Bias and sensitivity of stereo judgements in the presence of a slanted reference plane.

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Abstract

The perceived depth of features is known to be affected by the presence of a slanted reference plane. Mitchison and Westheimer (1984) reported that two lines appear to be at the same depth when they lie in a plane approximately parallel with the reference plane. We measured the perceived depth of two lines presented in front of a regular grid of dots that was either fronto-parallel or slanted about a vertical axis. The effect of the slanted grid on perceived depth diminished as the grid was moved further in disparity from the lines. We also found that the slanted grid affected the sensitivity to differences in disparity. The minimum threshold for detecting changes in disparity is normally lowest in the fixation plane and rises systematically with increasing pedestal disparity. In the presence of a slanted reference plane, the minimum threshold is at or close to the plane of equal perceived depth and rises with increasing disparity from this plane.

Key words: binocular stereopsis, perceived depth, stereoacuity, *reference plane*

Introduction

The perceived depth generated from stereopsis is not a simple function of binocular disparity. One strong influence is the position and disparity of neighbouring features. For example, when points lie close together (within a few arcmin) they may be perceived to be at the same depth ('disparity pooling': Westheimer, 1986; Westheimer and Levi, 1987; Parker and Yang, 1989). In other configurations, the apparent depth difference between points may be exaggerated ('disparity contrast': Anstis, Howard and Rogers, 1978; Graham and Rogers, 1982; Mitchison and Westheimer, 1984; Westheimer, 1986; Westheimer and Levi, 1987; Kumar and Glaser, 1991). Another example of the effect of nearby features on perceived depth is the insensitivity of the visual system to smooth gradients of disparity, particularly in the horizontal direction (Wallach and Bacon, 1976; Rogers and Graham, 1983; Gillam, Flagg and Finlay, 1984; Mitchison and McKee, 1990; Mitchison and Westheimer, 1990). Such effects are not purely explicable in terms of mechanisms in the disparity domain. An illustration of this point is the reduction in perceived depth that occurs when two vertical lines, presented at different disparities, are joined together by two horizontal lines to form a square: the horizontal lines do not alter the disparity content of the stimulus but they can, nevertheless, change the way it is perceived (McKee, 1983).

Although in many cases the spatial interactions between neighbouring points with different disparities bear a resemblance to properties of spatial contrast vision, the analogy is not an exact one (Brookes and Stevens, 1989; Mitchison, 1993; Morgan and Lunn, 1995). Psychophysical evidence suggests that changes in the local gradient of disparity are of primary importance in determining perceived depth (Mitchison and Westheimer, 1984, 1990; Stevens and Brookes, 1988; Gillam, Chambers and Russo, 1988; Rogers and Cagenello, 1989) but whether this reflects the output of second derivative, centre-surround mechanisms operating in the disparity domain remains to be determined.

In the experiments described here, we measured the effect of a slanted grid of dots on the perceived depth of two vertical lines as a function of their disparity with respect to a grid of regularly-spaced dots (see figure 1). The stimulus is similar to that used in a study by Mitchison and Westheimer (1984). They found that the disparity of the lines relative to the plane of the grid determined the perceived depth of the lines. We found that the effect of the grid diminished as it was moved further in disparity from the lines. We also asked whether the altered pattern of perceived depth in the neighbourhood of the grid has any effect on the *sensitivity* to differences in disparity. For example, the minimum threshold for detecting changes in disparity is normally lowest in the fixation plane and rises systematically with increasing pedestal disparity (Ogle, 1953; Blakemore, 1970; Badcock and Schor, 1984; McKee, Levi and Bowne, 1990). We found that adding a

Figure 1: about here

slanted reference plane changed the pattern of thresholds such that the minimum of the disparity function is at or close to the plane of equal perceived depth and rises with increasing disparity from this plane.

Methods

Apparatus

The stimuli were composed of dots drawn by computer-generated signals on two Hewlett-Packard 1332A monitors, each equipped with a P4 phosphor. The images on the monitors were superimposed by a beam-splitting pellicle. Orthogonally-oriented polarizers placed in front of the monitors and the subject's eyes ensured that only one screen was visible to each eye.

Stimuli were viewed in a dimly-lit room. The background luminance was low (0.005 cd/m^2 measured with a Pritchard photometer) and the dots were bright (space-averaged luminance of 6 cd/m^2 for a 1.6 by 1.6 arcmin lattice, see Harris and Watamaniuk, 1995). Viewing distance was 1.5m.

Stimuli

The stimulus was a 7 by 7 grid of dots subtending 2 by 2 degrees (at the viewing distance of 1.5m) with two vertical lines in front of the grid (see figure 1). The lines were each made up of nine vertically aligned dots, subtending 1 degree in total. The comparison line was always presented 10 arcmin to the right of the screen centre. The test line was presented at -50, -30, -10, +30 and +50 arcmin (where positive values indicate lateral positions to the right of the midline). We chose to present the lines in positions midway between the grid columns because we found in a pilot experiment that stereoacuity thresholds were raised when the test line was presented at a similar lateral position to a column in the grid.

On different experimental runs the grid was either fronto-parallel or slanted around a vertical axis, in which case the grid width in the right eye's image was 1.1 times that in the left eye. The mean disparity of the grid, when present, was 4 arcmin behind the fixation plane (except for data shown in figure 4). The disparity of the comparison line was fixed throughout a run. The disparity of the test line varied from trial to trial around a mean 'pedestal' disparity.

Stimuli were presented for 150 ms after which the screen remained blank until the subject responded by pressing one of two mouse buttons. A fixation cross was then presented in the centre of the screen flanked by a pair of nonius lines (24 arcmin long, separated vertically by 1 degree). Once the nonius lines appeared aligned, the subject pressed a mouse button to initiate a trial; the fixation cross and nonius lines disappeared before the stimulus presentation.

Psychometric procedure

In experiment I, the subject's task was to judge whether the test line was in front of or behind the comparison line. Two of the observers were the two authors, so they were fully aware of the grid configuration and its reported effect on perceived depth. Nevertheless, they tried to make the same judgement when the grid was present as when they viewed the comparison and test lines alone. They (and the naïve subject) were instructed to ignore the grid behind the test and comparison lines. The data indicate that the subjects were not merely setting the relative depth of the test and comparison lines to match the apparent slant of the grid. For one thing, the point of subjective equality (PSE) settings generally do not match the exact tilt of the grid, and for another, the effect of the grid falls off systematically with its disparity from the two lines. In experiment II, the subject's task was to judge whether the depth separating the test line from the comparison line was larger or smaller than the mean of the test set, i.e. to make an incremental judgement of depth (c.f. McKee et al., 1990).

At least seven different test disparities were presented during a run of 100 trials. The range (but not the mean) of the test disparities was adjusted during the run by a simple adaptive procedure that depended on the subject's performance. This procedure is particularly suitable for testing thresholds about a known bias. When the centre of the range of stimuli presented is different from the subject's PSE, subjects often note that they are pressing one button more than the other which can perturb their response behaviour and hence the estimate of the PSE. In order to reduce this effect, we used a pilot run of 50 trials to estimate the PSE and, in the experimental run, the tested disparities were arrayed about this value. Measured values of the PSE could and did change from this initial estimate during the experimental run. However, it is difficult, whatever procedure is used, to rule out the possibility that the range of stimulus disparities presented has some effect on the measured PSE. A minimum of 200 trials (2 runs) was used to estimate each bias or threshold shown in the figures.

The data were fitted to a cumulative normal function by probit analysis (Finney, 1973). For experiment I, figures 2, 3, 4 and 5 show the bias (i.e. the mean) of the psychometric function. Standard errors were generally smaller than the size of the symbols and are not shown. For experiment II, figures 6, 7, 8 and 9 show thresholds (the standard deviation of the fitted cumulative Gaussian) and error bars indicate plus and minus one standard error.

Subjects

Subjects were the two authors and one naïve subject. All had normal or corrected-to-normal acuity.

Results

Experiment I: Biases in perceived depth

Figure 2 shows how the slanted grid affects the perceived depth of the test line relative to the comparison line. The position of the grid is shown by the dotted lines; in this first experiment, its mean disparity was always 4 arcmin behind the fixation plane. The open symbols show the position of the comparison line; it was always presented 10 arcmin to the right of the midline and had different disparities in different experimental conditions. The solid symbols show, for different lateral positions, the disparity at which the test line was perceived to be at the same depth as the comparison line (i.e. the 50% point of the psychometric function).

There are three features of the data to be noted. First, for all comparison disparities tested there were significant biases in the perceived depth of the test line and these were always in the direction of the grid. Figure 3 shows that there is no appreciable bias in the absence of the grid nor in the presence of a fronto-parallel grid. Second, the slope of the data in figure 2 (i.e. the change in bias per unit of lateral displacement) was never as great as the slant of the grid (shown as a dotted line). This means that the data cannot simply be accounted for by supposing that the test and comparison lines are perceived to be at equal depths when they have equal disparity relative to the plane of the grid. The data lie somewhere between the slant of the grid and true fronto-parallel.

Third, the slopes of the data in figure 2 diminish when the comparison line is furthest in depth from the grid (table 1 gives the slopes of regression lines through the data). A shallower slope means that, for any given lateral position of the test line, the perceived bias in depth is smaller. There are two possible explanations. It might relate to the absolute disparity of the lines or it might reflect their disparity with respect to the grid. Data in figures 4 and 5 indicate that it is the second of these factors that is most important.

Figure 4 shows the result of repeating one condition from the experiment, in which the comparison line was presented in the fixation plane, but in this case the grid was presented 8 arcmin behind the fixation plane instead of 4 arcmin behind. This manipulation should have little effect if the absolute disparity of the lines is the most important factor in determining the bias. However, as figure 4 shows, the biases are reduced for each lateral position of the test line. The slopes of regression lines fitted through the data are

Figure 2: about here

Figure 3: about here

shown in table 1. For both subjects, the change in slope caused by changing the disparity of the grid is statistically significant ($p < 0.01$).

In fact, the change in bias with lateral position was similar to that observed when the grid was at -4 arcmin and the comparison line was at +4 arcmin (i.e. the same *relative* configuration but further forward in depth by 4 arcmin). These two sets of data are plotted together in figure 5 (where the ordinate shows the disparity of the test line relative to the grid). The data agree well, indicating that relative rather than absolute disparity is most important in determining the extent of the bias in perceived depth.

Experiment II: Depth increment thresholds

Stereoacuity thresholds are known to be lowest in the fixation plane and to rise rapidly as the pedestal disparity of the test line is increased (Ogle, 1953; Blakemore, 1970; Badcock and Schor, 1985; McKee et al , 1990). It is also known that a slanted reference plane raises stereoacuity thresholds (Kumar and Glaser, 1992). What is not known is whether, in the presence of a slanted reference plane, the minimum stereoacuity threshold still occurs when the test line and comparison have the same disparity or whether it occurs when they *appear* to lie in the same depth plane.

The stimulus configuration was the same as in experiment I except that a wider range of pedestal disparities was used. The task was to judge whether the depth separating the test line from the comparison line was larger or smaller than the mean of the test set, i.e. to make an incremental judgement of depth (c.f. McKee et al., 1990). A comparison line was presented in the fixation plane (10 arcmin to the right of the midline, as in experiment I). Twenty practice trials were presented before each experimental run. Figures 6 to 9 show the threshold and standard errors derived from data combined from at least two runs of 100 trials. Two subjects (AG and SPM) collected data with the test line presented 10 arcmin to the left of the midline; the third subject (VU) collected data with the test line at all the lateral positions used in experiment I.

Figure 4: about here

Figure 5: about here

Figure 6: about here

Figure 6 shows depth increment thresholds plotted against the absolute disparity of the test line for subjects AG and SPM. When the test and comparison lines were presented alone, thresholds rose with increasing pedestal disparity, consistent with previous reports (Ogle, 1953; Blakemore, 1970; Badcock and Schor, 1985; McKee et al , 1990). The presence of a fronto-parallel grid generally improved performance (possible reasons for this are considered in the Discussion) but the shape of the function was not affected. The minimum threshold still occurred when the test line was in the fixation plane.

The presence of a slanted grid, on the other hand, did affect the shape of the threshold function. Thresholds measured with crossed (positive) pedestal values were lower than for the fronto-parallel grid condition, while thresholds for uncrossed pedestal disparities were higher (data on uncrossed disparities were gathered for subject SPM only). As a result, the minimum of the function shifted towards +1.5 arcmin (i.e. the disparity at which the two lines were perceived to lie at the same depth).

The most surprising aspect of the data is that a slanted grid can improve performance compared to that measured in the presence of a fronto-parallel grid. At first sight, this appears to contradict previous reports of a deterioration in stereoacuity in the presence of a slanted reference plane (Kumar and Glaser, 1992). In fact, there is no conflict since previous experiments have not measured depth increment thresholds for different pedestal disparities as we have done. The conditions in which depth increment thresholds improved were those in which the slanted grid reduced the apparent depth difference between the test and comparison lines.

Figure 7 re-plots the data to show thresholds as a function of the pedestal disparity of the test line relative to *perceived* fronto-parallel. Against a slanted grid, a pedestal of 1.5 arcmin was required for the test line to appear at the same depth as the comparison line and so, in figure 7, data for the slanted grid condition has been shifted to the left by 1.5 arcmin. When re-plotted in this way, the data for fronto-parallel and slanted grids are roughly superimposed. The small discrepancies between the two conditions

Figure 7: about here

Figure 8: about here

(at 0 arcmin for SPM and -2 arcmin for AG) suggest that absolute disparity has a residual effect on sensitivity. However, the general pattern of the data indicates that the apparent depth difference between the lines is a more important factor than absolute disparity in determining depth increment thresholds.

Thresholds for other positions of the test line

The same overall conclusion is supported by the results for subject VU shown in figure 8. In this case, thresholds were measured for a wider range of lateral positions of the test line but a smaller number of pedestal disparities at each position. The comparison line was always in the fixation plane and 10 arcmin to the right of the midline, as in the previous experiment.

The symbols used in figure 8 have been chosen to emphasise the conditions in which the apparent depth of the test and comparison lines were similar in the presence of a fronto-parallel and slanted grid, not when they had the same absolute disparities. Thus, the filled circles show conditions in which the pedestal disparity of the test (i.e. the disparity of the test in the centre of the range used in the experiment) was such that it appeared to be at the same depth as the comparison line. Against a fronto-parallel grid, this was zero disparity but against a slanted grid the test had a different pedestal disparity at each lateral position, determined by the results of experiment I (figure 2). These disparities are labelled 'SG-zero' pedestal disparities in figure 8 because they correspond to the perceived fronto-parallel plane in the presence of a slanted grid.

In terms of *apparent* depth, the zero disparity case shown in Figure 8a (fronto-parallel grid) is the same as the 'SG-zero disparity' case shown in Figure 8b (slanted grid). Note that the pattern of thresholds plotted as filled symbols in both figures are very similar. The *apparent* incremental depth of the 'SG-zero disparity' stimuli for a flat grid (Figure 8a) and the '2 × SG-zero disparity' stimuli for the tilted grid (Figure 8b) are also very similar. Again, the pattern of thresholds shown by open squares in each figure is similar. When the '2 × SG-zero disparity' stimuli are presented in front of a flat grid, the apparent depth is much greater, and the pattern of thresholds (open triangles in Figure 8a) is dramatically different compared to the same thresholds measured with a tilted grid. Consistent with the results shown in Figure 7, apparent depth, not absolute disparity, appears to be the major factor controlling the thresholds.

Figure 9: about here

Thresholds measured without a comparison line

It could be argued that the comparison line is irrelevant to the task, since the grid forms an adequate reference against which the depth of the test line can be judged. Figure 9 shows thresholds gathered with no comparison line present. The conditions chosen were ones that might be expected to yield the lowest thresholds under different hypotheses: if absolute disparity is an important factor then thresholds should be lowest when the test line is in the fixation plane; if relative disparity is most important then thresholds would be expected to be lowest when the test line is close to the grid. For a fronto-parallel grid, the test line was either in the fixation plane or 1.5 arcmin behind the fixation plane (and hence closer to the grid). For the slanted grid, the test line was presented in the fixation plane either to the left or the right of the midline. On the left, its disparity relative to the plane of the grid was 3 arcmin; on the right it was 5 arcmin.

Thresholds with a comparison line present are shown in the last column of Figure 9. All of the other thresholds measured in the absence of the comparison line are higher than those shown in this last column. There is no other systematic effect of either absolute disparity or disparity relative to the grid. These results show that observers were using the comparison line when making their judgements and were not simply making a depth judgement relative to the grid.

How might the grid cause a change in thresholds?

Psychophysically determined thresholds reflect noise processes in the visual system. What are the noise processes that could underlie the thresholds in experiment II? Any model must explain both the improvement in thresholds when a grid (either slanted or fronto-parallel) is displayed behind the test and comparison lines and also why a slanted grid can shift the minimum in the threshold function to a non-zero pedestal disparity. Here we briefly examine two types of model. We suggest that, in the fronto-parallel grid condition, thresholds follow Webers law, i.e:

$$\text{Threshold} \propto k(\text{relative disparity}) + c \tag{1}$$

which McKee et al (1990) showed held true for depth increment thresholds. For the slanted grid, the data are better described by:

$$\text{Threshold} \propto k(\text{apparent depth difference}) + c \tag{2}$$

Figure 10: about here

particularly for subject SPM. We assume that the slanted grid has the effect of recalibrating the visual system's estimate of the fronto-parallel so that the relative disparity determining thresholds is the disparity of the test line with respect to this recalibrated plane (d_t in figure 10). The idea, originally proposed by Andrews (1964), is that the origin of the metric for describing any perceptual variable, in this case slant, is dependent on the statistics of the input and is continuously being 'corrected'. Andrews used the example of motion adaptation in the waterfall illusion to illustrate how a biased 'visual diet' can cause the system to re-calibrate itself. As a result, the input corresponding to 'zero perceived motion' would change. By the same token, a scene with a predominant slant in one direction could change the visual system's definition of fronto-parallel and hence the apparent depth difference on which, we hypothesise, thresholds depend.

Both slanted and fronto-parallel grids reduced thresholds compared to those measured without any grid present. One possible explanation is that, in the absence of a visible reference frame, the visual system's definition of fronto-parallel is more prone to vary over the course of a test block than when a grid is presented behind the test and comparison lines. For non-zero pedestal disparities, there is a bias in the mean slant of the input, so a gradual recalibration of the definition of fronto-parallel could take place. One subject observed that the apparent pedestal depth appeared to shrink over the duration of a test block in the no-grid condition, whereas it was stable when the grids were present. If the test disparity is measured against a shifting baseline like this, then inevitably thresholds will be raised.

A closely related possibility is that the disparity of the test line is measured relative to all the other elements in the stimulus and, when the number of elements is greater, the estimate is more reliable. Figure 9 shows that the comparison line contributes to sensitivity as well as the grids. If we assume that each of the seven grid columns and the comparison line provide an independent estimate of the disparity of the test then these samples of signal magnitude, if summed optimally, would necessarily improve thresholds. We examined whether the integration model ('d' additivity') of signal detection theory (Green and Swets, 1966) could explain the observed threshold improvement, as well as the shift in the minimum of the functions shown in Figure 6.

To estimate their combined effect, we weighted the relative contributions of the comparison and each grid line. The 'no grid' data in Figure 6 demonstrate that thresholds rise as the disparity separating the test and the comparison lines increases. For the model, we assumed that lines closer to the test line provide a more precise estimate than lines farther from the test,

Figure 11: about here

Figure 12: about here

so they should be weighted more heavily. The weights were determined from linear functions fitted to the 'no grid' data for each subject; these functions were then used to equate the d' values associated with the comparison line and each grid column. For example, according to the fitted function for subject SPM, the threshold for a pedestal disparity of 2 arcmin is roughly twice the threshold at zero disparity, so a 2 min disparity was given half the weight (equivalent d') of zero disparity. We used the square root of the sum of the squared equivalent d' values to predict thresholds for each pedestal disparity, relative to the zero disparity threshold estimated from the fitted 'no grid' functions:

$$d'_{cg} = \sqrt{(d'_c)^2 + (d'_{g1})^2 + (d'_{g2})^2 + ... + (d'_{g7})^2)} \tag{3}$$

$$\text{Pedestal disparity threshold} = \text{Zero disparity threshold}/d'_{cg} \tag{4}$$

where d'_c, d_{g1}, d_{g2} etc. are the equivalent d' values associated with the comparison line and each of the grid columns, and d'_{cg} is the d' value calculated from combining these individual estimates. The dashed lines in the upper graphs in Figure 11, labeled 'Prediction (fronto-parallel)', are the threshold functions predicted from the combination of the seven columns in the fronto-parallel grid plus the comparison line. The dotted lines, labeled 'Prediction (slanted)', shown in the lower graphs in Figure 11 are the predicted threshold functions for the slanted grid and comparison line combination.

The predictions account quite well for the improvement in subject AG's thresholds, but do not match the shape of the functions, particularly the minimum in his data at zero disparity for the fronto-parallel grid condition. The predicted functions fail totally to account for subject SPM's data, falling far below her thresholds. Indeed, the mismatch between her data and the predictions suggests that she is making non-optimum use of the information in the grid columns. Perhaps only the grid columns in the vicinity of the test line were used by this subject to enhance her estimate of the disparity signal. We tested this speculation by calculating her predicted functions if only 2, 3 or 4 columns of the grid were included in our estimated thresholds. As the upper graph in Figure 12 shows, the three-column prediction provides a beautiful fit to her data for the fronto-parallel condition. The four-column prediction fit almost as well, but the two-column prediction fell above her measured thresholds.

We next used these same three grid columns (the second, third and fourth from the left) to predict the data for the slanted grid condition. The lower graph in Figure 12 reveals that this prediction does not capture the shape of the function, fitting some threshold values exactly, but failing to predict the true minimum. Predictions from the two- and four- grid column calculations were even less accurate in their representation of her slanted grid thresholds. Generally, this approach predicts that the threshold for -1.5 min should be below the threshold at +1.5 min, because the disparity separating the grid columns from the test line is smaller at -1.5 min than at +1.5 min. In fact, the contrary is true for subject SPM; her threshold at -1.5 is significantly higher than her threshold at +1.5 min.

Discussion

Our principal finding is that the bias in perceived depth induced by the presence of a slanted reference plane diminishes as the disparity between the reference plane and the test line is increased (e.g. figure 2). We also found that depth increment thresholds tend to a minimum at the disparity at which two features are perceived to be at equal depths (e.g. figure 7).

Several formulations have been proposed for predicting the perceived depth of a feature surrounded by others at different disparities (Mitchison and Westheimer, 1984; Stevens and Brookes, 1988; Gillam, Chambers and Russo, 1988). Most are very similar and involve a calculation of the change in disparity gradient in the neighbourhood of the feature. In all of these examples, features that lie at the same disparity with respect to the background should be perceived to be in the same depth plane. We did not find this result. Instead, we found that the distorting effect of a slanted grid was weaker when it was presented further in depth from the test line. Formulae for predicting perceived depth would have to be modified to account for this effect. For example, the measure proposed by Mitchison and Westheimer (1984), which they called 'salience' (L) is defined as:

$$L = \sum w_i \cdot (d_i - d) \qquad (5)$$

where d is the disparity of the test object, d_i is the disparity of its neighbours and w_i is a weighting factor for each test-neighbour pairing. The weighting factors are independent of the disparity difference $(d_i - d)$, so salience is a linear function of the disparity of a line with respect to the background features. To account for our bias data (figure 2), the weighting factors, w_i, should depend not only on the lateral separation of neighbouring features but also on their disparity with respect to the test line.

The diminishing effect of the reference plane as it is removed further in depth from the test and comparison lines is consistent with what Gogel (1972) described as the 'depth adjacency effect'. He measured the perceived relative depth of stimuli presented close to an 'Ames trapezoidal window', whose slant was misperceived due to an illusory perspective effect. The window acted as a reference plane against which the relative depth of points was perceived correctly but, because the slant of the window was perceived incorrectly, points presented at the same depth appeared to be at different depths. He also showed that this bias in perceived depth gradually declined as the points were removed further in depth from the reference plane.

Apart from experiments on perceived depth, there is little psychophysical evidence on the extent to which features located in one depth plane affect the disparity processing of those in a different depth plane. Mitchison (1988) discusses the possibility that, in a stereo matching algorithm, unambiguously paired features standing out in front of a surface might be treated independently from those in the surface. In general, one can imagine the ecological advantages of a system that processes disparity signals with respect to a locally defined reference plane (e.g. points protruding from a surface) while at the same time processing the disparity of foreground objects independently from any slant of the background.

The evidence from experiment II shows that the slanted grid can affect stereoacuity thresholds in a way that is related to its effect on perceived depth. The minimum threshold tends towards the plane in which the test and comparison lines are perceived to be at equal depths. This can be most clearly seen for one subject (subject SPM) in figure 7 although the trend is also present for the second subject. The most striking feature of the data is that the slanted grid can *reduce* depth increment thresholds. This only occurs when the effect of the grid is to reduce the apparent depth difference between the test and comparison lines. Examples of such a reduction in thresholds are evident in the data for all three subjects (figures 6 and 8). Any model based solely on the absolute disparity of the test and comparison (or the relative disparity between the two lines) cannot easily explain this result. Instead, the results imply that the relative disparity of the lines with respect to the grid plays an important role in determining thresholds.

In the previous section, we have discussed two possible explanations of the effect of a grid on thresholds. According to one explanation, the visual system makes multiple, independent samples of the disparity of the test and comparison lines with respect to each of the grid columns. This can explain why thresholds should be reduced in the presence of a grid but not why the minimum threshold should shift to a different pedestal disparity. According to the other explanation, the visual system constructs a plane through the comparison line (the perceived fronto-parallel) against which the test disparity is measured. Increased variability in constructing such a plane might explain why thresholds are higher when no grid is presented. In the presence of a grid, on the other hand, the relative disparity of the test line with respect to the apparently fronto-parallel plane may be the main source of noise contributing to thresholds (a 'Weber error'). This could explain why we found depth increment thresholds were lowest close to the plane in which test and comparison lines appear to lie at the same depth.

Conclusion

There is a tendency for points parallel to a locally-defined reference plane to appear fronto-parallel (Mitchison and Westheimer, 1984). Consistent with previous reports (Gogel, 1972), we have shown that this effect diminishes as the points are removed further from the reference plane. We have also shown that depth increment thresholds are affected by the presence of a slanted reference plane and suggest that, in this case, the visual system may construct a slanted reference system for comparing disparities. Further evidence for disparity processing organised around slanted rather than fronto-parallel planes is presented in a subsequent paper (see also Glennerster and McKee, 1997).

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References

Andrews, D.P. (1964) Error-correcting perceptual mechanisms. *Quarterly Journal of Experimental Psychology*, **16**, 104-111

Anstis, S.M., Howard, I.P. and Rogers, B.J. (1978) A Craik-O'Brien-Cornsweet illusion for visual depth. *Vision Research*, **18**, 213-217

Badcock, D.R. and Schor, C.M. (1985) Depth-increment detection function for individual spatial channels. *Journal of the Optical Society of America, A*, **2**, 1211-1215

Blakemore, C. (1970) The range and scope of binocular depth discrimination in man. *Journal of Physiology (London)*, **211**, 599-622

Brookes, A. and Stevens, K.A. (1989) The analogy between stereo depth and brightness. *Perception*, **18**, 601-614

Finney, D.J. (1971) *Probit Analysis.* 3rd ed. Cambridge University Press

Gillam, B., Chambers, D. and Russo, T. (1988) Postfusional latency in stereoscopic slant perception and the primitives of stereopsis *Journal of Experimental Psychology:Human Perception and Performance*, **14**, 163-175

Gillam, B., Flagg, T. and Finlay, D. (1984) Evidence for disparity change as the primary stimulus for stereoscopic processing. *Perception and Psychophysics*, **36**, 559-564

Glennerster, A. and McKee, S.P. (1997) Sensitivity to depth and lateral displacement on a slanted reference plane. *Investigative Ophthalmology and Visual Science*, **38**, S907

Gogel, W.C. (1972) Depth adjacency and cue effectiveness. *Journal of Experimental Psychology*, **92**, 176-181

Graham, M and Rogers, B.J. (1982) Simultaneous and successive contrast effects in the perception of depth from stereoscopic surfaces. *Perception*, **11**, 247-262

Green, D.M. and Swets, J.A. (l966) *Signal Detection Theory and Psychophysics*, New York: John Wiley & Sons, Inc., Chapter 9, pp 235-275.

Harris, J.M. and Watamaniuk (1995) Speed discrimination of motion-in-depth using binocular cues. *Vision Research*, **35**, 885-896

Kumar, T. and Glaser, D.A. (1991) Influence of remote objects on local depth perception. *Vision Research*, **31**, 1687-1699

Kumar, T. and Glaser, D.A. (1992) Depth discrimination of a line is improved by adding other lines nearby. *Vision Research*, **32**, 1667-1676

McKee, S.P. (1983) The spatial requirements for fine stereoacuity. *Vision Research*, **23**, 191-198

McKee, S.P. and Levi, D.M (l987) Dichoptic hyperacuity: The precision of nonius alignment. *Journal of the Optical Society of America A*, **4**, 1104-1108.

McKee, S.P., Levi, D.M. and Bowne, S.F. (1990) The imprecision of stereopsis. *Vision Research*, **30**, 1763-1779

Mitchison, G.J. (1988) Planarity and segmentation in stereoscopic matching. *Perception*, **17**, 753-782

Mitchison, G.J. (1993) The neural representation of stereoscopic depth contrast. *Perception*, **22**, 1415-1426

Mitchison, G.J. and McKee, S.P. (1990) Mechanisms underlying the anisotropy of stereoscopic tilt perception. *Vision Research*, **30**, 1781-1791

Mitchison, G.J. and Westheimer, G. (1984) The perception of depth in simple figures. *Vision Research*, **24** 1063-107

Mitchison, G.J. and Westheimer, G. (1990) Viewing geometry and gradients of horizontal disparity. In *Vision: coding and efficiency.* ed. Blakemore, C., Cambridge University Press

Morgan, M.J. and Lunn, P.D. (1995) The analogy between stereo and brightness: a reexamination. *Perception*, **24**, 901-904

Ogle, K.N. (1953) Precision and validity of stereoscopic depth perception from double images. *Journal of the Optical Society of America*, **43**, 906-913

Parker, A.J. and Yang, Y. (1989) Spatial properties of disparity pooling in human stereo vision. *Vision Research*, **29**, 1525-1538

Rogers, B.J. and Cagenello, R. (1989) Disparity curvature and the perception of three dimensional surfaces. *Nature*, **339**, 135-137

Rogers, B.J. and Graham, M. (1983) Anisotropies in the perception of three-dimensional surfaces. *Science*, **221**, 1409-1411

Stevens, K.A. and Brookes, A (1988) Integrating stereopsis with monocular interpretations of planar surfaces. *Vision Research*, **28**, 371-386

Wallach, H. and Bacon, J. (1976) Two forms of retinal disparity. *Perception and Psychophysics*, **19**, 375-382

Westheimer, G. (1986) Spatial interaction in the domain of disparity signals in human stereoscopic vision. *Journal of Physiology*, **370**, 619-629

Westheimer, G. and Levi, D.M. (1987) Depth attraction and repulsion of disparate foveal stimuli. *Vision Research*, **27**, 1361-1368

Figure legends

Figure 1

Front and plan views of the stimulus for experiments I and II. The grid subtended 2 by 2 degrees and the lines were 1 degree high. The cyclopean position of the comparison line was always 10 arcmin to the right of the centre while the test line was presented midway between one of the other pairs of dot columns. The grid was either fronto-parallel or slanted about a vertical axis such that its horizontal extent was 10% greater in the right than the left eye.

Figure 2

Solid symbols show the results from experiment I for three observers. The hollow symbols show the lateral position and disparity of the comparison line in different conditions. Solid symbols of the same shape show, for different lateral positions of the test, the disparity at which the test line appeared to lie at the same depth as the comparison line (i.e. the point of subjective equality (p.s.e) or 50% point of the psychometric function). The position of the grid is indicated by the dashed line. Standard errors were smaller than the size of the symbols and are not shown. Slopes of regression lines through the data are given in table 1.

Figure 3

Biases measured in experiment I with (a) no grid and (b) a fronto-parallel grid presented behind the fixation plane. Data are shown for two observers.

Figure 4

Biases, for two observers, measured when the comparison line was in the fixation plane and the centre of the grid was 8 arcmin behind. The dashed line shows data re-plotted from figure 2, in which the centre of the grid was only 4 arcmin behind the fixation plane.

Figure 5

Data for two observers re-plotted from figures 2 and 4. In both conditions, the comparison line was 8 arcmin in front of the centre of the grid but its absolute disparity was either +4 arcmin (grid at -4 arcmin) or 0 arcmin (grid at -8 arcmin). Slopes of regression lines through the data are given in table 1.

Figure 6

Depth increment thresholds plotted against the disparity of the test line (experiment II). A comparison line, separated laterally from the test line by 20 arcmin, was presented in the fixation plane. The two lines were presented alone or in front of a fronto-parallel or slanted grid of dots.

Figure 7

Data for the fronto-parallel and slanted grid conditions re-plotted from figure 6 on a different x-axis. Zero on this scale indicates the disparity at which the test line appeared to be at the same depth as the comparison line (0 and +1.5 arcmin for the fronto-parallel and slanted grids respectively). Hence, compared to figure 6, all the points for the slanted grid condition have been shifted to the left.

Figure 8

Depth increment thresholds for observer VU plotted against the lateral position of the test line. Results are shown for data collected in the presence of a fronto-parallel grid (a) and a slanted grid (b). The comparison line was always in the fixation plane and 10 arcmin to the right of the centre of the screen (shown by the arrow on the x-axis). The icons in the key show the position of the grid (solid line), the comparison line (open circle) and the different possible positions of the test line (crosses) under different conditions. In the 'zero disparity' condition, the test line was always presented in the fixation plane. In the 'SG-zero' condition, the pedestal disparities of the test line were such that the test and comparison lines appeared to have an equal depth when presented against a slanted grid. The values of the pedestal disparities were obtained from the results of experiment I (see figure 2), and for both subjects were 4.1, 2.6, 0.80, -0.64, and -1.9 arcmin for lateral positions -50, -30, -10, 30 and 50 arcmin respectively. In the '2 $\times$ SG-zero' condition, the pedestal disparity of the test line was twice that in the SG-zero condition at each lateral position.

Figure 9

Depth increment thresholds are shown for four conditions in which the test line was presented alone, without a comparison line. These are (from left to right): test line in the fixation plane with a fronto-parallel grid; test line 1.5 arcmin uncrossed disparity with a fronto-parallel grid; test line in fixation plane and 10 arcmin to the right of the centre of a slanted grid (so the disparity of the test line with respect to the grid was 5 arcmin); and test line in fixation plane and 10 arcmin to the left of the centre of a slanted grid (so the disparity of the test line with respect to the grid was 3 arcmin). Also shown (far right) are the thresholds measured when both test and comparison lines were presented in the fixation plane against a fronto-parallel grid.

Figure 10

Top view of the slanted grid (large dots), the test line (T) and the comparison line (C) which was displayed in the fixation plane. The dashed line shows the apparently fronto-parallel plane through the comparison line. As the results from experiment I show, this plane is slanted in depth but not to the same degree as the grid. The disparity of the test line with respect to the apparently fronto-parallel plane (d_t) appears to be important in determining depth increment thresholds in the presence of a slanted grid.

Figure 11

Fits to the stereoacuity data of figure 6 using the model described in the text. The upper graphs show the predicted thresholds for the fronto-parallel grid condition for each subject. The model assumes that independent estimates of the test line disparity are made with respect to each of the grid columns and the comparison line. The lower two graphs show predicted thresholds when the grid is slanted.

Figure 12

As for figure 11, except that predictions were calculated assuming that only the three grid columns close to the test line, rather than all the grid columns, contributed to the estimation of the test line disparity.

Table 1

Slopes and regression coefficients of the best-fitting straight lines through the data in figures 2 and 4. The slope (i.e. disparity gradient) of the grid was -0.10.