THE APERTURE PROBLEM IN STEREOPSIS

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ABSTRACT

Stereoacuity was determined for gratings and Gabor patches as their orientation was varied. Acuity was constant for 1 cyc/deg and 2 cyc/deg gratings over the range 0-80 deg when it was expressed as the interocular phase shift. The same was true of an 8 cyc/deg elongated Gabor patch. Thus the threshold for these stimuli was well predicted by a constant shift at right angles to the orientation of the carrier grating. However, the threshold disparity at right angles to the major axis of an oriented Gaussian patch rose as it was tilted away from the vertical. Also, thresholds for a circularly symmetrical Gaussian patch rose steeply with the angle of the disparity away from the horizontal. We conclude that stereo matching depends upon the horizontal component of angular disparity. The apparent insensitivity of grating stereoacuity to orientation can be explained by the invariance of horizontal disparity with orientation when disparity is expressed as a horizontal phase shift in the grating profile.

***Key words*: Stereopsis, motion, orientation selectivity.**

INTRODUCTION

The well-known "aperture problem" in detecting the motion of a stimulus varying along one spatial dimension arises because the vector component of motion parallel to the stimulus orientation has no effect upon the image (Fig. 1a). If the true motion vector is decomposed into a parallel and an orthogonal component to the stimulus orientation, only the orthogonal component can be detected (Hildreth,1983; Hildreth & Koch,1987).

Fig. 1 about here

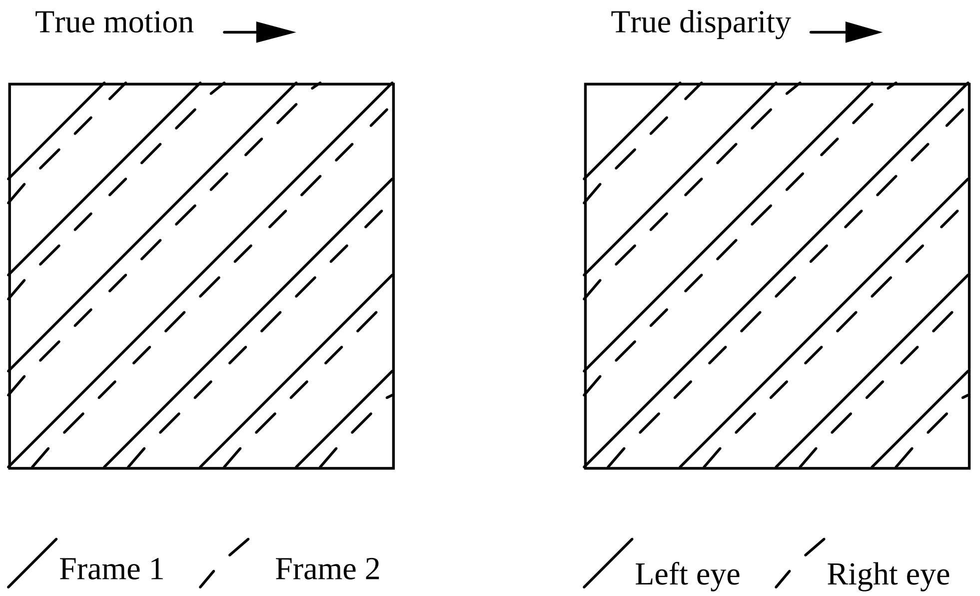

Fig. 1 legend: The figure illustrates the aperture problem for motion (left) and the analogous problem for stereo (right). In the case of motion, the displacement of a one-dimensional stimulus, such as a grating, between two frames cannot give the true direction of motion. Movements in any direction could result in the observed displacement within the aperture (the rectangular box). In the case of stereo (right hand figure) any direction of spatial shift between the eyes could result in the same disparities observed within the aperture. In particular, a purely vertical shift could mimic the effects of a horizontal disparity. The "aperture problem" is a feature of one-dimensional stimuli, rather than of apertures per se. In fact, the problem would exist for infinite stimuli without apertures.

The aperture problem in motion has been much discussed, but an analogous problem in stereoscopic vision has been relatively neglected (Fig. 1b). If an oblique grating occupies different positions within an aperture in the two eyes, the relative shift within the aperture could be due to a horizontal disparity, a vertical disparity, or to any mixture of the two. Suppose that an oblique grating were actually viewed behind an aperture. If the threshold for detecting the disparity depended solely upon the horizontal disparity between points of corresponding luminance on the grating, then depth thresholds expressed as the change in distance from the observer would be independent of orientation. If, on the other hand, the relevant disparity were the phase shift of the grating within the aperture (i.e. the disparity between points of corresponding luminance taken at right angles to the bar orientation) then real depth thresholds would increase with the angle of the grating from the vertical.

Several investigators have reported that depth thresholds for rods indeed increase in proportion to the cosine of the angle of tilt of the rods in the frontal plane and that the threshold expressed as a phase shift at right angles to the rods remains constant (see Howard & Rogers,1995 pp. 167-8 for review). Morgan & Castet (1995) reported a similar result for a 1 cyc/deg sinewave grating viewed through an aperture in static visual noise. Both Morgan & Castet (1995) and Howard and Rogers (1995) point out that the finding would be consistent with the detection of a phase shift in the one-dimensional stimulus, rather than the detection of a horizontal disparity. But an alternative explanation is that disparity detection depends on a phase shift in the horizontal luminance profile (Schor, Wood, & Ogawa,1984; DeAngelis, Ohzawa, & Freeman,1991; DeAngelis, Ohzawa, & Freeman,1995; Morgan, 1996). Suppose that to achieve a given activation difference between horizontally-separated receptive fields in the two eyes, the grating must be given a constant phase shift in its *horizontal* luminance profile. Note that as the grating is tilted away from the vertical its horizontal spatial frequency decreases, in proportion to the cosine of the angle, so to achieve a constant (horizontal) phase shift the (horizontal) disparity must increase.

Therefore, the dependence of stereoacuity upon orientation does not necessarily imply the existence of orientationally-tuned, phase-shift sensitive stereo mechanisms. The experimental findings are compatible with horizontally-separate receptive fields. The crucial stimulus consists of small, circularly symmetric blobs, with a varying angle between them. Phase shift detectors such as those would detect a constant interocular spatial shift between blobs, irrespective of the angle of that shift in the frontoparallel plane. Horizontally-separated detectors should respond, at best, to only the horizontal component of the spatial shift.

We shall report here that stereoacuity for circular gaussian blobs is best predicted by the horizontal component of the disparity, except at disparity angles >=80deg, when stereo matching breaks down entirely. The results are in complete contrast to those for gratings. Oriented Gabor patches behave in a manner intermediate between gratings and blobs. We conclude that the receptive fields underlying stereoacuity are predominantly horizontally separated between the two eyes, as has usually been supposed.

GENERAL METHODS

Apparatus: Stimuli were presented on a raster-scanning visual display (Barco Calibrator II(tm)) under control of a Cambridge Research Systems VSG(tm) graphics card running in pseudo-12 bit grey level mode, with a resolution of 960(h) x 702 (v) pixels, and a frame rate of 140 Hz. One pixel subtended a visual angle of 0.7 x 0.7 arcmin. Linear grey-level look-up tables (LUT's) were constructed by fitting a power function to luminances measured with a Minolta (tm)photometer. Stereo separation of the images in the two eyes was achieved by Ferro-magnetic stereo goggles (Cambridge Research Systems VSG) linked to the frame synchronization signal. The effective monocular frame rate was thus 70Hz, with left and right eye frames being interleaved.

Stimuli: The viewing distance was 200 cm. The background stimulus was a rectangle of size 1.86 x 6.7 deg, containing 17 x 60 random dots, each of size 10 x 10 pixels (0.11 deg^2). The dots were randomly black (0 luminance) or white (41 cd/m2). The stimulus was presented in a square (0.86 deg^2) aperture within the background random dots. When the stimulus was a grating it completely filled the aperture. When it was a Gabor patch it was centered in the aperture with the rest of the aperture set to the mean luminance of the patch. The aperture was imaged in the fixation plane with zero disparity relative to the surround dots. Before and after each grating presentation the aperture was filled with random dots like those in the surround. The gratings (Experiment 1) or Gabor patches (Experiments 2 and 3) were presented within the aperture with a phase difference between the eyes. The carrier and envelope were always moved by the same amount. When the stimuli were vertically oriented the phase shift was identical to a horizontal disparity; at other angles the equivalent horizontal disparity could be calculated from the cosine relation discussed above. Since all the stimuli we used had continuous luminance profiles, sub-pixel phase shifts could be generated by grey-level interpolation (Morgan & Aiba,1985).

Psychophysics: On each trial the stimulus was presented for 500 msec and the observer had to decide whether the grating was in front of the aperture or behind (the single-stimulus method of binary choice). During the stimulus presentation observers attempted to maintain fixation. Over a series of 64 trials, the stimulus was presented with a range of crossed and uncrossed horizontal disparities, determined by an adaptive method of constant stimuli (APE: Watt & Andrews,1981). By performing a Probit Analysis (Finney,1971) every trial on the data collected so far during that threshold determination, APE determined the most efficient range of stimuli for measuring the standard deviation and mean of the observer's psychometric function. Feedback was given in the form of a tone following an incorrect response. If the observer has a bias (in this case, a preference for deciding "in front" or "behind") , APE tracks the bias by presenting a stimulus range centered on the observer's point of subjective equality (the 50% point on the function.) Thresholds were defined as the standard deviation of the psychometric function, corresponding to the 82% correct point in a "yes-no" detection task, although it should be noted that the presence of biases will mean that the observer is not necessarily "correct" on 82% of cases with a threshold stimulus. In each condition of stimulus orientation at least four independent threshold measurements were taken, and the data presented here are the means and 95% confidence limits of these independent measurements.

Procedures: Each session began with the apertures filled with random noise. The observer made sure that the left and right eye images were fused, and then pressed a button to initiate a 0.5 sec stimulus presentation. The apertures were then re-filled with random noise until the observer initiated the next trial by pressing one of two buttons to indicate the decision "in front" or "behind". The task was self-paced and the observer could rest at any time. The room in which the experiment took place was dark except for the light from the display, and observers could choose to listen to background music to relieve tedium.

Subjects: The main observers were the two authors (EC and MM) both of whom have corrected-to-normal vision and no abnormalities of stereoscopic vision as measured by the TNO test.

EXPERIMENT 1

The stimuli were 1 cyc/deg and 2 cyc/deg gratings

Results (Experiment 1): The results (Fig. 2) show that thresholds for detecting the interocular phase shift of the grating were independent of grating orientation over a wide range. Only when the angle reached 80 tilt from the vertical did thresholds begin to systematically increase. It follows from that constancy that horizontal disparities increased with tilt from the vertical, and were well predicted by dividing the threshold phase shift obtained with the vertical grating (we call this the baseline threshold) by the cosine of the angle of tilt (broken curve in Fig. 2).

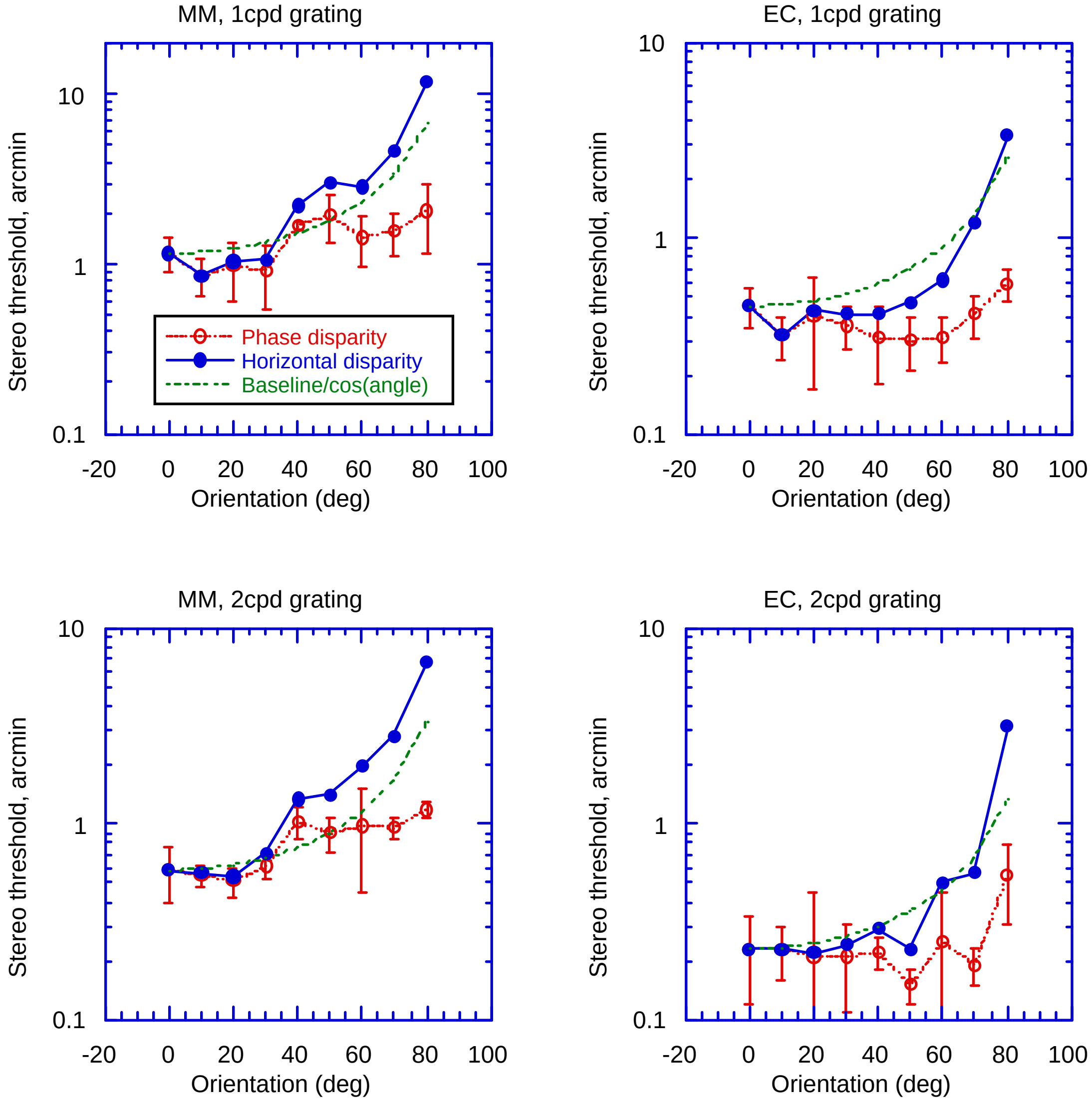

Fig. 2 legend: Results of Experiment 1, which measured stereoacuity (vertical axis) for gratings as a function of their orientation (horizontal axis). The top two panels show results for a 1cyc/deg grating and the bottom two for a 2 cyc/deg grating (left hand panels: observer MM; right hand panels: observer EC.) The vertical error bars represent 95% confidence limits. The unfilled circles express the data as shifts orthogonal to the orientation of the grating in one eye relative to the other eye (Phase shifts). The filled circles replot the same data expressed as the horizontal disparity between points of corresponding luminance in the two eyes. The dotted line shows the predicted rise in threshold if the baseline threshold at 0 deg is divided by the cosine of the angle.

Discussion: Experiment 1. The fact that phase thresholds but not horizontal disparities were independent of angle might seem to imply that it is phase shifts, and not horizontal disparities, that are detected. But we have argued above this may not be the correct interpretation. An alternative is that horizontal disparities are indeed what the observer detects, but that they are detected as horizontal phase shifts in the continuous luminance profile. Since the horizontal period of a grating increases with its tilt from the vertical, increasingly large horizontal disparities will be needed to produce a constant horizontal phase shift. Just as the phase shift of the grating is independent of its angle, so is its horizontal disparity divided by its horizontal period. Thus the finding that phase shifts are constant at threshold does not tell us whether it is phase shifts, or horizontal disparities, that are detected.

The peculiarity of the one-dimensional grating as a stimulus is that phase shifts are indistinguishable in their effects from horizontal disparities. This is indeed the aperture problem for stereopsis, as we outlined it in the Introduction. Two-dimensional stimuli may be expected to provide further information. If the stimulus is a spatially-localized Gabor patch, then phase shifts and horizontal disparities are distinguishable. A shift of a Gabor patch at right angles to its orientation will leave areas that can be matched along horizontal lines in the image. If matching along horizontal lines is crucial for stereopsis, stereoacuity may be expected to break down as the angle of the patch from the vertical is increased. This prediction was tested in the next Experiment.

EXPERIMENT 2

Methods: The stimuli were oriented Gabor patches (8cyc/deg) or a simple Gaussian patch (0 cyc/deg) with an aspect ratio of 2:1 (σ_X=0.1 deg; σ_Y=0.2 deg). Disparities were introduced by shifting the patch in one eye in a direction orthogonal to its major axis of orientation, which was also the orientation of the grating contained within the envelope in the 8 cyc/deg stimulus. Note that when the grating was phase shifted the envelope was shifted by a corresponding amount, so that the phase of the grating within the envelope was always the same (it was in cosine phase). In the case of the simple Gaussian patch, the envelope was shifted in exactly the same way as for the Gabor patch. The orientation of the patches was systematically changed as in Experiment 1 to determine stereoacuity at each orientation.

Except for the stimuli all the Methods were identical to those in Experiment 1. One of the authors (MM) acted as observer.

Experiment 2: Results. The results (see Fig. 3) with the 8 cyc/deg Gabor patch were similar to those with gratings in Experiment 1. The threshold phase shift was constant over a wide range of angles, up to 80 deg from vertical, and this implied that threshold horizontal disparity increased with the angle. The increase was slightly greater than that predicted from the cosine relationship, and this was because the threshold phase angle also showed a slight increase.

In the case of the simple Gaussian patch (0 cyc/deg) there was even clearer evidence for an increase in threshold phase angle with angle from the vertical. In fact, the increase quite closely followed the increase predicted from the cosine of the angle. Another way of saying the same thing, is that the horizontal vector component of the disparity was constant at threshold.

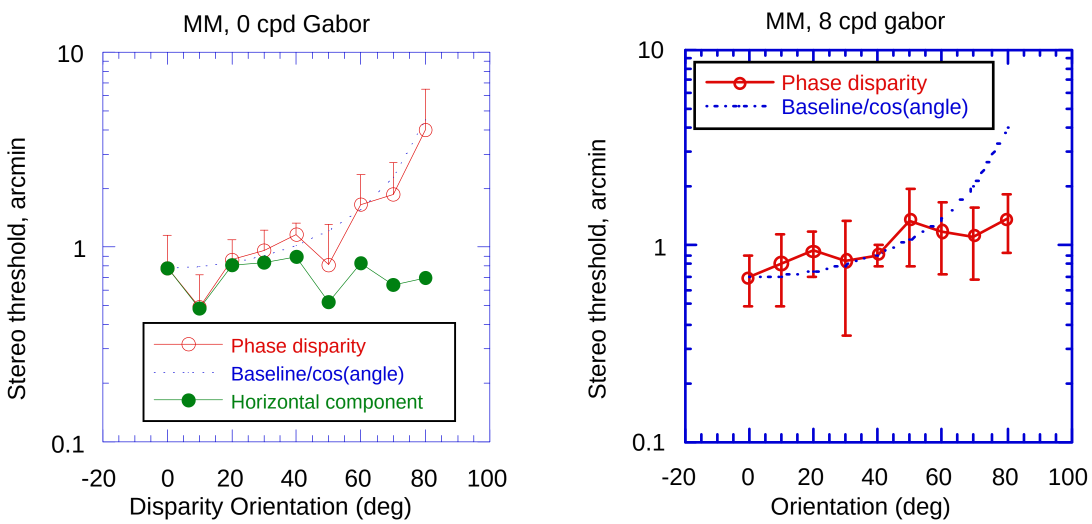

Fig. 3 legend: Stereoacuity thresholds for Gabor patches with the same envelope size but with different frequencies of grating : 0 cyc/deg (left panel) and 8 cyc/deg (right panel). For further explanation see the legend to Fig. 2 and the text. Note that thresholds for the 0 cyc/deg stimulus (a Gaussian patch) are well predicted by the horizontal vector component of disparity, while those for the 8 cpd carrier are better predicted by a constant phase disparity.

Experiment 2: Discussion: The data from the Gaussian patch are not consistent with the detection of phase shifts by disparate receptive fields tuned to phase shifts at all orientations. Rather they suggest that disparities are detected predominantly by fields tuned to phase shifts along the horizontal meridian. In the tilted and phase-shifted Gaussian patches there is no correspondence of the luminance profile along horizontal lines in the image, particularly at the tips of the patches, and this would seem to have disturbed stereo matching. The 8cyc/deg Gabor patches may have escaped the correspondence problem because smaller receptive fields were involved. Those centered in the patches would have acted themselves as small apertures, making the stimuli functionally similar to the large gratings in Experiment 1.

The prediction from this analysis is that stereoacuity would be even more adversely affected if small, circularly symmetric stimuli were used. It is no longer meaningful to speak of the orientation of these stimuli, but we can still speak of the orientation of the disparity shift between the eyes. When this is horizontal matching can occur along horizontal lines. When the disparity angle is 40 deg, on the other hand, there is very little overlap between the stimuli along horizontal lines and stereoacuity should be adversely affected.

EXPERIMENT 3

Methods: The stimuli for MM were circular Gaussian patches with $\sigma_X = \sigma_Y$ = 0,05 deg. EC found the task too difficult with such small patches, so for him the viewing distance was halved, making $\sigma_X = \sigma_Y$ = 0.1 deg. The stimulus in one eye was presented in a randomly-jittered position within the aperture, which had the same luminance as in the previous experiments, and the stimulus in the other eye was presented with a disparity, defined as the distance of its centre from the centre of the patch in the first eye. The disparity could be in any direction, varying from a purely horizontal disparity (0 deg) to a predominantly vertical disparity (80 deg). For every direction, the disparity could be either to the left or the right, giving rise to a crossed or uncrossed horizontal component of disparity, and the observer's task was to decide whether the stimulus was in front of behind the plane of the aperture. The other Methods were the same as in the previous Experiments.

The observers were the two authors, MM and EC.

Results: Fig.4 shows that thresholds, expressed as the distance between the centroids of the dots between the two eyes, rose rapidly with the angle of the disparity. Note that we now use the term "centroid disparity" rather than "phase shift" because the latter term applies meaningfully only to gratings. Nor is it meaningful in the case of the circular Gaussian to measure distance between corresponding luminance points along a horizontal epipolar, as we did in the case of gratings, because no such corresponding points exist when there is a disparity. Instead, we measure the horizontal component of the disparity, that is, the horizontal separation between points of equivalent luminance, such as the centroid point. Fig. 4. shows that the horizontal component of the disparity is much more constant at threshold than is the centroid disparity, as if the observer were able to match the points, ignoring the vertical disparity component. However, there were limits to the ability to do this, since neither observer could achieved reliable thresholds with disparity angles >=80deg, unlike the case with gratings and Gabor patches.

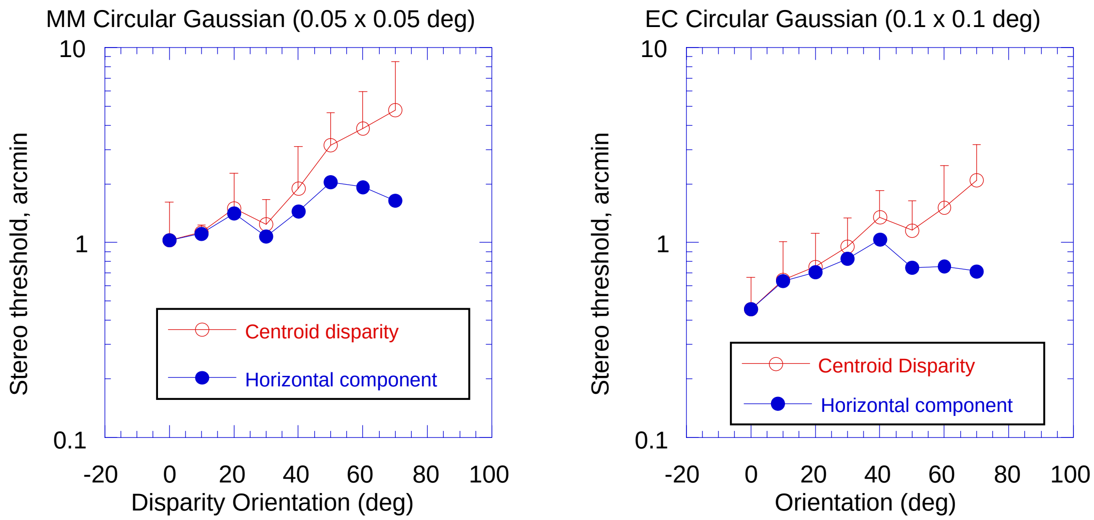

Fig. 4 legend: Results of Experiment 3, which measured stereoacuity for small, circular Gaussian blobs. The orientation (horizontal axis) refers to the angle of the disparity between the centroids of the blobs in the two eyes. centroid disparity refers to the distance moved by the centroid of the blobs between the two eyes. The horizontal component refers to the horizontal vector of the centroid disparity, i.e. to centroid*cos(angle). Note that threshold centroid disparity increases with angle, unlike the case for phase disparity with Gabor patches and gratings (Experiments 1-3), but that threshold horizontal disparity is more nearly constant over angle. Angles of >=80 deg did not produce reliable thresholds.

Experiment 4

The results of Experiment 3 suggest that disparities of circular Gaussian blobs are detected by, at best, only the horizontal component of their disparity. However, this is not the case with oriented gratings or Gabor patches containing an oriented grating, which are detected by the disparity phase shift. Is the improvement due to the orientation of the grating, which in previous experiments has always been at right angles to the direction of the disparity, or would introduction of a vertical grating also improve stereoacuity for oblique disparities? The final experiment compared stereoacuity for horizontal and 70 deg disparities, using a 4 cpd Gabor patch with the grating oriented either at 0 or 70 deg. A Gaussian patch with the same envelope as the 4 cpd Gabor was also included.

Methods: Stereoacuity was measured for 6 different stimuli, shown schematically as a-f in Fig. 5. Stimulus **a** was a simple Gaussian patch with $\sigma_X = \sigma_Y$ = 01 deg. The direction of the disparity was horizontal. Stimulus **b** was the same Gaussian patch, with the direction of the disparity 70 deg. Stimulus **c** was a 4 cpd Gabor patch with the same Gaussian envelope as **a** and **b**, and the disparity direction 70 deg (i.e. orthogonal to the grating). Stimulus **d** was a vertically oriented 4 cpd with the direction of the disparity horizontal. Stimulus **e** was a 70 deg oriented Gabor with a horizontal disparity. Finally, stimulus **f** was a vertically-oriented 4 cpd Gabor with a 70 dg disparity.

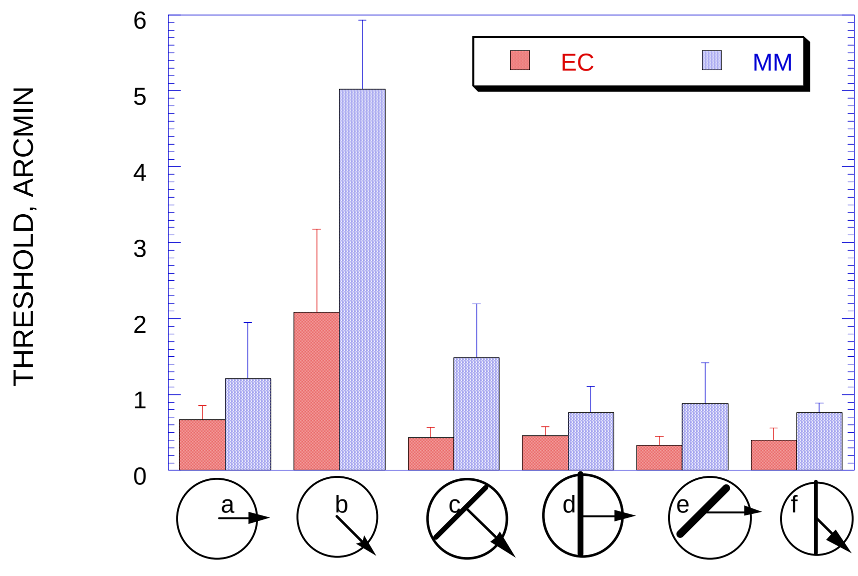

Fig. 5 legend: Results of Experiment 4, in which stereoacuity was measured in 6 different stimulus conditions (a-f) as illustrated schematically in the drawings at the bottom of the figure. In the drawings, the circle represents a circular Gaussian envelope. The bar, when present indicates the orientation of a 4 cpd grating inside the envelope. The arrow indicates the direction of the disparity. The stereo thresholds (vertical axis) are shown separately by differently shaded bars for the two observers (MM and EC) and the error bars represent 95% confidence limits. Thresholds refer to the centroid disparity of the blobs in the two eyes, as explained in the legend to Fig. 4.

A disparity shift of the Gaussian blob was harder to detect when the disparity angle was 70 deg vs 0 deg (**a vs b).** However, the striking result was that introducing a 4 cpd grating into the patch also made the disparity easy to detect, whatever the orientation (0 vs. 70 deg) of the disparity, or of the grating (**c-f**). There were no significant differences between the conditions when the grating was present, in either observer.

SUMMARY AND CONCLUSIONS

Centroid disparities of circular Gaussian bobs are best detected when the disparities are horizontal. Disparities of gratings or Gabor grating patches are detected equally well at all angles up to 70-80 deg. For gratings, the threshold phase shift of the grating at right angles to its orientation (the phase disparity) is independent of angle.

These findings can be explained most economically by supposing that stereoscopic matching occurs preferentially along horizontal epipolar lines. The obvious mechanism would consist of binocular neurones that have horizontally-separated sub-fields in the two eyes (Barlow, Blakemore, & Pettigrew,1967). In the case of circularly-symmetrical stimuli and receptive fields, vertical disparities could be tolerated so long as the stimuli still fell within the receptive field, and threshold disparity would be predicted by the horizontal component of the disparity. With a sufficiently large angle the vertical component of the disparity would take the stimuli outside the receptive field and matching would break down. These are the results we observed with circular Gaussian patches. Matching broke down completely at disparity angles >=80 deg. At smaller angles the threshold was determined by the horizontal component of the disparity.

The situation with oriented grating stimuli is more complex. Elongated, horizontally-separated receptive fields of the same orientation as the grating could signal a horizontal disparity. They could also signal disparities at non-horizontal orientations. At first sight, this would seem to imply that threshold would be determined by the horizontal separation between points of corresponding luminance in the two eyes. We find, to the contrary, that threshold is constant when expressed as the phase shift of the grating. However, as we argued in the Introduction, the disparity threshold of horizontally-separated detectors is most likely to be dependent on the horizontal phase shift between the eyes, and since this depends on the horizontal period of the grating, which changes with the angle, a constant orthogonal phase shift would be expected.

An alternative to the view that all disparity detectors are horizontally separated is that oriented detectors are positionally separated at right-angles to their preferred orientation, in such a manner as to detect a phase shift of oriented components. This would imply, however, that non-oriented detectors are organized differently, with a preference for horizontal disparity. It will probably take detailed physiology rather than further psychophysics to resolve this issue. The existing physiological evidence is equivocal. DeAngelis et al. (1991) did not measure the position of the envelope of their phase-sensitive cells, and so their data do not speak to the issue of phase *vs* horizontal disparity sensitivity. LeVay & Voigt (1988) explicitly measured disparity sensitivity of orientationally-tuned cells in cat Area 17 and 18 by moving the stimulus at right-angles to the cells' preferred orientation, as did Nelson, Kato, & Bishop (1977). This orthogonal disparity was effective in stimulating the cell, but the result does not rule out the possibility that a horizontal shift would have been equally effective. Indeed, it almost certainly would have been: this is the aperture problem. Only a detailed point-wise map of the relative receptive field positions in the two eyes can resolve this issue.

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