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Interaction of Stereo, Texture and Outline Cues in the Shape Perception of Three-Dimensional Ridges

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We report five psychophysical experiments that employed a cue conflict paradigm to investigate integration by the human visual system of surface shape information from stereo, texture and outline cues.† The experiments used convex parabolic and triangular three-dimensional ridge stimuli, with amplitudes (base to peak) in the range 3–9 cm, viewed from 57 cm. The observers' task was to judge ridge amplitude using a scale of two-dimensional drawings of ridge profiles. Cue integration was studied using both vertically and horizontally oriented ridges and both real ridges and stereograms of ridges. The main findings were: (a) stereo strongly dominated all horizontal ridge stereograms; (b) texture and outline cues strongly dominated low (3–6 cm) but not high (9 cm) amplitude vertical ridge stereograms; (c) stereo strongly dominated all real ridge stimuli. These results are evidence against explanations of the vertical/horizontal stereo anisotropy which propose that it derives from stereo mechanisms being tuned only to disparity cues with non-zero second-order spatial derivatives or to disparity discontinuities. They also show that radically different results can be obtained when stereo mechanisms are explored using stereograms and real surfaces and possible reasons for this are discussed.

Stereopsis Texture Cue integration Stereo anisotropy

INTRODUCTION

The past two decades have seen a great deal of psychophysical and computational research on depth cues considered in isolation one from another. Many so-called *shape from ... stereo, texture, motion, shading, contour* algorithms have now been described. One strength of these algorithms is that each is designed to be implemented as an independent process, thereby admirably satisfying the *principle of modular design* (Marr, 1981). Nevertheless, an important issue raised by these algorithms is how their outputs are to be integrated, or indeed whether some *shape from* ... modules might be designed to specialize in processing two or more cues concurrently, with information from one cue fully integrated from the outset in the processing of another. For reviews of the recent depth cue integration literature see Bulthoff and Mallot (1987, 1988), Bulthoff (1991) and Aloimonos and Shulman (1989).

In the present paper, we report five psychophysical experiments that measured observers' perceptions of the amplitude of three-dimensional ridges (amplitude range 3–9 cm, all viewed from 57 cm; see Figs 1 and 2 for our definitions of ridges). We used a cue conflict paradigm in which stereo was pitted against a combination of texture and outline depth cues (the latter two always signalling the same ridge amplitude). Cue conflict has often been used before to investigate disparity processing mechanisms (for a review, see Stevens & Brookes, 1987, 1988) but there were several distinguishing features in our use of this paradigm.

First, we set out to investigate what we hoped would prove to be small cue conflicts. The largest conflict studied was a difference of 6 cm in ridge amplitude (*ca* 10% of viewing distance) and generally it was much less than this. This maximum meant that the difference between slants of the steepest tangent planes to the ridges signalled by each cue was no greater than about 20°. We have previously discovered evidence that stereo and texture cues are pooled for this range of horizontal planar surface slants whereas larger conflicts can give rise to a species of rivalry in which one or other cue dominates at any given moment (Buckley, 1988; Buckley, Frisby & Mayhew, 1988; Buckley, Frisby & Spivey, 1991). This outcome indicates the existence of mechanisms that pool data about three-dimensional

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†If a rectangular lamina is rotated out of the fronto-parallel plane then the retinal projections of its perimeter are trapezoidal. We follow Clark, Smith and Rabe (1956) in using the term *outline cue* for this type of depth information. The kind of outline cue that was present from our three-dimensional ridges can be seen in Fig. 1.

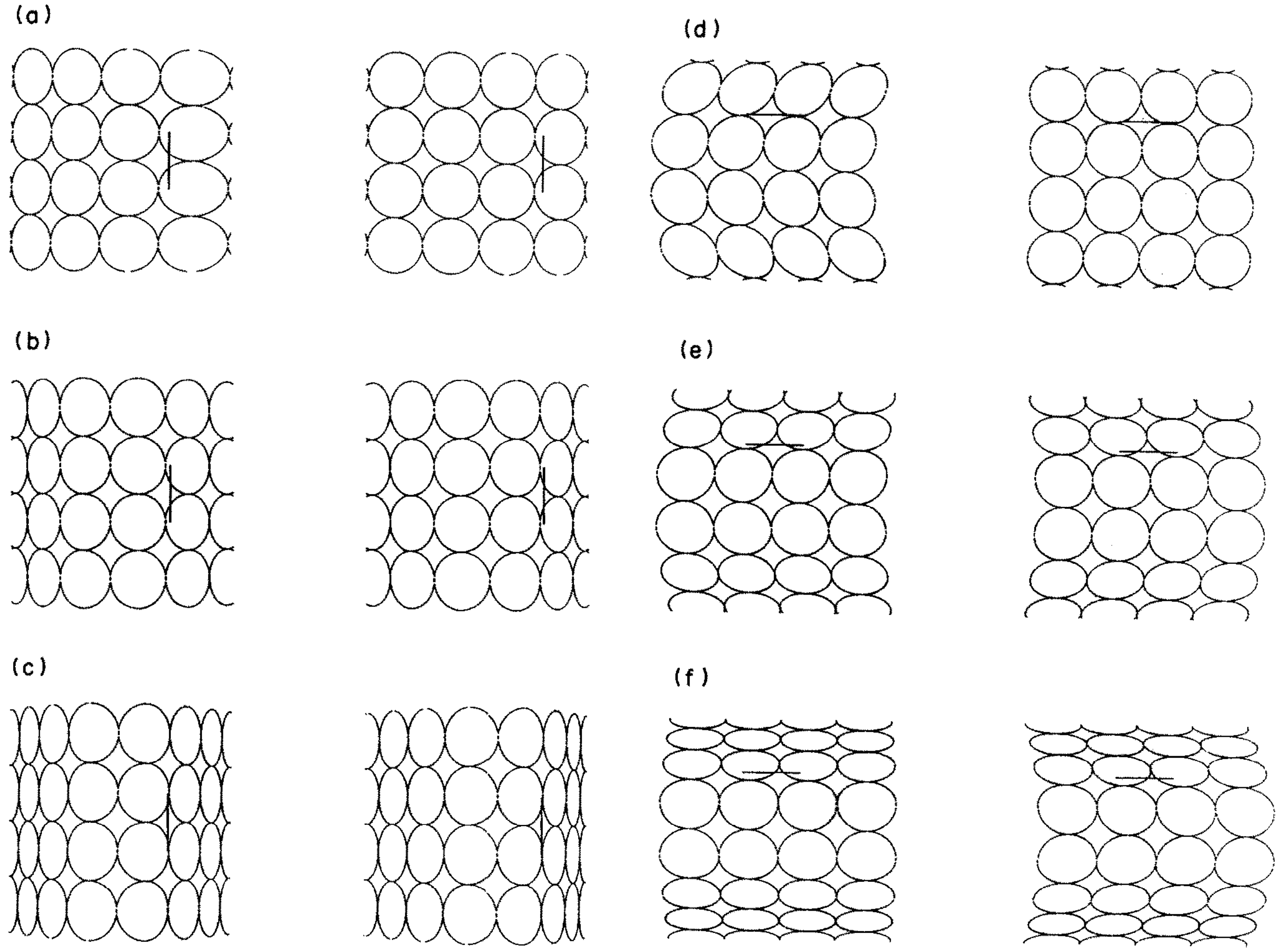


FIGURE 1. Ridge stereograms with parabolic depth profiles similar to those used in Expt 1, arranged for cross-eyed fusion. The requirements of this form of viewing mean that the stimuli are not exact replicas of those used in the experiment but they are sufficiently similar to give a realistic impression of what observers saw. The texture and contour cues are appropriate for a viewing distance of 57 cm. The short straight lines are to help prevent incorrect fusions (see text, but note that in the experiment they were placed at the peaks of the ridges). (a–c) Vertical ridges. (d–f) Horizontal ridges. In all six stereo-pairs the stereo cue remains constant (i.e. portrays the same ridge amplitude). In (b) and (e) the stereo and texture/outline cues are consistent. In (a) and (d) the texture/outline cues signal a lower ridge amplitude than stereo, which is itself set to the same amplitude as in (b) and (e). Conversely, in (c) and (f) the texture/outline cues are signalling a higher ridge amplitude than stereo. If the reader observes the same type of vertical/horizontal anisotropic cue interaction as the observers in the experiment, then the texture/outline cue will be seen to have a marked effect on the perceived amplitude for the vertical but not the horizontal ridges. Some highly practiced observers of difficult stereograms, however, including the second author, find that although they may experience strong domination by texture/outline cues on *initial* exposure to the vertical stereograms, with careful and sustained viewing they see as much depth build up over time as occurs from the outset for the equivalent horizontal stimuli.

shape from different cues only if those data are reasonably similar.* We aimed our experiments at studying possible pooling mechanisms of this type by keeping cue conflicts small.

A second distinguishing feature of our experiments was that they studied cue integration for ridges with both vertically and horizontally oriented axes. We have previously discovered a substantial surface orientation anisotropy in cue integration for planar surfaces. Using stereograms, the perceived slant of planes rotated around the horizontal axis was found to be roughly the average of the stereo and texture cues for small slant cue conflicts (range $0 \pm 20°$) whereas the texture cue tended to be dominant for planes rotated around the vertical axis (Buckley, 1988; Buckley *et al.*, 1988). This finding adds further weight to the evidence for a vertical/horizontal anisotropy for various aspects of stereo processing. For example, Rogers and Graham (1983) reported that a depth analogue of the Craik–O'Brien–Cornsweet illusion (Anstis, Howard & Rogers, 1978) was manifest when the cusp discontinuity was oriented vertically but not horizontally. Also, stereograms showing planar slants around a vertical axis often produce slant underestimates (e.g. Youngs, 1976) whereas this is not so likely for slants around horizontal (Buckley, 1988). A similar anisotropy in perceived depth has been noted for

*The limits on "similarity" implemented by such mechanisms would presumably be determined by the noise expected on each channel. An error model for the recovery of surface information from each cue would be required to arrive at a principled choice of "small" cue conflicts but such data are not available. Nor did we think it a sensible starting point to try to obtain them before establishing the general character of the cue integration observed for the ridge stimuli.

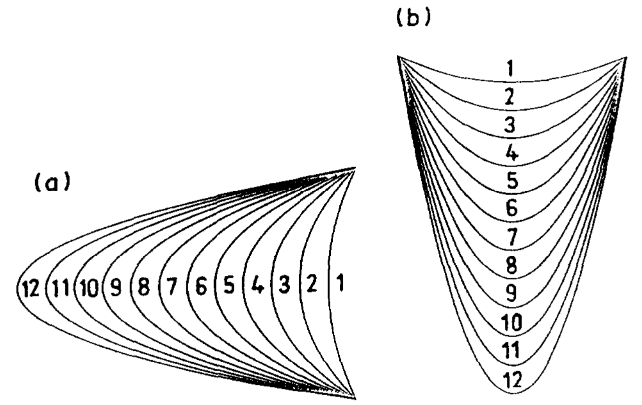


FIGURE 2. The response scales used by the observers in all the experiments involving parabolic ridges (not drawn to scale). (a) Was used for horizontal ridges, (b) for vertical. Note that in the experiments the bases of the scales were 8 cm across and each end of the base was fixed to be in line with the edges of the base of the surface in the stimulus, which were about 10 cm away. The parabolas had amplitudes of 1–12 cm in steps of 1 cm. The observer's task was to select a number guided by the scale that reflected perceived ridge amplitude, using intermediate numbers as appropriate. For Expt 3, which used triangular ridges, similar scales were used except that the parabolas were replaced by triangular ridge profiles.

vertical and horizontal cylindrical ridges although with wide individual differences (Rogers, Holmes & Cagenello, personal communication). Finally, longer latencies have been reported for detecting vertical planar slants than horizontal ones (Gillam, Chambers & Russo, 1988).

Third, Gillam, Flagg and Finlay (1984) suggested the importance of disparity change as the primary stimulus for stereoscopic processing, by way of explaining their observations of long perceptual latencies for vertical surfaces. Gillam *et al.* (1988) explored this idea further and noted that "relative disparity, unlike absolute disparity, does not change across a (planar) surface slanted around a vertical axis" (p. 173). Hence, they reasoned, long latencies for vertical surfaces might be explicable if the visual system generally relied on *changes* in relative disparity, having to fall back on highly non-local comparisons to extract surface slant if relative disparity information remains constant, as it does for vertical but not horizontal planar slants.* Stevens and Brookes (1987, 1988) have also suggested, from cue conflict studies, that stereo might in general be a stronger cue where the "surface exhibits curvature or edge discontinuities, i.e. where the second spatial derivatives of disparity are non-zero" (1987, p. 371). Stevens, Lees and Brookes (1991) report further data supporting this idea while also noting a "more complex interaction involving some measure of the consistency between the surface topography suggested by different cues" (p. 428). The idea that disparity processing pays particular regard to surface curvature or discontinuity features is an interesting notion and the main objective of the present study was to test it by exploiting the finding that texture strongly dominates stereo for vertical planar stimuli (Buckley, 1988). This result permitted us to ask the question: could stereo be made to play as strong a role as texture for vertical surfaces if disparity cues were provided with non-zero second-order spatial derivatives or a sharp discontinuity? This was achieved by comparing cue integration for vertical and horizontal three-dimensional ridge surfaces with parabolic and triangular depth profiles respectively.

Fourth, we were interested in checking whether observations made using stereograms were replicable using *real* three-dimensional ridges. Despite their many advantages, it is not always remembered that most stereograms are intrinsically depth cue conflict stimuli in which disparity is pitted against accommodation for at least some regions of the field of view. The likelihood of this being an important factor is increased by the synkinesis that exists in the disparity-driven and accommodation-driven control of vergence. Hence we used the cue conflict paradigm to investigate whether the operation of disparity mechanisms is different in natural viewing and stereogram viewing of putatively the same three-dimensional surface shape. As will become clear later, we find that in both cases taking into account the accommodation cue helps explain our data.

METHODS

We begin by describing methodology common to all experiments.

Stereogram display device

Observers were seated in a darkened room and viewed stereograms displayed as red/green anaglyphs on a high quality Mitsubishi (C3419-CELP) RGB monitor driven by a Pluto (Io Research Ltd) colour graphics system. The screen was viewed from approx. 57 cm through red and green filters mounted in a head-rest. A shutter close to the head-rest was used to obscure the monitor when stimuli were being loaded to the Pluto screen memory from a host SUN. The most distant edges of the 8×8 cm ($8 \times 8°$) ridges were arranged to appear in the plane of the screen and so only for those locations were the disparity cues fully in accord with accommodative vergence and accommodation cues. Head movements were restrained by tightly fitting head-rest which incorporated a chin-rest.

Surface texture

The surface texture elements used throughout were circles† of 2 cm diameter on the portrayed scene surface

*The idea remains well worth examination despite the report by Frisby, Bradshaw, Buckley and Crawford (1992) of a failure to find long latencies for vertical planes lacking discontinuities. Their experimental paradigm was different from that used by Gillam *et al.* (1984, 1988) but why these studies should have produced different findings is unclear.

†Circles were chosen because they present line segments of all orientations. Cagenello and Rogers (1990) and Rogers and Cagenello (1989) have reported that texture line orientation can have an effect on measurements of stereo thresholds for discriminating vertical and horizontal rotations from frontoparallel. Although the present experiments were suprathreshold, by ensuring that all orientations were present in all stimuli we hoped to circumvent this factor having an important bearing on our results.

(not on the screen). These circles projected into the two stereo images as ellipses whose shape was determined by the size of the stereo and texture cues present in any given condition (Fig. 1).

Arrangements of circles on the surface were of two types: "regular" or "jittered" (Figs 1 and 3 respectively). We started out with a regular lattice for Expt 1 in order to have the texture cue convey as strong a depth impression as possible. That is, we suspected the "virtual lines" formed by the junctions between circles in a regular lattice (Fig. 1) would enhance the effectiveness of the texture cue. However, the intrinsic stereo ambiguity of regularly repeating patterns on plane surfaces means they can be fused in many different ways (the *wallpaper illusion*). We doubted this was a serious hazard for our stimuli because there were always two sources of disambiguating information: the outline edges of the ridges and a short (1 cm) straight line inserted in each stimulus at the apex of the ridge and oriented along the ridge axis specifically to prevent this happening. Observers were asked to report if these short lines were ever seen as double, which would indicate incorrectly fused circle elements. This occurred only very occasionally, in which case the observer was asked to look away and then make a fresh attempt to re-fuse the display. But in addition to these precautions, in certain experiments we checked on the possible intrusion of a wallpaper illusion by testing whether the results were any different for a jittered texture layout which removes completely the ambiguity on which the wallpaper illusion depends.

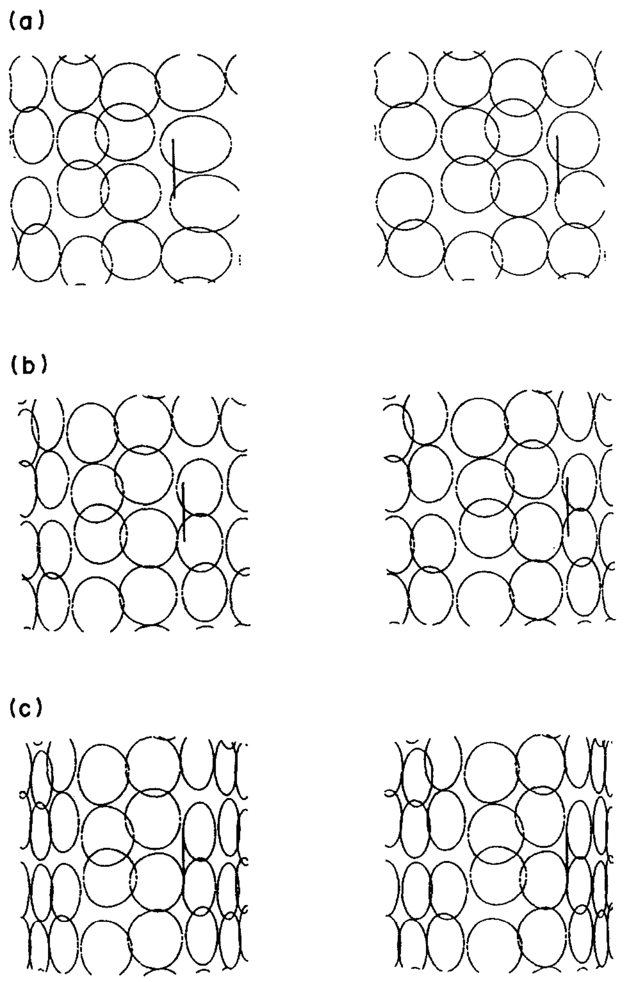


FIGURE 3. As for Fig. 1(a–c) but with jittered texture.

Stereogram generation

A computer graphics technique described by Ninio (1981) was used to create and store stereograms prior to the experiments. His method takes points lying on the desired binocularly-viewed scene surface and then computes perspective projections to create left and right stereo images suitable for the geometry of the stereoscopic apparatus. If texture elements are evenly distributed over the desired scene surface then this technique ensures that image projections contain geometrically-correct texture gradient cues to the required surface shape. The texture gradient and outline cues in the cue conflict conditions were controlled in the left eye's view only, with the imposition of the required stereo disparity cue then determining the positions of matching elements in the right eye's image.

The accuracy of the computer program for generating the stereograms was checked by comparing its output with video pictures of a sample of real ridges possessing the required surface texture and outline cues. No appreciable discrepancies were found.

Outline cues

Youngs (1976) found that outline shape had a strong effect on the perceived slant of a simple untextured stereogram of a quadrilateral: stereograms containing converging outlines were seen as more slanted than ones with parallel contours (see also Kumar & Glaser, 1992). This is a strong effect which also occurs for textured stereograms (Buckley, 1988). In the present experiments, the outline cue was arranged to convey the same amplitude information as the texture cue and hence it too was always manipulated only in the left image. Thus the cue conflict was always texture/outline vs stereo.

Ridge amplitude judgements

The observer was asked to judge the amplitude of the surface by matching it to one of a series of numbered depth profiles displayed in response scales (Fig. 2; cf. Todd & Akerstrom, 1987). These were mounted on a large matt black frontoparallel screen which surrounded the monitor. Observers were encouraged to use intermediate numbers on the scale if they wished to record intermediate judgements of perceived amplitude. The scales were positioned to the left of the display for the horizontal stimuli and below it for vertical stimuli.

Different ridge profiles (parabolic or triangular) were used in different experiments (Figs 1, 2 and 6) but in each case ridge amplitude was the only shape parameter varied.

It is worth noting that vergence eye movements were needed to fuse all the stimuli, given standard definitions of Panum's fusional limits (Boff & Lincoln, 1988), as the disparity ranges of the various amplitudes were as follows (in deg visual angle): 3 cm = 0.36°, 5 cm = 0.63°, 6 cm = 0.77°, 7 cm = 0.91°, 8 cm = 1.06° and 9 cm =

1.22°. Observers were free to scan the stimuli as they wished. It is reasonable, therefore, to assume that vergence movements were constantly being made, with data arising from local fusions established within Panum's limit contributing to the overall fused percept of the stimulus.

Real ridge stimuli

All experiments began by training the observer in the use of the amplitude response scales for a sample of accurate full-scale models of the kind of parabolic ridges portrayed in the experimental stereograms, with amplitudes 2, 4, 6, 8 and 10 cm (viewing distance to base of ridges was about 57 cm). These real ridge stimuli were made by bending cardboard bearing a print-out of a regular lattice of 2 cm diameter circles (cf. the texture used for the experimental stimuli) over a wooden former that was itself invisible to the observer. The only obvious differences between the resulting texture/outline cue and that for the anaglyphs were: (a) for these real stimuli the circles were dark on a white background, whereas contrast was reversed in the anaglyphs; (b) the outline cue was created by the real edge of the white card being seen against the black surround, whereas for the anaglyphs it was a subjective contour formed by the interrupted circle outlines (Fig. 1). Care was taken with the lighting of these real ridges to avoid shading depth cues.

Training with feedback on real ridges raises the possibility of the introduction of unwanted cognitive factors, such as observers learning fixed responses to stimuli rather than making judgements on what they see from trial to trial. We think this factor played a small part, if any, because the stereo and texture/outline cues were always consistent in training whereas in subsequent experimental trials only about 25% of conditions were consistent, so that at least 75% were seen only in the experimental runs. A further feature designed to avoid unwanted cognitive factors was that the consistent conditions in the experiment did not always overlap entirely with those used for training.

Observers

The 26 observers were unpaid volunteers aged between 22 and 26. All had normal or corrected to normal vision. Equal numbers of men and women were used in each experiment. With the exception of one observer in Expt 1, none had participated previously in psychophysical experiments using stereograms. Each observer served for only one experiment and each was screened for good stereopsis using the Titmus Randot Test (criterion for inclusion was stereoacuity of 30 sec arc or better). They were also tested on their ability to see depth in some anaglyph stimuli (consistent cues) before being launched into training.

Experimental design

All experiments used a fully repeated measures design, with presentations spread over a sequence of two or three experimental sessions, each lasting up to *ca* 40 min. Each observer was shown a different pseudorandom order of stimuli which avoided more than two successive presentations of the same amplitude level being carried by the same cue. Where different sessions were devoted to different kinds of stimuli, counterbalancing was used to control order effects. The interval between stimulus presentations was at least 30 sec. Two judgements of amplitude were collected per stimulus condition and the means of these were analysed using ANOVAs.

Experimental sequence

Each experiment had four stages.

(i) Observers were trained in the use of the amplitude response scales using the real ridge stimuli with amplitudes of 2, 4, 6, 8 and 10 cm. These training stimuli were presented at 57 cm in a separate apparatus against a matt black frontoparallel background on which were mounted copies of the response scales shown in Fig. 2. Training presentations continued until the criterion was reached of two correct scale choices with no intervening errors for each of the training surfaces.

Half of the observers were trained first on the vertical and then on the horizontal surfaces and half had the opposite order. The time to reach criterion varied between observers, but was usually about 10–15 min.

If the vertical/horizontal stereogram anisotropy in depth estimation were to be replicated to some degree in natural viewing, then some differences in performance might have been expected during training on the vertical and horizontal ridge models. It is therefore of interest to note that observers took roughly the same number of trials to reach criterion level for the two types of stimuli (in Expt 1, 16.7 and 14.7 trials were needed for the vertical and horizontal cases respectively; n.s. using the Wilcoxon matched pairs test). Moreover, inspection of individual responses did not suggest an initial tendency to underestimate appreciably the vertical ridges, which was then "trained away" by the feedback given.

(ii) Once the training criterion of accuracy had been attained the observer moved across the experimental room to the anaglyph apparatus. Half the observers viewed the vertical ridges first, half the horizontal ridges first. Four practice trials using two ridges with cues in accord were used to help the observers settle to the anaglyph judging task; data from these trials were discarded. They were instructed to use the response scales in the same way as in training on the real ridges. It was further impressed upon observers that the ridge amplitudes seen in training may not necessarily appear in the stereograms. To help ensure use of the correct scale, vertical or horizontal, the appropriate one for any given session was illuminated while the other was cast in shadow.

(iii) The third stage, which followed on smoothly from the second, comprised randomly-ordered *monocular* (left eye) presentations of the left halves of the eight stimuli whose cues were all in accord. These were therefore

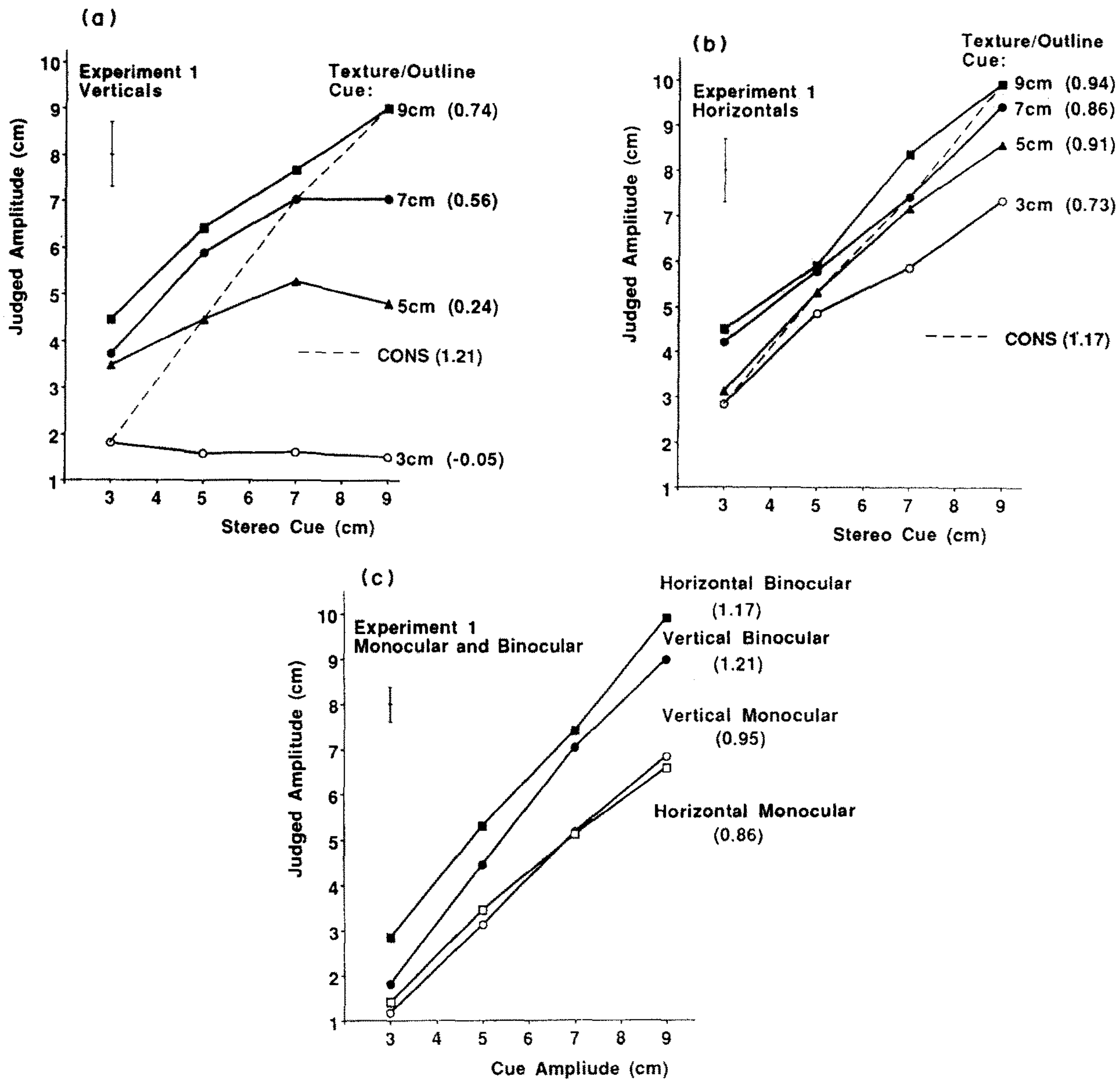


FIGURE 4. Group means from Expt 1 ($N = 6$). (a) Vertical and (b) horizontal parabolic ridges. The error bar at the top left corner of each graph is the mean of the 16 standard errors calculated for each of the means shown from the individual observer means. This bar therefore reflects differences between observers and not the error variation used in the various ANOVAs cited in the text, as they were repeated measures designs. (c) Means for the vertical and horizontal monocular judgements, together with, for easy comparison, the means of the binocularly viewed stimuli from (a) and (b) which had consistent texture/outline and stereo cues. In (c) the error bar is for the monocular means only. See text for details.

solely texture/outline presentations. Two readings were taken per stimulus. The observers then had a rest of at least 30 min.

(iv) The fourth stage was a repeat of the second using the reverse presentation order to collect a second judgement for each stimulus. It began with four practice trials of two of the stimuli for which cues were in accord and for which the data were again discarded.

The results of each experiment will now be described in turn. For brevity and clarity, the conditions used in each study are presented as a header. Although group means are presented throughout, checking each observer's data individually revealed that the group means were not misleading.

EXPERIMENT 1

Stereograms, Parabolic Profiles, Vertical and Horizontal Ridge Orientations, Amplitude Cues of 3, 5, 7 and 9 cm, Regular Texture

All permutations of the four levels of stereo and texture/outline cues were included, producing 16 stimuli for each ridge orientation (vertical and horizontal).

Figures 4(a, b) display the group means ($N = 6$) for the vertical and horizontal ridges respectively. Amplitude judgement is plotted on the ordinate, stereo cue amplitude is on the abscissae and the parameter is the level of the texture/outline cue. Alongside each line in parentheses is the slope of its best-fitting straight line.

These give an indication of the power of the stereo cue at each level of the texture/outline cue. The present experiments used inexperienced observers of stereograms (with one exception). Inspection of their individual data shows they all produced the general pattern of results shown in Fig. 4.

The dotted lines (labelled CONS) link together points arising from conditions in which the three cues were consistent. Points on each of the solid lines have the same level of the texture/outline cue and comprise one point from a consistent cue pairing and three from inconsistent pairings. If the observers had judged the consistent conditions veridically (i.e. as taught to do so in training on real ridges with consistent cues), then the dotted CONS lines should have had a slope of 1 and they should have passed through the 9/9, 7/7, 5/5 and 3/3 points. In fact, the consistent cue pairings produced judgements quite close to veridical but with some undershoot for shallow vertical ridges and some overshoot for steep horizontal ridges, producing slopes for both CONS lines of about 1.2.

Separate ANOVAs* for the two ridge orientations showed that both the stereo and texture/outline cues produced significant main effects in both cases. The vertical ridges, however, unlike the horizontals, also showed a significant interaction between the two cues. The smallest significant F for these tests was $F_{3,5} = 11.38$ ($P < 0.01$). These ANOVAs reflect the very different pattern of cue integration evident in Fig. 4(a, b) for the two ridge orientations. Stereo was by far the stronger cue for the horizontal ridges (slopes $\geqslant 0.73$), although the separations between the lines for the various values of the texture/outline cue show this cue had some effect on perceived ridge amplitudes. For vertical ridges, the picture is one of stereo being completely overwhelmed by the most shallow (3 cm) texture/outline cue, and then of a progressively greater influence of stereo (steeper slopes) as the texture/outline cue itself signalled higher ridge amplitudes. This picture is in keeping with Rogers (personal communication) who has found that the stereo anisotropy exists only for relatively shallow depth corrugations.

The question arises as to what the data would have looked like if they had been produced by an equal weighting of the two cues. One approach to answering that question is to generate predictions for the inconsistent cue conditions on the assumption that the judged amplitudes for the consistent pairings were determined equally by stereo and by texture/outline. As the CONS lines had slopes of about 1.2, this approach generates equal-weighting predictions of slopes of half that size for the solid lines (i.e. of about 0.6 for the present experiment). While the assumption on which this approach is founded can of course be questioned, it nevertheless provides a helpful baseline for judging the meanings of the slopes actually observed. It further emphasises the strong domination by stereo for the horizontal ridges (slopes generally much greater than 0.6). For the verticals the pattern was varied. There was complete domination by texture/outline for low levels of that cue. Stereo played an increasing role as the texture/outline cue itself was increased, until for the 9 cm texture/outline conditions stereo had a somewhat greater effect (slope = 0.73) than predicted on the assumption of equal weighting. The slope of 0.73 is caused by the fact that, when the stereo cue was signalling 3 cm, the 9 cm texture/outline cue failed to "pull up" perceived ridge amplitude as much as predicted by the equal-weighting hypothesis.

We find it remarkable that the vertical ridge conditions with a 3 cm texture/outline cue *showed no appreciable effect of varying the stereo cue, from 3 to 9 cm, despite these ridges being seen as non-planar*. Remarks volunteered by some observers when viewing the 3 cm texture/outline vs 9 cm stereo vertical ridge condition suggested that it caused "eye strain". Perhaps those observers found it difficult to produce the vergence shifts required for fusion of the disparate texture elements when the texture/outline cue was working strongly in the opposing direction, i.e. encouraging vergence positions close to the monitor screen. It is of interest to observe here that the cue of accommodation was working in the same direction as texture/outline in this cue pairing. We discuss further the possible role of accommodation in our experimental paradigm when we review results from all experiments. Meanwhile, we note that no "eye strain" difficulties were reported for any vertical ridges other than the 3 cm texture/outline vs 9 cm stereo conflict, nor for any horizontal stimuli. Also, despite these difficulties experienced by some observers, as far as we could judge all managed to fuse the vertical 3 cm texture/outline vs 9 cm stereo stereograms successfully before making their judgements. Observers were reminded throughout that they should achieve correct fusion before responding (see precautions described in the Methods section). We investigated this issue further in Expt 5.

We turn now to the monocular conditions. They were included to check that the texture/outline cue was effective when presented without stereo. Figure 4(c) displays the group means for the monocular conditions, along with the comparable (i.e. consistent cue) binocular conditions. The first point to observe in Fig. 4(c) is that the texture/outline cue was sufficient on its own to generate three-dimensional ridge perceptions, although the overall means for the monocular conditions were well below those for the equivalent binocular ones ($F_{1,5} = 62.48$, $P < 0.001$). This undershoot might have reflected the role of accommodation which was always signalling zero ridge amplitudes. A second point is that the means for the vertical cue-consistent binocular conditions fell below those for the equivalent horizontal ones, whereas this did not happen for the monocular data ($F_{1,5} = 7.75$, $P < 0.05$). This is an example of the depth underestimation aspect of the stereo anisotropy. The final point worthy of mention is that there was no significant

*Cited significance levels are those obtained after applying where necessary conservative epsilon corrections for departures from covariance homogeneity assumptions (Howell, 1987). For brevity and simplicity, F values are cited only for significant effects.

three-way interaction between the factors of vertical/horizontal ridges, monocular/binocular viewing and cue amplitude. This suggests that the anisotropy observed for cue integration in the cue-conflict stereograms was not caused simply by differences in the power of the texture/outline cue as a function of surface orientation, although it is unsafe to assume that the performance of a "monocular depth cue" under monocular viewing can be extrapolated straightforwardly to its role under binocular viewing.*

The main outcome of Expt 1 is evidence for a marked vertical/horizontal anisotropy in cue integration. The weakness of the stereo cue for vertical ridges when opposed by texture/outline is in keeping with previous demonstrations of stereo being relatively poor for vertical *planar* surfaces (Buckley, 1988; Buckley *et al.*, 1988). However, the fact that the anisotropy was observed here for *ridges* is evidence against theories which suggest it is dependent on the absence/presence of disparity cues with non-zero second spatial derivatives, or discontinuities.

Subsequent experiments sought to check the generality of this conclusion using different versions of the ridge amplitude judgement task.

EXPERIMENT 2

Stereograms, Parabolic Profiles, Vertical and Horizontal Ridge Orientations, Amplitude Cues of 5, 6, 7 and 8 cm, Regular and Jittered Textures

This study replicated Experiment 1 except for the following.

(a) The range of ridge amplitudes was reduced to 4 cm. The difficulties reported by some observers in Expt 1 for the 3 cm texture/outline vs 9 cm stereo condition led us to think that an amplitude difference of 6 cm may have posed too great a cue conflict for the kind of cue integration we had set out to study. The largest conflict in ridge amplitude employed in Expt 2 was thus set at 3 cm. No observer reported any difficulties in fusing these or any other conditions.

(b) Surface textures were of two types: regularly-arranged circles, as in Expt 1, and an irregularly-jittered layout of circles of the same size (Fig. 3). This factor was included because we were concerned that, when the texture/outline cue signalled a shallow amplitude, this encouraged observers to fuse the two stereo halves incorrectly, in the way that happens in the wallpaper illusion, notwithstanding the procedural precautions taken to the contrary (see Methods). Jittering the texture elements prevents incorrect fusions of the texture elements.

All permutations of the four levels of stereo and texture/outline cues were again included, producing 16 stimuli for each ridge orientation. Session time was lengthened (to *ca* 45 min) by the inclusion of the jittered texture conditions but, to help avoid observer fatigue, the monocular conditions were restricted to 5, 6, 7 and 8 cm for the jittered textures and 5 and 8 cm for the regular textures. The overall means for the regular and jittered textures were 5.73 and 6.07 cm respectively. This difference was not significant, nor did this factor produce significant interactions. Hence the group means ($N = 4$) shown in Fig. 5 are pooled over this factor.

The data were again analysed by ANOVAs. For the vertical ridges, the only significant result was the texture/outline main effect ($F_{3,9} = 22.49$, $P < 0.01$). Conversely, for the horizontals the only significant result was the stereo main effect ($F_{3,9} = 40.93$, $P < 0.001$). This is therefore an even stronger pattern of anisotropy than that found in Expt 1.

The conclusions we draw from Expt 2 are that the surface orientation anisotropy in cue integration observed in Expt 1 was not the outcome of using large cue conflicts, nor was it dependent on using regular textures.

EXPERIMENT 3

Stereograms, Triangular Profiles, Vertical and Horizontal Ridge Orientations, Amplitude Cues of 5, 6, 7 and 8 cm, Regular Textures

This study replicated Expt 2 except for one main difference: it used triangular instead of parabolic convex ridges (stereograms in Fig. 6). Its goal was to explore whether a sharp discontinuity in disparity would create a different pattern of cue integration. A further difference was that only regular textures were used in view of the absence of evidence from Expt 2 that jittered textures produced different results.

The group mean data ($N = 4$) are set out in Fig. 7. They show an identical pattern of anisotropy to that found in Expt 2. Thus, for the verticals only the texture/outline main effect was significant ($F_{3,9} = 20.69$, $P < 0.01$), whereas for the horizontals only the stereo main effect was significant ($F_{3,9} = 74.53$, $P < 0.001$).

ANOVAs comparing the regular-textures data of Expts 2 and 3 produced no significant interactions between the parabolic/triangular factor and any others. The only significant difference between these studies was in their overall means which were 5.73 and 4.55 cm for the parabolic and triangular ridge stereograms respectively ($F_{1,6} = 6.20$, $P < 0.05$). This suggests some weakening of the depth cues when presented as triangular ridges, rather than the strengthening expected if sharp disparity discontinuities were of special significance for stereopsis. The difference would however require further experiments to check its reliability before meriting further discussion.

The conclusion we draw from Expt 3 is that a triangular depth profile proved just as ineffective as a parabolic one in strengthening the stereo cue for vertical ridges.

*As this three-way interaction was non-significant in the monocular data of all experiments, we make no further reference to the monocular data although the monocular group means will be presented for each experiment.

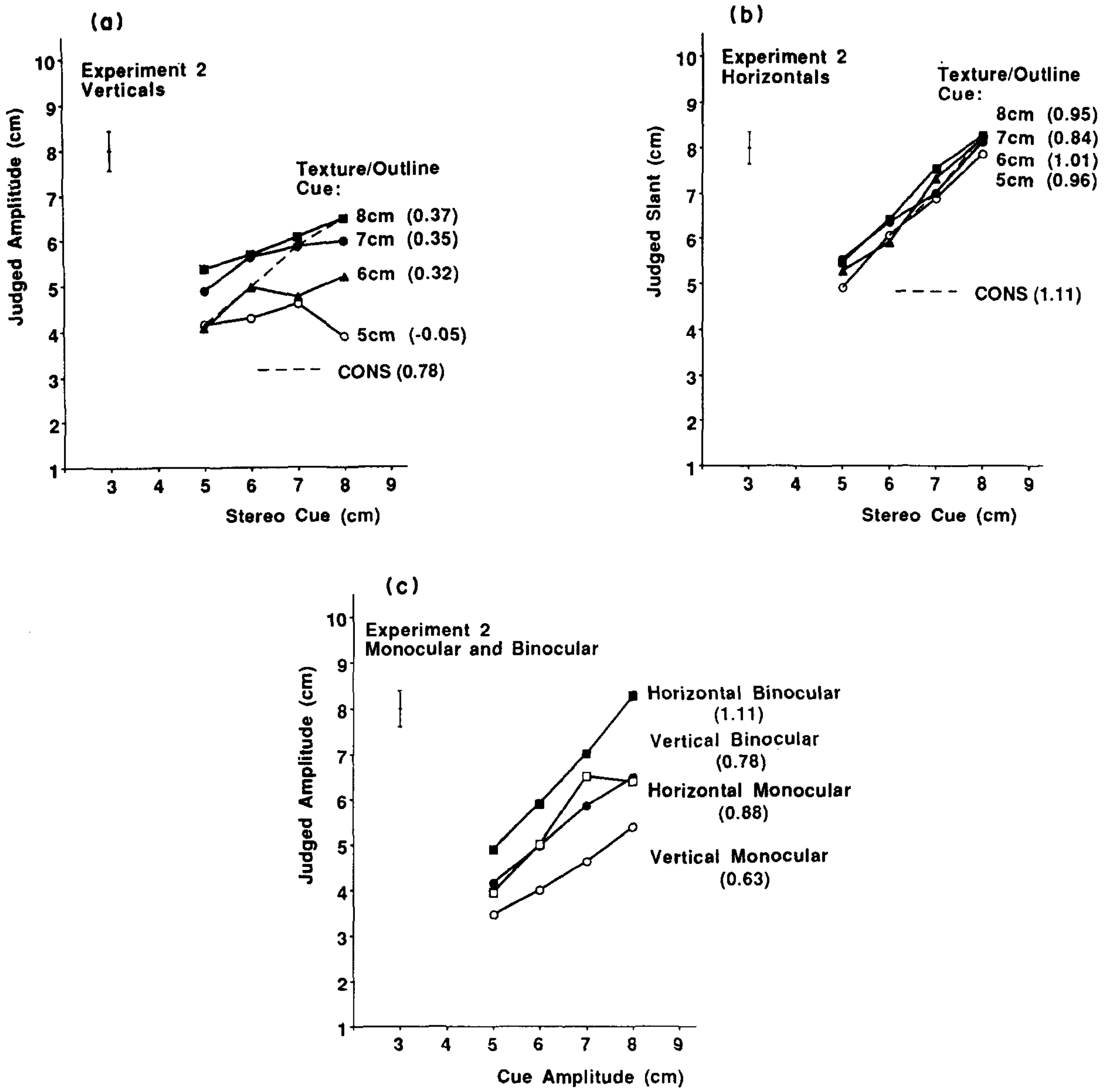


FIGURE 5. Results of Expt 2, stereograms of parabolic ridges ($N = 4$) in the same format as Fig. 4.

EXPERIMENT 4

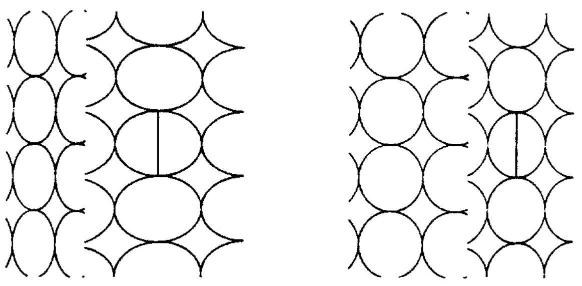
Real Stimuli, Parabolic Profiles, Vertical and Horizontal Ridge Orientations, Amplitudes 5, 6, 7 and 8 cm, Regular Textures

In this study the parabolic ridge stimuli were not stereograms but three-dimensional models made by pasting textured card on to a variety of wooden ridge-shaped formers whose amplitude determined the size of the stereo cue. Hence these models were similar to the training stimuli used in all experiments except that in 75% of conditions the texture/outline cue was arranged to be inconsistent with stereo. Inconsistent texture cues were achieved by distorting the shapes of the elements on the card in a way that took into account the perspective projection of the card, once bent onto the wooden former, as seen by the observer's left eye at the 57 cm viewing distance (Fig. 8). Thus for monocular viewing with the left eye, the texture was designed to appear as regularly-arranged circles on a surface of the required amplitude, which for the inconsistent conditions would be different from that of the wooden former and for the consistent conditions would be the same. In all cases the edges of the card were cut to provide an outline cue in accord with the texture cue.

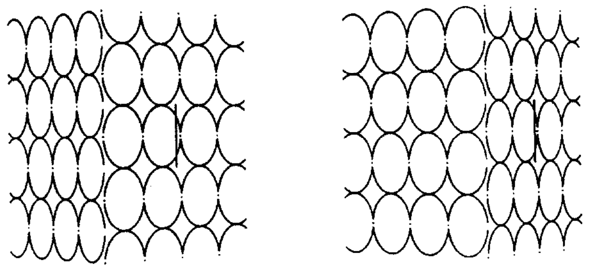
Figure 9 plots the group mean data ($N = 6$). The striking difference from the previous (stereogram) studies is that stereo now strongly dominated both the vertical and the horizontal ridges (smallest $F_{3,15} = 106.17$, $P < 0.001$). Although the data present a clear picture of strong stereo dominance for these real ridges, there was nevertheless some effect from the texture/outline cue for the verticals. Thus the slight separations between the various graphs in Fig. 9(a) were significantly different ($F_{3,15} = 7.09$, $P < 0.05$). This slight texture/outline effect in Expt 4 achieved significance because of reduced data variability, perhaps because of the use of real ridges.

We conclude from Expt 4 that a very different pattern of cue integration became evident for the real ridges. In

(a)



(b)



(c)

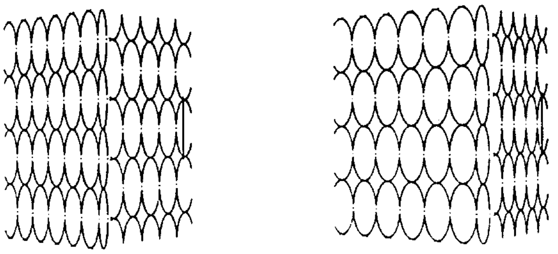


FIGURE 6. Stereograms of vertical triangular ridges, matching those of Fig. 1(a–c).

particular, the vertical/horizontal anisotropy found for stereograms was absent.

Tests for additional depth cues in the real stimuli beside those intended

During Expt 4 various monocular readings (left eye) were collected to check whether the real stimuli provided additional cues over and above the intended texture/outline and stereo cues. For example, the real stimuli may have contained subtle shading cues despite the care taken to avoid them; or there may have been a cue available from perspective-induced variations in the line thickness of the texture elements; or perhaps observers gained some benefit from small head movements despite the tightly-fitting head-rest. These and other possible cues would all be consistent with the stereo cue of these real three-dimensional ridges and hence may have served to strengthen it. In order to check this possibility, monocular readings were included and taken for four horizontal and four vertical real ridges. Table 1 shows these conditions and the group means. For these stimuli disparity was absent due to monocular viewing but other depth cues of the type listed above would have been present just as in the equivalent binocular stimuli (whose means are shown in parentheses). The important point to note is that the factor of real ridge amplitude was not significant, which is against expectations if effective extraneous monocular cues were present. In contrast, the overall means for the 5 and 8 cm values of the texture/outline cue were significantly different (verticals, $F_{1,4} = 19.76$; horizontals, $F_{1,5} = 12.79$; $P < 0.05$) for both. These results suggest that the precautions taken to avoid extraneous monocular depth cues associated with the real stimuli playing an important role had been successful.

One possible depth cue that might have been generated by binocular viewing of the real ridges, but left unchecked by the monocular conditions just described, is a potential stereo cue arising from the very fine texture of the smooth card on which the circles were printed. However, we suspect this factor was of negligible importance in our experiments because we could not detect the card texture in the viewing circumstances of the experiment, i.e. it appeared uniformly white and smooth.

EXPERIMENT 5

Stereograms and Real Stimuli but Vertical Ridges Only, Parabolic Profiles, Stereo Cue Amplitudes 3, 5, 7 and 9 cm, Texture/Outline Cue Amplitudes 3 and 9 cm, Two Levels of Texture Density, Regular and Jittered Texture

The texture cue manipulations used in previous experiments inevitably produced variations in the density of texture elements between stimuli (Fig. 1). For example, the texture cue for a 9 cm ridge in Expt 1 introduced into each image roughly twice as many circles as did the texture cue for a 3 cm ridge (*ca* 40 vs *ca* 20 circles respectively). This happened simply because scene surface area varies with ridge amplitude, so that images from higher ridge amplitudes inevitably have more texture elements, and hence edges, than do images from ridges of lesser amplitude. This factor may have inadvertently strengthened one or other cue differentially in proportion to ridge amplitude.

The potency of this density factor was checked in Expt 5 using two levels of texture density (Fig. 8) in conjunction with two levels of texture/outline cue. Thus "high density" 3 cm ridge conditions were created which produced just as many texture elements in the left and right images as appeared in the images of the 9 cm ridges used previously (the latter designated henceforth as "high density" 9 cm ridges). Equally, more sparsely covered "low density" 9 cm ridge conditions were created to match the density of the 3 cm ridges used in Expt 1. Density was manipulated by choosing appropriate sizes for element diameters to achieve the required densities of 20 and 40 elements per stimulus (Fig. 8).

The opportunity was also taken in Expt 5 to check previous findings by including both real stimuli and stereograms in a repeated measures paradigm using stereo cues in the range of 3–9 cm (cf. Expt 1) and both jittered and regular textures. However, to avoid long

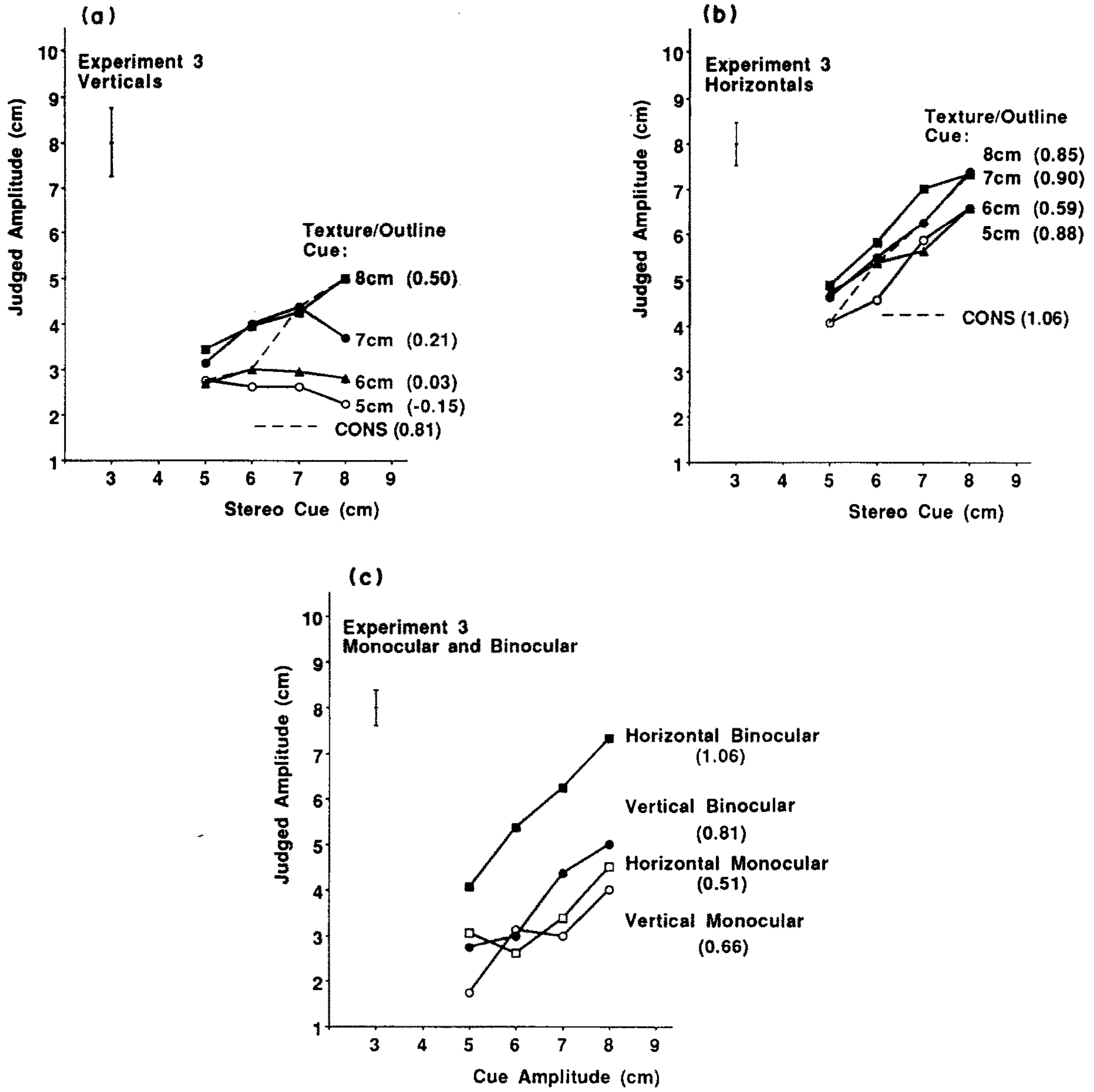


FIGURE 7. Results of Expt 3, stereograms of triangular ridges ($N = 4$) following the same format as Fig. 4.

experimental sessions, the latter factor was explored only for a few stimulus conditions. Jittered texture was used for all cue levels but regular textures were used only for conditions incorporating 3 and 9 cm amplitudes in any combination. It turned out that here, unlike in Expt 2, the overall means for the two texture types (regular = 4.79 cm, jittered = 5.34 cm) were significantly different ($F_{1,5} = 8.00$, $P < 0.05$). However, there were no significant interactions between this factor and any other, from which we conclude that it had no important bearing on our main experimental questions. The group means ($N = 6$) plotted in Fig. 10 are from the jittered textures only.

The texture/outline cue was sampled at just two levels, 3 and 9 cm. In this study we were interested mainly in checking previous findings for the 3 vs 9 cm cue conflict conditions for the vertical ridges: inclusion of the intermediate 5 and 7 cm stereo cues simply ensured that observers saw ridge amplitudes spanning the entire range. This avoided a potential cognitive bias against intermediate judgements, as might have arisen if only 3 and 9 cm ridges had been included for both cues.

There was a small main effect of density, with the denser stimuli being judged 0.36 cm higher in amplitude overall ($F_{1,5} = 12.48$, $P < 0.05$). There were, however, no significant interactions between density and other factors. We conclude that a density effect can be neglected in discussing the main features of these results.

The pattern of anisotropy shown in Fig. 10(a) for the vertical stereograms replicates the pattern found in Expt 1 for vertical stereograms (recollect that horizontal ridges were not included in the present experiment). Thus, for the stereograms, the interaction was significant ($F_{3,15} = 7.09$, $P < 0.05$): the 3 cm texture/outline cue strongly dominated all levels of the stereo cue, whereas cue integration was observed for conditions including the 9 cm texture/outline cue. For the real ridges [Fig. 10(b)] stereo dominated the texture/outline cue throughout ($F_{3,15} = 80.21$, $P < 0.001$) and the interaction was not significant.

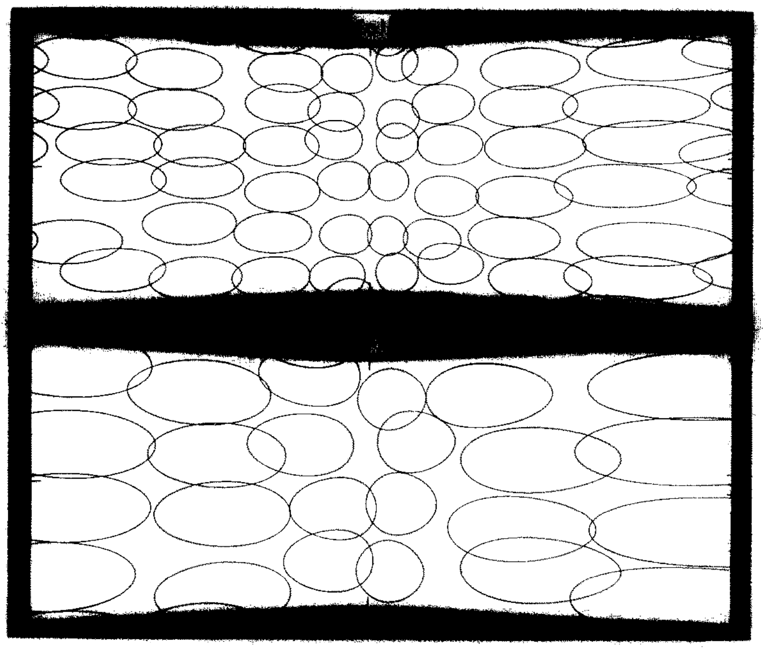


FIGURE 8. Two reduced-scale versions of the cards used in Expt 5 to generate real models with texture/outline cues inconsistent with stereo. When pasted on to a wooden former shaped to be a vertical parabolic ridge with 9 cm amplitude and 8 cm base and viewed from 57 cm, the texture/outline cues in the left eye's view would be consistent with a ridge of 3 cm amplitude. In Expt 5 density was explored as a factor, by manipulation of the sizes of the diameters of the circles on the intended surface as portrayed by texture/outline cues, such that, for example, in (a) the surface has *ca* 40 elements ("high" density) and in (b) *ca* 20 elements ("low" density).

In view of the spontaneous reports from some observers in Expt 1 regarding "eye strain" from the 3 cm texture/outline vs 9 cm stereo condition, all observers in Expt 5 were explicitly asked whether they experienced difficulties with this stimulus. Three (out of 6) said they did so, using such remarks as they found this stimulus "very difficult", "very unstable", "difficult to fuse", "made me feel that I'm looking in the wrong place". These problems were reported just as frequently for those stimuli bearing jittered textures as those with regular textures. No difficulties were reported for other conditions, including the real ridges.

The main conclusion we draw from Expt 5 is that the weakness of stereo in combating a conflicting texture/outline cue for vertical ridge stereograms cannot be ascribed to a texture density factor operating in the earlier experiments. Also, this experiment confirmed that stereo was not a weak cue in the real vertical ridge stimuli.

GENERAL DISCUSSION

The main objective of the present study was to test whether, in human vision, the role of stereo in a cue conflict paradigm would be appreciably strengthened when disparity cues were arranged to have non-zero second spatial derivatives or sharp discontinuities. The answer to this question from five experiments, that used a total of 26 naive observers and non-planar disparity cues in the form of parabolic and triangular ridges, is a clear negative. Particularly striking examples of how non-planar disparity cues failed to strengthen stereo came from the vertical ridge stereograms in which a texture/outline cue for a shallow ridge amplitude was pitted against stereo cues for a high ridge amplitude. In these cases, varying the stereo ridge cue over the amplitude ranges 3–9 cm or 5–8 cm had hardly any effect at all on perceived ridge amplitude [Figs 4(a), 5(a), 7(a) and 10(a)].

Our experiments also produced clear and consistent evidence of a vertical/horizontal cue integration anisotropy in stereograms of three-dimensional ridges, for both parabolic and triangular profiles. In stereograms of horizontal ridges stereo strongly dominated the texture/outline cue, whereas the reverse was true for stereograms of shallow vertical ridges (amplitudes up to *ca* 5–6 cm). This anisotropy was not seen for real ridges, for which stereo was the strongly dominant cue throughout [but see Frisby and Buckley (1993) for results showing that texture can compete effectively against stereo for real stimuli when the latter are large ground planes]. The weakness of the stereo cue in the vertical stereograms is therefore in sharp contrast to the situation that obtained in the equivalent horizontal stereograms and real ridges. What could underlie this pattern of results? Although we do not offer here an explanation of the fundamental basis of the stereo anisotropy, we suggest some aspects of the present results indicate a significant role played by accommodation cues.

For example, perhaps the lack of anisotropy in the *real* ridge data was due to the presence of an accommodation cue arising from the real ridges. For these stimuli, the disparity cues were everywhere supported by accommodative cues, by virtue of the method used to create them (i.e. three-dimensional models). Hence, relatively weak stereo cues in the vertical real ridges would have been assisted by accommodation cues operating against the conflicting texture/outline cues. This factor might explain, in whole or part, the loss of the anisotropy for the real ridges.

Introducing accommodation as an important factor can also help explain why the vertical *stereograms* revealed such a weak role for stereo when presented in conjunction with a shallow texture/outline cue. Stereograms are in general cue conflict stimuli if accommodation is taken into account because, to a greater or lesser degree, disparity is usually everywhere in conflict with accommodation (an exception would be a stereogram of a smooth surface everywhere appropriate for the state of accommodation). In the stereograms used here, disparity and accommodation were signalling the same depths only at the most distant edges of the ridges, which lay in the plane of the monitor screen. Hence, in these stimuli accommodation would be supporting the texture/outline cue for a shallow ridge. The opposite result would be expected when stereo cues for a high amplitude ridge were supported by high texture/outline cues. In this case, texture/outline and stereo would operate together against the influence of accommodation, thereby tending to produce higher amplitude judgements. This is the pattern of results evident in Figs 4(a), 5(a), 7(a) and 10(a): as the texture/outline cue becomes larger, so the steepened curves reflect an increasing role played by stereo in the vertical stereograms.

This line of reasoning cannot, however, explain why the horizontal stereograms, unlike the vertical ones, failed to show strong dominance of texture/outline cues for a shallow ridge amplitude over stereo cues for a high ridge amplitude. Accommodation would work in favour of shallow texture/outline cues in both the vertical and horizontal stereograms (i.e. it signalled zero ridge

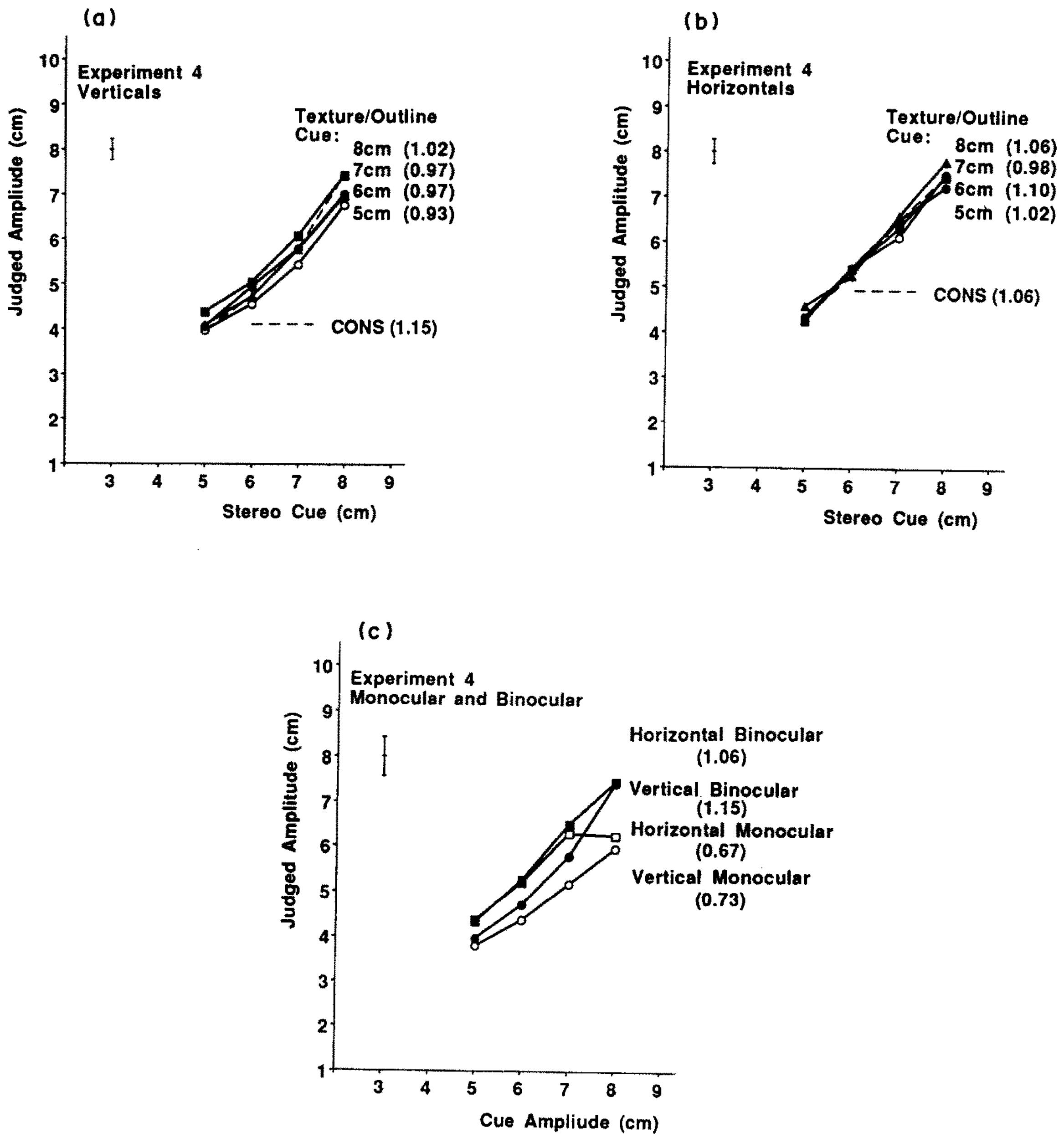


FIGURE 9. Results of Expt 4, real parabolic ridges ($N = 6$) following the same format as Fig. 4.

TABLE 1. Experiment 4: monocular judgements to real parabolic ridges

		Real ridge amplitude 5 cm	Real ridge amplitude 8 cm	Means pooled over real ridge amplitudes	Difference between pooled means to show texture effect
Vertical ridges (N = 5)					
Texture/outline cue amplitude	5 cm	3.75 (*3.85*)	4.20 (*6.80*)	3.98 (*5.33*)	1.72* (*0.40**)
	8 cm	5.75 (*4.25*)	5.65 (*7.20*)	5.70 (*5.73*)	
Means pooled over texture/outline cue		4.75 (*4.05*)	4.93 (*7.00*)		
Differences between pooled means to show ridge amplitude effect		0.18 (n.s.) (*2.95*†)			
Horizontal ridges (N = 6)					
Texture/outline cue amplitude	5 cm	4.38 (*4.33*)	5.29 (*7.50*)	4.83 (*5.92*)	1.12* (*−0.06*) (n.s.)
	8 cm	5.66 (*4.25*)	6.25 (*7.46*)	5.98 (*5.86*)	
Means pooled over texture/outline cue		5.02 (*4.29*)	5.77 (*7.48*)		
Differences between pooled means to show ridge amplitude effect		0.75(n.s.) (*3.19*†)			

No stereo cues were by definition present during monocular presentations of the real ridges. However, as the ridges were the same as those used to generate stereo cues under binocular viewing, data from the latter conditions are given in parentheses, below each monocular mean, for comparison (but see also Fig. 9). ANOVA results are indicated as follows: *$P < 0.05$; †$P < 0.001$; n.s. = not significant. Data for one observer are missing for the vertical ridges as the decision to include these monocular conditions was taken after that observer was run.

amplitude in both cases). Hence even if we are right in suggesting that accommodation played an important role, some additional factor needs to be introduced to explain why the stereo cue in the horizontal ridges was sufficiently strong not to need help from accommodation cues.

Support for accommodation playing an important role in determining the results from the vertical stereograms comes from the difficulties reported by some observers with the vertical stereograms that presented a 3 cm vs 9 cm conflict between texture/outline vs stereo. Their introspections suggest they had problems in generating the vergence movements necessary for fusion. We think they overcame these difficulties prior to making their amplitude judgements (because of the checks in our experimental procedure). Nevertheless, these introspections drew our attention to the possible significance in our experiments of disruption of the normal sykinesis between disparity and accommodation, with accommodative vergence sometimes pitted strongly against disparity-driven vergence and hence to the role of accommodation as a cue.

It could be argued against this possibility that the accommodative change required when scanning from base-to-peak of even the highest amplitude ridges (9 cm) was modest, being about one-third of a dioptre. But if this is deemed insufficient to explain why the real ridges produced no sign of a vertical/horizontal anisotropy, one seems forced back to considering whether, despite all our precautions, the real stimuli contained monocular depth cues that assisted the stereo cue, such as shading, head-movement parallax and texture from the cardboard surface of the three-dimensional models. We re-iterate, however, that we believe we were successful in controlling our presentations so that these cues had little or no effect (recollect the negative evidence from the monocular conditions, Table 1).

Further studies are needed to test the truth of these speculations about the role of accommodation in shaping the detailed nature of the vertical/horizontal anisotropy in cue integration observed here. What is clear, however, is that the present experiments provide no evidence in support of explanations of the anisotropy which predict that it should be appreciably reduced if disparity cues are arranged to carry non-zero second order spatial derivatives or disparity discontinuities. These experiments are also a sobering reminder of the sharply differing results that can be obtained when stereo mechanisms are explored using stereograms and real surfaces.

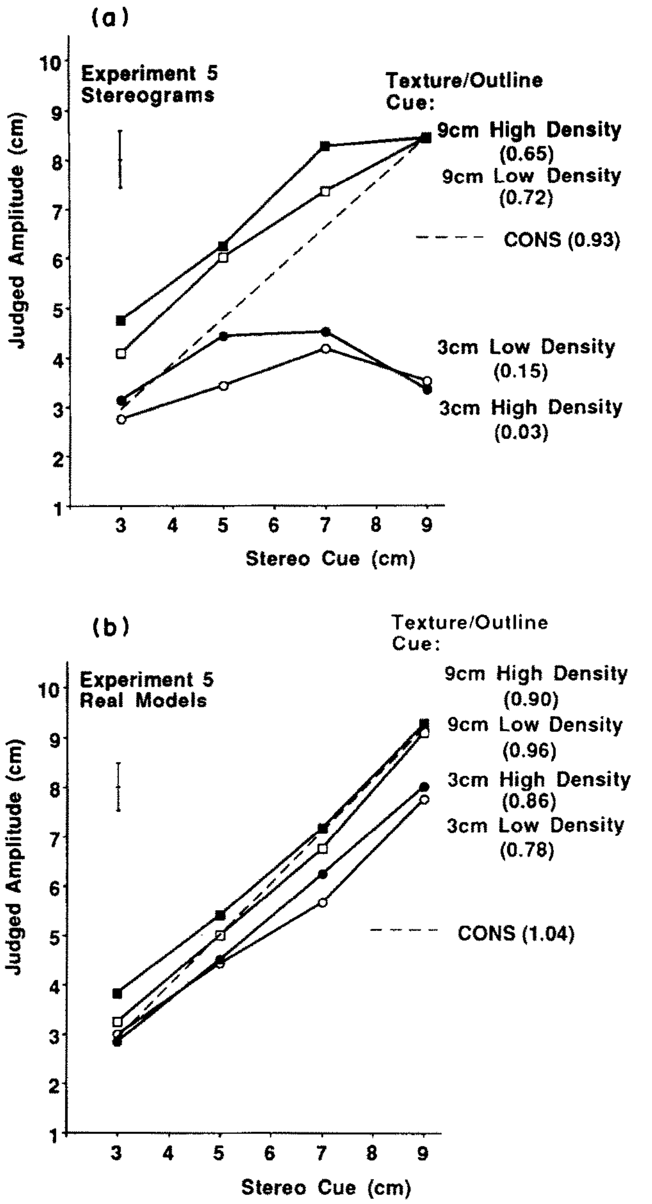


FIGURE 10. Results of Expt 5 ($N = 6$): (a) stereograms and (b) real models.

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