Local and non-local effects on surface-mediated stereoscopic depth

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The magnitude and precision of stereoscopic depth between two probes is often determined by the disparity each has to a common background. If stereoscopic slant of the background is underestimated, a bias is introduced in the PSE of the probes (G. Mitchison & G. Westheimer, 1984). Using random dot stimuli, we show here how more remote surfaces can influence probe PSE via their influence on perceived background surface slant. The bias was reduced when frontal flanking surfaces were placed above and below the background surface, increasing its perceived slant. In a similar experiment, the flankers were slanted and the central background surface was frontal. For flankers alone, probe bias did not diminish up to a 4.4° separation of flankers and probes. When the central surface was present, the effect of the flankers on probe bias was mediated by this surface and diminished with flanker separation, presumably because of the diminishing contrast slant of the background surface. Stereoscopic depth between probes is thus influenced by a common background surface, by neighboring surfaces acting (contiguously or non-contiguously) on the background surface, and by distant surfaces acting directly on the probes.

Keywords: binocular vision, 3-D surface and shape perception, depth

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Introduction

It is well established that perceived stereoscopic depth between two objects depends on their relative horizontal disparity. It is by now also established that the stereoscopic depth of isolated objects is influenced by their disparity relative to a background surface. Furthermore, biases in perceived background surface slant can produce biases in the perceived relative depth of detached objects seen against these surfaces. The presence and magnitude of such biases can be used to explore the possible influence of surfaces more remote than the immediate background. This is the goal of the present paper. We conclude that stereoscopic depth perception is influenced by the total configuration of objects and surfaces.

When the only information for the slant around a vertical axis of an isolated surface is a horizontal gradient of binocular disparity, the slant perceived is often strongly attenuated relative to geometric prediction (Gillam, Flagg, & Finlay, 1984; Mitchison & Westheimer, 1984; Rogers & Graham, 1983).[1] The misperception of slant can introduce a bias in the perceived relative position of small objects near the slanted surface. For example, when two small depth probes are placed equidistant from the observer in front of (Mitchison & Westheimer, 1984) or adjacent to (Gulick & Lawson, 1976) a textured surface whose stereo slant is attenuated, they do not appear equidistant. The local stereoscopic depth of each probe relative to the surface is more or less accurately perceived, but because the surface slant is underestimated, the probe further from the surface looks nearer to the observer than the one closer to the surface. The point of subjective equality (PSE) of the probes, therefore, has a bias related to the underestimation of the surface slant. A similar result was obtained by Glennerster and McKee (1999), who found in addition that the PSE bias was reduced when the standing disparity of both test lines relative to the surface increased. This biasing effect of a surface on the perceived relative depth of nearer probes resembles an earlier observation by Gogel (1972) that when the stereoscopic slant of a surface is reduced (or reversed) by perspective, a bias is introduced into the perceived relative depth of two stereoscopically viewed probes adjacent to the opposite ends of the surface (Figure 1).

The bias introduced in the perception of the relative stereoscopic position of isolated objects by the underestimation of the stereoscopic slant of a background surface is robust across viewing conditions. The probes in Gogel's (1972) and Gulick and Lawson's (1976) experiments were much farther apart laterally (approximately 4°) than those of Glennerster and McKee (1999)

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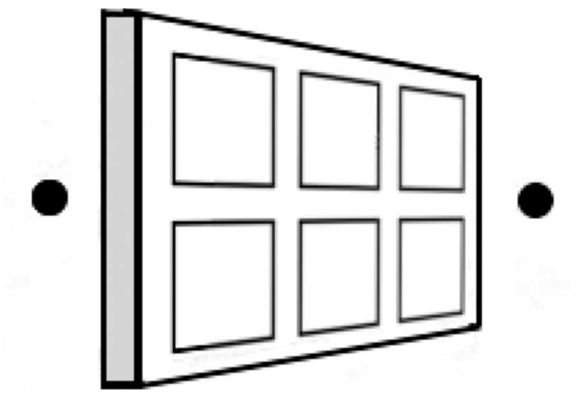

Figure 1. Front view diagram of stimuli used by Gogel (1972). The window had a trapezoid shape and was oriented in depth so that its small end (right side in figure) was closer in depth than the large end.

and Mitchison and Westheimer (1984), which were separated by less than 1°. In addition, Glennerster and McKee (1999) and Mitchison and Westheimer (1984) used 150-ms exposures, whereas Gogel (1972) and Gulick and Lawson (1976) used exposures long enough for eye movements to occur. These observations, under a range of conditions, indicate that two probes may not be directly related to each other stereoscopically when a background surface is present, but that each may be related stereoscopically to proximal elements on the background surface, with the background surface slant mediating the perceived depth between them. The former is a local process; the latter is a process operating over a longer range, which can link local processes. It is an obvious advantage to use a surface to mediate between the local depths when probes are sufficiently far apart to have a weak depth signal relative to each other (e.g., Ogle, 1956). Such probes may have stronger relative depth signals with respect to angularly close elements of the background, which are linked by intervening disparities across the surface or by perspective integration. In Glennerster and McKee's (2004) study, for example, the dots on the background had greater angular proximity to the probes than the probes had to each other.

In our studies, we explore the possibility that remote surfaces acting stereoscopically or perspectivally on the immediate background surface of objects may change both the apparent slant of the background and also the PSE of objects seen relative to it. Such secondary influences on the PSE of targets have not, to our knowledge, been explored previously.

An important manipulation in all of the following experiments relies upon a prior observation about stereoscopically slanted surfaces. It has been found by a number of investigators (Gillam, Chambers, & Russo, 1988; Gillam et al., 1984; Kaneko & Howard, 1996; van Ee & Erkelens, 1996a, 1996b) that the poor slant response to a single surface, which is slanted stereoscopically around a vertical axis, gives way to a strong slant response when a frontal plane surface is placed either above or below the stereoscopically slanted surface in what Gillam et al. (1988) and Howard and Rogers (2002) have called a "twist" configuration. Gillam et al. attributed the particular effectiveness of the twist configuration in enhancing stereo slant to the presence of a gradient of relative disparities along the abutment of the two surfaces.[2]

In the present experiments, this "twist" factor was used to alter the perceived stereoscopic slant of the background surface in a probe PSE task. If this manipulation changes the bias in the PSE of the probes seen against the center of the surface, it would show a novel contextual influence on surface-mediated stereoscopic depth. It would also indicate that slant information deriving entirely from discontinuities at the boundary of a surface can spread so that it participates in local processes with respect to the center of the surface.

Experiment 1a

The goal of Experiment 1a was to examine the effect on the PSE of two laterally separated probes of adding nonlocal information to increase perceived background surface slant around a vertical axis. We did this in two ways: (1) by placing flanking frontal plane surfaces above and below the background surface and (2) by embedding the stereoscopically slanted background surface within a perspective/shading context consistent with its stereoscopic slant. Both in the condition in which the flankers were added and the condition in which the perspective/shading was added, the basic background surface was unchanged. Only its context was modified.

Methods

The stereoscopic stimuli were generated on a Matrox graphics board, and left and right eye images were displayed side by side on a Mag Triniton monitor. These images were combined using the mirrors of a custom-made Wheatstone stereoscope. The viewing distance was 1 m. There were four stimulus conditions, each of which included two small test probes that were 2-mm squares (6.9′) separated horizontally by 62 mm (3.55°). The method of constant stimuli was used to obtain the PSE in depth of the probes for the four stimulus conditions. In the first stimulus condition, the probes were presented alone (probes-alone condition). In the other three stimulus conditions (shown in Figure 2), the probes were presented stereoscopically in front of a vertical rectangular textured background either with or without a surrounding context. The rectangle was made up of 960 square cells that were arranged in an array 80 mm high (4.58°) × 120 mm wide (6.87°). Each cell had a randomly assigned probability of

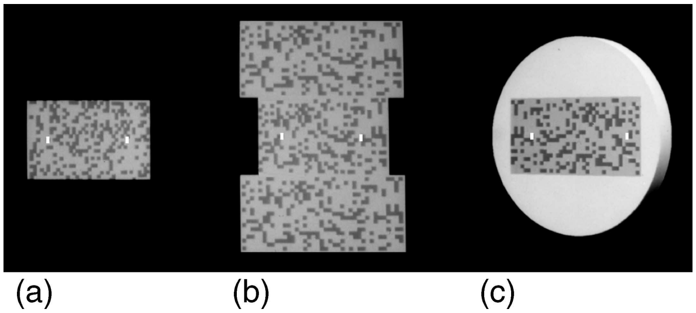

Figure 2. Front view of Experiment 1a stimuli. The small white rectangles are the probes.

0.5 of being dark. The overall shape of the rectangle was clipped to a constant height in both eyes so that it did not produce a perspective cue to slant. It was stereoscopically slanted around a vertical axis by imposing a horizontal magnification of 5.75% on one eye's image. This had the effect of creating a gradient of horizontal disparity consistent with a slant of 40° either to the left or right depending on which eye was magnified. The two eyes' views differed only by the relative compression, so there was no perspective gradient. In one background condition (Figure 2a), the central rectangular surface was the only background to the probes. This stimulus will be referred to as the central-surface-alone condition. In the second background surface condition (Figure 2b), the same rectangle was presented as a background with flanking rectangles of the same size and composition placed immediately above and below it. These flanking rectangles were stereoscopically in the frontal plane. Thus, they provided gradients of relative disparity along the upper and lower boundaries of the slanted central rectangle (see Gillam, Blackburn, & Brooks, 2007; Gillam et al., 1988, 1984). This stimulus will be referred to as the central-surface-plus-flankers condition. In the third background surface condition (Figure 2c), the same rectangle was surrounded by the perspective rendering of a slanted circular disk with 154-mm diameter (8.8°) and 15-mm thickness (0.86°). The perspective slant of the disk was equivalent to the stereoscopic slant of the central rectangle. The disk was rendered with Gouraud shading appropriate to its slant. This stimulus will be referred to as the central-surface-plus-disk condition.

The test probe on the side of the surface that was slanted forward had a disparity of 17.9′ relative to the surface region behind it. The disparity of the other probe relative to the surface region behind it was equal to one of nine values: 0.1′, 15.9′, 23.2′, 27.4′, 30.1′, 32.8′, 37.0′, 44.3′, or 60.1′. There was a disparity of 12.2′ between the surface regions behind the two probes. This resulted in a relative disparity (and depth) between the two probes equal to −30′ (−100 mm), −14.2′ (−50 mm), −6.9′ (−25 mm), −2.7′ (−10 mm), 0′ (0 mm), +2.7′ (10 mm), +6.9′ (25 mm), +14.2′ (50 mm), or +30′ (100 mm).

For each observer, the PSE and JND of the relative depth of the test probes were obtained for the probes alone and for the same probes with the three background conditions. On each trial, the observer was required to report which of the two probes appeared nearer. The 9 relative probe depths for each of the 4 conditions were presented 20 times in random order to obtain psychometric functions. Four observers participated, only one of whom (BG) had any knowledge of the experiment and its predictions. The others were from the first year subject pool at the University of New South Wales.

Results

Bias

The psychometric functions for each condition and observer are shown in Figure 3. The PSEs for each observer and condition are shown in Table 1a.[3] When the probes were presented with no background, it can be seen from Figure 3 that there was a tendency in all observers to perceive the left probe as nearer. This must have been an artifact of some aspect of the stimulus situation that we were unable to isolate. The true baseline condition is shown in the second graph for each observer, which shows the effect on probe settings of placing the textured rectangle behind them with a horizontal disparity gradient consistent with either left or right slant (central-surface-alone condition). This clearly introduces a strong bias related to the direction of stereoscopic slant of the background as shown by the lateral separation of the curves for the opposite background slants for the same probe task. The strong effect of background slant on PSE can also be seen in Table 1a, which shows the biases for each condition and observer as differences in PSE for the two directions of slant. The effect of the different stimulus conditions on this bias was of primary interest. The third and fourth graphs represent PSEs under the same conditions but with the addition of either frontal planes above and below the central surface (central-surface-plus-flankers condition) or a large shaded disk around the central surface (central-surface-plus-disk condition). The bias was clearly reduced in both cases as shown by the reduced separation of the two curves for opposite slants of the background in Figure 3 and the reduced biases in Table 1a. Table 1b shows the degree to which the central-surface-plus-flankers and the central-surface-plus-disk conditions reduced the bias compared to the central-surface-alone condition for the four observers. Table 1b also shows the 95% confidence interval for the reduction in bias for each observer. As the confidence interval for each observer does not contain zero, the reduction in bias is statistically significant at the 0.05 level.[4]

Precision

Table 2a shows the JNDs for each condition for each observer. Table 2b shows the reduction in JND when a

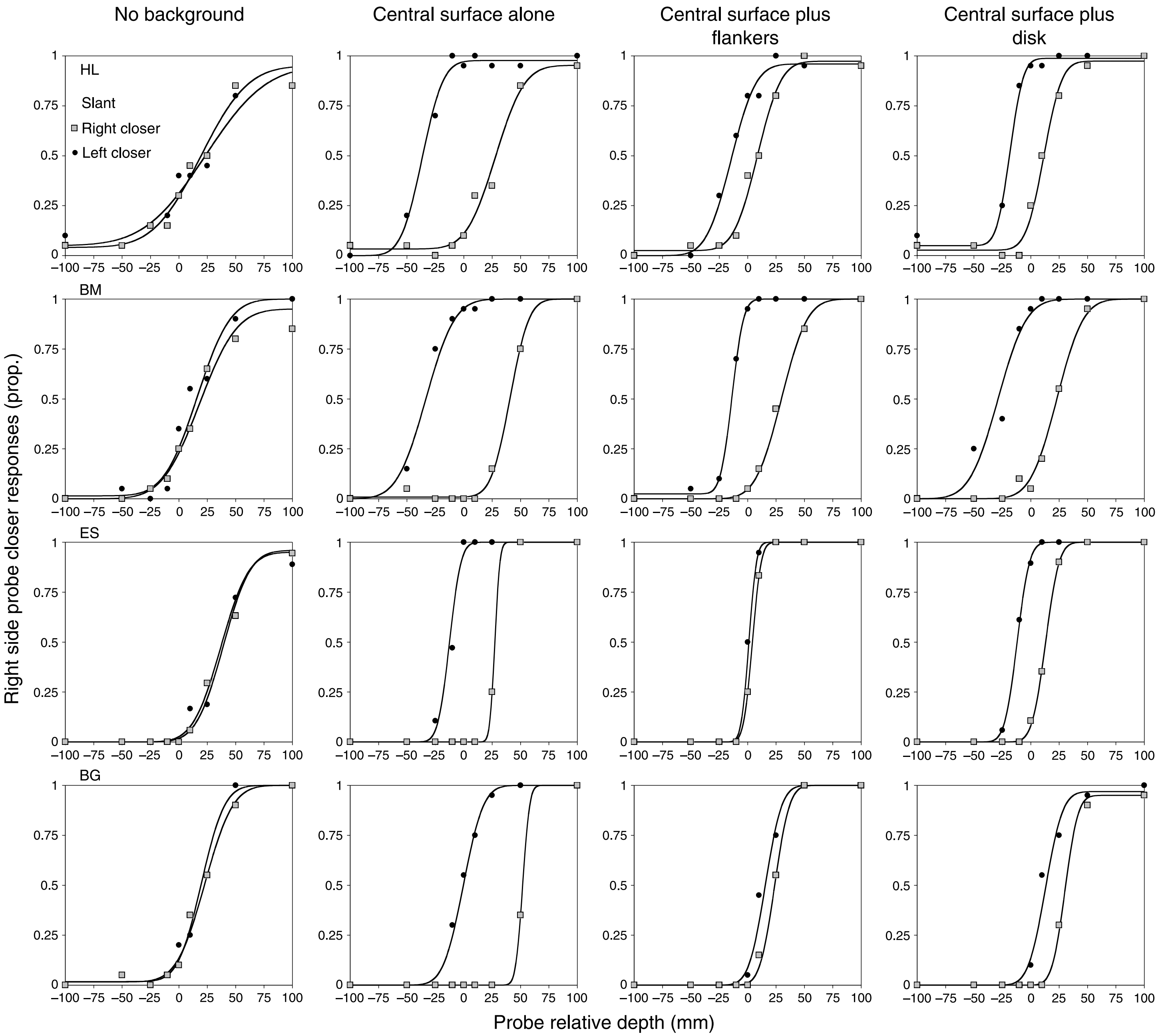

Figure 3. For each observer, the proportion of trials the right probe appeared closer is plotted against the physical relative depth of the probes (mm). The solid lines show the best fitting logistic function that was used to calculate the PSEs in Table 1a and the JNDs in Table 2a. For each observer, the slanted rectangle introduced a large bias in the PSE of the probes (rectangle-alone condition). This PSE bias was reduced in the rectangle-plus-disk condition and the rectangle-plus-flankers condition.

background surface was placed behind the probes compared with the condition in which the probes were presented alone. The confidence intervals (Table 2b) show that this reduction in JND (averaged across all background surfaces) was significant for two of the three naive observers.[5] Without the background, observers have to rely on relative depth across a considerable separation and the judgment is not very precise. The increase in precision when a background is present indicates that at least for the majority of naive observers the probe judgments under these conditions are made locally between each probe and elements on the adjacent part of the background texture and that these local judgments are then related by means of the slant of the background. Any imprecision introduced by the extra step of relating the local depths by means of the background is more than offset by the

	HL			BM			ES			BG		
	Slant			Slant			Slant			Slant		
Condition	−ve	+ve	PSE bias	−ve	+ve	PSE bias	−ve	+ve	PSE bias	−ve	+ve	PSE bias
No background	23	19	−4	16	18	2	37	39	2	20	23	3
Central surface alone	−37	28	65	−33	41	74	−13	27	40	0	52	52
Central surface plus flankers	−15	9	23	−14	30	44	1	4	3	16	23	7
Central surface plus disk	−18	12	30	−29	23	52	−12	13	25	13	30	17

Table 1a. PSE and PSE bias for each observer and condition in Experiment 1a (mm).

	HL			BM			ES			BG		
		95% C.I.s			95% C.I.s			95% C.I.s			95% C.I.s	
Condition	Reduction	Lower	Upper	Reduction	Lower	Upper	Reduction	Lower	Upper	Reduction	Lower	Upper
Central surface plus flankers	41	27	58	31	17	47	37	29	45	45	36	55
Central surface plus disk	35	19	50	22	7	40	15	6	26	35	22	48

Table 1b. Reduction in PSE bias (mm) compared to central surface alone in Experiment 1a.

increased precision in making local probe-to-background depth judgments compared with making direct longer range probe-to-probe comparisons.

Discussion

In this experiment, the presence of a stereoscopic background whose slant was underestimated introduced a very strong bias in the PSE of probes placed in front of it. This bias could be greatly reduced by contextually increasing the slant information, either by adding more effective stereoscopic information or by adding perspective information. These results indicate that local stereoscopic information can be integrated with non-local slant information affecting the background to achieve stereoscopic depth. Under normal circumstances, in which slant is correctly estimated, this would be a useful means for using stereopsis to relate widely separated elements that do not provide good direct relative depth information.

	HL		BM		ES		BG	
	Slant		Slant		Slant		Slant	
Condition	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve
No background	57	44	31	35	26	25	22	26
Central surface alone	20	27	27	18	11	5	19	7
Central surface plus flankers	23	22	11	24	7	8	15	14
Central surface plus disk	13	17	27	25	12	13	16	12

Table 2a. JND for each observer and condition in Experiment 1a (mm).

HL			BM			ES			BG		
	95% C.I.s			95% C.I.s			95% C.I.s			95% C.I.s	
Reduction	Lower	Upper	Reduction	Lower	Upper	Reduction	Lower	Upper	Reduction	Lower	Upper
30	13	80	11	−6	14	16	7	37	10	−4	13

Table 2b. Effect of the presence/absence of a background surface on the JND in Experiment 1a.

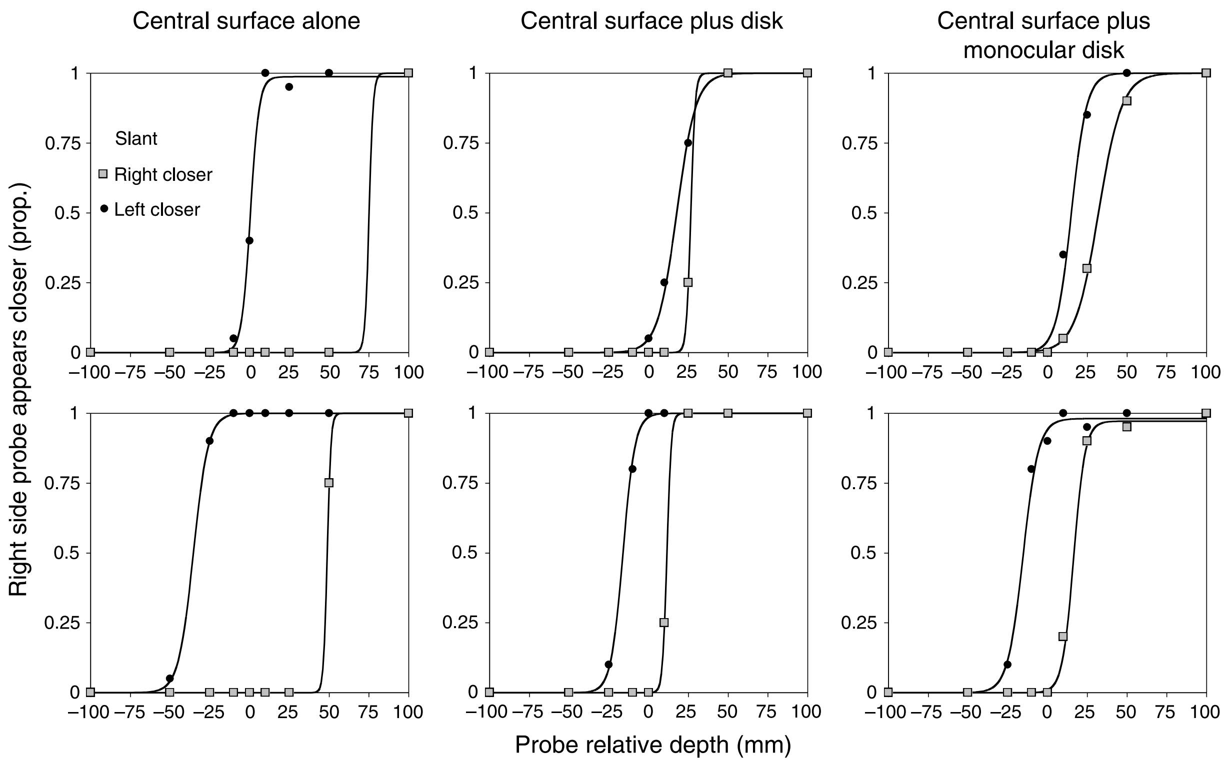

Figure 4. Plots of the proportion of right probe closer responses against probe relative depth (mm) for observer BG (upper graphs) and SB (lower graphs) in Experiment 1b. The solid lines show the best fitting logistic function that was used to calculate the PSEs shown in Table 3a.

Experiment 1b

In Experiment 1a, the central-surface-plus-disk condition was entirely binocular. It is, therefore, possible that the additional information about slant provided by the disk, which succeeded in reducing the bias in the PSE of the probes, was binocular information, e.g., curvature disparity or shadow disparities rather than monocularly available perspective information. In a control experiment, we used the same methods as in the main experiment but included a condition in which the disk was present in one eye only. The rectangle was present in both eyes. This was quite comfortable to view and did not produce rivalry. The other two conditions included were the original condition in which the disk was present in both eyes and the central-surface-alone condition. Two observers were used (BG and SB). The psychometric functions for the three conditions are shown in Figure 4 and the PSEs in Table 3a. The result of the main experiment was confirmed: the bias in the central-surface-alone condition was greatly reduced by adding the disk. Figure 4 and Table 3a show that this reduction occurs whether the disk is monocular or binocular. Table 3b shows the difference in the PSE bias (with confidence intervals) between the binocular and monocular disk conditions for the two observers. This difference was not significant and the confidence intervals are quite narrow indicating that the PSE bias was similar in magnitude for the binocular and monocular disks. Thus, we can conclude that the additional information about slant produced by the disk was largely perspective information, which is available monocularly.

	BG			SB		
	Slant			Slant		
Condition	−ve	+ve	PSE bias	−ve	+ve	PSE bias
Central surface alone	0	75	75	−36	48	84
Central surface plus disk (binocular)	18	27	9	−16	12	28
Central surface plus disk (monocular)	15	32	17	−15	16	31

Table 3a. PSE and PSE bias for each observer and condition in Experiment 1b (mm).

BG			SB		
	95% C.I.s			95% C.I.s	
Difference	Lower	Upper	Difference	Lower	Upper
0	−2	17	0	−5	11

Table 3b. Difference in PSE bias between the monocular and binocular disks (mm) in Experiment 1b.

Experiments 2 and 3 investigated some of the parameters of surface–flanker relationships that influence the PSE of the probes under conditions similar to the central-surface-alone and central-surface-plus-flankers conditions of Experiment 1a.

Experiment 2

Experiment 2, using the same general arrangement, explored the effect of varying the vertical separation between the flankers and the probes. This was done by varying the height of the slanted textured central surface against which the probes were seen. Since the frontal plane flankers (if present) always abutted the upper and lower boundaries of the slanted surface, they were increasingly separated vertically from the probes, which remained in a central position, as surface height increased. By evaluating the bias in probe PSE for different surface heights, this experiment allowed us to determine how far the slant enhancement produced by the gradient of relative disparities at the upper and lower boundaries of the surface would propagate vertically.

Methods

Stimuli were generated with anti-aliasing using the Psychtoolbox plug-in for Matlab (Brainard, 1997) on a PowerPC G5 computer. The stimuli were presented on two Samsung Syncmaster 957df monitors with a resolution of 1600 × 1200 and combined by means of a custom-made Wheatstone stereoscope with mirrors arranged so that the optical distance was 86 cm. Pixel size was 0.88 arcmin. Head position was stabilized with a chin rest. Black apertures set 15 cm from the eyes occluded the edges of the monitors.

Stimuli

Examples of the stimuli used are shown as stereograms in Figure 5. The basic stimulus (Figure 5a) was a central rectangular surface. The surface was 6.85° wide and varied in height. Black dots (2.6′ in diameter) with an average density of 93 dots/degree^2 covered the surface in a pseudorandom texture as described by Gillam and Ryan (1992). The luminance of the dots was 0.2 cd/m^2, and they were clearly visible against a white background with a luminance of 26 cd/m^2. Slant around the vertical axis was produced by horizontal magnification of one eye's image of the surface by either 4% or 8%. This produced a smooth change in disparity across the surface, corresponding to a slant of either 26° or 45° with respect to the frontal plane.

Two small black circles, 8.8 arcmin in diameter, served as the probes. One of the probes was presented 2.06° to the left of the center of the central surface. The other probe was presented 2.06° to the right of center of the central surface. When the probes were in the frontal plane,

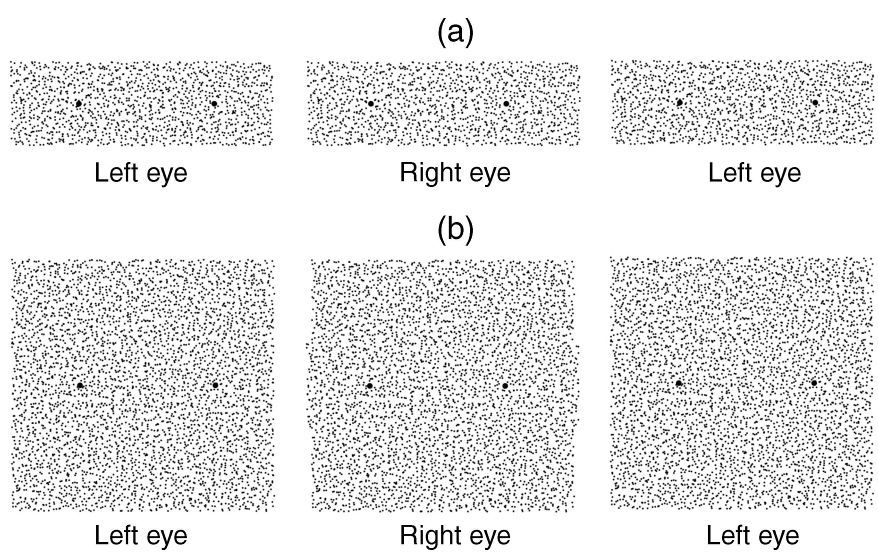

Figure 5. Stereograms of Experiment 2 stimuli (examples). The two large circles in each image are the probes, which were in front of a slanted rectangular surface. (a) The slanted surface alone. (b) The same surface with frontal plane rectangles abutting the top and bottom edges. Only the smallest surface height is shown (2.2°). Left pair for uncrossed fusion and right pair for crossed fusion.

the disparities of the two probes relative to the surface regions directly behind them were 10.9′ and 20.7′ in the 4% slant condition and 5.9′ and 25.7′ in the 8% slant condition.

The central surface, which was stereoscopically slanted, was presented with (Figure 5b) or without (Figure 5a) a pair of flanking surfaces, which were stereoscopically in the frontal plane. The flanking surfaces were 2.2° high and 6.85° wide with surface texture generated in the same way as the texture on the slanted surface. The flanking surfaces were vertically aligned with the central surface with a disparity that matched that of the center of the slanted surface. One of the flanking surfaces abutted the upper edge of the slanted surface and the other abutted the lower edge of the slanted surface.

The central surface had one of four heights (2.2°, 4.4°, 6.6°, or 8.8°), two directions of slant (left side nearer and right side nearer), two slant magnitudes (26° and 45°), and two configurations (with or without flanking surfaces). Additionally, the probes were presented in one condition without any background surface. The task for this probes-alone condition was otherwise the same as in the conditions with background. Each of the conditions was presented between 7 and 10 times in a random order.

Observers were instructed to adjust the depth of the probes so that they appeared equidistant relative to the observer. Bracketing around the PSE was encouraged. The left arrow key increased the disparity of the left probe in the near direction and increased the disparity of the right probe in the far direction. The right arrow key shifted the disparity of the probes in the opposite direction, so that the left probe appeared to recede in depth while the right probe appeared to move nearer. No feedback was provided. At the beginning of each trial, the relative disparity of the probes was randomly selected within the range of −6 to +6 arcmin. The observer ended the trial by pressing the space bar key and the relative disparity of the probes was recorded.

Data were collected from each observer in two 1-h sessions, which were conducted on different days separated by no more than a week.

Observers

Seven undergraduates from the first year subject pool at the University of New South Wales participated. They were naive concerning stereoscopic vision and the aims of the experiment.

Results

Figure 6 shows the mean PSE of the probes as a function of the height of the central surface for each condition as well as the PSE for the probes alone (shown as zero on the x-axis of Figure 6). The relative disparity of the probes was coded to be positive when the left probe

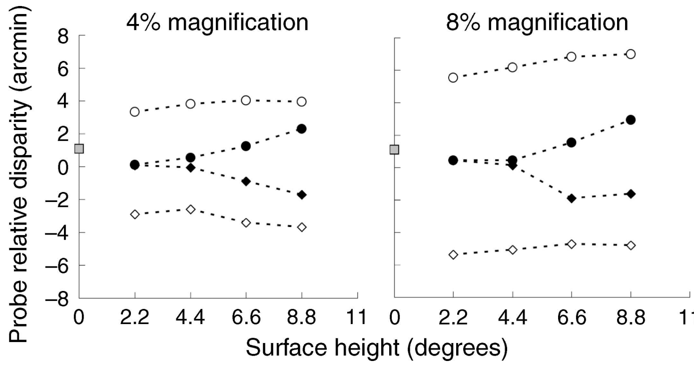

Figure 6. Group data for Experiment 2. Mean PSE of the probes as a function of surface height. Open symbols show the central-surface-alone condition (Figure 5a) and closed symbols show the central-surface-plus-flankers condition (Figure 5b). Circles and diamonds show left side closer and right side closer slants, respectively (N = 7). Errors bars are not shown because they are inappropriate for correlated data (Cumming & Finch, 2005).

was stereoscopically closer than the right probe and vice versa. For the probes alone, there was a slight bias in that at PSE the left probe was set to be stereoscopically slightly closer than the right (disparity of 1 arcmin). When the central stereoscopically slanted surface was present without flankers, there was a strong bias in the PSE of the probes, as expected. When the surface was slanted so that its right side was stereoscopically nearer (diamonds in Figure 6), the right probe had to be stereoscopically nearer than the left probe for them to appear equidistant. The opposite was the case when the surface was slanted left nearer (circles in Figure 6). This bias remained strong as the height of the slanted surface increased. When frontal plane flanking surfaces were added to the central surface, the probe bias was very strongly reduced (solid symbols in Figure 6). The bias was effectively eliminated when the central surface was short and, hence, when the gradient of relative disparities between the central and flanking surfaces was vertically close to the probes. As the central surface increased in height and the flanking surfaces were increasingly distant from the probes, the probe bias increased, thus showing that the flankers were having less effect. However, a reduced bias in the presence of the flanking surfaces persisted even when these were separated vertically by 4.4° from the probes.

The results were analyzed using a multivariate analysis of variance with planned orthogonal contrasts. The Decision-Wise error rate (α = 0.05) was controlled for each of the contrasts. The sign of the alignment settings for the left side closer slants was reversed so that the expected direction of the bias was the same for both directions of slant. The main effect of the presence/absence of flanking surfaces was significant ($F_{(1,6)}$ = 29.04). The main effect of magnification magnitude was significant ($F_{(1,6)}$ = 7.11). The main effect of linear trend for surface height was significant ($F_{(1,6)}$ = 76.00). The main effect of direction of slant ($F_{(1,6)}$ = 0.90) was not significant. The interaction between the main effect of presence/absence of flanking surfaces and the main effect of linear trend was significant, indicating that the bias increased with surface height to a greater extent when the flanking surfaces were present ($F_{(1,6)}$ = 16.36). The flanking surfaces reduced the bias more for the 8% than the 4% magnification ($F_{(1,6)}$ = 49.66).

Discussion

A strong reduction in probe bias was found in the presence of frontal plane flankers. Bias increased (with probe PSE becoming less accurate) as the central surface height increased, thus moving the flankers farther away from the probes. As for Experiment 1a, we attribute the effect of the flankers to a gradient of relative disparities that increases the apparent slant of the central surface. However, even at a 4.4° separation, the addition of flankers still reduced the bias appreciably. This would seem to indicate that, starting at the horizontal boundaries, the slant effect propagates vertically along the surface, with a weakening of this effect as the vertical distance of the boundaries from the center of the surface increases. Thus, the effect of the flankers on the probes would be mediated by their effect on the central surface. It is possible, however, that the flankers may have acted directly on the probes. Since the flankers were in the frontal plane, seeing probe PSE relative to them would reduce the bias. This possibility would involve giving some direct influence to more remote reference surfaces even in the presence of a more proximal surface, with this influence diminishing with the distance of the remote surface from the probes. Whichever explanation is correct, the results of this experiment reinforce the conclusion from Experiment 1a that it is not sufficient to speak of a single reference surface for determining the depths of detached points in space. Experiment 3 was designed to throw additional light on the processes by which more remote surfaces transmit an influence to the PSE settings of detached probes.

Experiment 3

This experiment examined the effect on probe bias of reversing the slant relations of Experiment 2 using the same textured surfaces. The central surface (if present) was in the frontal plane and the flankers were slanted. It was expected that a central frontal plane surface would exhibit slant contrast in the presence of slanted flankers placed above and below it (Brookes & Stevens, 1989; Gillam & Blackburn, 1998; Gillam et al., 1984; Graham & Rogers, 1982; Pierce, Howard, & Feresin, 1998; van Ee, Banks, & Backus, 1999; van Ee & Erkelens, 1996a, 1996b). The issue of interest to us is whether the probes have a bias when seen against a surface with no surface disparity gradient whose slant is produced by contrast. In Experiments 1a, 1b, and 2, we concluded that the probe bias was due to a perceptual underestimation of the stereoscopic slant of the surface against which the probes were seen. It might also be possible to induce a probe bias by causing a frontal plane surface to appear slanted via slant contrast. In another condition, we examined probe bias with the same slanted flankers but no intervening central surface; we were thus able to examine the effect of flankers alone, at various separations from the probes, on probe PSE—an issue of interest in itself and also relevant to the possible interpretation of the results of Experiment 2 as a direct effect of the flankers.

Methods

Examples of the conditions are shown as stereograms in Figure 7. The separation of the stereoscopically slanted flankers from the probes was varied, and the space between them was either (a) blank (no central surface), (b) filled with a central surface in the frontal plane (which varied in height to maintain abutment with the flankers as flanker separation increased), or (c) blank except for a centrally placed frontal plane surface of constant height (which became increasingly separated from the flankers as they increased in separation). These stimulus variations allowed us to examine the possible effect on the PSE of placing different mediating surfaces within the gap between the flankers.

Stimuli

The flanking surfaces were stereoscopically slanted by magnifying one eye's image by 6%, consistent with a slant of 37°. The probes were situated as in Experiment 2: 2.06° to the left and right of the center of the images. When the probes were in the frontal plane, the disparity of each probe relative to the surface region directly behind it was 8.4 arcmin for one probe and 23.2 arcmin for the other. As in Experiment 2, the horizontal edge of each of the flanking surfaces was vertically separated from the probes by 1.1°, 2.2°, 3.3°, or 4.4°. Thus, in the condition where the region between the flankers was filled (Figure 3b), the height of the central surface varied and always had the same vertical dimension as the separation of the flankers. In the condition with a constant central surface (Figure 3c), its height was always 2.2°, with the surface placed centrally within the gap between the flankers. At the smallest flanker separation (2.2°), constant height and variable height conditions were identical. At the greater flanker separations, a gap of either 0.55°, 1.1°, or 2.2° separated each edge of the central surface from a flanking surface. The flankers-only condition (Figure 3c) lacked a central surface, so the probes were seen against a white background.

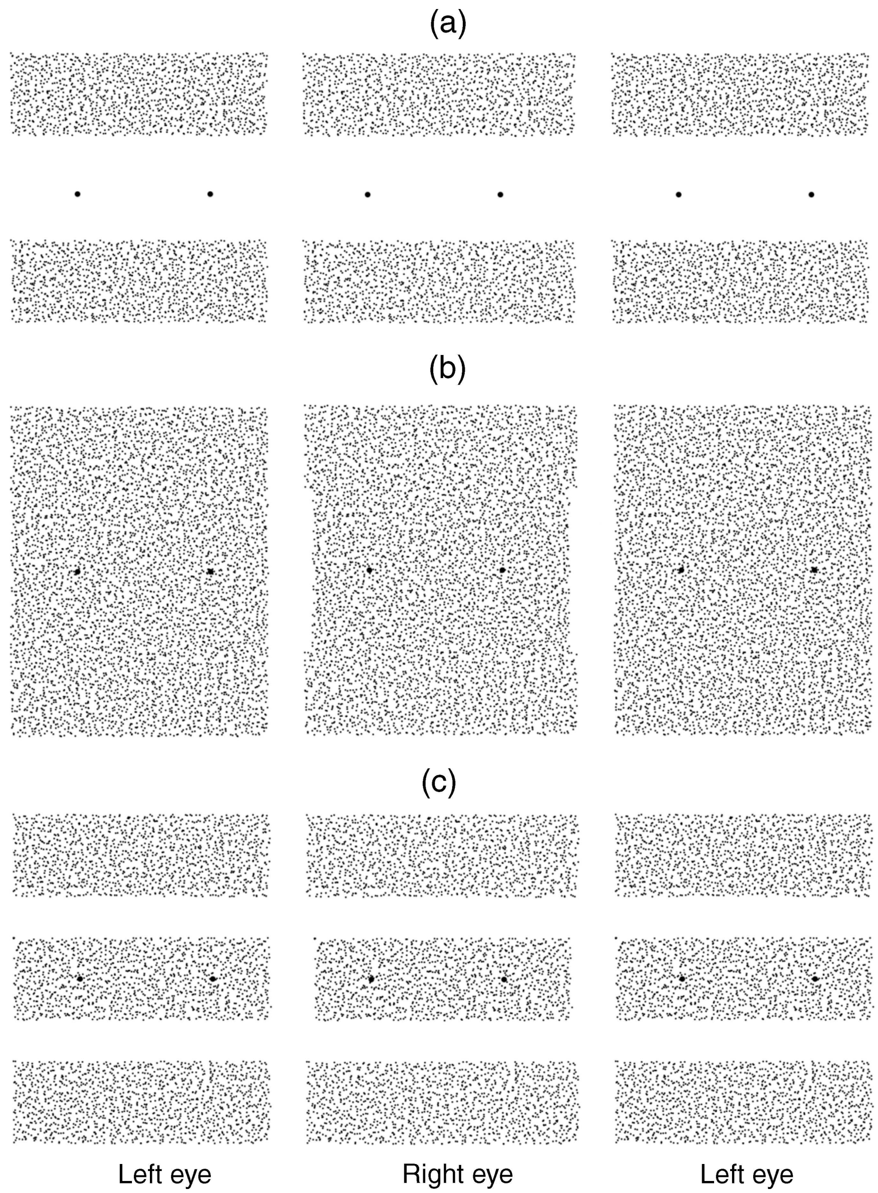

Figure 7. Some examples of Experiment 3 stimuli drawn to scale and shown as stereograms (the middle and right images are for crossed fusion and the left and middle images are for uncrossed fusion). Slanted rectangles (flankers) were presented above and below the probes. (a) The central rectangle was omitted so the probes were seen against a white background. (b) The probes were presented against a frontal plane rectangle that had variable height abutting the flankers. (c) The central rectangle was always 2.2° high so a gap separated each flanker from the central rectangle.

Procedure

The three stimulus configurations, combined with four flanker separations and two directions of slant, as well as a probes-alone condition, were each presented in random order at least 5 times. (Two observers completed 7 and 9 trails per condition in the same time period.) The procedure was otherwise the same as described in Experiment 2.

Observers

Ten undergraduates studying at the University of New South Wales participated. They were naive with respect to stereopsis and to the basis of the experiment.

Results

Unlike the case in Experiment 2, three of the 10 observers had very large average standard deviations (3.3, 3.8, and 4.2 arcmin) compared to the remaining seven observers who had similar small average standard deviations (1.4, 1.5, 1.8, 1.9, 1.9, 2.0, and 2.0 arcmin). The following analysis excluded the three highly variable observers (although this did not make much difference to the mean results). The mean data for the remaining seven observers are shown in Figure 8. The bias in the probes-alone condition is shown at the zero position on the *x*-axis. The mean probe PSE settings, as a function of the vertical

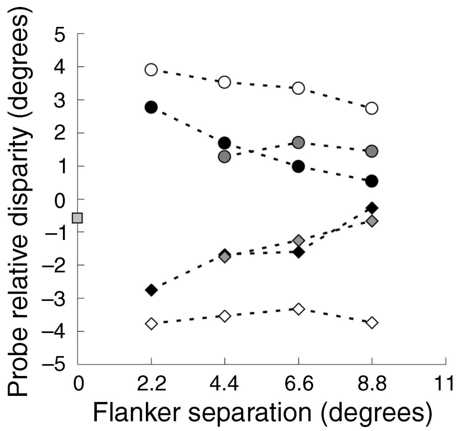

Figure 8. Group data for Experiment 3. Mean PSE of the probes as a function of flanker separation. Open symbols show the slanted flankers-alone condition. The black and gray symbols show the conditions where a frontal plane surface intervened between the flankers. The intervening surface either abutted the flankers (black symbols) or was separated from the flankers by a gap (gray symbols). Circles and diamonds show left side closer and right side closer flanker slants, respectively (N = 7).

separation between the flanking surfaces, are shown for the three surface conditions. As in Experiment 2, the relative disparity of the probes was coded to be positive when the left probe was placed stereoscopically closer than the right probe. There was a small bias when the probes were presented alone. At PSE, the right probe was set to be slightly closer than the left (disparity of 0.5 arcmin).

When the slanted flankers were present without a central surface, there was a large bias in the frontal plane settings of the probes. This varied little with flanker separation. When the flanking surfaces were stereoscopically slanted with the left side nearer, the probes appeared in the frontal plane when the left probe was nearer than the right probe. The opposite was the case for right side nearer. The bias extended to a flanker–probe separation of over 4° when no surface intervened between the flankers. This bias was considerably reduced, however, when a frontal plane surface intervened. Under these conditions, the bias was large for small flanker separations and diminished as flanker separation increased. This was true whether the intervening surface was of constant height or extended vertically to fill the space between the flankers.

The data were analyzed by means of a multivariate analysis of variance with planned contrasts. The sign of the alignment settings for the left closer slants was reversed so that the expected direction of the bias was the same for both directions of slant. Since the contrasts were not all orthogonal to each other, the number of contrasts correlated with a given contrast was used to perform a Bonferroni adjustment of the α level ($\alpha = 0.05$). Comparing flankers alone and the condition with a central surface of variable height, there was a significant main effect of presence/absence of the central surface ($F_{(1,6)}$ = 46.01). The main effect of the linear trend of flanker separation ($F_{(1,6)}$ = 28.36) was significant, whereas the main effects of side ($F_{(1,6)}$ = 0.04) and quadratic trend ($F_{(1,6)}$ = 0.25) were not significant. There was a significant interaction between the main effect of linear trend and the main effect of presence/absence of the central surface, indicating that the bias decreased with flanker separation/surface height to a greater extent when the central surface was present ($F_{(1,6)}$ = 12.85). The comparison between the two central surface conditions (constant height and variable height) across corresponding flanker separations (4.4°, 6.6°, 8.8°) was not significant ($F_{(1,6)}$ = 2.33). Averaged across these two surface conditions, the linear trend for flanker separation was significant ($F_{(1,6)}$ = 15.82), whereas the main effects of quadratic trend ($F_{(1,6)}$ = 0.67) and side ($F_{(1,6)}$ = 0.01) were not significant.

Discussion

Without a central surface, the slanted flankers produced a bias in the probes. When the flanking surfaces were stereoscopically slanted with the left side nearer, the probes appeared equidistant when the left probe was nearer than the right probe, and vice versa. There was an approximately constant effect of the flankers on probe bias as their separation increased up to 8.8° such that each flanker surface was 4.4° from the probes. The approximate constancy of the effect of flankers on bias with their separation from the probes is relevant to the interpretation of Experiment 2. The increasing probe bias found in Experiment 2 with increasing central surface height and consequent flanker separation is very unlikely to have been due to a diminishing direct effect of the flankers on probe bias, since we found no such diminishing effect in Experiment 3 when we presented the flankers without a central surface. It is possible that the *direct* influence of flankers for a given separation is different when other surfaces intervene or that frontal plane flankers (Experiment 2) act differently as a framework from slanted flankers (Experiment 3). We consider both of these possibilities unlikely. We conclude that the increasing bias we found with increasing surface height in the flanker conditions of Experiment 2 resulted from the increasing separation of the gradients of relative disparity produced by the flankers (which diminished perceived slant) and was not due to the separation of the flankers themselves.

In Experiment 3, a different flanker effect was found when a mediating frontal surface was present. Only with a mediating surface between the flankers did the bias decrease strongly with flanker separation. We attribute this to the effect of the flankers on the mediating surface and indirectly on the probes. It is interesting that this decrease in bias with flanker separation was the same for the mediating surfaces of constant height and of variable height. The decrease in the bias for the variable height surface, with abutting central surface and flankers, was presumably determined by a diminishing effect of the gradient of relative disparities at the boundary as the surface becomes taller, possibly because in that case the boundary becomes more eccentric in the visual field when observers are concentrating on the probe task. A similar effect of surface height was also shown in Experiment 2 using a slanted central surface and frontal plane flankers. The effect of the boundary diminished with its vertical distance from the probes. For the short constant height central surface in Experiment 3, the contrast effect presumably diminished as the separation of the flankers increased because separating the central and flanking surfaces attenuated the boundary slant signal itself. Gillam and Blackburn (1998) showed that the slant contrast effect on a frontal plane surface as well as the slant enhancement of a slanted surface diminished as two surfaces in a twist configuration were separated along their central vertical axes. Nevertheless, they found some contrast effect up to the maximum separation they tested, which was 2°.

Experiment 3 shows very clearly that the relative depth of individual elements cannot be accounted for by considering only their disparities relative to a local reference surface. Were that the case there would have been no probe distortion in Experiment 3 where the immediate reference surface was in the frontal plane. The distortion was produced by a contrast effect from neighboring surfaces.

The large bias for the flanker-only conditions was largely unabated at the largest flanker–probe separation tested (4.4°). Local relative disparities were absent in this condition, which resembles the experiment of Kumar and Glaser (1991). These authors found that a stereoscopically slanted frame 12.44° wide and 9.36° high could produce a bias in the PSE of centrally placed dots within the frame.

The large bias for the flanker-only conditions raises the possibility, as in Experiment 2, that a direct effect of the flankers on the probes contributed to the bias in the slant contrast conditions. However, as already indicated we do not believe that a direct effect of the flankers can account for the bias in the slant contrast conditions, because this bias showed a strong dependency on flanker separation, which was not exhibited by the flankers-alone condition. The critical factor is the relationship between the flankers and the mediating surface as discussed above.[6]

Given that the bias in the flankers-alone condition is unchanged across a large range of probe–flanker separations, it is interesting that the boundary discontinuity effect diminishes comparatively rapidly with separation of the boundary from the probes. This suggests two separate influences exerted by context on relative stereoscopic depth that depends differently on distance. Both the Kumar and Glaser (1991) effect and our result for the flankers-alone condition suggest that a normalization of slant occurs for a framework that extends a more or less undiminished influence on isolated objects over considerable distances. On the other hand, the results with mediating surfaces suggest that relative slant information (such as occurs at surface discontinuities) exerts an influence on the depth of isolated objects that is strongly dependent on distance.

General discussion

Our data support other data (Glennerster & McKee, 1999, 2004; Gogel, 1972; Mitchison & Westheimer, 1984) indicating that the stereo depth of individual points is encoded relative to a reference surface. Glennerster and McKee (2004) argued that encoding disparities with reference to a surface allows these disparities to be specified in a manner that is invariant with head movements or surface slant. He and Ooi (2000), who found a biasing effect on the PSE of probes placed on a stereoscopically slanted illusory rectangle, argue that locating objects on a surface converts a complex set of depth comparisons between diverse objects into a basically 2-D comparison (coordinates relative to the X and Y dimensions of the surface). They do not deal with the situation in which the probes do not lie on the surface. This would presumably involve a 3-D description (X, Y, and Z coordinates with respect to the surface). These are useful points about the advantages of a single reference surface. Our data indicate, however, that the concept of a single reference surface is not sufficient. A surface is not usually isolated. Its perceived slant and its role as a reference surface may be strongly influenced by its stereoscopic and perspective context.

Another important point arising from our data is that different kinds of stereoscopic interactions may operate differently with respect to stimulus separation. We suggest that the normalization of stereoscopic frameworks (which is not based on relative information) may operate over long distances (rather like the influence of a tilted room on the apparent orientation of a bar straight ahead of the observer). On the other hand, slant interactions from surface to surface, which are essentially relative in nature, may be more restricted in the distances over which they have an influence; this is especially true when gradients of relative disparity are involved, as in the twist configurations used in our experiments.

The effect on probe PSE of the gradient of relative disparity at the surface boundaries in both Experiments 2 and 3 diminished with their vertical distance from the boundaries. Nevertheless, the effects of such boundary slant information can clearly spread across a surface to some extent, influencing the depth of objects seen against parts of the surface well away from the boundaries. Just how the slant information at surface boundaries extends across the surface remains to be explored. It is interesting to note that all the surfaces in our experiments appeared planar.

Overall, our results show that the stereoscopically perceived relative depth of objects can be mediated by their common background surface or by more remote surfaces acting directly on the objects themselves. We also show that the perceived relative depth of objects can be strongly influenced by manipulating the perspective of the background surface or by remote surfaces acting (contiguously or non-contiguously) on the background surface. Such secondary influences, mediated by the background surface, have not, to our knowledge, been demonstrated previously. This resembles the use of a common background such as the ground plane to establish spatial relations among individual objects that are in contact with the ground (Gibson, 1950) or are in contact with other surfaces whose spatial relations are in turn determined by their contact with the ground (Meng & Sedgwick, 2001, 2002). In the stereoscopic case, however, local disparity can establish the relation of an object to its background, so that physical contact is not necessary for a background to be useful in relating isolated objects.

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Footnotes

[1]There are a number of proposed explanations for the underestimation of stereoscopic slant around a vertical axis including the inadequacy of compression as opposed to shear transformations (Gillam et al., 1988; Rogers & Graham, 1983) and the ambiguity of horizontal gradients of disparity with respect to slant/head position (Erkelens & van Ee, 1998; Mitchison & Westheimer, 1984).

[2]This is not just a slant contrast effect since the same slant enhancement does not occur when a stereoscopically frontal surface is placed *beside* the stereoscopically slanted one in a "hinge" configuration (Gillam et al., 2007, 1988).

[3]PSEs were obtained by fitting a logistic function to the data using the *psignifit* toolbox (version 2.5.6) for Matlab, which implemented the maximum likelihood method (Wichmann & Hill, 2001).

[4]The bootstrap method (15,000 simulations) was used to calculate 95% confidence intervals shown in Table 1b. The appropriate Bonferroni correction of the alpha level was applied ($\alpha = 0.05 / 2$).

[5]The increases in precision we found in the presence of a textured background agree with the findings of Glennerster and McKee (1999). However, Norman and Todd (1998) reported a decline in the precision of relative depth judgments for small disparate areas when these were placed on the surfaces of complex randomly shaped objects. This may be related to a difficulty of integrating local disparities on complex curved surfaces.

[6]An anonymous reviewer has suggested that the influence of the flankers on the probes in the "no central surface" condition may be mediated by a stereoscopically interpolated surface stretching continuously between the two flankers. However, we see no hint of an interpolated surface in either our actual display or in our illustration of it. Furthermore, we would not expect to see an interpolated surface in our display because its configuration does not closely resemble any configurations that, to our knowledge, have been reported to produce stereoscopic surface interpolation (see Wilcox & Duke, 2005).

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