Stereoacuity and Colour Contrast

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We have measured the contrast dependence of stereoacuity using both horizontally and vertically oriented, isoluminant (red–green) and isochromatic (yellow–black), 0.5 c/deg Gabor patches. For comparison, contrasts were computed in multiples of detection threshold, where detection threshold was defined as the contrast required for the stimulus to be simultaneously detectable in each eye. Disparity thresholds (1/stereoacuity) for vertical chromatic Gabors were higher than those for vertical luminance Gabors by a factor of between 4 and 9 depending on contrast, and declined less steeply with contrast. Disparity thresholds for horizontal chromatic Gabors were very high (130–210 min arc) compared with horizontal luminance Gabors (by a factor of between 9 and 17) and were only measurable at contrasts above 10 times simultaneous monocular detection threshold. These results support the view that chromatic stereoscopic processing is less precise than luminance stereoscopic processing, and that there is a special deficit in the processing of disparity with horizontally oriented chromatic stimuli. The implications of these results for the role of colour vision in stereopsis are discussed.

Stereoacuity   Isoluminance   Colour contrast

INTRODUCTION

In natural scenes there are two potential sources of information about the spatial layout of objects: luminance contrast and colour contrast. The role of colour contrast in spatial vision has recently attracted considerable attention [see reviews by Mullen and Kingdom (1991) and Regan (1991)], and in particular, a large number of studies have examined the role that colour information plays in stereopsis. Some of these studies have examined whether stereopsis is supported by colour cues in the presence of luminance cues, either when the two types of cue are rivalrous (Treisman, 1962; Julesz, 1971; Kovacs & Julesz, 1992; Stuart *et al.*, 1992), or ambiguous (Ramachandran *et al.*, 1973a; Akerstrom & Todd, 1988; Jordan *et al.*, 1990). However the bulk of studies have examined whether stereopsis can be supported by colour cues alone, i.e., at isoluminance, and it is with this issue that this study is primarily concerned.

The status of stereopsis at isoluminance has produced contradictory findings. Studies have shown that while stereopsis with random-dot-stereograms is severely degraded (Lu & Fender, 1972; Gregory, 1977; de Weert, 1979; de Weert & Sazda, 1983), with figural stereograms, in which the target forms are visible monocularly, stereopsis is maintained, although with reduced quality

(Ramachandran *et al.*, 1973b; Comerford, 1974; Gregory, 1977; de Weert, 1979; de Weert & Sadza, 1983; Grinberg & Williams, 1985; Osuobeni & O'Leary, 1986, 1991; Tyler & Cavanagh, 1991). On the other hand, Livingstone and Hubel (1987) have disputed that stereopsis is possible at isoluminance with either random-dot or figural stereograms, while Scharff & Geisler (1992), on the basis of data analysed using a cone contrast metric, argued that random-dot-stereograms are processed by some subjects as efficiently when isoluminant as when isochromatic.

We have previously suggested (Simmons & Kingdom, 1994) that some of these apparently contradictory findings might be due to the differences in the range of stimulus conditions employed by each study. In particular, the range of disparities and colour contrasts may not always have been optimal, or even sufficient, to stimulate chromatic stereoscopic mechanisms. To understand why this may be so, consider the procedure commonly used to measure stereopsis at isoluminance. First, a stimulus is established with a fixed disparity in which depth is apparent under conditions of adequate luminance contrast. The ratio of red to mean luminance [$(R/(R + G)$ ratio] is then varied to establish whether or not depth is impaired at or close to objective isoluminance (Lu & Fender, 1972; Comerford, 1974; Gregory, 1977; de Weert, 1979; de Weert & Sadza, 1983; Livingstone & Hubel 1987). This procedure leaves open the possibility that the colour contrast at the isoluminant point may simply not have been adequate to support stereopsis and that the disparity chosen might not be within the range suitable for a chromatic stereoscopic mechanism. While some studies have measured stereo-

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scopic performance using a range of disparities (e.g. Osuobeni & O'Leary, 1986, 1991; Tyler & Cavanagh, 1991), and others have measured stereoscopic performance at a range of colour contrasts (Jordan *et al.*, 1990; Scharff & Geisler, 1992), only the studies of Grinberg and Williams (1985) and Simmons and Kingdom (1994, 1995) have measured stereoscopic performance at a range of both colour contrasts and disparities. The study by Grinberg and Williams (1985) only measured stereoscopic performance under blue-cone isolated conditions, and their results may therefore not be generalisable to the more commonly employed red–green stimuli. To our knowledge however, no-one has measured the contrast dependency of stereoacuity at isoluminance.

In our previous study (Simmons & Kingdom, 1994) we measured contrast thresholds for stereoscopic depth identification (front vs back) at a range of disparities, for both red–green isoluminant and yellow–black isochromatic, 0.5 c/deg vertically oriented Gabor patches. We found that the disparity tuning of the chromatic and luminance mechanisms was similar, but while stereoscopic judgments were possible at detection threshold in the case of the luminance stimuli, they were not for colour (the way in which the detection threshold was measured is described below). A subsequent study (Simmons & Kingdom, 1995) extended these initial results to larger disparities and also included measurements with horizontally oriented Gabor stimuli. The motivation behind the use of horizontally oriented stimuli was that the stereoscopic depth of isoluminant random-dot-stereograms, which are orientationally broad-band, appeared to be particularly impaired. The results of these studies implied that chromatic stereoscopic mechanisms were a less contrast-sensitive analogue of their luminance counterparts. However, measuring the contrast required to make a stereoscopic depth judgement in the region of, or beyond, the best disparity for making that judgement, does not provide the basis for estimating the *precision* with which that judgement can be made. To do this it is necessary to measure stereoacuity, that is the *minimum* disparity required for making a stereoscopic judgement. Comparing the stereoacuity of isoluminant and isochromatic stimuli therefore allows us to compare the precision with which chromatic and luminance stereoscopic mechanisms operate.

In this study we have measured stereoacuity as a function of contrast using both isoluminant and isochromatic 0.5 c/deg Gabor stimuli. In order to compare performance for the colour and luminance conditions we have scaled contrasts in terms of multiples of detection threshold, a standard procedure used for comparing chromatic and luminance performance for a wide range of tasks (Switkes *et al.*, 1988; Webster *et al.*, 1990; Krauskopf & Farrel, 1991; McIlhagga & Mullen, 1995). As in our previous studies, the detection threshold we have used as the basis for this comparison is the contrast required to simultaneously detect the stimuli in each eye. This is distinct from the binocular detection threshold

(which determines the amount of contrast required to see a stimulus in *either or both* eyes) used conventionally in studies of stereopsis (e.g. Frisby & Mayhew, 1978; Smallman & MacLeod, 1994; Hess & Wilcox, 1994; Halpern & Blake, 1988). The simultaneous monocular detection threshold is the most appropriate for scaling stimulus contrast in order to compare stereoscopic judgements because, unlike binocular detection, stereopsis requires a signal present in both eyes at the same time (Simmons, 1992).

METHODS

The stimuli, apparatus, calibrations, and method of stimulus generation are given in Simmons and Kingdom (1994), and will only be briefly described here.

Stimuli

The stimuli were isoluminant and isochromatic 0.5 c/deg Gabor patches, with a non-truncated 1 deg SD Gaussian envelope, resulting in a spatial bandwidth of approx. 1.1 octaves (FWHM). These stimulus parameters were designed to minimize luminance artifacts in the chromatic stimuli due to chromatic aberration (Scharff & Geisler, 1992). The stimuli were vertically or horizontally oriented and arranged as in Fig. 1. The stimuli appeared in a high-contrast white fixation circle of radius 3 deg which was present throughout the experiment and was designed to provide a strong depth reference at zero disparity. The luminance of the fixation stimulus at the eye was approx. 10 cd/m^2.

For the luminance stimuli, modulation of the red and green guns of the monitor were in spatial phase, whereas for the chromatic stimuli they were in spatial anti-phase. For both stimulus classes the contrasts reported are the Michelson contrasts [i.e., $(L_{max} - L_{min})/(L_{max} + L_{min})$] of the Gabor's carrier grating before multiplication by the Gaussian envelope. This measure of contrast would be directly proportional to one based directly on the Gabor stimulus itself, such as $(L_{max} - L_{mean})/L_{mean}$. The luminances L were those measured with the photometer. The contrasts defined in this manner were constrained to be equal on each gun, whatever the overall ratio of the red luminance to overall mean luminance. This ratio [the $R/(R + G)$ ratio] could be independently adjusted, and controlled the relationship between the mean luminances on each of the guns. Adjustments of this value from low to high would thus vary the colour of the background field of the display from greenish through yellow to reddish.

The mean luminance at each eye was approx. 2 cd/m^2. At this low photopic luminance the rod photoreceptors were almost certainly not saturated, but the subjective method for determining the isoluminant point (see below) should have kept their contribution to a minimum [see Simmons & Kingdom (1994) for a further discussion of this point]. A 2–3 min adaptation period preceded each experimental session.

Stereo display method

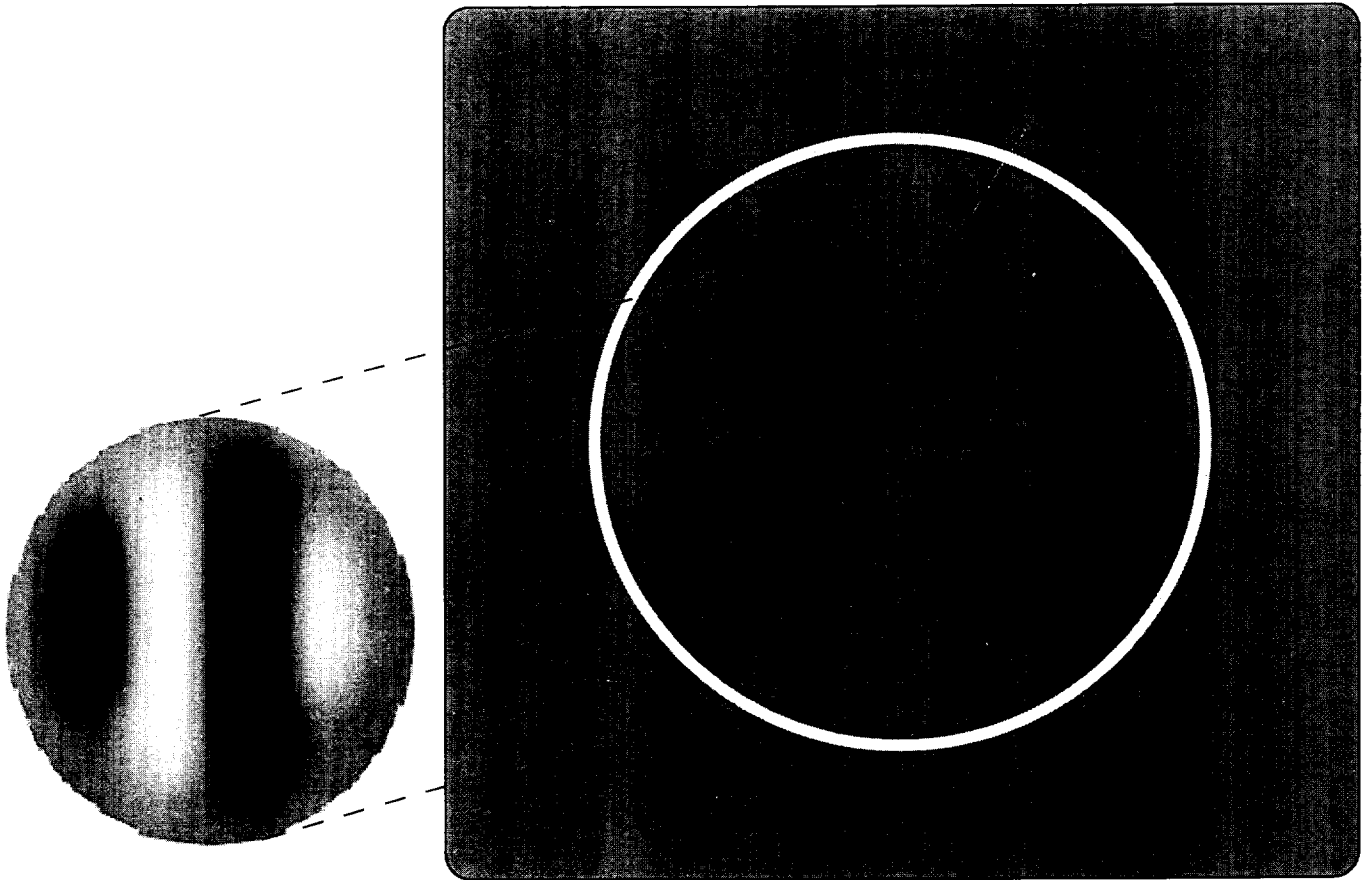Stimulus separation was obtained using a pair of

FIGURE 1. Schematic diagram of the stimulus configuration. The Gabor stimulus appeared in front of, behind or at the level of the fixation circle, which in the figure is drawn elliptically to convey perspective. For dimensions and further details, see Simmons and Kingdom (1994).

liquid-crystal shutters (Displaytech Inc.) synchronised to the monitor frame rate of 160 Hz, resulting in a refresh rate of 80 Hz in each eye. This frequency is well above that required for flicker fusion in foveal vision and, accordingly, no stimulus flicker was observed. It is well known that interocular crosstalk can be a problem when using liquid crystal shutters to separate stereo half-images. This crosstalk is largely caused by slow phosphor decay which results in (say) the left-eye stimulus still being faintly visible when the right-eye shutter is in the open state. We have previously shown that at low contrasts this crosstalk is undetectable (Simmons & Kingdom, 1994). However, at the higher contrasts we used the crosstalk would certainly be visible. Control experiments indicated that the contrast of the crosstalk was approx. 20 dB (factor of 10) lower than that of the actual stimulus. However, given the evidence that low-contrast stereoscopic signals have little effect on perceived depth in the presence of higher-contrast signals (Boothroyd & Blake, 1984), and recent evidence for a contrast similarity constraint on stereo matching (Smallman & McKee, 1995), we assume here that the crosstalk did not significantly affect performance.

Subjects

Subjects were the two authors. Both were colour normal. One (FK) was emmetropic and the other (DS)

wore his prescribed optical correction. By the time of data collection both authors were experienced in stereoscopic depth discriminations.

Procedure—isoluminance setting

The isoluminant point was determined by finding the $R/(R + G)$ ratio which provided the worst stereoacuity at stimulus contrasts 20 db above detection threshold. Pilot studies determined the approximate $R/(R + G)$ ratio for worst stereoacuity, and then more detailed measurements were made at a range of $R/(R + G)$ values around the isoluminant point. The results are shown in Fig. 2. Although we took the $R/(R + G)$ value providing worst stereoacuity as the isoluminant point, there is likely to be a window of error of about $\pm 2\%$, given the resolution of our sampling and the size of the error bars. The isoluminant points determined in this way were for horizontal Gabors, FK = 0.48, DS = 0.52, vertical Gabors, FK = 0.505, DS = 0.52. The small difference in isoluminant point between the horizontal and vertical stimuli for FK was unexpected, and we are unable to provide a definite explanation for it. Most likely it reflects a difference in the nature of the chromatic stereo-processing mechanisms for horizontal and vertical stimuli.
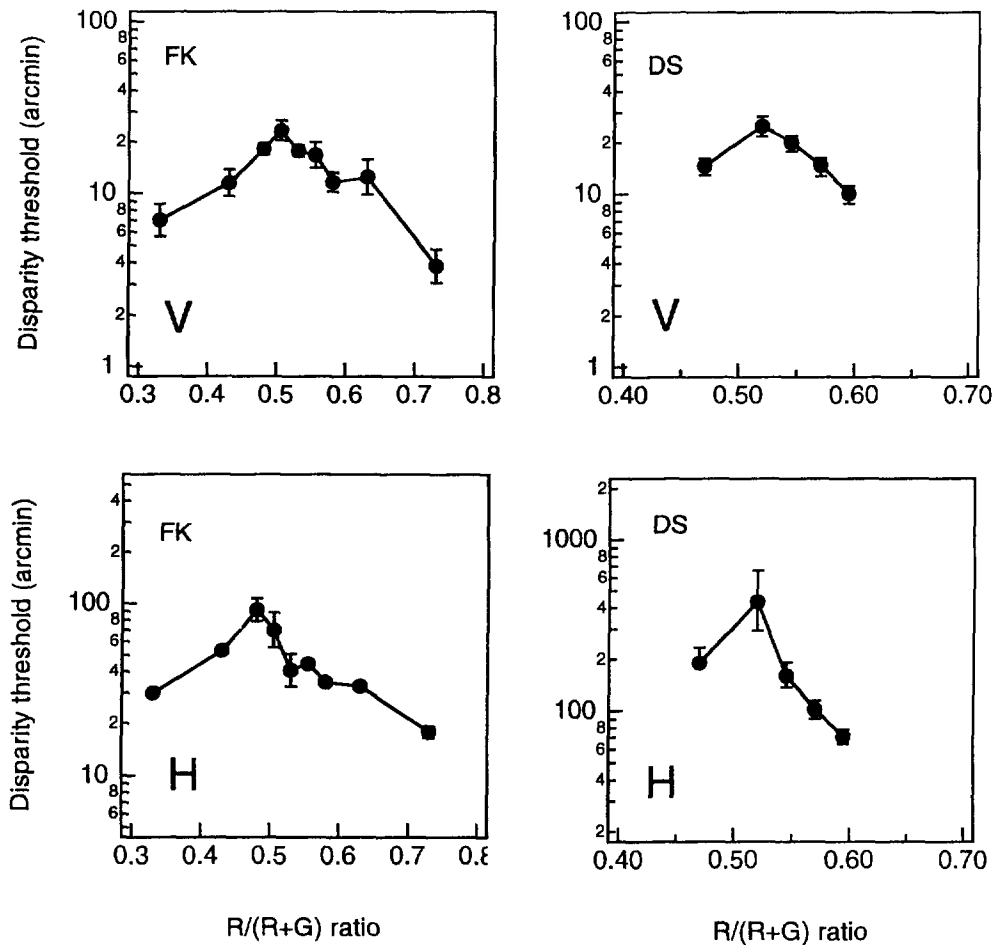
FIGURE 2. Disparity thresholds as a function of the $R/(R + G)$ ratio for stimuli at 20 db above detection threshold. V = vertical Gabors, H = horizontal Gabors. The data points are weighted means. Error bars are 68% confidence limits. The $R/(R + G)$ value of the maximum disparity threshold was used as the isoluminant point for the chromatic stimuli.

Procedure—stereoacuity

In the main series of experiments, stimuli were constructed with seven equally spaced disparities, chosen on the basis of pilot experiments such that some appeared behind, and some in front of the reference stimuli. For the vertical Gabor stimuli, the range of disparities was always constrained to lie between -30 and $+30$ min arc of perceived zero disparity, which corresponds to a range of plus or minus a quarter cycle of the Gabor carrier (0.5 c/deg). This ensured that the resulting psychometric function was not contaminated with the effects of any false matches between the bars of the stimuli. With the horizontal Gabors no such constraint was necessary. One of these stimuli was presented at random in a single temporal interval 200 msec long. Stimulus onset and offset were abrupt. The subject was asked to judge whether the stimulus appeared to be in front of or behind the disparity reference. In the course of a single experimental session only one contrast was employed. A given experimental run consisted of 40 presentations at each of seven disparities, giving a total of 280 trials. The duration of a run was 5–10 min. A period of between 2 and 3 min adaptation took place before each experimental run, which should have been sufficient for adaptation.

Procedure—contrast detection

The detection experiments were performed in concurrent sessions with the stereoacuity experiments. The stimuli were presented centred on fixation. In the detection experiments there were two presentation intervals, in one of which the stimulus was presented. The subject was asked to decide whether the stimulus had appeared in the first or second interval. During the course of a single experimental run, binocular and monocular presentations were randomly interleaved. The stimulus configuration and duration were the same as in the stereoacuity experiments. Although the binocular thresholds were not used for this study (see below), they were collected as part of a separate study on binocular summation.

Data analysis

Stereoacuity psychometric functions, each based on 40 trials per disparity, were fitted using Probit analysis (Finney, 1971). The Probit analysis yielded a mean value and a standard deviation of the best fitting cumulative Gaussian function. These parameters were taken to be perceived zero disparity and the disparity threshold, respectively. A "bootstrap" procedure (Foster & Bischof, 1991) was used to determine 68% confidence limits

on the disparity threshold, and these confidence limits are the error bars plotted on the figures. Individual threshold measures were combined using a weighted geometric mean, where the weights were determined by the bootstrap estimates of variance [see Simmons (1992) for details].

For the detection thresholds a maximum-likelihood procedure, similar to that employed by Watson (1979), was used to fit the simple-detection psychometric functions with Weibull–Quick functions. This procedure yielded estimates of the threshold α, and slope β, parameters of the psychometric function. The contrast thresholds used to scale the stimulus contrast into multiples of detection threshold were calculated by combining the individual monocular detection probabilities so as to determine the probability of simultaneous monocular detection. The details of this procedure have been given elsewhere (Simmons & Kingdom, 1994).

To measure the slope of the contrast dependence of stereoacuity we performed least-squares linear regression analyses to each log transformed data set using the

graphics/analysis package Igor (Wavemetrics Inc.), run on a Macintosh computer.

RESULTS

Figure 3 shows the main body of results. Disparity thresholds (1/stereoacuity) are plotted as a function of contrast, where contrast is expressed in multiples of the threshold for simultaneous monocular detection. The different symbols represent the results from three different experimental sessions at each contrast, and the continuous line through each data set represents the weighted mean of those measures. As stated in the Methods, a ±30 min arc limit was imposed on the disparities tested with the vertical (though not the horizontal) Gabors. Thus, any disparity threshold greater than 30 min arc for the vertical patterns in Fig. 3 was an estimate based on an extrapolation of the measured psychometric function.

For both the vertical (V) and horizontal (H) stimuli, disparity thresholds at equivalent contrasts are higher for the chromatic (open symbols) than the luminance (solid
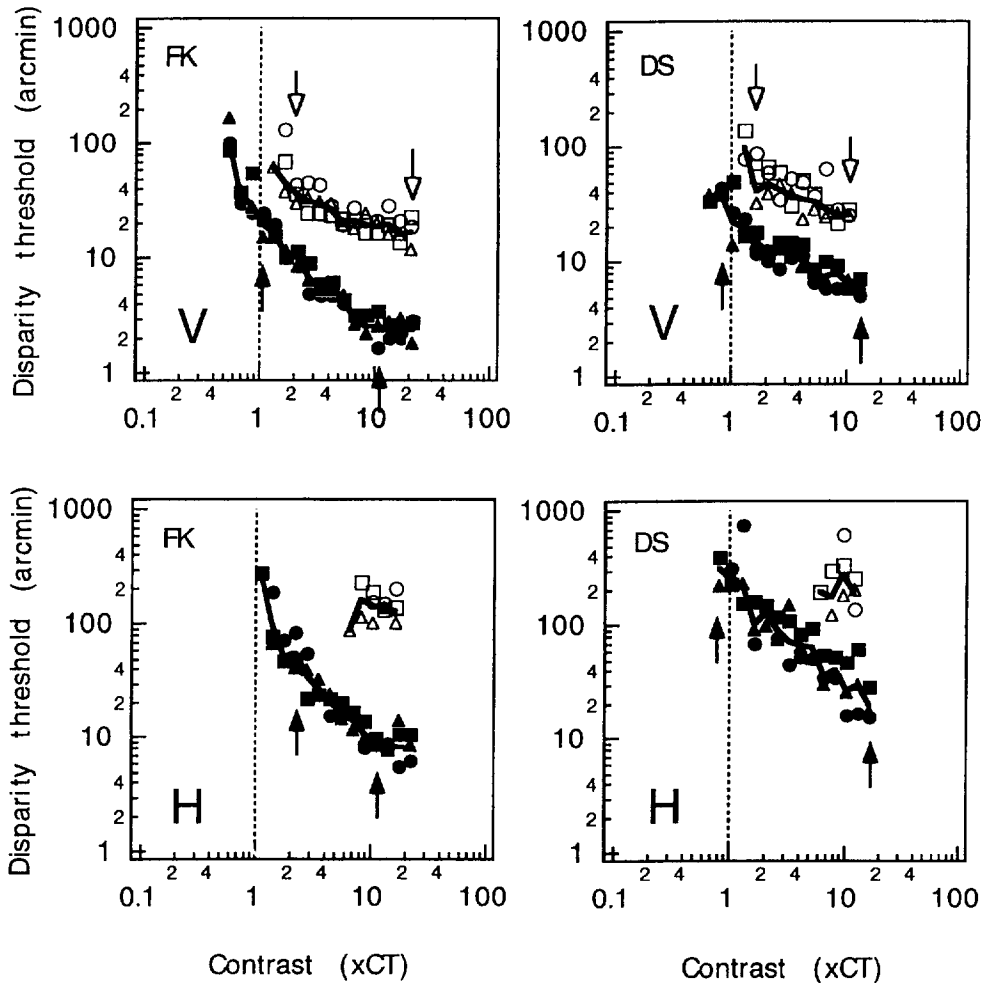

FIGURE 3. Disparity thresholds as a function of contrast, where contrast is given in multiples of the contrast threshold for simultaneous monocular detection. Open symbols are for chromatic Gabors, solid symbols for luminance Gabors. V = vertical Gabors, H = horizontal Gabors. Each data point represents the disparity threshold from a single session, and different symbols represent data from different sessions. Error bars are not shown for clarity, but they are typically the size of the symbols themselves. The heavy continuous line through each data set represents the weighted mean of the thresholds. The arrows define the range of points used to estimate the slopes of all except the horizontal chromatic functions.

TABLE 1. Parameters of the linear regression analysis of the data shown in Fig. 3

	Slope				Disparity threshold at CT × 10			
	Vertical		Horizontal		Vertical		Horizontal	
	Lum	Col	Lum	Col	Lum	Col	Lum	Col
FK	1.01	0.353	1.25	—	2.0	18.9	7.8	129
DS	−0.75	−0.67	−1.01	—	6.3	26.1	24.8	211

Lum = luminance stimuli, Col = chromatic stimuli. On the left of the table are given the slopes of the linear fits of log disparity threshold vs log contrast. Note that no figures are given for the horizontal chromatic stimuli. On the right are given disparity thresholds at 10 times simultaneous monocular detection threshold.

symbols) stimuli. Moreover, for both chromatic and luminance stimuli, disparity thresholds for horizontal stimuli were higher than for vertical stimuli.

All conditions showed an improvement in stereoacuity with contrast except the horizontal chromatic stimuli. With the horizontal chromatic stimuli, it was impossible to obtain any performance except at the highest contrasts, which meant there was only a narrow range of contrasts for which performance could be measured. Close inspection of Fig. 3 reveals that some of the plots, for example FK's luminance conditions, appear to show three phases of contrast dependence: an initial sharp decline in disparity thresholds at or near detection threshold, followed by a less steep decline up to about 10 times detection threshold, followed by a flattening of performance. The existence of the first two of the three phases has been reported before (Cormack *et al.*, 1991). In order to obtain a more quantitative picture of the different contrast dependencies, we measured the slopes of each function on a log–log plot (equivalent to the exponent of the best fitting power function to a linear–linear plot) in the region where there was neither an apparent initial steep decline, nor an apparent flattening, in each case determined by visual inspection. In some cases there was no apparent initial decline, in others no flattening, and in one case (DS's horizontal luminance condition) neither an apparent initial decline nor flattening. The upper and lower limits of the range of contrasts used for these fits are delineated by arrows in Fig. 3, and the slope estimates are given in Table 1. Although there is a degree of uncertainty in the choice of inflection points by visual inspection, it is unlikely that the slope estimates would significantly vary, given the number of data points in each function.

Table 1 also provides estimates of the disparity thresholds at 10 times detection threshold, obtained from the linear regression analysis described above. Since an estimate of disparity threshold could be made for all four classes of stimulus at this contrast, it provides an appropriate basis for comparison. The lowest disparity thresholds were for the vertical luminance Gabors, around 2 min arc for FK and 6 min arc for DS. The highest disparity thresholds were for the horizontal chromatic Gabors, around 130 min arc for FK and 210 min arc for DS. The *relative* disparity thresholds at 10 times detection threshold between the various conditions were as follows: colour/luminance vertical:

FK = 9, DS = 4; colour/luminance horizontal: FK = 17, DS = 9; horizontal/vertical colour: FK = 7, DS = 8; horizontal/vertical luminance: FK = 4, DS = 4.

DISCUSSION

The principal aim of this study was to compare stereoacuity for isoluminant red–green and isochromatic yellow–black, 0.5 c/deg Gabors. Stereoacuity was measured as a function of contrast, and in order to equate performance across conditions, contrast was defined in terms of multiples of the contrast required for simultaneous monocular detection. With vertical chromatic Gabors we obtained measurable stereoacuities with a clear contrast dependence, but with a performance systematically worse than with luminance stimuli. These results show that while purely chromatic stimuli can support stereo judgements, they do so with less precision than their luminance counterparts. This supports similar conclusions from a number of previous studies on stereopsis with chromatic stimuli (Ramachandran *et al.*, 1973b; Comerford, 1974; Gregory, 1977; de Weert, 1979; de Weert & Sadza, 1983; Grinberg & Williams, 1985; Osuobeni & O'Leary, 1986; Tyler & Cavanagh, 1991; Simmons & Kingdom, 1994, 1995). It has been argued that stereoacuity is a measure of the reliability of stereoscopic depth information (Simmons, 1992). If so, our results show that chromatic stereoscopic information is less reliable than its luminance counterpart.

Our finding that stereoacuity is poorer for chromatic than luminance stimuli might at first seem at odds with the results of Scharff and Geisler (1992), but as we have argued in our previous study, this is not necessarily the case (Simmons & Kingdom, 1994). Scharff and Geisler, using a cone contrast metric, found that two of the three subjects for whom a measurable level of performance was obtained performed a depth-discrimination task equally well at isoluminance as at other ratios of red-to-mean $[R/(R + G)$ ratio] luminance. They concluded that chromatic and luminance stereo information are processed with equal efficiencies, and that any differences in performance observed in other studies were due to the reduced effective contrast of the stimuli, caused inevitably by the overlap in spectral sensitivities of the L and M cones. However, because chromatic detection is superior to luminance detection when measured in cone contrast (see Geisler, 1989), we might well expect that if

contrast were normalised to detection, chromatic stereoacuity would be worse that luminance stereoacuity, and indeed this is what we have found.

Contrast dependence of stereoacuity at isoluminance

For all except the horizontal chromatic Gabor stimuli, stereoacuity was found to improve with contrast. The only stimulus for which the results can be validly compared with those of previous studies is the vertical luminance stimulus. When the data were fitted with a straight line on a log–log plot, between any initial steep decline and any final flattening of the function, the vertical luminance stimuli showed slopes of -1.0 for FK and -0.75 for DS (Table 1). This is on average somewhat steeper than the previous findings of Legge and Gu (1989), who for 0.5 c/deg sine-wave gratings found slopes of -0.84, -0.63 and -0.47 for the three subjects tested. One possible reason for this is that in sampling our contrast space so finely (17 contrasts for FK, 14 for DS), and hence being able to infer the slope of the middle, linear (on a log–log plot) part of the range, our slope estimates were uncontaminated by the effects of any flattening of the function at high contrasts. In terms of a comparison of the contrast dependencies of the chromatic and luminance stimuli, this can only be made for the vertical Gabors, since no contrast dependency was measurable for the horizontal chromatic stimuli. For the vertical chromatic stimuli we found a clear contrast dependence with slopes of 0.353 for FK and 0.67 for DS, both less than their luminance counterparts. The significant differences in the slopes between the two subjects found for both the colour and luminance stimuli should not be seen as surprising, given the significant between-subject variation in the contrast dependency of stereopsis that is commonly reported for luminance stimuli (Legge & Gu, 1989; Halpern & Blake, 1988) and in stereoscopic performance at isoluminance (Scharff & Geisler, 1992).

Previous studies have attempted to infer the nature of the mechanism for stereopsis on the basis of the measured contrast dependence of stereoacuity, for example whether disparity is encoded via a process of cross-correlation (Cormack *et al.*, 1991) or through the extraction of spatial primitives in the binocular neural image (Legge & Gu, 1989). To attempt to do this for our results would, however, be unwise for two reasons: (i) because the between-subject variation found here, like other studies, precludes making generalisations concerning the precise nature of the dependency; and (ii) because such inferences are inherently problematic as one is forced to make assumptions about the way contrast itself is transduced during stereoscopic processing. The magnitude of any compressive nonlinearity imposed prior to or at the stage of stereoscopic processing will affect the slope of the contrast dependency of stereoacuity over and above that due to the nature of the stereoscopic processing itself (Halpern & Blake, 1988; Cormack *et al.*, 1991). Indeed, it is quite possible that the shallower slopes found for the chromatic stereoacuities reflect a

higher degree of contrast response compression. We must, therefore, be satisfied at this juncture with having demonstrated that stereoacuity appears to rise less steeply with colour contrast compared to luminance contrast.

Other spatial tasks for which a comparison of the chromatic and luminance contrast dependence have been made include orientation discrimination (Webster *et al.*, 1990), spatial frequency discrimination (Webster *et al.*, 1990) and vernier acuity (Krauskopf & Farrell, 1991). All these studies normalised their contrasts to detection threshold. Webster *et al.* (1990) found both orientation and spatial frequency discrimination thresholds to be a factor of about 2 worse for colour than luminance, but the pattern of contrast dependence was similar. Krauskopf and Farrell (1991) found the chromatic stimuli to be only slightly worse than the luminance stimuli, but again the contrast dependence was similar. Taken together with our present results on stereoacuity, these findings reinforce the general conclusion that spatial tasks are performed somewhat worse when using colour contrast than luminance contrast, at least when the contrasts are normalised for detection.

Comparison of horizontal and vertical stimuli

Our principal motivation for measuring performance with horizontal as well as vertical Gabor patterns arose from our ultimate aim of understanding why stereopsis is so degraded in isoluminant random-dot-stereograms, which are orientationally broad-band. We found that in all conditions stereoacuities were worse for horizontal than vertical stimuli at equivalent contrasts. Why might this be so? In vertical Gabor patterns, disparity information can be provided by any phase sensitive stereoscopic mechanism, that is any mechanism sensitive to the fine detail, or "carrier", in the patterns. In horizontal Gabor patterns on the other hand, this disparity information is substantially reduced and possibly absent altogether, and this must ultimately be the cause of the reduced performance. There are a number of ways in which the stereo-disparity of horizontal patterns might in principle be detected, and these have been considered in detail elsewhere (Simmons & Kingdom, 1995). One possibility is the "non-linear" stereoscopic mechanism recently isolated by Wilcox and Hess (1995) for luminance Gabors. This mechanism is believed to process the disparity of the Gabor envelope. Simmons and Kingdom (1995) provided some evidence for such envelope-based disparity processing in horizontal luminance Gabors, at least at relatively large disparities. However, the similarity in the slopes for the horizontal and vertical luminance stimuli (see Table 1) suggests a common mechanism for the stereoacuity judgements in this study, and this favours 'off-orientation' looking. In this scheme, disparity-tuned mechanisms tuned to orientations other than vertical detect the disparity with the horizontal patterns.

The most interesting finding with the horizontal Gabors, however, was when they were chromatic. We found it necessary to go to about ten times the contrast

threshold for simultaneous monocular detection in order to obtain any measurable stereoacuity (below this contrast, the psychometric functions were completely flat), and even above this contrast the sensation of stereoscopic depth was extremely poor. Note that a simultaneous monocular detection threshold is higher than the more conventionally employed binocular detection threshold, in this study by a factor of two. This doubles the amount of contrast required for measurable stereoacuity to 20 times binocular contrast detection threshold for the horizontal chromatic Gabors. Moreover, we cannot rule out the possibility that the residual stereoscopic performance we did obtain at such high contrasts may have been due to luminance artifacts in the ostensibly isoluminant stimuli. On the assumption, however, that the performance measured with horizontal chromatic Gabors was valid, a comparison of the relevant disparity thresholds at an equivalent contrast shows that such poor performance was not due to a *de facto* worse stereoacuity with horizontally oriented stimuli. The ratio of disparity thresholds between vertical chromatic and vertical luminance stimuli at 10 times simultaneous monocular detection was 9 for FK and 4 for DS, whereas with horizontal stimuli these ratios were 17 for FK and 9 for DS, respectively. In other words, although stereoacuity was worse in general for horizontal compared with vertical stimuli, it was especially so when they were chromatic. It should also be noted that the difference between FK's vertical chromatic and luminance disparity thresholds (a factor of 9) was much smaller at lower contrasts (see Fig. 3).

It is worth comparing these stereoacuity results with our previous study, in which the critical variable was the amount of contrast needed for a front–back stereoscopic judgement at a given disparity (Simmons & Kingdom, 1995). There, we argued that the critical comparison between the luminance and chromatic stimuli should be made at their respective best disparities. Contrast thresholds for best disparity depth identification were higher for colour than luminance by a factor of only 1.8 for vertical Gabors, but 7 for horizontal Gabors. Taken together with these earlier findings, the current stereoacuity results reinforce the conclusion that there appears to be a special difficulty in the processing of horizontal Gabor disparities at isoluminance. This specific impairment suggests that whatever mechanisms are available for processing disparities in horizontal patterns, our colour vision is near blind to them. This would include the non-linear, envelope-based, mechanism described above. A possible objection to this conclusion is that using simple detection thresholds to compare the horizontal chromatic with luminance stimuli is inappropriate. If the chromatic envelope was much less detectable than the luminance envelope, then it would not be surprising that envelope-based chromatic stereoacuity would also be much worse. There is, of course, no way of independently measuring the detectability of the envelope in our stimuli, because envelope contrast and carrier contrast are tied for a Gabor patch. Further experiments using stimuli in which

envelope and carrier contrast are separable, such as contrast modulated gratings, are therefore needed to test for this possibility. Nevertheless, with this caveat in mind, the absence of such a non-linear chromatic stereo mechanism implied by our results is particularly pertinent in the light of recent claims that chromatic motion processing relies *solely* on such a non-linear mechanism (Boulton et al., 1993). Perhaps then the chromatic inputs to stereopsis and motion processing are organised upon fundamentally different lines. Our results also suggest that one of the reasons for the reduced depth in isoluminant random-dot-stereograms might be the absence of a mechanism sensitive to features in the stimulus beyond the quarter cycle limit, such as the contrast envelope pattern.

The relationship between chromatic and luminance stereoscopic processing

Previously we have argued that chromatic stereopsis is a less contrast-sensitive analogue of luminance stereopsis, on the basis of the similarity of the disparity tuning we observed using vertical chromatic Gabors (Simmons & Kingdom, 1994). Such an interpretation would be consistent with there being a common pathway for the processing of luminance and colour disparity information, but with a reduced input from the latter. While the present results support the first part of this conclusion, i.e., that chromatic stereo processing is certainly less contrast sensitive, there is no clear evidence in our data that the chromatic stereo mechanism is a luminance analogue, and thus organised into a common pathway. Were the contrast dependence for chromatic and luminance stereoacuity consistently similar then such a conclusion might be warranted, but given the marked differences in one of our subject's (FK's) data between the chromatic and luminance vertical Gabor's contrast dependencies, no such conclusion can be made. Moreover, the anisotropy in the relative precision with which the disparities of the horizontal and vertical stimuli are processed, depending on whether they are isoluminant or isochromatic, tends to argue against a common neural architecture for the processing of chromatic and luminance disparity information. The issue thus remains open as to whether a common mechanism underlies chromatic and luminance stereopsis, capable of combining additively chromatic and luminance information, or whether separate pathways with distinct properties exist.

REFERENCES

Akerstrom, R. A. & Todd, J. T. (1988). The perception of stereoscopic transparency. *Perception & Psychophysics, 44*, 421–432.
Boothroyd, K. & Blake, R. (1984). Stereopsis from disparity of complex grating patterns. *Vision Research, 24*, 1205–1709.
Boulton, J. C., Baker, C. L. & Mullen, K. T. (1993). Nonlinear motion perception at isoluminance. *Investigative Ophthalmology and Visual Science (Suppl.), 34*, 1033.
Comerford, J. P. (1974). Stereopsis with chromatic contours. *Vision Research, 14*, 975–982.
Cormack, L. K., Stevenson, S. B. & Schor, C. M. (1991). Interocular correlation, luminance contrast and cyclopean processing. *Vision Research, 31*, 2195–2207.

Finney, D. J. (1971). *Probit analysis.* Cambridge: Cambridge University Press.

Foster, D. H. & Bischof, W. F. (1991). Thresholds from psychometric functions: Superiority of bootstrap to incremental and probit variance estimators. *Psychological Bulletin, 109,* 152–159.

Frisby, J. P. & Mayhew, J. E. W. (1978). Contrast sensitivity function for stereopsis. *Perception, 7,* 423–429.

Gregory, R. L. (1977) Vision with isoluminant colour contrast: 1. A projection technique and observations. *Perception, 6,* 113–119.

Grinberg, D. L. & Williams, D. R. (1985). Stereopsis with chromatic signals from the blue-sensitive mechanism. *Vision Research, 25,* 531–537.

Halpern, D. L. & Blake, R. R. (1988). How contrast affects stereoacuity. *Perception, 17,* 438–495.

Hess, R. F. & Wilcox, L. M. (1994). Linear and non-linear filtering in stereopsis. *Vision Research, 34,* 2431–2438.

Jordan, J. R., Geisler, W. S. & Bovik, A. C. (1990). Color as a source of information in the stereo correspondence process. *Vision Research, 30,* 1955–1970.

Julesz, B. (1971). *Foundations of cyclopean perception.* Chicago: University of Chicago Press.

Kovacs, I. & Julesz, B. (1992). Depth, motion, and static-flow perception at metaisoluminant color contrast. *Proceedings of the National Academy of Sciences, USA, 89,* 10,390–10,394.

Krauskopf, J. & Farrell, B. (1991). Vernier acuity: Effects of chromatic content, blur and contrast. *Vision Research, 31,* 735–749.

Legge, G. E. & Gu, Y. (1989). Stereopsis and contrast. *Vision Research, 29,* 989–1004.

Livingstone, M. S. & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience, 7,* 3416–3468.

Lu, C. & Fender, D. H. (1972). The interaction of color and luminance in stereoscopic vision. *Investigative Ophthalmology, 11,* 482–489.

McIlhagga, W. H. & Mullen, K. T. (1995). Detection of colour and luminance contours. *Vision Research.* In press.

Mullen, K. T. & Kingdom, F. A. A. (1991). Colour contrast in form perception. In Gouras, P. (Ed.) *The perception of colour.* Volume 6 in *Vision and visual dysfunction,* (Cronly-Dillon, J. Ed.) pp. 198–217. Oxford: Macmillan.

Osuobeni, E. P. & O'Leary, D. J. (1991). Effect of chromatic aberration on isoluminance stereothreshold. *Optometry and Visual Science, 68,* 552–555.

Osuobeni, E. P. & O'Leary, D. J. (1986). Chromatic and luminance difference contribution to stereopsis. *American Journal of Optometry and Physiological Optics, 63,* 970–977.

Ramachandran, V. S., Rao, V. M., Sriram, S., & Vidyasagar, T. R. (1973a). The role of colour perception and 'pattern' recognition in stereopsis. *Vision Research, 13,* 505–509.

Ramachandran, V. S., Rao, V. M. & Vidyasagar, T. R. (1973b). The role of contours in stereopsis. *Nature, London, 242,* 412–414.

Regan, D. (1991). Spatial vision for objects defined by colour contrast, binocular disparity and motion parallax. Chapter in Regan, D. (Ed.), *Spatial vision.* Volume 10 in *Vision and visual dysfunction* (Cronly-Dillon, J. Ed.) pp. 135–163. Oxford: Macmillan.

Scharff, L. V. & Geisler, W. S. (1992). Stereopsis at isoluminance in the absence of chromatic aberrations. *Journal of the Optical Society of America A, 9,* 868–876.

Simmons, D. R. (1992). Spatiotemporal properties of stereoscopic mechanisms. D. Phil Thesis, University of Oxford, U.K.

Simmons, D. R. & Kingdom, F. A. A. (1994). Contrast thresholds for stereoscopic depth identification with isoluminant and isochromatic stimuli. *Vision Research, 34,* 2971–2982.

Simmons, D. T. & Kingdom, F. A. A. (1995). Differences between stereopsis with isoluminant and isochromatic stimuli. *Journal of the Optical Society of America A., 12,* 2094–2104.

Smallman, H. S. & MacLeod, D. I. A. (1994). A size-disparity correlation in stereopsis at contrast threshold. *Journal of the Optical Society of America A, 11,* 2169–2183.

Smallman, H. S. & McKee, S. P. (1995). A contrast ratio constraint on stereo matching. *Investigative Ophthalmology and Visual Science (Suppl.), 36,* 230.

Stuart, G. W., Edwards, M. & Cook, M. L. (1992). Colour inputs to random-dot stereopsis. *Perception, 21,* 717–729.

Switkes, E., Bradley, A. & DeValois, K. K. (1988). Contrast dependence and mechanisms of masking interactions among chromatic and luminance gratings. *Journal of the Optical Society of America A, 5,* 1149–1162.

Treisman, A. (1962). Binocular rivalry and stereoscopic depth perception. *Quarterly Journal of Experimental Psychology, 14,* 23–37.

Tyler, C. W. & Cavanagh, P. (1991). Purely chromatic perception of motion in depth: Two eyes as sensitive as one. *Perception & Psychophysics, 49,* 53–61.

Watson, A. B. (1979). Probability summation over time. *Vision Research, 19,* 515–522.

Webster, M. A., DeValois, K. K. & Switkes, E. (1990). Orientation and spatial frequency discrimination for luminance and chromatic gratings. *Journal of the Optical Society of America A, 7,* 1034–1049.

de Weert, C. M. M. (1979). Colour contours and stereopsis. *Vision Research, 19,* 555–564.

de Weert, C. M. M. & Sadza, K. J. (1983). New data concerning the contribution of colour differences to stereopsis. In Mollon, J. D. & Sharpe, L. T. (Eds), *Colour vision. Physiology and psychophysics* (pp. 553–562). London: Academic Press.

Wilcox, L. M. & Hess, R. F. (1995). Is the site of non-linear filtering in stereopsis before or after binocular combination? *Vision Research, 36,* 391–399.