Depth perception in disparity gratings

Observation of sinusoidal spatial modulation of luminance has proved a valuable tool in the study of visual processing of luminance distributions on the retina. Information on the limits of processing capability has been gained in such diverse fields as the optics of the eye, neurophysiology of the retina, movement and orientation sensitivity and cortical processing of spatial frequency. In the field of stereoscopic vision, Blakemore and Fiorentini and Maffei have found that when luminance gratings of slightly different spatial frequencies were presented to each eye, an apparently tilted grating was perceived even if one monocular grating was moving quickly relative to the other. Furthermore, tilt is perceived from gratings of the same spatial frequency but differing in contrast by 50% or more. These phenomena are not easy to explain on the basis of disparities at corresponding retinal points, but seem to require more global processing of the whole image.

Julesz has reached a similar conclusion on the basis of experiments with random-dot stereograms, which have the unique advantage of eliminating all correlated monocular cues to the stereoscopic figure (although the random dot texture acts as a monocular textural cue that the figure has a constant depth and works against the disparity information to some extent). Stereopsis can be obtained under several conditions which make it difficult to conceive of a local disparity process that could produce depth perception. For example, alternation of two stereograms at 20 Hz does not destroy perception of a stereoscopic figure. Furthermore, in ambiguous stereograms the depth perceived depends on the global organisation of nearby dots.

It would be of value to combine the advantages of random-dot stereograms and of sinusoidal modulation techniques in the study of spatial limitations of cyclopean depth perception. I have previously studied the effects of sinusoidal modulation of binocular disparity along a vertical axis on stereoscopic perception using line stereograms. The main stereoscopic processing limitations noted were a sharp high frequency limitation in sensitivity about three cycles per degree (c.p.d.) and a disparity scaling effect, in which the maximum disparity that could evoke a depth percept was directly proportional to the retinal angle subtended by each cycle of the vertical modulation. Thus, the disparity limit is scaled in proportion to size of the modulation cycles. The experiments reported here show that the line stereogram results are replicated using random-dot stereogrtings as stimuli and are probably general properties of the stereoscopic system.

Generation of random-dot disparity gratings with a large range of disparity variation required a slight modification of Julesz's concept (see Fig. 1). A second technique enabled threshold sensitivity to be measured over a great range of amplitudes and frequencies of disparity modulation without generating a vast number of individual stereograms. By analogy with the demonstration stimulus for luminance grating sensitivity it is possible to produce continuous variations of both amplitude of disparity and spatial frequency as a frequency-swept, amplitude-decayed stereograting (Fig. 1). The boundary between perception of the flat random-dot texture and the rippled surface of the stereogram is determined by the spatial frequency limits of disparity processing in the visual cortex.

For demonstration, the monocular cues of the disparity

![Figure 1](image-url)
ripple at the edges of the right hand matrix is present, but these were masked to straight edges during quantitative experiments. The edge ripple in relation to the straight edge of the left-hand matrix indicates the precise disparity present down each edge of the figure. Readers may verify that no changes in texture density correlated with the disparity variations are evident in Fig. 1.

To ensure that maximal stereoscopic information was available, free eye movements and long and active viewing times were encouraged. The stereograms were viewed through a Smith orthonator stereoscope. Each subject was fully optically corrected, since individual dots were close to the limit of visual resolution. The stimuli were Xerox copies of the Calcopp plot which had a luminance of 3 cd m⁻² and were viewed at a distance of 200 cm. Subjects were instructed to concentrate on each bar indicated in turn, and decide where in the matrix the bar disappeared into a flat surface. They then directed the experimenter in marking the point on the matrix with a red mark invisible to the subject. A complete set of spatial frequencies was measured twice.

The results of the measurements of spatial frequency limitations of stereosensitivity for two subjects (Fig. 2) are in general agreement with line stereosensitivity limits⁴. The maximum frequency for which the stereogram can be resolved (Fig. 2a) is about 4 c.p.d. (compared with 3 c.p.d. in line stereograms⁵), and is only slightly affected by a tenfold reduction in dot density. (Note that at this frequency there are 7 dot widths or 70 dot positions per cycle.) The slight discrepancy between the uppermost points in Fig. 2a and the lowermost in Fig. 2b is probably due to measurement error and may also be influenced by edge effects at the edge of the grating.

Similar results may be obtained for previously published stereograms containing both vertical and horizontal gratings⁶. The grating becomes invisible as viewing distance is increased so that the grating subtends about 4 c.p.d. This is not due to lack of acuity for the monococular textural information, since in stereograms of the same texture at the same viewing distance a large stereoscopic figure such as a square is readily visible.

High spatial frequency sensitivity may also be studied by removing high or low spatial frequency information from one matrix of a stereogram⁷. Once again stereopsis is difficult (impossible for all five observers I tested) when there are no low spatial frequency cues to the stereoscopic figure, whereas lack of high spatial frequency information hardly affects stereoscopic perception.

As with all measures of stereolimits there is a lower and an upper disparity for which perception of depth falls to threshold. The former will be called stereoacuity and the latter the upper depth limit. Stereoacuity falls in the region of the resolution of the Calcopp plotter, so it could not be measured by the present method. For the upper depth limit, the maximum disparity (Fig. 2b) decreases with increasing frequency, corresponding to a disparity scaling effect which conforms reasonably well with the equation (solid line in Fig. 2b):

\[ \eta = a / \nu \]

where \( \eta \) is peak-to-peak binocular disparity in arc degrees, \( \nu \) is spatial frequency in c.p.d. and \( a \) is a scaling constant that has the values of approximately 0.3 for J.Z. and 0.6 for C.W.T. These values may be compared with values of about 0.5 for C.W.T. and 0.33 for another subject using line stereograms⁴.

This disparity scaling equation describes a limit in rate of change of disparity across the retina. This limit applies equally to global stereopsis from random-dot stereograms and qualitative stereopsis from line stereograms⁸. The similarity of the scaling constant \( a \) for the two types of

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**Fig. 2 Stereo sensitvity for two subjects, J. Z. (○) and C.W.T. (●). a, Region of maximum frequency, plotted in terms of peak-to-peak disparity variation versus spatial frequency of sinusoidal stereograting. — —, 40% dot density; — —, 4% dot density. b, Region of maximum disparity in same coordinates, showing conformity to disparity scaling effect. To obtain stereograms with sufficiently low rate of change over a full range of spatial frequencies and amplitudes the gratings used were, a, 1-10 c.p.d., 0.5-5 arc min and b, 0.75-7.5 c.p.d., 5-50 arc min in spatial frequency and peak-to-peak amplitude range. Both these stereograms were produced with a dot density of 40% by area, but as a check on the effect of dot density a was also produced with dot density of 4%. Variability of the data is shown as the average standard deviation of all pairs of readings (vertical bar above and below one point in Fig. 2). In regions where the function is vertical the bar represents horizontal variability, since the direct viewing technique does not constrain the variability to one dimension.
stimuli suggests that the disparity scaling limit is determined by the arrangement of disparity detectors in cyclopean space rather than by the difference in orientation between monocular line segments17.

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