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Surface orientation, modulation frequency and the detection and perception of depth defined by binocular disparity and motion parallax

Mark F. Bradshaw [a], Paul B. Hibbard [b,*], Andrew D. Parton [a], David Rose [a], Keith Langley [c]

[a] Department of Psychology, University of Surrey, Guildford, Surrey, GU2 7XH, UK
[b] School of Psychology, University of St. Andrews, St. Mary's College, South Street, St. Andrews, Fife, KY16 9JP, UK
[c] Department of Psychology, University College London, Gower Street, London WC1E 6BT, UK

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Abstract

Binocular disparity and motion parallax provide information about the spatial structure and layout of the world. Descriptive similarities between the two cues have often been noted which have been taken as evidence of a close relationship between them. Here, we report two experiments which investigate the effect of surface orientation and modulation frequency on (i) a threshold detection task and (ii) a supra-threshold depth-matching task using sinusoidally corrugated surfaces defined by binocular disparity or motion parallax. For low frequency corrugations, an orientation anisotropy was observed in both domains, with sensitivity decreasing as surface orientation was varied from horizontal to vertical. In the depth-matching task, for surfaces defined by binocular disparity the greatest depth was seen for oblique orientations. For surfaces defined by motion parallax, perceived depth was found to increase as surface orientation was varied from horizontal to vertical. In neither case was perceived depth for supra-threshold surfaces related to threshold performance in any simple manner. These results reveal clear differences between the perception of depth from binocular disparity or motion parallax, and between perception at threshold and supra-threshold levels of performance.

Keyword: Disparity motion parallax depth processing

1. Introduction

Binocular disparity and retinal motion are powerful visual cues to the three-dimensional structure of surfaces in our environment. This has been demonstrated by measuring depth sensitivity functions for sinusoidal modulations defined by binocular disparity or motion parallax (Bradshaw & Rogers, 1999; Rogers & Graham, 1982; Tyler, 1974, 1983). In both domains, sensitivity to horizontally oriented depth corrugations differs as a function of modulation frequency where both functions peak at frequencies around 0.2–0.4 cpd, and decrease at both higher and lower frequencies. Although primarily descriptive, these sensitivity functions based on depth corrugations have proved useful in predicting perceptual outcomes in certain circumstances. For example, our susceptibility to the Craik–O'Brien–Cornsweet illusion, defined by disparity or motion parallax, can be explained in terms of our relative insensitivity to low frequency information, as revealed by the disparity or motion parallax sensitivity functions (Anstis, Howard, & Rogers, 1978; Rogers & Graham, 1983).

An important factor determining our perception of depth from binocular disparity or motion parallax is the direction in which it varies. Typically, variations in binocular disparity in the vertical direction (which lead, for example, to the perception of slant or curvature around a horizontal axis) are more readily perceived than the equivalent variations in the horizontal direction. This *orientation anisotropy* is evident at threshold, and also affects perceived depth magnitude and the time required for depth to be

* Corresponding author. Fax: +44 01334 46 3042.
E-mail address: pbh2@st-andrews.ac.uk (P.B. Hibbard).

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perceived (Bradshaw & Rogers, 1999; Bradshaw, Hibbard, & Gillam, 2002; Hibbard, Bradshaw, Langley, & Rogers, 2002; Mitchison & McKee, 1990; Wallach & Bacon, 1976). Similarly, for a monocular observer making horizontal head movements while viewing a surface shape defined by the motion parallax arising from these head movements, a similar orientation anisotropy exists which affects threshold perception and perceived depth magnitude (Allison, Rogers, & Bradshaw, 1978; Cornilleau-Peres & Droulez, 1993; De Vries & Werkhoven, 1995; Rogers & Graham, 1983).

Evidence from both domains therefore suggests that the visual system's ability to use binocular disparity or motion parallax to recover depth information depends on the spatial structure of depth variations as well as their magnitude. In particular, the direction in which the change in disparity or motion is greatest is an important factor determining the extent to which this information can be used. It is perhaps surprising therefore that empirical research has concentrated almost exclusively on surfaces in which the visual cues change along the cardinal directions only (Bradshaw & Rogers, 1999). Indeed, for parallax defined surfaces there are no published data which define the sensitivity function for vertically oriented surfaces as a function of modulation frequency. We provide these data here. Moreover, the question that naturally arises in this context is what happens to threshold and supra-threshold perception at intermediate orientations between horizontal and vertical. In the case of stimuli defined by luminance contrast, sensitivity to obliquely oriented stimuli cannot be predicted from sensitivity to stimuli at cardinal orientations, and accounting for these differences has placed important constraints on models of visual encoding (Essock, DeFord, Hansen, & Sinai, 2003; Hansen & Essock, 2004). It is similarly important to understand the influence of orientation of surface corrugations on the perception of depth from binocular disparity or motion parallax.

The aim of this paper therefore is to address this question and to establish the effect of corrugation orientation and spatial frequency on both (i) a threshold detection task and (ii) a supra-threshold depth-matching task on surfaces defined by binocular disparity (Experiments 1a and b) and motion parallax (Experiments 2a and b).

In collecting the range of data that we present here, for surfaces defined by binocular disparity and motion parallax, we provide a comprehensive description of how the perception of depth from cues is affected by orientation and spatial frequency. In addition, the data also allow for a descriptive comparison between the cues. Marked similarities between the processing of binocular disparity and motion parallax have often been noted. For example, the shapes of their depth sensitivity functions are similar over a range of spatial frequencies for horizontally oriented surfaces (Rogers & Graham, 1982). Such similarities may be manifest in a range of circumstances and add weight to the claim that information from the two domains comes together at some stage in the visual system. The fact that similar simultaneous and successive contrast effects can be created in both domains, and that cross adaptation is possible, adds to this idea (Bradshaw & Rogers, 1996; Nawrot & Blake, 1991; Rogers & Collett, 1989; Rogers & Graham, 1984). The data presented here will allow a more comprehensive comparison of the two cues in relation to different dependent variables and when threshold and supra-threshold tasks are employed.

2. Experiment 1a—binocular disparity detection thresholds

This experiment determined detection thresholds for corrugated surfaces defined by binocular disparity and how they varied with the (i) orientation and (ii) modulation frequency of the surface corrugation.

2.1. Observers

Four observers (ADP, PBH, SJW and MFB) who had normal, or corrected to normal, visual acuity and stereo acuity of <20″ participated in the experiment.

2.2. Stimuli

The stimuli were random dot stereograms depicting surfaces that were sinusoidally corrugated in depth. Each stimulus subtended a circular region with a diameter of 10°. The central corrugation of the surface was marked by two thin lines, 1.5° in length, offset by 1° from either side of the stimulus at the orientation of the corrugations. A fixation cross and nonius lines were presented in the centre of the screen between each trial to enable observers to maintain steady fixation. Dots were presented on the surface with a density of 37.7 dots deg^{-2}. Each dot had a Gaussian luminance profile with a standard deviation of 1.78′; the luminous intensity of a dot was 7.0×10^{-5} cd. Individual dots were positioned with subpixel accuracy. The background luminance of the screen was 0.15 cdm^{-2}. Disparity thresholds were measured for four corrugation frequencies (0.1, 0.2, 0.4 and 0.8 cpd) and five surface orientations (0°, 22.5°, 45°, 67.5° and 90°), where 0° refers to a horizontally oriented corrugation in which binocular disparity is modulated in a vertical direction.

2.3. Apparatus

Stimuli were generated on an Apple Macintosh 7500 computer and presented using two 12 in. monochrome Apple monitors arranged in a standard Wheatstone configuration and viewed through two first-surface mirrors set at ±45° to the median plane. The luminance output of each monitor was linearised. The viewing distance was 95 cm; at this distance, each pixel subtended 1.2′.

2.4. Procedure

The method of constant stimuli was used to determine threshold performance. The observer's task was to report whether the corrugation at the centre of the dot pattern, and marked by the two white lines, was concave (a trough) or convex (a peak), by pressing one of two response keys. It should be noted that this task does not require the overall shape of the corrugation to be identified, merely that the sign of a non-zero disparity in the centre of the stimulus be correctly detected. On each trial, the disparity signal was randomly chosen from seven possible values corresponding to −3, −2, −1, 0, 1, 2 or 3 times the "step size". The sign of the disparity determined whether the central corrugation was a peak or a trough. The step size for each condition was chosen in pilot trials. An experimental session consisted of 280 trials (in four blocks), corresponding to 40 trials at each of the seven disparity levels. Frequency of seeing plots were generated from each data set and the best-fitting cumulative Gaussian curve was determined using the probit technique (Finney, 1971). The 75% point on the psychometric function was taken as the threshold value. Prior to commencing each block the observer viewed a supra-threshold surface (with a simulated peak-to-trough depth modulation of between 200 and 600″) of the same orientation and corrugation frequency as the test stimuli. Each stimulus was presented for 2 s. The experiment was run over several days with the order of presentation of stimulus blocks randomised.

2.5. Results

Figs. 1A (PBH) and B ($N=4$) depict the disparity thresholds for the range of modulation frequencies as a function of the orientation of the corrugation. Thresholds are clearly influenced by both the orientation and spatial frequency of the depth corrugation. For the two lowest frequencies (0.1 and 0.2 cpd), thresholds rise as surface orientation rotates from horizontal to vertical. The effect of surface orientation was not evident for the two highest spatial frequencies tested (0.4 and 0.8 cpd). This dissociation is clearly seen in the group data shown in Fig. 1B.

Figs. 1C (PBH) and D ($N=4$) depict disparity thresholds as a function of the modulation frequency of the surface for both horizontally and vertically oriented corrugations. These panels correspond to the disparity sensitivity functions (DSF). Lowest thresholds were found for horizontal corrugations around 0.4 cpd, with thresholds tending to increase for both the higher and lower frequencies. For subject PBH the minimum threshold (maximum sensitivity) was 2.5″ peak-to-trough disparity at 0.4 cpd. This corresponds to a depth difference between the peaks and troughs of the corrugations of around 1/5 mm (Bradshaw & Rogers, 1999). The orientation anisotropy is clearly evident in both panels C and D where thresholds rise particularly steeply for the low frequency, vertically oriented depth modulations. In fact only

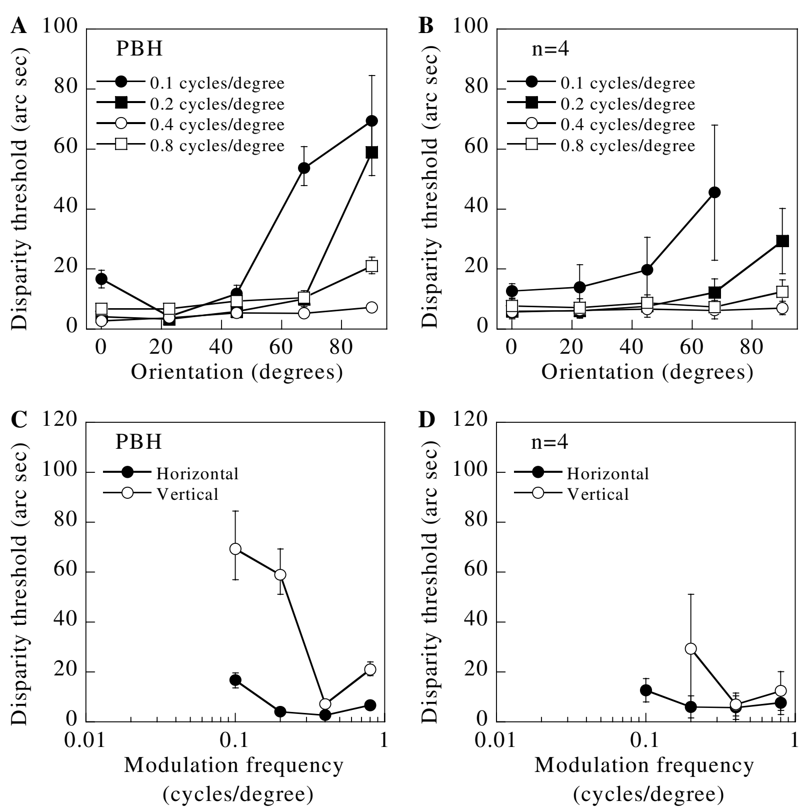

Fig. 1. (A) Binocular disparity thresholds plotted as a function of surface orientation for a single observer PBH. Data are plotted separately for 0.1, 0.2, 0.4 and 0.8 cpd. (B) Shows the mean results for the four observers. No data point is plotted for vertical corrugations at the lowest frequency, as it was only possible to obtain a threshold for one observer (PBH) in this condition. (C and D) Show disparity threshold functions for horizontally and vertically oriented surfaces as a function of modulation frequency, for observer PBH and for the mean across observers, respectively. Error bars depict ± SE.

PBH recorded a reliable threshold for vertical corrugations at 0.1 cpd, which further illustrates the profound insensitivity to low frequency vertical oriented depth modulations of most subjects (Hibbard et al., 2002). In other respects, results were similar for all observers. Interestingly, the other three observers produced thresholds of similar magnitude to PBH when the surface was oriented near vertical (67.5°).

3. Experiment 1b—binocular disparity depth matching

This experiment assessed whether the magnitude of depth perceived in supra-threshold corrugated surfaces defined by binocular disparity varies with the orientation and the spatial frequency of the corrugation.

3.1. Observers

Ten observers participated in the experiment. All observers had normal, or corrected to normal, visual acuity and stereo acuity of <20″.

3.2. Stimuli and apparatus

The random dot stimuli were identical to those used in Experiment 1a. The apparatus was also the same as described for Experiment 1a.

3.3. Procedure

The observer's task was to adjust the magnitude of the depth in a horizontally oriented reference surface corrugation until it appeared to match that of a test surface. The reference and test surfaces were shown in alternation, with each displayed for 2 s. There was no time limit for a trial (the reference and test being presented alternately until the observer had made a final match) and observers were instructed to perform the task as accurately as possible. The test surface had a fixed peak-to-trough disparity of 300″ and an orientation selected at random from one of five angles (0°, 22.5°, 45°, 67.5° and 90°). Four settings were made for each orientation and for two different corrugation frequencies (0.2 and 0.8 cpd). The experiment was run in two blocks (one for each corrugation frequency) with the order of presentation of the blocks randomised across observers.

3.4. Results

Figs. 2A (PBH) and B ($N = 10$) depict the mean disparity settings for the two corrugation frequencies tested as a function of surface orientation.

Settings are close to unity for horizontal stimuli since observers are matching two identical surfaces in this case. However, observers introduced greater amounts of disparity (in order to equate perceived peak-to-trough depth) when the test surface approached orientations near 45°, which indicates that a greater amount of depth is perceived in oblique orientations from the same magnitude of disparity. Such a relationship is clearly not evident for the threshold data depicted in Figs. 1A or B above. This different pattern of results highlights the need to study a range of orientations, rather than basing our understanding of binocular processing simply on results from horizontal and vertical depth corrugations.

4. Experiment 2a—motion parallax detection thresholds

This experiment determined detection thresholds for corrugated surfaces defined by motion parallax generated by horizontal head movements and how they varied with the (i) orientation and (ii) modulation frequency of the surface corrugations.

4.1. Observers

Five observers, (ADP, PBH, SJW, MFB and RFW) who had normal, or corrected to normal, visual acuity participated in the experiment.

4.2. Stimuli

The stimuli were random dot kinematograms (RDKs) depicting surfaces that were sinusoidally corrugated in depth. Each stimulus subtended a circular region with a diameter of 20°. The horizontal movement of the individual

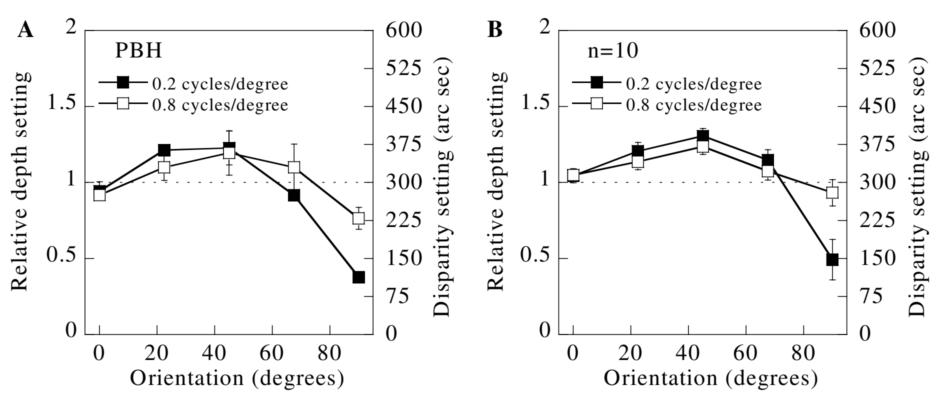

Fig. 2. Depth-matching functions for corrugations defined by binocular disparity as a function of surface orientation (A) results for observer PBH and (B) mean data for the 10 observers. Error bars depict ± SE.

dots in the RDKs was linked to the observers' side-to-side head movements, so as to be consistent with the motion that would be observed from a real three-dimensional surface in a similar manner to that described by Rogers and Graham (1979). The individual elements of the RDKs were blobs with a Gaussian luminance profile, with a standard deviation of 1.78′ and a maximum luminance of 23 cdm^{-2}. The background luminance of the screen was 0.15 cdm^{-2}. The mean density of the elements was 37.7 dots deg^{-2}. Motion parallax depth discrimination thresholds were measured for five different corrugation frequencies (0.05, 0.1, 0.2, 0.4 and 0.8 cycles/degree) and five different surface orientations (0°, 22.5°, 45°, 67.5° and 90°). Horizontal head motion was used to make the information provided by motion parallax (horizontal retinal motion) as similar as possible to the information provided by binocular viewing (horizontal binocular disparities). One remaining difference is that, in the motion parallax condition, the velocities of individual dots varied over time, providing additional information that is not available in the binocular condition. The stimuli used in the binocular disparity and motion parallax conditions were on the whole identical in terms of their dot density, and the orientations and spatial frequencies tested. An exception to this was that an additional low spatial frequency (0.05 cycles/degree) was added in the motion parallax condition. The size of the stimuli was increased in the motion parallax condition to accommodate this frequency.

4.3. Apparatus

Stimuli were generated on an Apple Macintosh G3 computer and presented on a 21 in. monochrome Radius monitor. The luminance output of the monitor was linearised. The observer viewed the stimuli monocularly via a headrest that was free to move horizontally side-to-side through a distance of ±6.5 cm, in a direction parallel to the monitor screen. When the headrest was in its central position the centre line of the stimuli was aligned with the observer's dominant eye. The viewing distance was 66 cm. At this distance, one pixel on the monitor subtended 1.9′. The horizontal position of the observer's head was monitored using a potentiometer and an ADC (National Instruments PCI 1200) to select a precomputed stimulus frame presented to the observer, which was determined by head position. Observers moved their head from side-to-side at a rate of 1 Hz paced by a metronome. All observers reported an impression of solid depth when viewing supra-threshold stimuli in this fashion (Hogervorst, Bradshaw, & Eagle, 2000).

4.4. Procedure

The method of constant stimuli was used to determine threshold performance. The procedure was identical to that described in Section 2.4.

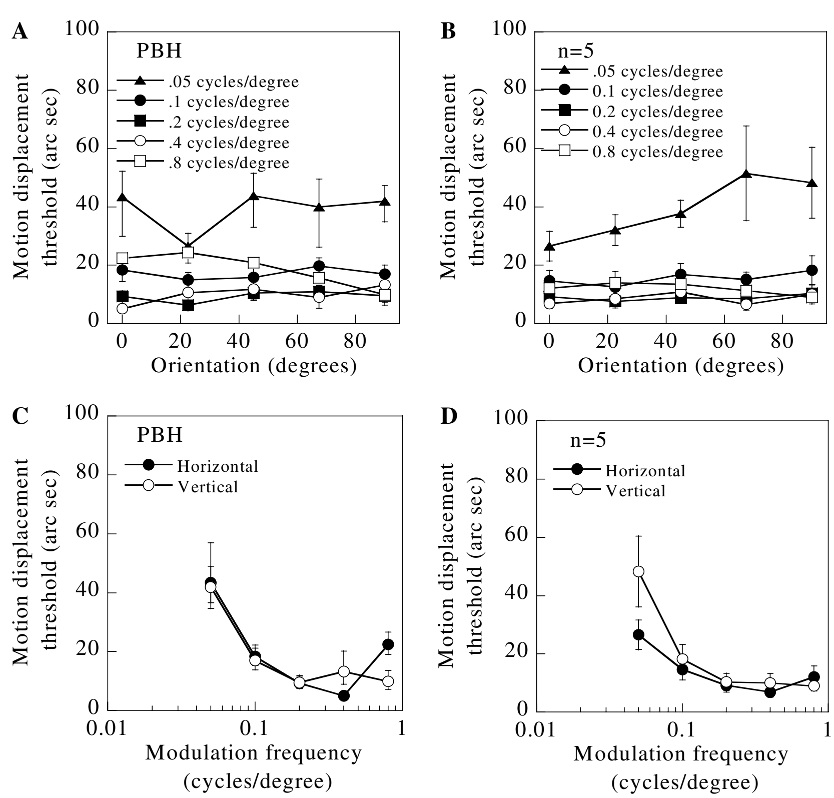

Fig. 3. (A) Motion parallax thresholds plotted as a function of surface orientation for a single observer PBH. Data are plotted separately for 0.05, 0.1, 0.2, 0.4 and 0.8 cpd. (B) Mean results for the five observers. (C and D) Motion parallax thresholds for horizontally and vertically oriented surfaces as a function of modulation frequency, for observer PBH and the mean across observers, respectively. Error bars depict ± SE.

4.5. Results

Motion parallax thresholds were computed as the difference in the total displacement for two dots positioned at a peak and trough of the corrugation as the observer makes one complete movement through ±6.5 cm.

Figs. 3A (PBH) and B ($N=5$) depict motion parallax thresholds for the range of modulation frequencies as a function of orientation. Thresholds were influenced by modulation frequency, increasing as the frequency was decreased. Effects of the orientation of the corrugation were also evident. Thresholds for the 0.05 cpd corrugation increased as orientation varied from horizontal to vertical whereas thresholds were invariant to orientation at other modulations frequencies (0.1–0.8 cpd).

Figs. 3C (PBH) and D ($N=5$) depict motion parallax thresholds as a function of the modulation frequency of the surface for both horizontally (0°) and vertically (90°) oriented surfaces. These panels correspond to the first reported motion parallax sensitivity functions for both horizontally and vertically oriented depth corrugations and so any orientation anisotropy typical of binocular disparity processing can be established. Thresholds tended to increase with decreasing modulation frequency, and showed little evidence of an orientation anisotropy, except at the very lowest spatial frequency tested. These latter results should be interpreted with some caution, as at this frequency the display contained just a single cycle of the depth modulation. However, Bradshaw and Rogers (1999) found little effect of the number of cycles of a stimulus on depth thresholds. The lowest threshold (maximum sensitivity) recorded for observer PBH was 5″, which was for horizontal corrugations with a spatial frequency of 0.4 cpd.

5. Experiment 2b—motion parallax depth matching

This experiment assessed whether the amount of depth perceived in a supra-threshold corrugated surface defined by motion parallax varies with the orientation and the spatial frequency of the corrugation. The design is the same as described for Experiment 1b.

5.1. Observers

Five observers took part in the experiment. All observers had normal, or corrected to normal, visual acuity.

5.2. Stimuli and apparatus

Stimuli and apparatus were the same as those described for Experiment 2a (Section 4.2) and the procedure was the same as that used in Experiment 1b (Section 3.2). Depth matches were made between surfaces with different orientations for three spatial frequencies of depth modulation: 0.1, 0.2, and 0.8 cpd.

5.3. Results

Figs. 4A (PBH) and B ($N=5$) depict the mean settings for the two corrugation frequencies tested as a function of orientation. Clearly, for all three corrugation frequencies tested, perceived depth increased as the surface orientation varied from horizontal to vertical.

These results are in marked contrast to those for the equivalent experiment for stimuli defined by binocular disparity, for which the maximum depth was perceived in surfaces oriented at oblique angles.

Settings are close to unity for horizontal stimuli since observers are matching two identical surfaces in this case. However, as the orientation of the test surface approaches vertical much more parallax (≈40%) is required in the reference surface to match the perceived depth generated in the test surface. That is, progressively more depth is seen in surface orientations from 22.5° to 90° relative to the horizontal reference when a fixed peak-to-trough motion parallax signal is present.

6. Discussion

The experiments reported in the present paper investigated the effect of surface orientation and modulation

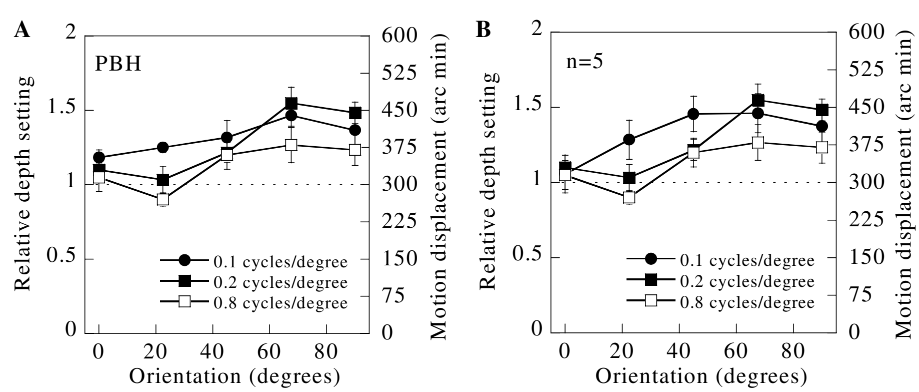

Fig. 4. Depth-matching functions for corrugations defined by motion parallax as a function of surface orientation. (A) Results for observer PBH and (B) mean data for five observers. Error bars depict ± SE.

frequency on a threshold detection task and a supra-threshold depth-matching task for corrugated surfaces defined by binocular disparity and motion parallax. Modulation frequency and orientation affected performance in both tasks.

The data from the threshold tasks (Experiments 1a and 2a) are summarised in Fig. 5 which shows threshold performance as a function of orientation and modulation frequency for surfaces defined by binocular disparity (panel A) and motion parallax (panel B).

For horizontal corrugations, lowest thresholds (peak sensitivity) occurred between 0.2 and 0.4 cpd and rose sharply at lower modulation frequencies. This effect was rather more pronounced for vertically oriented corrugations—the orientation anisotropy (Bradshaw & Rogers, 1999).

Similar threshold sensitivity functions for motion parallax defined surfaces were established and although the profound difficulty experienced in the binocular disparity conditions in obtaining thresholds for low frequency vertical corrugations was not encountered, sensitivity still fell off rapidly for these stimuli. Here, however, for vertically oriented corrugations peak sensitivity occurred at the highest modulation tested (0.8 cpd). A similar anisotropy was reported by Nakayama, Silverman, MacLeod, and Mulligan (1985) who used a relative motion detection task.

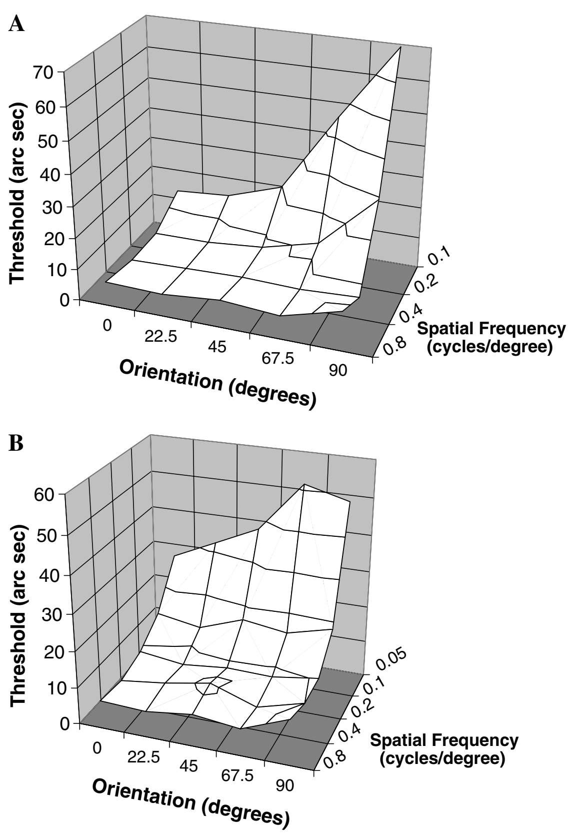

Fig. 5. (A) Binocular disparity and (B) motion parallax thresholds plotted as a function of surface orientation and modulation frequency. The data point in (A) for binocularly defined vertical corrugations with a frequency of 0.1 cpd come from observer PBH only, as it was not possible to measure thresholds for the other observers.

Fig. 5 also shows that surface orientation affected detection thresholds for both depth cues in a similar manner. At the lower modulation frequencies tested, thresholds increased as the orientation of the corrugation changed from horizontal to vertical whereas for the higher frequencies, thresholds remained relatively constant. In both domains, this is an effect that is evident exclusively for low spatial frequencies of depth corrugation.

A more complex pattern of results was observed for the supra-threshold depth-matching task. For stimuli defined by binocular disparity, the greatest depth for both modulation frequencies tested was perceived in surfaces presented at the oblique orientation of 45°. This result is consistent with Regan, Hong, and Regan (2000) who reported that evoked potentials for cyclopean gratings in random dot stereograms were greater for oblique gratings than for either horizontal or vertical gratings. In contrast, for stimuli defined by motion parallax, perceived depth increased as surface orientation varied from horizontal to vertical for all modulation frequency tested.

The difference between the effect of orientation at threshold and supra-threshold levels of disparity for the stereoscopic images is similar to the oblique effect for contrast defined stimuli. It is known that, for narrowband stimuli, oblique orientations are seen worse than horizontal or vertical orientations, both in terms of contrast thresholds and the amount of salience for high contrast stimuli. A different pattern of results exists for broadband stimuli, however, which show a standard oblique effect for contrast threshold, but an inverse effect at supra-threshold, in that oblique orientations have greater salience than cardinal orientations when matched for contrast. These results were explained on the basis of normalization models for broadband stimuli (Essock et al., 2003; Hansen & Essock, 2004). Although such an explanation might be proposed to account for the current data, it should be noted that the spatial variations in binocular disparity or motion of the stimuli used in the current experiment were not broad in their spatial frequency bandwidth.

These results might also be related to the phenomenon of contrast overconstancy (Georgeson, 1991; Georgeson & Sullivan, 1975). In parafoveal vision, the apparent contrast of high spatial frequency gratings is greater than that of lower spatial frequencies, even though threshold sensitivity to these frequencies is lower. This effect was accounted for by Georgeson (1991) in terms of both a greater compression in the response to high spatial frequencies and a normalization stage, and may be thought of as a compensation for lower sensitivity for these stimuli.

It is also possible that the results might be explained on the basis of the spatial summation that occurs in the processing of disparity and motion. The solution of the binocular correspondence problem, for example, is thought to be solved by the application of a cross-correlation between the left and right eyes' views (Banks, Gepshtein, & Landy, 2004). Since this correlation is performed over an extended area of the image, it will act to smooth variations in disparity within the window, thus reducing the magnitude of the disparities detected and therefore the perceived depth. The amount of smoothing will depend on the size of the window. Tyler and Kontsevich (2001) showed that spatial summation occurs over a greater region for the detection of horizontally oriented stimuli than for vertically oriented stimuli. This, they argued, might relate to the statistical properties of natural images. Since disparity information is expected to covary with luminance information to some degree, variations in disparity will be accompanied by variations in luminance. While vertically oriented luminance variations might play a role in the detection of vertical disparity edges, this would not be possible for horizontally oriented edges, which cannot convey information about binocular disparity in the same way. Tyler and Kontsevich (2001) proposed that the increased spatial summation that they observed could act to compensate for this limitation. This extended spatial summation might account for the increased sensitivity to horizontal stimuli for random dot stimuli such as those used here, where there is no covariation between luminance and disparity information, and therefore no difference in the information provided for different orientations of stimuli.

This difference in the shape and size of the summation window for different orientations of surface modulation would not however predict any difference in the amount of depth seen. Since for horizontal modulation a summation window is proposed that is elongated in a direction parallel to contours of constant depth, no increase in spatial averaging, and consequent reduction in perceived depth, is predicted. On the basis of the data presented in the current study, one might expect a summation window for motion parallax that decreases in its extent in a direction orthogonal to contours of constant depth as the orientation of such contours varies from horizontal to vertical. For binocular disparity, the summation window would have its minimum extent in this direction for oblique orientations. This is inconsistent with the prediction of Tyler and Kontesvich. However, it should be borne in mind that the underlying filters may have different optimal parameters at threshold and supra-threshold depth magnitudes. As the local variation in depth or motion increases (i.e., as depth magnitude, or the spatial frequency of depth corrugations increases), the area over which spatial summation occurs should decrease (Kanade & Okutomi, 1994; Langley, 2005). Similarly, it is also possible that the optimal orientation and frequency tuning of the filters (Hibbard & Langley, 1998) may be affected by such changes in the stimuli. It is therefore not necessary for the results for the supra-threshold task to be directly predictable from the results for the threshold task.

One potentially useful way to describe the supra-threshold data for stereoscopic stimuli is that the amount of perceived depth is a weighted sum of the amount of shear disparity (vertical gradients of horizontal disparity) and expansion–compression disparity (horizontal gradients of horizontal disparity). The pattern of results observed is what would be predicted if the weight given to shear disparity was greater than the weight given to expansion–compression disparity. The results for motion parallax defined stimuli would then be what would be predicted if expansion–compression, rather than shear, were the more dominant component.

Other differences in the results for the two types of stimulus suggest that processing of motion information occurs over a relatively coarse spatial scale. This is evident first in the threshold data for the motion defined stimuli. Both the orientation anisotropy and the increase in thresholds with lower spatial frequencies are only clearly evident for the lowest modulation frequency tested, a frequency that was not tested for stimuli defined by binocular disparity. This shift of the trends observed for motion stimuli is also evident in the supra-threshold data, where the only hint of an inverse oblique effect again occurs only for the lowest frequency tested. The results for disparity and motion demonstrate the same trends, but these occur at different spatial scales, although it should be noted that the same pattern of results was observed for supra-threshold disparity stimuli at both low and high spatial frequencies.

Why this shift in the spatial scale of processing might occur is not clear, although one possibility is the difference in the information provided by the two cues. Horizontal head movements were used to make the information available from disparity and motion as similar as possible, however one difference between the two cues is that the velocity of an individual dot for motion parallax stimuli will vary over time. If this information were to be used, then integration over an extended period of time (and therefore a horizontally extended region of space) would be necessary, which may account for the coarser spatial scale of processing found for motion parallax stimuli.

It is important to consider the implications of such differences between the processing of depth defined by the two cues for models of depth cue combination. Simple weighted averaging of depth specified by stereo and motion has been observed in some studies (Rogers & Collett, 1989; Tittle & Braunstein, 1993). The implications of the differences found in the current study for such averaging are minimal, since they are restricted to differences in sensitivity to the two cues, or to the amount of perceived depth. This would be expected to influence the relative weights attributed to the two cues, and the individual estimates that are to be averaged, and would therefore be expected to influence the amount of depth perceived from a combined-cue stimulus, but not the perceived relief structure of the surface.

In summary, this paper provides a comprehensive set of data on the effects of orientation and modulation frequency on the perception of depth from binocular disparity and motion parallax. At threshold, results from both domains suggest that for low frequency modulations, thresholds increase as surface orientation approaches vertical. Peak sensitivity for disparity defined surfaces occurs around 0.4 cycles/degree whereas for vertical corrugations defined by parallax peak sensitivity occurred at the highest frequency tested. In the supra-threshold task, results showed that for disparity defined surfaces, maximum depth was perceived for oblique corrugations, whereas for parallax defined surfaces maximum depth was perceived for vertical corrugations. These functions were manifest at all modulation frequencies tested.

Acknowledgments

The data reported here are contained in A. Parton (2000, University of Surrey, Unpublished Ph.D. Thesis) and was reported in preliminary form at ECVP (Parton, Bradshaw, Rogers, & Davies, 1996).

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