulus disparity or perspective. Following the presentation of each test stimulus, subjects matched the slant or inclination of the visible comparison display (not seen during the test display) to the furthest and nearest extent of the depth oscillation of the test surface. For static presentations, subjects matched the final slant or inclination of the test surface following each stimulus presentation. We also asked subjects to report if the percept changed in any way over the 30-s observation time. Eight subjects with normal acuity and binocular vision participated fully in this study. For these subjects, each stimulus condition was presented in random order over two sessions. Two additional subjects participated in the trials with the irregularly textured displays. For fair comparison between the grid and the irregularly textured display, the results of the latter subjects were not included in comparisons of means for various conditions or in the averaged data in Fig. 2.

3.2. Results

3.2.1. Static presentation

For both slant and inclination there were differences between the responses for the irregularly textured and grid patterns. For static presentations, repeated measures analysis of variance indicated a significant ($P < 0.01$) effect of type of disparity–perspective transformation and a significant interaction between transformation condition and pattern type for both slant and inclination. Magnitude estimates were averaged across the two directions of slant and inclination for each of the subjects.

3.2.1.1. Concordant displays. Mean perceived slant and inclination were stable and largest when disparity and perspective were concordant (see Fig. 2). Average slant estimates were $17.8 \pm 2.1°$ (mean values shown here with $\pm 95\%$ confidence intervals) and $16.8 \pm 3.0°$ for the grid and textured pattern, respectively. Average inclination estimates were $16.4 \pm 2.9°$ for the grid pattern and $15.3 \pm 2.9°$ for the textured pattern. Both perceived slant and inclination were close to but significantly less than the veridical value of 20°.[2]

3.2.1.2. Disparity-alone displays. Under the disparity-alone transformation of the irregular pattern, a few subjects (two for inclination and three for slant) reported that the depth built up over the 30-s observation period. The others subjects did not remark on any changes over time. One subject, EK, gave slant (and inclination on one trial) responses in the opposite direction to that expected from disparity — a slant/inclination reversal. Subjects on average reported about 10° of slant or inclination from horizontal size and shear disparity in the irregular pattern, which is half the theoretical value. With the grid pattern, little depth was seen when horizontal disparity alone specified slant or inclination (Fig. 2). Two subjects who viewed this stimulus saw small slants and inclinations in the reversed direction to that expected from the disparity (including subject EK). Fig. 2 shows that, on average, perceived slant and inclination were significantly smaller for the static disparity-alone transformation in the grid pattern than in the irregular texture.

3.2.1.3. Perspective-alone displays. When the depth of the irregularly textured surface was specified only by perspective, subjects reported that the depth was transient and faded away over the 30-s observation period. This was the case for ten of ten and eight of ten subjects for inclination and slant, respectively. Subjects reported small inclinations with most inclination matches less than 2°. The exception was subject EK, who was prone to slant/inclination reversal in the disparity-alone condition, and who reported inclination from perspective-alone with the irregular texture averaging 11.3°. For slant, the subjects showed more variation, with a range of zero to 12.8° and with only two subjects reporting no slant. EK, who was prone to slant reversals, perceived the largest slants on average (12.8°).

For the grid pattern, the effects of perspective appeared stronger and more consistent. All eight subjects saw slant or inclination in the direction specified by perspective with a range of 7.9–19.9° for slant and 3.4–19.4° for inclination. The percept appeared much more stable than for the irregularly textured surface. Inclination appeared to fade for only two subjects and slant faded for only one subject. Fig. 2 shows that, on average, static perspective of the grid pattern produced significantly greater slant and inclination than did static perspective of the irregular texture. The two subjects prone to inclination reversal with the grid stimulus in the disparity-alone condition perceived the largest inclinations in the grid pattern under the perspective-alone condition. However the subject prone to slant reversal with the grid pattern had a response to slant from perspective-alone that was only slightly larger than the group mean.

3.2.1.4. Opposite displays. When the perspective and disparity cues specified opposite depth, subjects showed increased inter-subject variability, particularly for inclination. For slant, nine of the ten subjects reported that the irregularly textured pattern initially looked slanted in the direction indicated by perspective but that the percept gradually switched over to slant in the direction indicated by disparity. EK, who was prone to depth reversals, continued to see the surface slanted in the direction of the perspective component but noted that the slant faded somewhat. For the grid pattern, however, the results were different. All subjects except one (who perceived no depth in this stimulus) had a stable percept of slant in the direction specified by the perspective cue.

The results for inclination with opposing cues were similar. Six of the ten subjects reported a reversal of inclination from the direction specified by perspective to that specified by disparity as time progressed when viewing the irregularly textured pattern. One subject reported that the depth was initially in the direction of the perspective component and faded over time. The effect of the perspective cue in the irregularly textured display appeared stronger for slant than inclination since three of the subjects saw the depth in the direction of the disparity component immediately for inclination whereas none did for slant. For the grid pattern, results were quite varied, with one subject not seeing any inclination, five (including the two subjects prone to depth reversals) seeing it according to perspective and two seeing it according to disparity.

3.2.2. Oscillating presentation

When the stimulus was a 0.45 Hz sinusoidal oscillation of disparity and/or perspective, the results were similar for both the grid and textured surfaces. For the oscillating presentation of slant and inclination, repeated measures analysis of variance indicated a significant ($P < 0.01$) main effect of only type of disparity–perspective transformation and non-significant effects of pattern type. The interaction between

[2] It is important to note that under concordant conditions in this and the following experiments only disparity and perspective indicated slant. Other residual cues such as accommodation and blur indicated a flat frontal surface. This residual cue conflict may be a factor in the underestimation of slant and inclination under concordant conditions.

transformation condition and pattern type was not significant. Since there was no evidence of directional bias, the magnitude estimates for each subject correspond to the average of the slant or inclination over both directions.

When disparity and perspective specified the same slant or inclination, all subjects perceived slant or inclination that was nearly veridical on average (Fig. 2). Thus, when kinetic disparity and perspective agreed a strong percept of changing depth was attained. When the two cues were in conflict, kinetic perspective cues dominated perceived depth for all subjects. When equal and opposite slant oscillations were specified by disparity and perspective, the subjects saw slant in the direction of the perspective cue, which was on average close to the theoretical value of slant from the perspective transformation. For the perspective-alone transformation, subjects again perceived nearly veridical slant or inclination in phase with the perspective oscillation. The average slant and inclination perceived in the oscillating perspective-alone condition was significantly higher ($P<0.05$) than that in the static perspective-alone condition.

For an oscillating stimulus, all subjects perceived less slant or inclination under the disparity-alone transformation than under the perspective-alone transformation. In the disparity-alone condition, three subjects perceived slant and inclination of the opposite sign to that specified by disparity. The other subjects perceived slant according to the disparity. One of the latter group of subjects saw slant in the direction of the disparity for the irregularly textured pattern but in the opposite direction for the grid pattern.

3.3. Discussion of experiment 1

In all subjects, kinetic perspective cues dominated perceived depth. This was true whether disparity was opposite to perspective, or held constant at zero slant. In all cases, perceived depth was affected little by disparity when perspective was changing. Kinetic disparity did induce oscillation in depth of the irregular pattern with perspective held constant (disparity-alone condition). However, not all subjects perceived depth according to disparity under this condition. This suggests that conflict with unchanging perspective plays a role even here.

The manner in which perspective–disparity conflict was resolved under static conditions was affected by the type of pattern, axis of rotation and individual differences. Subjects saw weak, transient slant and inclination under the perspective-alone transformation when the irregularly textured stimulus was used. When strong perspective information was present (grid pattern) the percept of depth in the direction of the perspective component was stronger. Perspective appears to be given higher weighting for slant than for inclination, as indicated by the persistent slant in the direction of perspective with the grid pattern under opposite conditions.

4. Experiment 2: time course

In experiment 1, observers reported that slant or inclination appeared to fade over time for static slant or inclination portrayed by perspective alone. Slant or inclination produced by disparity alone appeared to build over time. When disparity and perspective indicated conflicting (opposite) slants or inclinations, slant or inclination appeared to switch gradually from the direction indicated by perspective to that indicated by disparity. In this experiment we investigated the effects of exposure duration on the slant and inclination percepts produced under various levels of perspective–disparity cue conflict.

4.1. Methods

The irregular stimulus pattern used in experiment 1 was used as a base image for this experiment (Fig. 1a). This base pattern was transformed to present various combinations of perspective and disparity cues to slant or inclination (see Section 2). The patterns were presented initially as static frontal surfaces until the subject indicated they were ready. A step change in slant or inclination indicated by disparity and/or perspective was then introduced and maintained for 0.1, 1.0, 10 or 30 s, after which the display was extinguished and the comparison surface was illuminated. Disparity or perspective corresponded to theoretical slants or inclinations of 0, ± 20 or $\pm 40°$. After each trial, subjects set the comparison surface to equal the apparent slant or inclination of the test surface observed at the end of the exposure. This procedure was designed to take samples of perceived slant or inclination at various time intervals. Five subjects with normal binocular vision were studied; four were naive with respect to the purposes of the study. Each experimental condition was repeated three times over the course of six experimental sessions.

4.2. Results and discussion

Repeated measures analysis of variance indicated a significant ($P<0.01$) effect on inclination estimates of inclination magnitude and a significant interaction between type of disparity–perspective transformation and exposure duration. These effects were also significant for slant estimates but there was also a significant interaction between slant magnitude, type of disparity–

perspective transformation and exposure duration (some of the lower order effects marginal to this interaction were also significant). To describe these interactions required us to look at the effects of exposure duration separately for each disparity–perspective transformation. We also considered whether this transform by duration interaction differed as portrayed slant was increased from 20 to 40°. There were no significant order effects or effects of direction (sign) of slant or inclination. As a result, magnitude estimates were averaged across the two directions of slant and inclination and across repeats for each of the subjects. Figs. 3 and 4 show the averaged slant and inclination estimates for the $\pm 20°$ conditions for each disparity–perspective transformation as a function of exposure duration.

The temporal dependence of the slant and inclination estimates on exposure duration can be described as follows:

1. Perceived slant and inclination were stable and largest when disparity and perspective were *concordant*. Individual subjects showed modest increases or decreases with exposure duration that tended to cancel out when averaged. Average slant and inclination estimates were 75–80% of the theoretical values and relatively constant as exposure duration was varied.

2. In contrast, under the *disparity-alone* transformation, depth gradually increased in the expected direction with exposure duration up to the maximum 30-s exposure studied. Initial slant and inclination were near zero or in the direction opposite that predicted by the disparity (a slant reversal, which was most common for the 20° slant condition) for the briefest 100 ms stimuli. As exposure time increased, slant and inclination estimates approached but generally fell short of those produced by the concordant transformation.

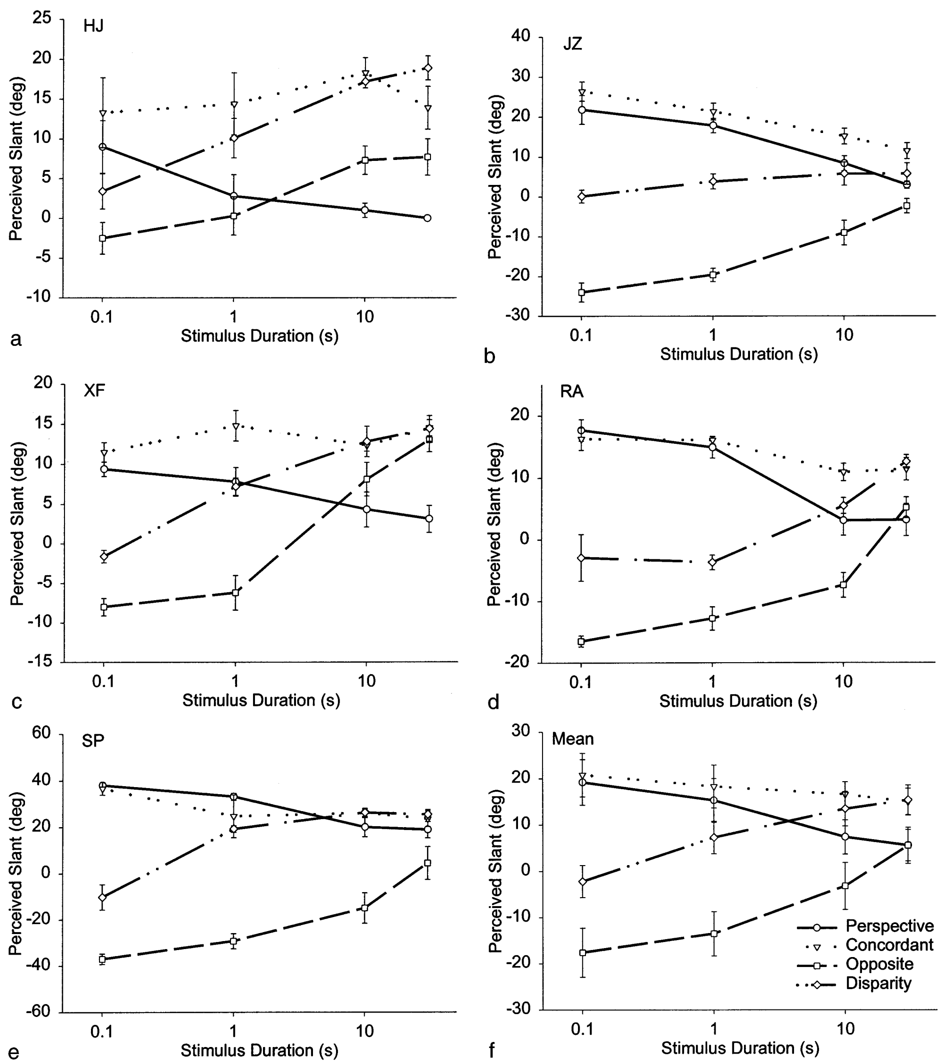

Fig. 3. Effect of exposure duration on slant estimates for five subjects (a–e) and averaged across subjects (f) from experiment 2. Surface slant of 20° was specified by perspective alone, disparity alone, concordant disparity and perspective, or opposing disparity and perspective (see text). Conventions for positive slant are the same as in Fig. 2. Error bars indicate standard error of the mean.

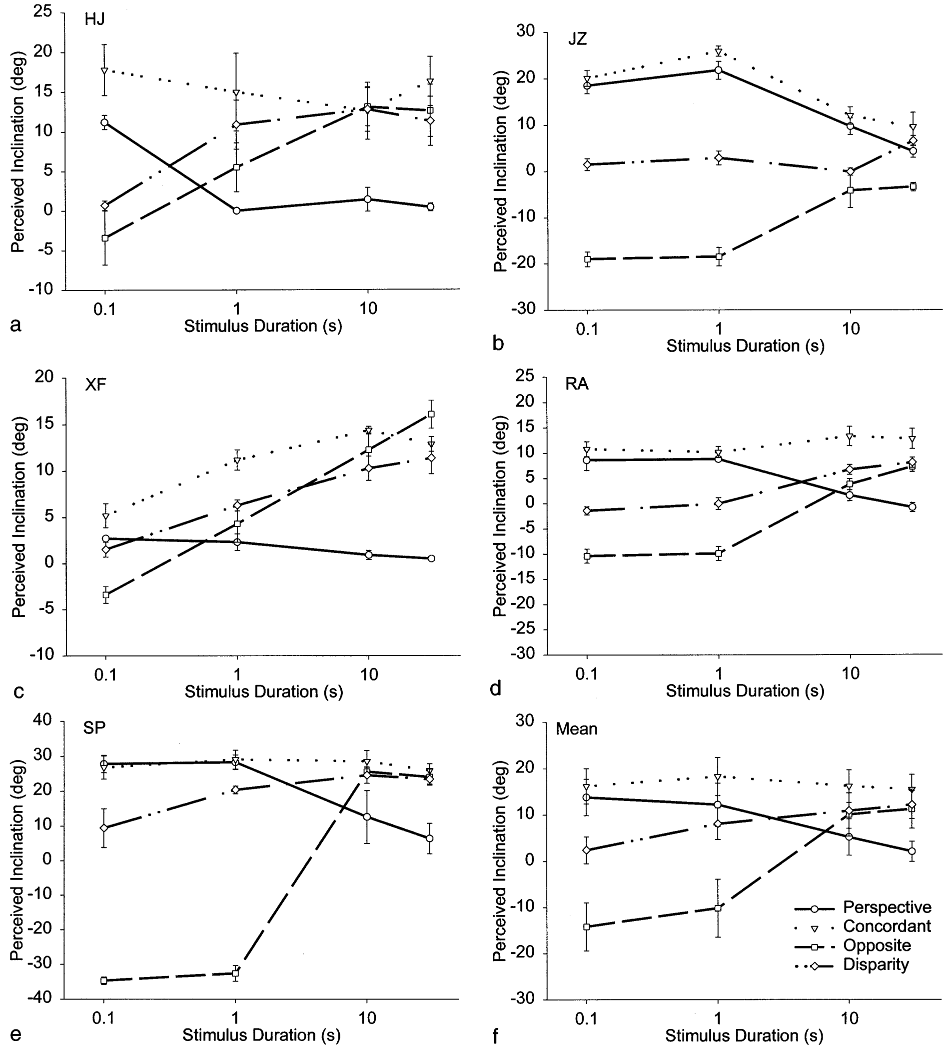

Fig. 4. Effect of exposure duration on inclination estimates for five subjects (a–e) and averaged across subjects (f) from experiment 2. Surface inclination of 20° was specified by perspective alone, disparity alone, concordant disparity and perspective, or opposing disparity and perspective (see text). Conventions for positive inclination are the same is as in Fig. 2. Error bars indicate standard error of the mean.

3. The pattern of results under the *perspective-alone* transformation depended on the magnitude of portrayed slant or inclination. Consider the ±20° conditions first. When the irregularly textured surface had perspective-alone, matched slant and inclination declined with increasing exposure duration. For the briefest presentations slant or inclination was nearly as large under the perspective-alone transformation as under the concordant transformation. After 30 s, however, slant or inclination was always smaller than at brief presentations and less than slant arising from the concordant or disparity-alone transformations. At the larger ±40° inclinations, the reports of three of the five subjects indicated that perceived inclination due to the perspective-alone transformation declined with exposure time. The other two subjects perceived near zero inclination under the perspective-alone transformation for all exposure durations. For the ±40° slant, three of the five subjects perceived slant declining with exposure duration although one subject showed a decline only between 10 and 30 s. Of the remaining two subjects, one reported near zero slant at all exposure durations and the other reported slant of approximately 50% of the theoretical slant from perspective at all exposure durations.

4. When perspective and disparity specified *opposite* depth, subjects showed increased inter-subject variation, particularly for large inclination angles. For the smaller (±20°) slants or inclinations, perceived slant or inclination was in the direction of the perspective for short durations. At the longest exposure times (30 s) under the opposite transformation, perceived inclination was generally in the direction of disparity and perceived slants were either in the direction of the disparity cue or in the direction of perspective but to a lesser extent than at brief durations. Between the short-

est and longest exposures, slant and inclination estimates gradually changed from the direction indicated by perspective towards that indicated by disparity. This pattern was also generally true for the larger ($\pm 40°$) slants, with the percept gradually changing from the direction indicated by disparity to that indicated by perspective. However, for the larger ($\pm 40°$) inclinations the results of only two of the subjects exhibited this pattern. Two of the other subjects showed a strong, relatively stable percept of inclination in the direction indicated by disparity (one of these subjects saw no inclination at the briefest exposure and inclination in the direction of disparity at other exposures). The remaining subject reported surface inclination in the direction indicated by perspective at all exposures. This subject also reported little inclination from the disparity-alone transformation at all exposure times for the larger test inclination.

The results indicate that, for isolated stimuli that undergo step changes in slant or inclination, perspective is weighted more heavily than disparity initially. As exposure time increases disparity is given increasing weight. When perspective and disparity are concordant a strong, rapid and stable percept of slant and inclination is produced. Under conditions of cue conflict, with patterns containing weak perspective information, changing perspective is initially relied upon but disparity eventually determines the percept. Van Ee and Erkelens (1996a, 1998) and Allison et al. (1999) found that slant and inclination percepts build slowly for large textured surfaces when depth is specified by disparity alone. The present results suggest that this was due to perspective cue conflict, which has a strong modulating effect initially but lessens as exposure time increases.

5. Experiment 3: relative disparity gradients

Gillam et al. (1988) and Van Ee and Erkelens (1996a) have shown that post-fusional latency for perceiving surface slant and inclination decreases in the presence of a visual reference. Thus changes in disparity gradients appear to be much more salient than disparity gradients themselves. We considered how cue conflict in slant and inclination perception is resolved in the presence of a visual reference.

5.1. Methods

The methods used in this experiment were similar to those used in experiment 2. The irregularly textured central test image (Fig. 1a) was presented after applying either the opposite or concordant transformations, which specified slants or inclinations of either 0, ± 20 or $\pm 40°$. As in experiment 2, disparity and/or perspective was introduced into the initially static frontal surfaces as a step change. The stimulus was surrounded by a zero-disparity surround consisting of a 65° wide rectangular grid of lines (8 arc min wide at 7° intervals). The central 36° of this surround pattern was not displayed to allow for display of the slanted and inclined test surfaces. There was no overlap between the centre and surround stimuli. The stimulus was presented for 1.0 or 30 s. Following this, subjects adjusted the comparison surface to match the slant of the central surface perceived at the end of the exposure period. Subjects then matched the perceived slant of the surround surface in order to reveal any slant contrast. The same five subjects as in experiment 2 participated in two experimental sessions. Over these two sessions each condition was presented four times.

5.2. Results and discussion

In the presence of a visual surround, subjects saw slant and inclination of the centre immediately in the direction indicated by disparity regardless of whether it was concordant with or opposite that indicated by perspective (Fig. 5). This was true of all but one subject who occasionally saw slant in the direction of perspective for the opposite trials. This occurred for the largest ($\pm 40°$) slants at the briefest 1.0 s presentation where three of the eight settings were in the direction of perspective and the other five were in the direction of disparity. For smaller slants and for both sizes of inclination, this subject's responses were similar to those of the other subjects and indicated slant and inclination immediately in the direction of disparity. On average, subjects saw nearly the same amount of slant and inclination for the 1.0 s presentation as for the 30.0 s presentation. Perceived slant and inclination were less for the opposite conditions than for the concordant conditions and this difference was more pronounced for the larger slants and inclinations.

In this experiment slant and inclination percepts in the opposite (conflict) condition were much less ambiguous than those obtained with an isolated stimulus (experiment 1). With an isolated stimulus, slant and inclination under opposite conditions were perceived initially in the direction specified by perspective and gradually changed to that specified by disparity. In contrast, in the presence of a zero-disparity surround, slant and inclination of the centre were immediately and usually unambiguously perceived in the direction specified by disparity. These percepts were also relatively stable over the two observation intervals. This confirms earlier reports that depth from spatial changes in disparity gradient is perceived rapidly and unambiguously while depth from a constant gradient of absolute disparity is perceived slowly (Gillam et al., 1988; Van Ee & Erkelens, 1996a). Presumably the

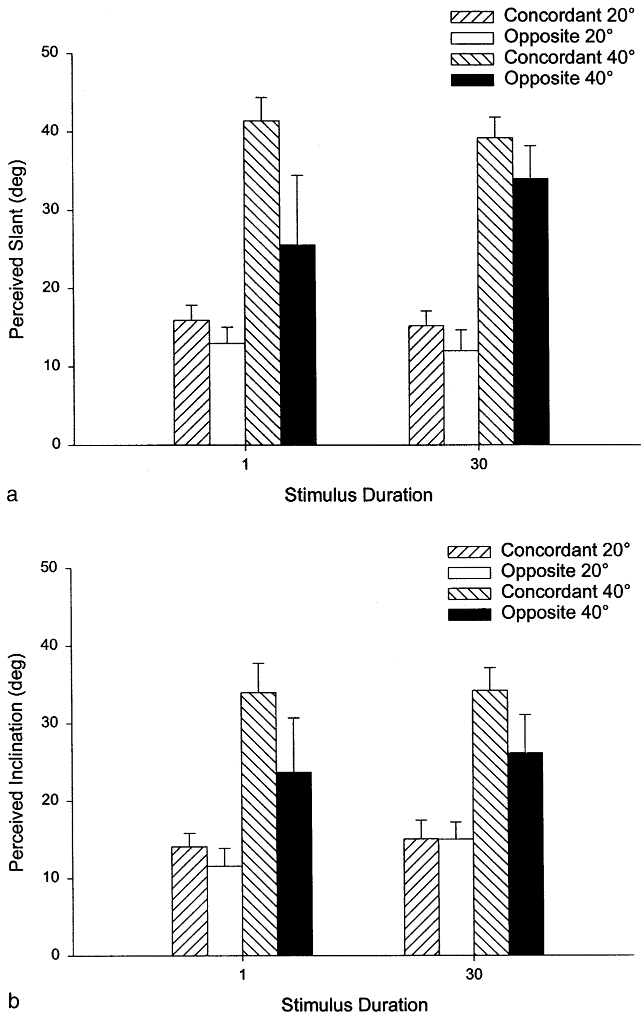

Fig. 5. Effect of exposure duration, in the presence or absence of a visual surround (experiment 3), on (a) slant estimates and (b) inclination estimates averaged across five subjects. Conventions for positive slant and inclination are the same as in Fig. 2. Error bars indicate standard error of the mean.

disparity induced change in relative slant or inclination between the centre and surround surfaces is determined rapidly and this signal is strong enough to overcome conflicting changing perspective.

The slant and inclination matches for the central surface in the presence of the surround tended to be larger than the matches for isolated stimuli. In the absence of the surround, depth normalisation (the tendency to perceive a stimulus as close to a perceptual norm, i.e. the frontal plane) could cause the surface to appear to have less slant or inclination than specified by disparity. Stereoscopic depth normalisation is promoted by conflicting perspective (Sato & Howard, 1998). The slant or inclination of the centre relative to the surround appears to be well perceived; the presence of a surround surface with strong cues to its fronto-parallel orientation therefore results in a more veridical slant or inclination estimate. A surface, such as the surround stimulus, in the presence of a slanted or inclined surface can appear to be slanted or inclined due to slant or inclination contrast. Slant and inclination contrast have recently been shown to be weakly induced in a zero-disparity surround by a central display and to be weakly induced in stimuli containing strong perspective (Van Ee & Erkelens, 1996b; Sato & Howard, 1998). Thus, contrast induced in our zero-disparity surround, which had strong perspective indicating a frontal orientation, was typically zero and seldom more than 2°. Thus, perceived slant of the central stimulus was close to that specified by disparity.

When the central surface had conflicting perspective and disparity the perspective distortion was readily apparent to all observers. When the two cues were concordant the central disk was perceived as a uniformly textured, slanted or inclined, circular disk. With our irregularly textured stimulus pattern the disparity was always dominant over perspective when a disparity reference surface was present. Other authors have found that perspective in regularly textured surfaces often dominates disparity, particularly initially, even in the presence of stereoscopic surface curvature or reference stimuli (Stevens et al., 1991). Perhaps, with regular textures containing strong perspective information, relative disparity would not have been as dominant in our experiment (see experiments 1 and 4). In any case, our results show that relative disparity gradients play a strong role in slant and inclination perception even at short latencies.

6. Experiment 4: effect of stimulus pattern

In experiment 1, the time course of the resolution of disparity–perspective conflict was strongly dependent on the type of pattern used. The irregular and grid patterns elicited significantly different responses, indicating that our attempts to change the degree of perspective–disparity conflict were successful. Several earlier studies have demonstrated that stimulus configuration can have a profound effect on the resolution of disparity–perspective 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, Landy and Maloney (1993) have provided evidence that, under cue conflict, percepts shift to the more reliable cue when noise degrades information from the other. Gillam (1968), Gillam and Ryan (1992), and Ryan and Gillam (1994) studied disparity–perspective cue conflict in slant perception using static patterned stimuli. The stimuli were horizontal and/or vertical lines with perspective specifying a frontal surface and disparity specifying slant or inclination. The patterns containing real or implicit contours perpendicular to the axis of stereoscopic rotation in depth showed a stronger attenuation effect of perspective than those containing contours parallel to the axis of rotation. Slant responses in monocular viewing were also stronger when lines with the appropriate perspective were perpendicular to the axis of rotation in depth than when they were parallel to it (Gillam 1968). They concluded that linear perspective (convergence of parallels) is a more powerful cue to surface orientation than compression or foreshortening (however see Andersen, Braunstein & Saidpour, 1998 for evidence of the importance of compression, particularly when it allows for determination of a horizon line).

In experiment 4, we looked at the effects of differences in the types and amount perspective information provided in patterned and textured displays under conflict conditions. Classically, perspective information about slant has been decomposed into scaling, compression and density cues (Sedgewick, 1986). Following the logic and stimuli of Gillam and Ryan (1992) we used variations of pattern configuration to vary the relative saliency of the linear perspective and foreshortening cues to surface slant and inclination. We then measured the effects of these manipulations on the resolution of disparity–perspective cue conflict as a function of time.

6.1. Methods

The dichoptic pattern was varied to reveal the relative contribution of the various components of perspective. Four patterned stimuli were used: a display of random dots, a display of horizontal lines, a display of vertical lines or a grid pattern (see Fig. 6). All patterns subtended 32° of visual angle. The random-dot pattern consisted of a number of white dots randomly placed on a black background (dot density approximately 8%). In the horizontal and vertical-line stimuli, approximately the same number of dots as in the random dot display was used but the dots were arranged into extended horizontal and vertical lines. Along each line, the dots were randomly positioned and provided a horizontal disparity signal. The grid pattern was formed by superimposing the horizontal and vertical-line stimuli. For slant about a vertical axis, the vertical-line stimuli resulted in slant being indicated mainly by foreshortening and the horizontal-line stimuli resulted in slant being indicated mainly by linear perspective. For inclination about a horizontal axis, the vertical-line stimuli resulted in inclination being indicated mainly by linear perspective and the horizontal-line stimuli resulted in inclination being

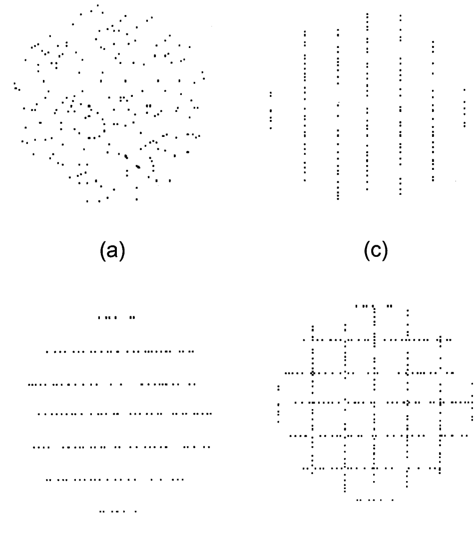

Fig. 6. Stimuli used in experiment 4 to study the effects of pattern configuration on the temporal resolution of disparity–perspective conflict in slant and inclination perception. Actual images were white on black rather than black on white and subtended 32°. (a) Random-dot pattern; (b) Horizontal-line pattern; (c) Vertical-line pattern; and (d) Grid pattern.

indicated mainly by foreshortening. The grid stimuli contained both foreshortening and linear perspective cues to both slant and inclination. The random-dot stimuli contained mainly texture gradient cues to slant and inclination. Since the dots were of finite size and homogeneously distributed (given the constraints of the pattern type) some scaling and density information was available from the dots themselves in all patterns. The dot size for all the base patterns was 16 arc min. The patterns were filtered by a circular Gaussian filter ($\sigma = 0.7$ pixels) and anti-aliasing was incorporated into the transformation routines to reduce the effects of finite pixel count. The four patterns were transformed with perspective-alone, disparity-alone, concordant or opposing cues specifying slants or inclinations of $\pm 40°$. As in experiment 2, disparity and/or perspective was introduced into the initially static frontal surfaces as a step change. The stimuli were presented for either 1 or 30 s. The presentation of each stimulus combination was repeated three times. Six subjects with normal binocular vision participated in this study.

6.2. Results and discussion

Repeated measures analysis of variance indicated significant ($P < 0.01$) effect of type of disparity–perspective transformation and significant interactions between pattern and transformation type and between transformation type and exposure duration on both slant and inclination estimates. The interaction between transformation type and exposure duration was investigated in experiment 2. For slant estimates there was also a significant three-way interaction between type of disparity–perspective transformation, pattern and exposure duration. For inclination there was a significant interaction between pattern type and duration. Thus for both estimates there is evidence that the effect of changes in pattern is a function of transformation type and viewing time. There were no significant effects of order or direction (sign) of slant or inclination. Therefore, magnitude estimates were averaged across the two directions of slant and inclination and across repeats for each of the subjects. Figs. 7 and 8 show the averaged slant and inclination estimates for each disparity–perspective transformation as a function of exposure duration and pattern.

When slant and inclination were specified by concordant disparity and perspective the result was a rapid, strong and relatively stable percept of depth regardless of pattern type used here. The contribution of perspective to the slant and inclination percepts appeared to decline relative to disparity when exposure time was increased. This was manifest as perceived slant and inclination increasing and decreasing with increasing exposure duration for the disparity-alone and perspective-alone conditions, respectively, and in the increasing influence of disparity with increased exposure time under opposite conditions. The degree of this temporal adjustment in the relative weighting of the two cues varied with the pattern displayed. In agreement with Gillam and Ryan (1992), we found that linear perspective is a more compelling monocular cue to surface slant or inclination than foreshortening for 30-s exposures of static stimuli. This was indicated by slant/inclination matches that were larger for perspective-alone, smaller for disparity-alone, and more in the direction of perspective for the opposite transformation with patterns that contained linear perspective (the grid and horizontal-line patterns for slant and the grid and vertical-line patterns for inclination). At brief exposures, the effects of pattern were diminished for slanted

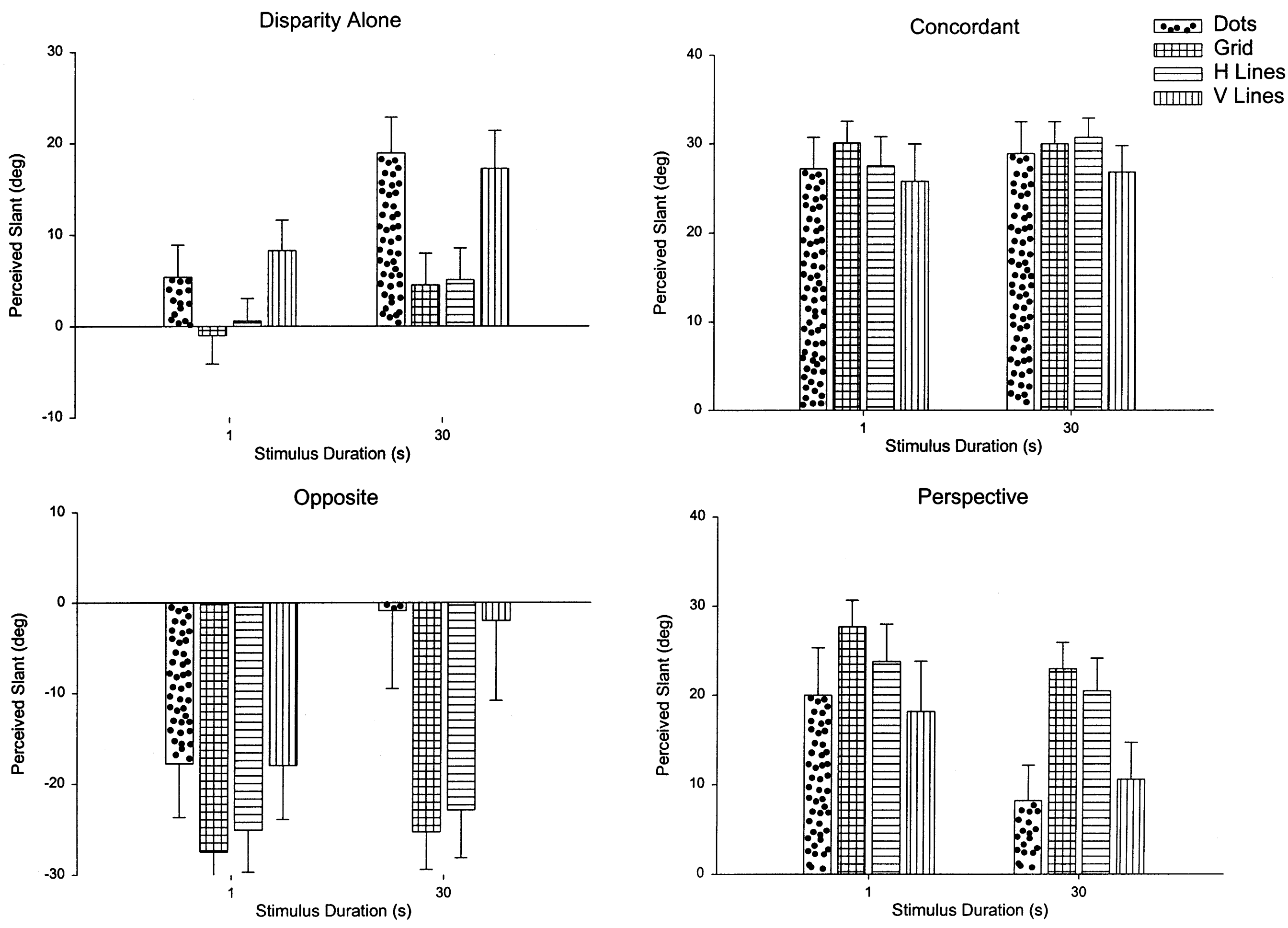

Fig. 7. Effect of exposure duration and pattern type on slant estimates for various types of disparity–perspective transformation averaged across six subjects (experiment 4). The figure shows results for surface slant of 40° specified by perspective alone, disparity alone, concordant disparity and perspective, or opposing disparity and perspective (see text). Conventions for positive slant are the same as in Fig. 2. Error bars indicate standard error of the mean.

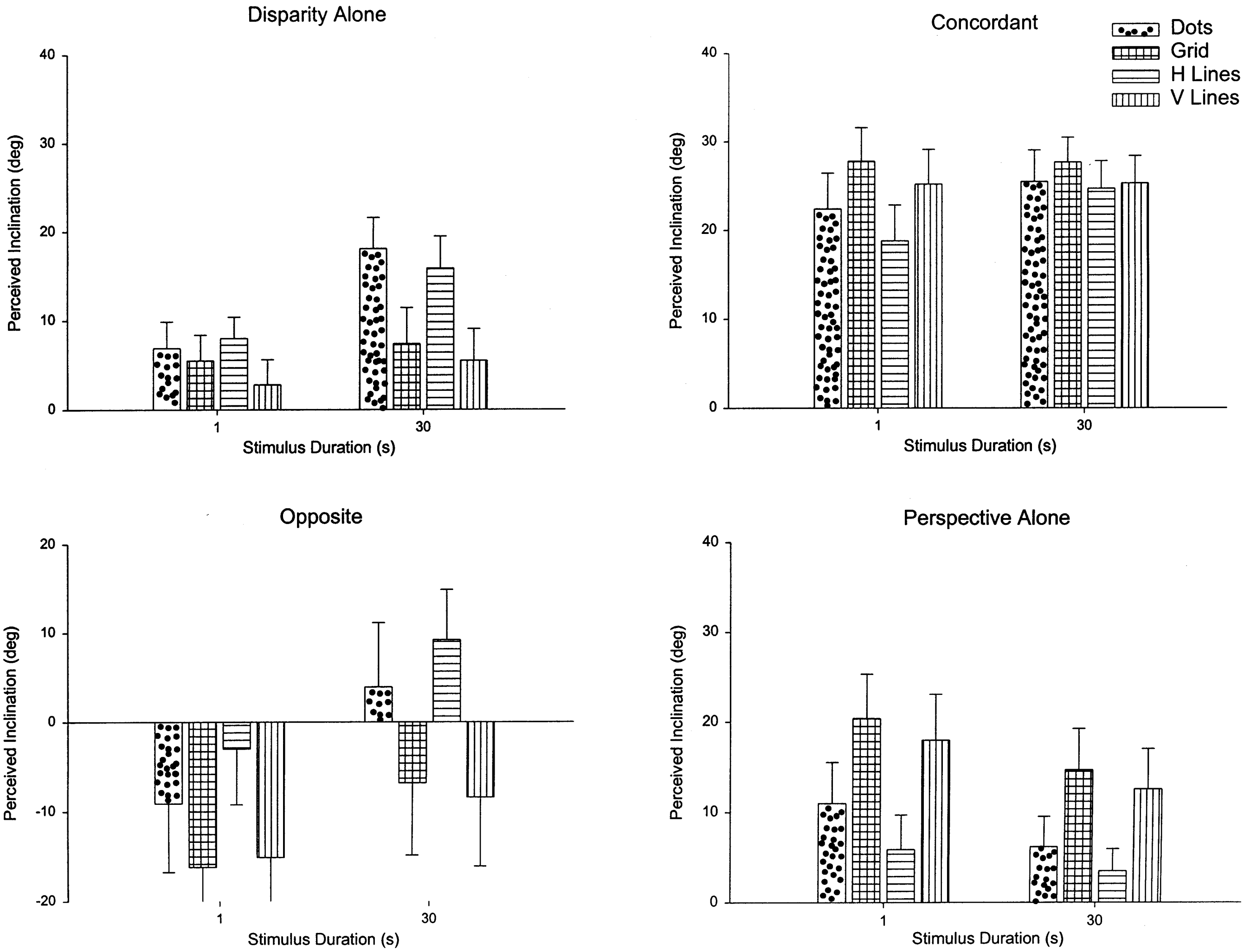

Fig. 8. Effect of exposure duration and pattern type on inclination estimates for various types of disparity-perspective transformation averaged across six subjects (experiment 4). The figure shows results for surface inclination of 40° specified by perspective alone, disparity alone, concordant disparity and perspective, or opposing disparity and perspective (see text). Conventions for positive inclination are the same as in Fig. 2. Error bars indicate standard error of the mean.

surfaces. The lack of a pattern effect indicates that the change in perspective information was roughly equally potent for slant changes in all four patterns even though the relative effectiveness of the patterns differed for the longer presentations (i.e. under static conditions). This was much less clear in the inclination case. For inclination there were substantial differences in the effects of pattern type at both exposures. For both slant and inclination, intersubject variability was highest under the opposite transformation for all pattern types. This was to be expected since cue conflict was most pronounced. Regardless of the average weights given to each cue by an individual, the relative weights appeared to be affected by exposure duration and pattern type in a similar manner in the subjects.

In experiment 1, the differences in inclination estimates between the grid and irregularly textured patterns were more clear cut than in experiment 4. Also, depth from static perspective was weaker with the irregular texture than with any of the stimuli in the current experiment. Although a more direct comparison is needed, this may indicate a more substantial difference in perspective information between the two stimuli in experiment 1 than between the stimuli here in experiment 4. In experiment 1, inclination under perspective-alone and opposite conditions was reported to be stable for the grid pattern but varied over time for the irregular texture (see also experiment 2). This suggests that the effects of differences in monocular information may have a temporal dependency provided the conflict is strong enough. Perhaps a more important difference between experiments 1 and 4 is that larger portrayed slants were used here in experiment 4 (40 vs 20°). Apparent motion induced by the large step change in slant may be beyond the range of the apparent motion system, making the change of disparity more salient.

Also, as we found in experiment 2, cue averaging appears to be less evident when large differences in slant are portrayed.

The irregular and grid patterns in experiment 1 and the patterns in experiment 4 elicited significantly different responses indicating that our attempts to change the degree of perspective–disparity conflict were successful. We did not find a clear dominance of perspective over disparity in determining slant as some have reported (Epstein & Morgan-Paap, 1974; Youngs, 1976; Stevens & Brookes, 1988) but rather that either cue can dominate in a stimulus dependent way. Our results confirm earlier conclusions that linear perspective (convergence of parallels) is a more powerful cue to surface slant and inclination than compression or foreshortening (Gillam, 1968; Gillam & Ryan, 1992; Ryan & Gillam, 1994). Our data further suggest that this distinction is most relevant for static perspective information since the differences between pattern type is less apparent at brief presentations or for kinetic stimuli.

7. General discussion

7.1. Cue integration

It is tempting to try to incorporate our results into a cue summation or fusion (of either the weak or modified weak variety) model. These types of models explicitly incorporate modularity of depth cues. Interactions between the depth cues is limited to averaging or summation of depth maps, or to strongly constrained interactions that make depth maps commensurate and hence additive. Such models are conceptually attractive, especially with minor extensions that allow modification of cue weights (from image to image) to incorporate behaviour analogous to standard statistical methods of robust estimation (Landy, Maloney, Johnston & Young, 1995). In studies with limited stimulus sets these types of models have often been found to describe the data well (for review see Landy et al., 1995) although the generality of these model is often difficult to gauge. The most recent linear models for slant perception have been described in Van Ee and Erkelens (1998) and Backus and Banks (1999).

In many conditions in the present experiments, slant and inclination responses were a compromise between the theoretical values specified by perspective and disparity. Furthermore, when exposure time was increased under conflict conditions, percepts gradually changed from the direction specified by perspective towards that specified by disparity. This might fit into a modified weak fusion model (Landy et al., 1995) with the weighting of the disparity cue being gradually increased at the expense of that of the perspective cue over time. The initial high weighting of continuously changing perspective would reflect the greater reliability of kinetic perspective compared with static perspective. However, in these experiments, weights assigned to disparity and perspective would be a function of observer, exposure duration, pattern type and possibly transform type. The number of free parameters would reduce the modelling exercise to little more than curve fitting with little explanatory or predictive power without a theoretical justification for assuming cue averaging. Under the conditions of strong cue conflict in this study, a simple cue averaging would be a poor choice of cue combination. Subjects might be expected to switch to idiosyncratic strategies of cue dominance or vetoing based on the assumed reliability of the cues (given the image characteristics) and we have found evidence for such behaviour. Thus, we have little justification for adopting such a model even if the data could be forced to fit it (note that a linear statistical model did fit well and was used empirically to analyse cue interactions). Large discrepancies in slant portrayed by monocular and binocular cues are typical of most stereograms and are certainly possible in natural scenes.

It would be interesting to also investigate the temporal properties of disparity–perspective cue integration under conditions of weak conflict — perhaps using perturbation analysis. In natural scenes, small differences in the estimates from various depth cues may be the norm. Under conditions of weak cue conflict or with noisy estimates, averaging across cues can improve estimate accuracy and reliability. Given that weighted cue averaging is appropriate when cues are reasonably concordant, Young et al. (1993) proposed a perturbation analysis procedure which measures the sensitivity of a percept to small variations in the various cues contributing to it.

7.2. Discontinuities of disparity

How disparity and perspective (and other) depth cues are integrated appears to be strongly dependent on the spatial layout of the surface. The visual system seems to be especially sensitive to discontinuities of disparity, and step changes in depth are well perceived (Gillam et al., 1988; Brookes & Stevens, 1989; Mitchison & McKee, 1990). In experiment 3, we found that percepts of relative slant and inclination from disparity gradient discontinuities are perceived rapidly even in the presence of conflicting change of perspective. Under these conditions, disparity was strongly dominant at both exposure durations. Thus, it is not possible to establish whether the dominance of the disparity cue at short exposures was due to spatial changes in disparity gradients being processed more rapidly than absolute disparity gradients or simply due to a greater saliency for spatial change of disparity gradient at all time intervals. Further studies varying the effectiveness of the perspective cue, perhaps under weaker conflict or with kinetic stimuli (where the kinetic perspective is especially dominant), may help to clarify this issue.

7.3. Slant reversals

Subjects occasionally reported slant or inclination in the opposite direction to that predicted by disparity. In the disparity-alone condition cue conflict was not eliminated since the unchanging perspective cue was set at zero, but not eliminated. Thus, the unchanging perspective would indicate unchanging slant. Anecdotally, we find that if subjects perceive slant or inclination in the direction predicted by disparity then they also perceive an apparent gradient of texture size and density consistent with the operation of a size constancy mechanism. Note that the apparent texture gradient is opposite in direction to the texture gradient resulting from a homogeneously textured surface slanting or inclining in the direction specified by disparity and gives conflicting information about the direction, or sign, of slant or inclination. In agreement with this proposal, Gillam (1993) has shown, and we have confirmed, that slant reversals are most pronounced when the stimulus is configured to provide strong perspective information.

The results of experiment 1 suggest that subjects prone to reversal are especially sensitive to perspective. Under conditions of static cue conflict (opposite transformation), these subjects made slant or inclination estimates that were more in the direction of the perspective component than other subjects. As well, compared to other subjects, they saw more depth when slant or inclination was defined by perspective-alone. The slant-shape paradox explanation of slant reversals requires that these subjects are also more likely to interpret the apparent perspective arising from disparity as depth. Subjects experiencing reversed slant typically did not notice any size distortions, a finding consistent with their attributing induced size changes to depth (Gillam, 1967).

In all subjects, the potency of perspective was enhanced with kinetic stimuli and short durations. Thus we expect that conflicting perspective has the strongest modulating effect on perceived depth and that slant reversals would be most prevalent at higher temporal frequencies or for shorter presentations. Slant reversals have been found to be more common for brief presentations and kinetic stimuli (Allison et al., 1999), a finding confirmed in the present experiments. In the opposite perspective–disparity condition, the conflict may be accentuated by apparent changes in the texture gradient induced by the changing disparity, which would support the objective change in the perspective gradient. This may explain why large responses in the direction of perspective were obtained in the opposite transformation trials with kinetic stimuli.

7.4. Latency of slant perception from disparity

The time required to match stereoscopic images has been identified as potential contributor to the latency of stereopsis (Julesz, 1971). However, this seems an unlikely explanation for the slow build-up of slant percepts since Gillam et al. (1988) explicitly state that their latency measures were post-fusional. Instead, they argued that the visual system is insensitive to gradients of absolute disparity (see also Anstis et al., 1978; Brookes & Stevens, 1989; Mitchison and McKee 1990; Stevens et al., 1991; Van Ee & Erkelens, 1996a). They proposed that the slow development of the slant percept is a result of the time required for the integration of depth across local depth differences. Stevens et al. (1991) similarly argue that gradients of disparity are not directly responded to but that depth is reconstructed from disparity contrast. Slant and inclination percepts then arise slowly as a result of integration over eye movements or of a filling in process from depth contrast at the edges of the display. As evidence against the eye movement hypothesis, Van Ee and Erkelens (1999) have recently reported that slant and inclination estimates were similar under free eye movements and fixation conditions. In all these studies the disparity cue was in conflict with perspective. Our results provide evidence that disparity–perspective cue conflict plays an important role in determining the time course of stereoscopic slant and inclination perception.

7.5. Size versus shear disparity

Subjects tend to perceive more depth for surfaces defined by horizontal shear disparity than by horizontal size disparity (Rogers & Graham, 1982; Mitchison & McKee, 1984, 1990) although considerable intersubject variability exists (Mitchison & Westheimer, 1990). This insensitivity to size disparity could explain why disparity was relatively less important for slant than for inclination judgements in the present experiments. On the other hand, it is possible that perspective is more salient for slanted surfaces and that this factor plays a role in the anisotropy.

Since the horopter deviates from the frontal plane, a given horizontal size disparity corresponds to different slants with respect to the frontal plane for centrally and eccentrically placed surfaces (Mayhew & Longuet-Higgins, 1982; Gillam & Lawergren, 1983). Additional information about stimulus eccentricity and distance is required to disambiguate slant from horizontal size disparity; this information could be provided by perspective (Gillam, 1993; Backus & Banks, 1999). Ryan and Gillam (1994) and Gillam and Ryan (1992) noted that the effects of adding static perspective cues were much stronger for slant than for inclination. This anisotropy was also found by Buckley and Frisby (1993) for texture–disparity conflict in specifying the depth of ridge structures. Our results confirm that conflicting static perspective information has more influence on slant than on inclination. Whether this anisotropy is due wholly to the relative ineffectiveness of size disparity (Wallach & Bacon, 1976; Rogers & Graham, 1982; Gillam et al., 1988) or in part to a particular saliency of perspective in slant perception is presently unclear. In this study, when disparity conflicted with kinetic perspective, perspective was dominant for both slant and inclination and no anisotropy was found. Presumably, kinetic perspective completely overwhelmed both types of disparity.

7.6. Kinetic versus static perspective

The differences in the resolution of disparity–perspective conflict between the kinetic and static conditions are striking and suggest that changing perspective (motion or kinetic perspective) is much more compelling than static perspective. The information provided by kinetic perspective is related to motion parallax. Both the kinetic depth effect and motion parallax are instances of 3-D structure from motion (Ullman, 1979). In our stimulus, motion was in the depth dimension rather than orthogonal to it, as in typical motion parallax studies (e.g. Rogers & Graham 1982; Ono, Rivest & Ono, 1986). In addition the motion was a perspective transformation, which is not necessarily the case for generalised structure from motion. For example, the silhouette of a rotating bent piece of wire appears as a three-dimensional rotating object even if viewed under parallel projection (Wallach & O'Connell, 1953; see also Braunstein & Andersen, 1984). Our results indicate that changing perspective (whether referred to as motion parallax or kinetic perspective) is particularly effective in determining change in surface orientation in depth.

In kinetic stimuli, kinetic perspective may be particularly compelling because stronger assumptions may be made than in the static case. A static, physically slanted surface could have a texture that increases in size with distance. Homogeneity of texture element size is a fairly general assumption but this constraint is often invalidated in nature. An example would be a pebble beach where the pebbles are distributed by weight and thus size. On the other hand, a dynamic texture transformation that does not correspond to a change in perceived depth requires that the surface be deforming. In other words, rigidity and cohesiveness assumptions in a display that is moving impose stronger constraints than simple homogeneity does in a static display. When the stimulus moves, the velocity gradients of kinetic perspective provide sufficient information to allow for determination of the surface slant given the assumption of rigidity (Braunstein, 1968). Gibson and Gibson (1957) found that changing perspective from cast shadows in the absence of changes in other depth cues produced a much stronger percept of slant than static perspective. Our data support the conclusion that kinetic perspective is a powerful cue to changing surface slant and inclination.

When step changes in slant or inclination are modest, apparent motion of the surface may be evident. As a result, motion perspective cues may exist over the step change and conflict with the change in disparity in the cue conflict conditions. When the slant or inclination portrayed is increased this apparent motion may no longer be evident. This may explain why some subjects saw slant or inclination consistently in the direction of disparity under conditions of cue conflict and saw little slant or inclination for perspective-alone transformations when portrayed slant or inclination was large (experiment 2). Alternatively, this may be a manifestation of a switch from cue averaging or fusion (Dosher, Sperling & Wurst, 1986; Landy et al., 1995) to a cue dominance or veto type of cue interaction (Bülthoff & Mallot, 1988). That this behaviour is more pronounced for inclination than slant may be a result of the essential ambiguity of slant from horizontal size disparity.

7.7. Summary

The main findings of this study can be summarised as follows. Perspective was found to play a determining role in slant and inclination perception immediately following step changes in the portrayed slant or inclination of a large, isolated, test surface. Perspective was also dominant over conflicting disparity for slant and inclination percepts arising from oscillatory changes in portrayed slant and inclination. Slant and inclination from disparity alone under these conditions were weak and prone to reversal. Disparity was increasingly relied on to determine the perceived slant or inclination of isolated static surfaces as exposure time was increased. However, in the presence of a zero-disparity reference surface, relative disparity determined slant or inclination percepts even for short exposures. Under static conditions, patterns that provide strong linear perspective cues to surface slant or inclination were seen more according to perspective than patterns providing mainly foreshortening or texture gradient cues. This effect of pattern was lessened under dynamic conditions and a significant effect of kinetic perspective was observed for all pattern types.

Acknowledgements

This work was supported by NSERC (Canada) and by DCIEM grant W7711-7-7393.

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