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Contrast Thresholds for Stereoscopic Depth Identification with Isoluminant and Isochromatic Stimuli

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Contrast thresholds for stereoscopic depth identification (crossed or uncrossed) were measured as a function of disparity using isoluminant (red–green) and isochromatic (yellow–black) 0.5 c/deg Gabor patches. For the purposes of comparison stimulus contrasts were scaled by their respective detection thresholds. The detection thresholds employed were computed from the monocular detection thresholds of the stereo half-images, based on the assumption that simultaneous detection of these half-images in each eye was a sufficient condition for stereopsis. It was found that the disparity tuning of both chromatic and luminance mechanisms was similar, with a performance peak for a binocular phase disparity of 50–120 deg. However, more contrast was required, relative to detection threshold, for the chromatic patterns to evoke a sensation of stereoscopic depth. These results suggest that stereopsis in the absence of luminance cues is supported by a less-contrast-sensitive analogue of the system that supports stereopsis in the presence of luminance cues. The results are also consistent with there being a lower density of disparity-selective mechanisms in the chromatic pathway. The implications of these data for previous studies of stereopsis at isoluminance is discussed.

Colour Stereopsis Contrast sensitivity Isoluminance Binocular vision

INTRODUCTION

It is now generally acknowledged that colour information has an important role to play in spatial processing (see Mullen & Kingdom, 1991 for a review). One well studied area of spatial vision is stereopsis. What is the role of colour information in stereoscopic vision?

Investigations of colour and stereopsis have largely focused on two questions: how colour information can assist in the solution of the stereo correspondence problem in the *presence* of luminance cues, and whether, in the *absence* of luminance cues (i.e. at isoluminance), stereoscopic judgements can be performed at all. Psychophysical studies have clearly demonstrated that colour information can drive stereo matching processes when the luminance information is rivalrous (Treisman, 1962; Julesz, 1971; Kovacs & Julesz, 1992; Stuart, Edwards & Cook, 1992) or ambiguous (Ramachandran, Rao, Sriram & Vidyasagar, 1973b; Akerstrom & Todd, 1988; Jordan, Geisler & Bovik, 1990). Computational studies have shown that colour information can help to increase the number of correct matches obtained with naturalistic stereo images (Brockelbank & Yang, 1989; Jordan & Bovik, 1991, 1992). There is less consensus, however, on the status of stereopsis at isoluminance.

The bulk of published psychophysical evidence suggests that stereopsis with random-dot patterns is severely degraded at red–green isoluminance (Lu & Fender, 1972; Gregory, 1977; de Weert, 1979; de Weert & Sadza, 1983). Yet, when "figural" stereograms such as lines or bars are used as stimuli, most studies report that stereopsis at isoluminance is maintained, although sometimes at the cost of reduced performance (Ramachandran, Rao & Vidyasagar, 1973a; Comerford, 1974; Gregory, 1977; de Weert, 1979; de Weert & Sadza, 1983; Osuobeni & O'Leary, 1986).

Livingstone and Hubel (1987) suggested that the contradictory findings concerning the status of stereopsis at red–green isoluminance were due in part to the technical difficulties in producing suitable stimuli and that previous demonstrations of stereopsis at red–green isoluminance with figural stimuli were caused by a range of luminance artifacts. They suggested a number of possible reasons for these artifacts, namely excessively coarse steps in red-to-green luminance ratio, chromatic adaptation to prolonged stimuli, variations in isoluminance with eccentricity and differences between the degree of variation between subjects, and unexplained individual differences between ability to use colour

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contrast information for stereopsis. Livingstone and Hubel (1987) reported that, with all the stimuli used in their study, a ratio of red-to-green luminances could always be found at which stereoscopic depth disappeared. This observation formed one of the cornerstones of their theory of parallel processing within the primate visual system.

Yet, in common with many previous studies of stereoscopic performance at red–green isoluminance (e.g. Lu & Fender, 1972; Comerford, 1974; Gregory, 1977; de Weert, 1979; de Weert & Sadza, 1982), Livingstone and Hubel (1987) used only a limited range of stimulus conditions. The conventional procedure in these studies was to establish a stimulus of fixed disparity in which the depth was apparent under conditions of adequate luminance contrast. The ratio of red-to-green luminances would then be varied to establish whether or not depth perception was impaired at or close to objective isoluminance. This procedure is flawed in isolation because (a) the colour contrast, which is independent of the red-to-green luminance ratio, may not have been adequate to support stereopsis despite the stimuli being easily detectable, and (b) the disparity chosen for the comparison may not have been appropriate for the sensitivity range of a chromatic stereo mechanism (should one exist), despite being suitable for the luminance mechanism.

Studies that are contemporary with, or more recent than, Livingstone and Hubel (1987) have all demonstrated that stereoscopic performance is maintained at isoluminance (Grinberg & Williams, 1985; Osuobeni & O'Leary, 1986; Jordan *et al.*, 1990; Tyler & Cavanagh, 1991; Scharff & Geisler, 1992). But while these studies took greater pains to avoid luminance artifacts, including those due to chromatic aberration in the eye (especially Scharff & Geisler, 1992), they did not all investigate the crucial stimulus parameters colour contrast and disparity. Grinberg and Williams (1985) varied both colour contrast and disparity range, but their study was confined to blue–yellow stimuli. Osuobeni and O'Leary (1986) used a wide range of disparities when they measured stereoacuity at a range of red-to-green luminance ratios and found a decrement in performance at isoluminance, but they did not try to improve performance at isoluminance by increasing the colour contrast of their bar stimulus. The same is true for Tyler and Cavanagh (1991). Although Jordan *et al.* (1990) and Scharff and Geisler (1992) measured colour contrast thresholds for stereo performance they only did this for single disparities (8 and 16 arc min respectively).

The consensus of these more recent studies is that some sort of stereo mechanism can function at red–green isoluminance. Given the existence of this chromatic stereo mechanism, the question arises as to the similarity between *the operation* of this mechanism and the luminance stereo mechanism. Manipulations of colour contrast and disparity range become important when investigating this question.

As far as stereopsis is concerned, there are arguably two crucial issues that must be addressed. The first is disparity tuning (i.e. the sensitivity of the mechanism as a function of disparity), in particular, what is the disparity tuning of the chromatic stereo mechanism, and is this tuning different from that of the luminance stereo mechanism? Should such a difference exist, it could explain some of the conflicting results of previous studies of stereopsis at isoluminance, by indicating that the disparities used to stimulate the chromatic mechanisms were outside its sensitivity range.

A second important issue is the relationship between chromatic stereo mechanisms and chromatic detection mechanisms. There is evidence to suggest that the mechanisms supporting stereopsis with isochromatic patterns are the same as those which support their detection (Simmons, 1992). This evidence is based on the observation that, for some combinations of disparity and spatial frequency, the contrast thresholds for the identification of stereoscopic depth (crossed or uncrossed) with isochromatic stimuli may be predicted from those for the monocular detection of the stereo half-images. Specifically, given appropriate conditions, the probability of correctly identifying the stereoscopic depth at a given contrast is the same or higher than that for detecting the stimulus simultaneously in both eyes. There is also evidence to suggest that the mechanisms that underlie the *detection* of low-spatial-frequency isoluminant patterns behave similarly to those which subserve the detection of isochromatic patterns at the same spatial scale (Losada & Mullen, 1994). Does this similarity extend to stereoscopic mechanisms? In particular, are the mechanisms supporting stereopsis at isoluminance the same as those underlying the detection of the stimulus, as has been shown for isochromatic patterns?

To address these questions about the chromatic stereo mechanism we measured the chromatic and luminance contrast thresholds for the correct identification of stereoscopic depth at a range of disparities. These contrast thresholds were compared to those for the simple detection of the same patterns. This method has been successfully used to investigate the nature and the spatial tuning of luminance stereo mechanisms (Hawken, Parker & Simmons, 1988; Mansfield & Simmons, 1989; Simmons, 1992; Smallman & Macleod, 1994).

METHODS

Stimuli

The stimuli used were isoluminant and isochromatic "Gabor" patches consisting of a sinusoidal modulation in colour or luminance contrast multiplied by a Gaussian envelope:

$$f(x, y) = L_0(1 + m \exp[-(x^2 + y^2)/2\sigma^2]\sin(2\pi nx)) \quad (1)$$

where f is the variation in luminance or chromaticity, x is distance along the horizontal, y is distance along the vertical, L_0 is the mean luminance or chromaticity, m is the contrast, σ is the standard deviation of the Gaussian modulation, and n is the spatial frequency of the sinusoid. Stimuli were always in sine phase to avoid any change in the mean luminance or chrominance during stimulus presentation. The spatial frequency of the patterns was always 0.5 c/deg, and the standard deviation of the Gaussian modulation was 1 deg, resulting in a spatial bandwidth of approx. 1.1 octaves (full width at half maximum). These stimulus parameters were designed to minimize luminance artifacts in the chromatic stimuli due to chromatic aberration (Scharff & Geisler, 1992). The stimuli were always vertically oriented.

The stimuli appeared in a high-contrast white fixation circle of radius 3 deg which was present throughout the experiment. A pair of high-contrast vertical nonius lines, each 36 arc min long and 1.8 arc min (1 pixel) wide, was present both before, between, and immediately after stimulus presentation. These nonius lines served as an additional disparity reference, and ensured that subjects' eyes were correctly positioned. The ensemble of fixation stimuli was designed to provide a strong depth reference at zero disparity, (see Fig. 1). The luminance of the fixation stimuli at the eye was approx. 10 cd/m^2.

Apparatus

The stimuli were presented using a BARCO Calibrator monitor, driven by a VSG2/2 graphics controller (Cambridge Research Systems) mounted on a DELL 486D/33 platform. Stimulus separation was obtained using a pair of liquid-crystal shutters (Displaytech Inc.) that were mounted in a set of optometric trial frames. The shutters were driven from the graphics controller in such a way that the shutters alternately opened and closed at the start of every frame, thereby presenting alternate frames to each eye. The frame rate of the monitor was 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 in a set-up such as this one. 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. For the purposes of this experiment, contrast detection thresholds for the monocular detection of the crosstalk were measured by placing an opaque patch over the eye to which the stimulus would normally be presented. It was found that the crosstalk was only detectable (i.e. above detection threshold) at contrasts above the ranges used in most of the experiments reported below. The exceptions to this exclusion were the data collected at the smallest disparities (3 and 6 arc min), but these data points are not crucial to the main conclusions of the study. In a second control experiment, contrast detection thresholds were compared under two conditions: (a) with one eye patched and with the stimulus presented

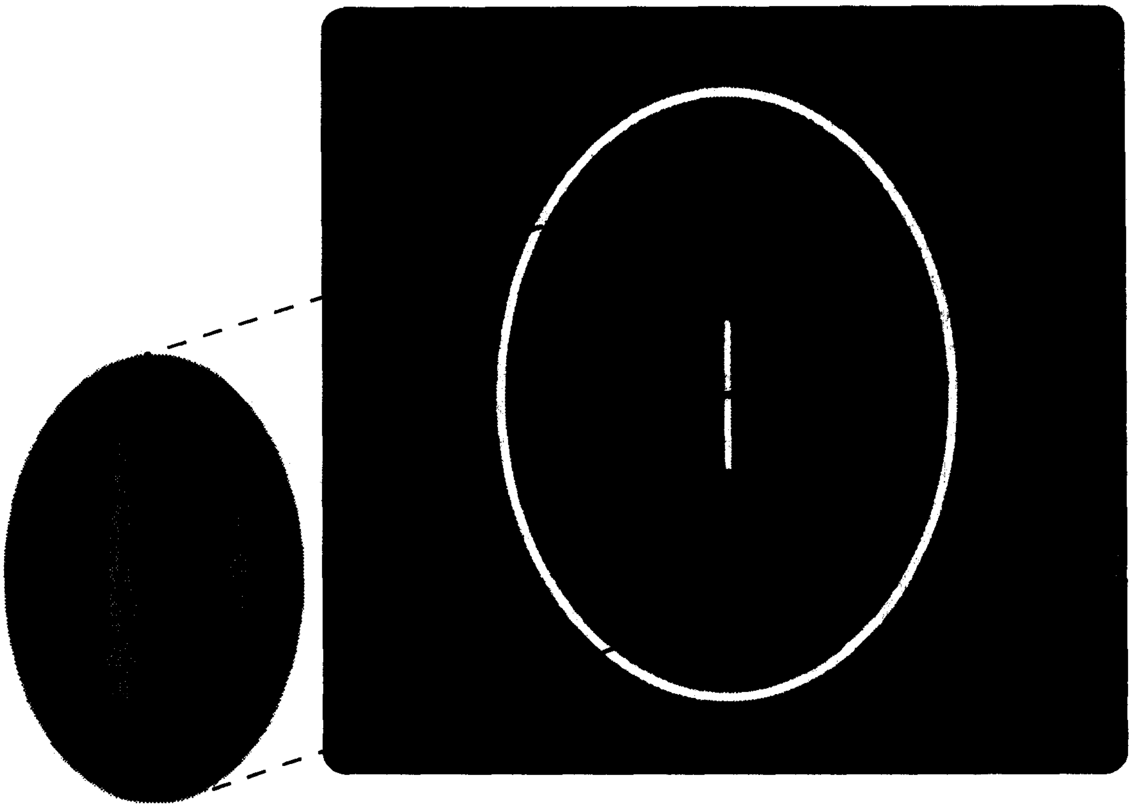

FIGURE 1. Schematic diagram of the stimulus configuration. Illustrated are the fixation circle and nonius lines (one presented to each eye) as they would appear when fused, although the break between the nonius lines is only for illustrative purposes (they were abutting in the actual experiment). The Gabor stimulus appeared in front of or behind these reference markers. The nonius lines were not present during stimulus presentation, although the circle was. For dimensions and further details see text.

only in the frames visible to the unpatched eye, and (b) with one eye patched and with the stimulus presented in frames both visible and invisible to the unpatched eye. The contrast detection thresholds were not significantly different in the two conditions. These control data suggest that the crosstalk was a largely irrelevant factor in these experiments and thus that measures to control its magnitude were not necessary.

After passage through the shutter glasses 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. The possible influence of the rod photoreceptors on the results is dealt with in the Discussion.

The size of the luminous part of the display was 16 deg wide and 11.5 deg high. The viewing distance was 114 cm. Experiments were carried out in a light-tight room with the lights turned off. The display was viewed with natural pupils.*

Calibrations

Luminance calibrations were carried out using a UDT 265 photometer. The red and green guns of the display were carefully linearized before any data were collected and the calibrations were periodically checked. During the course of data collection no significant drifts in the display properties were observed. Additional radiometric calibration (for the purposes of assessing cone contrasts) was performed using a UDT 260 radiometer with a calibrated head.

The spectral properties of the stimulus were assessed using data obtained from a calibration of another monitor of the same make (phosphor properties vary little from monitor to monitor) and using the manufacturer-supplied spectral transmission data for the shutter glasses. The CIE coordinates of the red and green phosphors were ($x = 0.623$, $y = 0.340$) and ($x = 0.278$, $y = 0.584$) respectively before passage through the shutter glasses and ($x = 0.614$, $y = 0.347$) and ($x = 0.270$, $y = 0.594$) respectively after passage through the shutter glasses.

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.

Stimulus generation and colour contrast

In the descriptions that follow, two classes of stimulus were used: luminance stimuli and chromatic stimuli. 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. $(L_{\max} - L_{\min})/(L_{\max} + L_{\min})$] on each gun, where 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 red to green luminances. 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.

Procedure—isoluminance setting

The isoluminant point was determined using the method of minimum motion (Moreland, 1982; Anstis & Cavanagh, 1983). A slowly drifting (0.6 deg/sec) sinusoidal chromatic grating of the same spatial frequency and size as the experimental stimulus was presented on the display. The colour contrast of the grating was set at a value of 15%, which was easily visible, but well below the maximum obtainable on the display. Subjects adjusted the ratio of red to green luminances in the display such that the drift speed appeared to slow. When the point of minimum drift speed was observed the subject pressed a button to indicate his choice. This process was repeated 10 times and means and standard errors were calculated. The setting was made with the shutter glasses in position, because the wavelength-dependent attenuation characteristics of the glasses had to be accounted for. The R/R + G values obtained were 0.530 (0.003) and 0.575 (0.003) for subjects FK and DS respectively, where standard errors are given in parentheses.

Procedure—depth identification

In the main series of experiments, stimuli were constructed with six disparities, three crossed and three uncrossed. One of these stimuli was presented at random in one of two temporal intervals, each 200 msec long, separated by a 1 sec gap. The other interval was blank. Stimulus onset and offset were abrupt. Two temporal intervals were used in order to match the uncertainty requirements of the depth task to those of the detection task,† thus allowing a valid comparison of the contrast requirements for each task. Irrespective of the interval in which the stimulus was presented, the subject was asked

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*The low luminance will have resulted in large pupils and thus increased effects of chromatic aberration. However, the low spatial frequency of the stimulus should have kept these effects to a minimum. See Scharff and Geisler (1992) for a detailed discussion of the size and significance of chromatic aberration artifacts in stereo experiments.

†In the detection task, the stimulus could appear randomly in one of two intervals, so the subject was *uncertain* as to which interval contained the stimulus. Uncertainty of this type is known to affect detection thresholds (Green & Swets, 1966; Pelli, 1985). We were concerned that, if only a single presentation interval was used for the depth-identification task, the reduced uncertainty might artificially enhance performance in the depth task, relative to the detection task. Although there is also uncertainty about disparity sign in the depth experiments, there is no evidence that this depth uncertainty can be strictly regarded as *orthogonal* in the manner formally required for an uncertainty condition (Green & Swets, 1966).

to judge whether the stimulus appeared to be in front of or behind the disparity reference. The nonius lines were always present except during stimulus presentation. In the course of the experiment, stimuli were presented at a range of colour or luminance contrasts. This range was selected to bracket the required contrast threshold. A given experimental run consisted of six presentations at each of the six disparities and five contrasts together with 30 zero-contrast "catch" trials to probe for subject biases. There were thus 216 trials in each experimental run. The duration of a run was approx. 10 min.

In a later experiment (data presented in Fig. 4) only two disparity values were employed, one crossed, the other uncrossed. The number of presentations at each disparity and contrast was increased to 10 min in each experimental run. Consequently the run was shorter, at 120 trials (including 20 "catch" trials).

In both cases, data from a number of runs were collated to construct psychometric functions relating the proportion of "front" responses to the stimulus contrast.

Procedure—contrast detection

Although a simultaneous detection and identification paradigm could not be employed, the detection experiments were performed in concurrent sessions with the depth-identification experiments. In the detection experiments there were also two presentation intervals, in one of which the stimulus was presented. The subject was now 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, stimulus duration and number of trials (216) was exactly the same as in the depth-identification experiments. Experiments were performed at a range of eccentricities which included those employed in the depth-identification experiments.

Data analysis

A maximum-likelihood procedure, similar to that employed by Watson (1979), was used to fit the depth-identification and simple-detection psychometric functions with Weibull–Quick functions. A "bootstrap" procedure (Maloney, 1990; Foster & Bischof, 1991) was used to determine 95% confidence limits on the estimates of the threshold (α) and slope (β) parameters of the fitted functions. These confidence limits are the error bars plotted on the figures.

Predictions for the contrast thresholds for depth identification were obtained by combining the probabilities of monocular detection in each eye so as to determine the probability of simultaneous monocular detection as follows (Simmons, 1992).

If probability of detection in the left eye, P_L, as a function of contrast, c, was given by

$$P_L(c) = 1 - 0.5\exp[-(c/\alpha_L)^{\beta_L}] \qquad (2)$$

where α_L and β_L are the threshold and slope parameters of the fitted psychometric function for the left eye, and probability of detection in the right eye, P_R, was given in terms of α_R, β_R, and c by

$$P_R(c) = 1 - 0.5\exp[-(c/\alpha_R)^{\beta_R}] \qquad (3)$$

then the probability of simultaneous detection in left and right eyes, P_D was obtained by multiplying (2) and (3) together and correcting for guessing thus

$$P_D(c) = 0.5(1 - \exp[-(c/\alpha_L)^{\beta_L}])(1 - \exp[-(c/\alpha_R)^{\beta_R}]). \qquad (4)$$

Contrast thresholds for simultaneous detection in each eye were then predicted by determining the contrast at which P_D was equal to 0.816 (threshold criterion for the Weibull–Quick function). Notice that there were no free parameters in this prediction. Examples of the application of this simple model to the data in this study are presented in the Appendix. The prediction was taken to be successful if the predicted performance was within the 95% confidence limits on the depth-identification contrast threshold.

This detection threshold is the most appropriate for comparison with contrast thresholds for stereoscopic judgements because, unlike binocular detection (i.e. detection of a stimulus performed with both eyes viewing that stimulus), stereopsis requires a signal present *in both eyes at the same time* (Simmons, 1992). Another way of thinking about this problem is that stereopsis is similar to a logical AND process, whereas binocular detection is more like a logical OR, although this does not necessarily imply that the detectors employed for the two tasks behave as AND and OR gates.

RESULTS

The results of the depth-identification experiments are shown in Fig. 2. Contrast sensitivity (the reciprocal of the contrast threshold) is plotted vs disparity for each condition (colour and luminance contrast) and each subject. Each panel of the figure incorporates two sets of data. Each set was collected as a block and spanned the different ranges of disparities: 3–18 arc min (circles) and 10–60 arc min (squares). These disparity ranges roughly correspond to the "fine" and "coarse" disparity ranges described by Tyler (1990). Notice that the luminance contrast data [Fig. 2(a, c)] are plotted with open symbols and that the colour contrast data [Fig. 2(b, d)] are plotted with solid symbols. The error bars are 95% confidence limits as determined by bootstrap analysis of the proportion-correct data (they are *not* standard errors). In these experiments "correct" was determined according to the sign of the disparity relative to fixation. Thus, for a crossed disparity the "correct" response was "in front" and for uncrossed disparities the "correct"

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*Binocular detection thresholds were measured concurrently for three reasons: (1) binocular trials interleaved with monocular trials were found to reduce the possible rivalry generated by having solely monocular trials; (2) a concurrent study of binocular summation was being performed; (3) the level of binocular summation can provide some information on the amount of neural summation expected in the depth-identification task (although it is difficult to make a quantitative estimate of this summation).

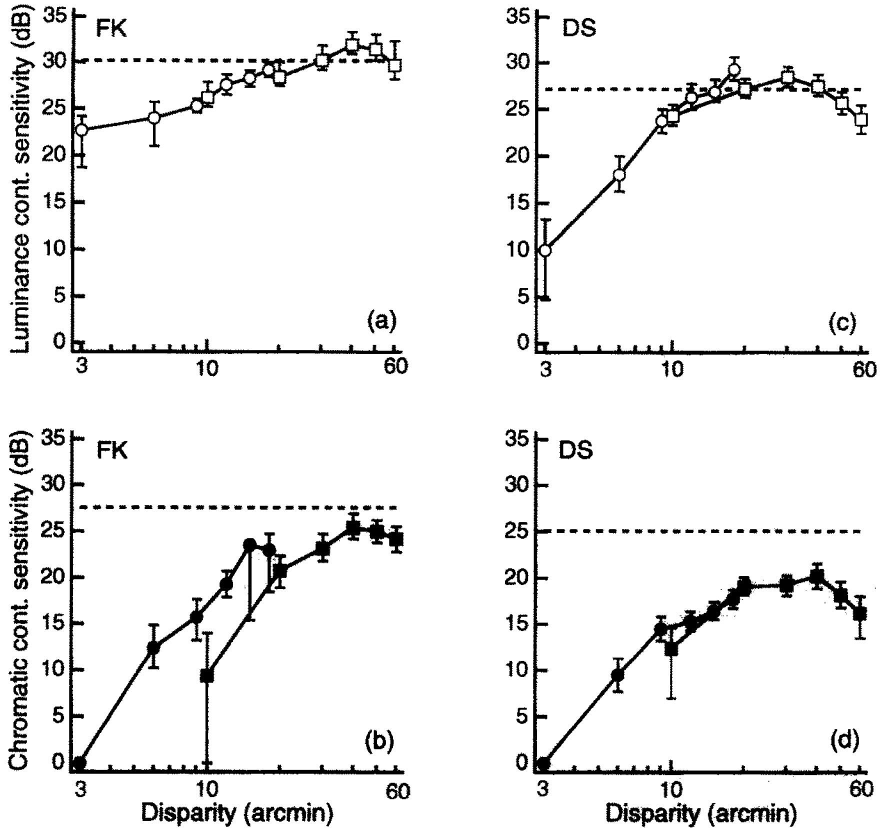

FIGURE 2. Contrast sensitivities in dB for depth identification plotted as a function of stimulus disparity in arc min for the two subjects. Open symbols indicate luminance contrasts (a, c) and solid symbols indicate chromatic contrasts (b, d). The different symbol shapes correspond to different stimulus disparity ranges (i.e. the limit of the possible disparity values that could occur during a given experimental run). Circular symbols indicate the "fine" disparity range (3–18 arc min) and the square symbols indicate the "coarse" disparity range (10–60 arc min). The error bars are 95% confidence limits determined by bootstrap analysis of the proportion-correct data (see text) and are *not* standard errors. The dotted horizontal line indicates the performance to be expected if the limiting factor was simultaneous detection in each eye at a retinal eccentricity of 20 arc min.

response was "behind". The plotted data are, therefore, averaged across disparity sign. This averaging process ignores the complicating effects of response biases and changes in the disparity perceived to be level with the fixation stimuli. Such shifts and biases were observed and their effects will be discussed below, but these averaged data summarize performance perfectly well, given the aims of this study. The dashed lines in Fig. 2 are the predicted depth-identification contrast sensitivities (see above) based on monocular detection data collected at an eccentricity of 20 arc min (this eccentricity is that required in each eye to obtain a disparity of 40 arc min). Over the eccentricity range used in this experiment (0–30 arc min) little variation in contrast detection threshold was observed for either isoluminant or isochromatic stimuli, which is consistent with previous studies (Mullen, 1991). The raw data used to make the predictions are presented in Table A1 of the Appendix.

The trends in the data are clearest over the coarse disparity range. Considering only the data collected over this range,* it can be seen from Fig. 2 that, in all four cases, performance peaks at around 30 or 40 arc min of disparity and tails off to either side. With isochromatic stimuli, the peak performance for both subjects is a little higher than that predicted from the monocular detection data. With isoluminant stimuli, performance never reaches the predicted level, although for FK the difference is just over 2 dB† at 40 arc min [Fig. 2(b)].

Over the fine disparity range there is less consistency between subjects and conditions. For both DS and FK depth identification with isoluminant stimuli is impossible at any contrast at the smallest disparity of 3 arc min,‡ but rises steeply to meet the coarse disparity data where the ranges overlap (although there is a small range effect in the data from FK). With isochromatic stimuli there is a noticeable difference between subjects. The performance of DS with these stimuli is very similar to that with isoluminant stimuli, except that

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*Although DS' contrast sensitivity to the 18 arc min disparity stimulus [at the limit of the "fine" disparity range in Fig. 2(c)] was slightly higher than that to the 30 arc min stimulus, this may be in part due to a range effect. In later experiments not reported here, performance with stimuli in the range 10–20 arc min was found to be quite labile.

†By convention, decibels of contrast, c, are given by the formula $\mathrm{dB}(c) = 20\log_{10}(c)$.

‡But note that presentations at this disparity, and also 6 arc min, may have been affected by the presence of detectable crosstalk (see Methods).

performance, relative to detection threshold, is better by 5–10 dB. For FK, performance with isochromatic stimuli is much better at the smallest disparities, but improves with disparity much less sharply than does his performance with isoluminant stimuli.

The comparison between performances in the four different conditions is facilitated by Fig. 3, in which the data from Fig. 2 are replotted in terms of the difference between the predicted and the measured contrast sensitivities for depth identification. This replotting of the data is essentially the same as scaling for detection threshold, and thus provides a more suitable metric for comparing performance between chromatic and luminance stimuli. For subject DS, the isoluminant and isochromatic contrast sensitivities are approximately parallel throughout the disparity range, whereas for FK, these sets of data are only parallel in the coarse disparity range. Error bars have been omitted from Fig. 3 for clarity.

One possible criticism of the data presented so far is that it has been assumed that the isoluminant point as defined by minimum motion is applicable to stereopsis mechanisms. A control experiment was thus performed to ensure that stereoscopic depth identification was possible at a range of red–green luminance ratios.

Figure 4 shows data from both subjects from an experiment in which contrast thresholds for depth identification and for monocular detection were measured for 40-arc min disparity stimuli at a range of red–green luminance ratios. Data are plotted as predicted–measured depth-identification contrast thresholds (DITs) as a function of R/R + G ratio relative to the subjectively determined isoluminant point.* The predictions were obtained from the monocular detection thresholds measured at each luminance ratio. The dotted horizontal line indicates the predicted performance level. Performance was always worst (or, at least, not significantly better than the worst performance) at the isoluminant point defined by the minimum-motion test, but gradually improved as the amount of luminance contrast in the stimulus increased.

DISCUSSION

Disparity tuning of the chromatic stereo mechanism

It appears, from Fig. 3, that the disparity tuning of the chromatic stereo mechanism sensitive to the 0.5 c/deg vertical Gabor stimulus closely follows that of the luminance stereo mechanism, at least for the coarse range of disparities. For both subjects and for both isoluminant and isochromatic stimuli over the coarse range, contrast sensitivities for depth identification peak at disparities between 30 and 40 arc min (although the peak is broader and flatter for subject DS). These disparities correspond to the 90–120 deg of binocular phase disparity† found to optimize performance in similar experiments with luminance stimuli by Smallman and MacLeod (1994).

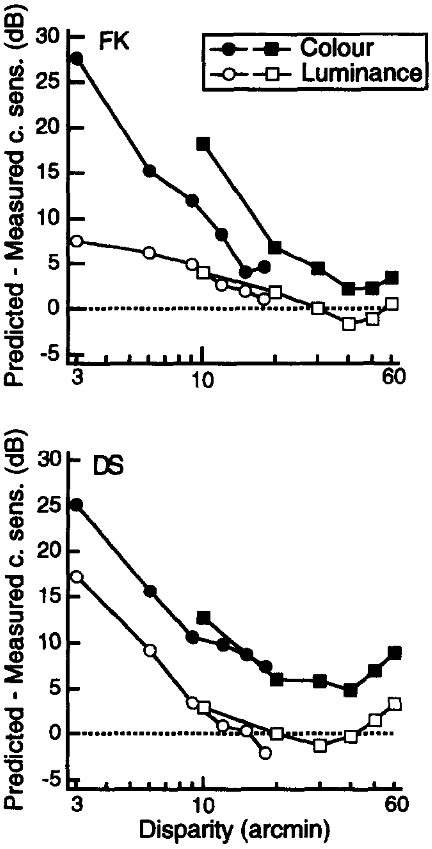

FIGURE 3. Predicted–measured contrast sensitivities for depth identification in dB plotted as a function of stimulus disparity. This plot is essentially equivalent to a scaling for detection threshold (see text). Symbols have the same allegiances as in Fig. 2.

The comparison between performance with isoluminant and isochromatic stimuli at smaller disparities is complicated by the influence of crossed/uncrossed biases and inter-subject differences. These complications are best explained by stating that mechanisms tuned to 0.5 c/deg are primarily concerned with processing disparities in the range 20–50 arc min, and so the performance of these mechanisms at smaller disparities is unreliable. A further complication is that the high contrasts necessary to reach a criterion level of performance with these small disparities suggests that mechanisms tuned to other spatial frequencies may well be contributing to performance. There are also the problems with these data due to the possible effects of shutter crosstalk. Crossed/uncrossed biases, and the influence of contrast on perceived stereoscopic depth (Schor & Howarth, 1986; Rohaly & Wilson, 1993), are the subject of a current study.

Relationship of stereoscopic mechanisms to detection mechanisms

The close proximity of the measured contrast sensitivities for depth identification with isochromatic stimuli

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*This value was calculated by subtracting the R/R + G value at isoluminance from that at the test point. For example, a relative R/R + G value of 0.100 for DS corresponds to an actual value of 0.675 (0.675 − 0.575 = 0.100).

†For dichoptically presented Gabor patterns, binocular phase disparity is defined as the difference between the phases of the carrier gratings with respect to their Gaussian envelopes.

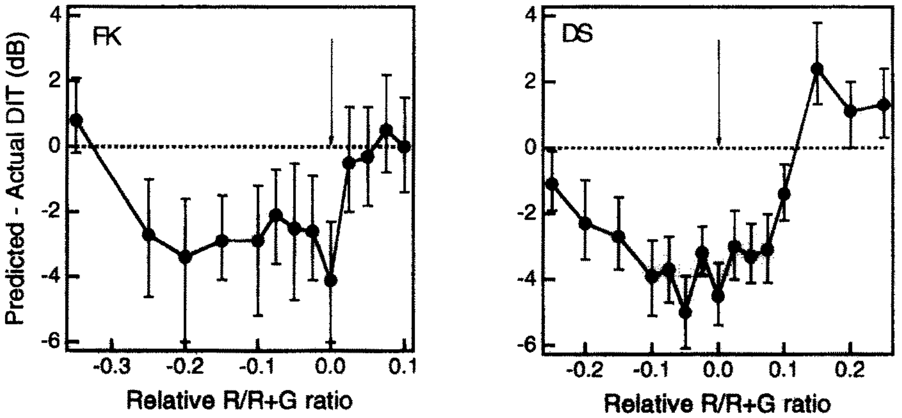

FIGURE 4. Predicted–measured contrast *thresholds* for depth identification (DITs) in dB plotted as a function of relative R/R + G ratio. This relative ratio is determined by taking the difference between the actual ratio and the ratio at minimum-motion isoluminance (see text). The error bars are again 95% confidence intervals determined by bootstrap analysis and the dotted horizontal line indicates the performance level predicted from monocular detection data collected at the same R/R + G ratio. The position of minimum-motion isoluminance is indicated by the vertical arrow.

and those predicted by the simultaneous-monocular-detection model described above confirms the results of Hawken *et al.* (1988) and Simmons (1992). For subject FK the prediction holds in the range 30–60 arc min, while for DS it holds in the range 12–40 arc min. Performance with isoluminant stimuli, however, never reached the predicted level, and was rarely closer than about 4 dB of contrast. This result, which has been replicated a number of times in experiments not reported here, has important implications for the role of chromatic mechanisms in stereo processing.

First, it appears that those mechanisms that are detecting the isoluminant stimulus at contrast threshold are *not* those that process its stereoscopic depth. Some additional contrast is required for depth identification over-and-above that required for simultaneous detection in each eye. Thus, the mechanisms that are most sensitive to chromatic contrast are not specialized for stereo processing.

Second, it has been argued on the basis of the proximity of the contrast thresholds for depth identification and those predicted from the monocular detection data for luminance stimuli, that there exist "labelled lines" for stereopsis within the luminance domain (Mansfield, 1990; Simmons, 1992). This argument is similar to that presented by Watson and Robson (1981) for the existence of labelled lines for spatial frequency and temporal frequency. If a given visual discrimination can be performed when the discriminanda are only just detectable, then the most sensitive detectors must be explicitly signalling the presence, and possibly even the magnitude, of the stimulus attribute that is forming the basis of the discrimination, because there are not enough active detectors to provide differential activity among a population tuned to different stimulus ranges. The labels proposed for stereopsis are "crossed" (in front of fixation) and "uncrossed" (behind fixation). From the results presented here, it is clear that correct depth identification is not possible with chromatic stimuli at contrast threshold, at least at the spatial frequency tested. Therefore, there is no evidence for labelled lines for stereopsis with isoluminant stimuli.

Note that the fact that depth-identification contrast sensitivities were sometimes significantly better than predicted by the model (see Fig. 2) probably reflects the influence of binocular neural summation (see, e.g. Anderson & Movshon, 1989). The model assumes that both eyes are essentially independent detectors, but there is considerable evidence for facilitatory interactions between the two eyes in detection and other tasks (see Blake & Fox, 1973; Blake, Sloane & Fox, 1981 for reviews). The simultaneous-detection model provides a lower bound on the contrast sensitivity for depth identification similar to that provided by probability summation in binocular detection tasks. Performance better than that predicted therefore provides further evidence for specialized binocular mechanisms and does not invalidate the labelled-line hypothesis.

The binocular detection data obtained during the course of the detection experiments showed no significant difference between the amounts of binocular summation with chromatic and luminance stimuli. In both cases the amounts of summation corresponded roughly to the factor of 1.4–1.5 (3–4 dB) improvement in detectability predicted by a number of models of binocular contrast combination (e.g. Campbell & Green, 1965; Legge, 1984; Anderson & Movshon, 1989). Although a calculation of the amount of binocular neural summation expected in the depth identification task appears at first to be straightforward, it is actually impossible without assuming some model for binocular contrast combination. We prefer to state simply that the depth-identification contrast sensitivities should be better than the prediction by some small amount (about 2 dB or less).

The isoluminant point for stereopsis

The control data presented in Fig. 4 demonstrate that, given our particular display set-up, we used the ratio of red-to-green luminances that most closely approximated phenomenal isoluminance for both motion and stereopsis mechanisms. Furthermore, given that the colour contrast thresholds at our phenomenal estimate of isoluminance were so close to (although not overlapping with) the predicted detection contrast thresholds, it seems unlikely that any luminance mechanism was controlling stereoscopic performance, at least at the disparity of 40 arc min, because any residual luminance contrasts in the stimulus would have been minute.

A further aspect of the dependence of depth identification contrast threshold on red-to-green luminance ratio is evidenced by the asymmetry of the curves in Fig. 4. In practical terms this meant that performance improved more rapidly with changing ratio if the red component was increased than if the green component was increased. A similar effect was commented on by Kovacs and Julesz (1992) who used a similar experimental set-up. A clear implication of this result is that increases in the red-gun luminance had more of an effect upon luminance stereo mechanisms than increases in the green gun luminance. Some of this asymmetry is explained in terms of the difference in the spectral properties of the red and the green phosphors. The spectral transmission function (STF) of the red phosphor was confined largely to wavelengths between 600 and 750 nm and thus was practically isolating for the L cone. The broader STF of the green phosphor resulted in approximately equal stimulation of the L and M cones. Yet, calculations have shown that this asymmetry in the phosphor properties cannot account for all of the asymmetry in the data, even when the spectral transmission properties of the glasses are taken into account.

The possible influence of rod photoreceptors

As was stated in the Methods, the low mean luminance of the display certainly did not saturate the rod photoreceptors, and thus they may have been involved in determining performance in some or all of the tasks investigated in this study. An anonymous reviewer pointed out that the spatial frequency of the stimulus would also be optimal for the scotopic system given the contrast sensitivity function for the rods (D'Zmura & Lennie, 1986). However, the same study (D'Zmura & Lennie, 1986) also suggested that the rod photoreceptors do not provide a luminance input to the visual system that is separable from that provided by the cones, so the influence of rods would presumably manifest itself as a luminance artifact in this study. Thus, if a rod component was present while collecting the luminance-contrast data, this should simply have been reflected in terms of a slightly higher contrast and thus should equally have affected detection and depth identification. If anything, such an artifact should have improved depth-identification performance with chromatic-contrast stimuli relative to detection threshold, and should thus only have reduced the gap between the contrast thresholds for depth and detection [this could explain the mismatch between the predictions of Scharff and Geisler (1992) and our own results (see below) and also the asymmetry found in performance as a function of R/R + G level, given that the rods will have been more sensitive to the green phosphor]. We therefore conclude that the low luminance will have had no effect on the conclusions of this study.

Implications for neural mechanisms

This study adds to the body of literature which confirms that stereoscopic depth perception can operate at isoluminance, provided that stimulus conditions are appropriate. The use of briefly presented, spatially localized and spatially bandpass stimuli together with the subjective determination of the isoluminant point with each individual subject and the low chromatic contrasts at which stereoscopic depth identification was possible, has also addressed the main criticisms of studies of stereopsis at isoluminance put forward by Livingstone and Hubel (1987). But there are two further important implications of these results which, at first sight, seem to be contradictory.

The similarity between the disparity tuning of the luminance and the chromatic mechanisms suggests that the processing of binocular disparity is similar in both domains, except that the chromatic mechanism requires a higher contrast relative to detection threshold in order to function. Therefore, it would be expected that, whatever the neural apparatus which underlies performance with isochromatic stimuli, that which underlies performance with isoluminant stimuli is likely to be similar in terms of receptive field organization and disparity sensitivity. Yet, unlike the luminance stereo mechanism, the chromatic stereo mechanism cannot function at contrast threshold. Hence the mechanisms that are most sensitive to chromatic contrast are not disparity selective. This result suggests that, relative to detection mechanisms, there are fewer disparity-selective chromatic mechanisms than disparity-selective luminance mechanisms (i.e. a lower density). A similar explanation has been put forward by Stuart *et al.* (1992) in order to explain the individual differences in performance that are very common in studies of colour and stereopsis (see also Scharff & Geisler, 1992).

Thus on one hand we have a chromatic stereo mechanism which is a less-sensitive analogue of the luminance mechanism, but on the other we have possible fundamental differences in the way these two mechanisms are organized. Perhaps this dilemma may be reconciled by appealing to the scatter of receptive-field properties within the visual system, particularly in V1 (Lennie, Krauskopf & Sclar, 1990). Clearly there are chromatic neural mechanisms which are also sensitive to binocular disparity, but these do not necessarily form an independent chromatic stereo channel by themselves. Unlike with the independent systems that have been postulated to explain chromatic detection thresholds (Cole, Hine & McIlhagga, 1993), these stereo mechanisms simply contribute to a unified stereo percept when in the more realistic situations where combinations of luminance and chromatic contrasts define visual features.

Relevance to previous experiments on stereopsis at isoluminance

It was suggested in the introduction that previous demonstrations of a disappearance of stereopsis at isoluminance (Lu & Fender, 1972; Gregory, 1977; de Weert, 1979; Livingstone & Hubel, 1987) may have been caused by the stimulus possessing inadequate colour contrast, or a disparity unsuitable for the chromatic stereo mechanism. The results presented here demonstrate that, with narrowband stimuli centred around 0.5 c/deg, the disparity tunings of luminance and chromatic stereo mechanisms are very similar, especially in terms of their peak sensitivity. Given this result, could inappropriate choices of disparity still be regarded as a factor in these previous studies? If the stimulus was bandpass-filtered so as to have a centre spatial frequency of 0.5 c/deg, and if the disparity was set to obtain the best performance using the luminance pattern, then good performance should have been obtained with the equivalent isoluminant pattern. However, it should be noted that in these studies the stimuli used always contained sharp discontinuities in chromaticity or luminance and hence energy at high spatial frequencies (above 2 c/deg). Given the well-known differences between the luminance and chromatic contrast sensitivity functions (see Mullen & Kingdom, 1991) luminance stereo mechanisms tuned to higher spatial frequencies [and thus probably smaller disparities (Smallman & MacLeod, 1994)] will have been able to use this high-spatial frequency information, but chromatic mechanisms will not.* Hence a similarity between the disparity tunings of chromatic and luminance stereo mechanisms at one spatial frequency does not rule out a dissimilarity between tunings when information may be combined across a greater range of scales.

Comparison with Scharff and Geisler (1992)

Scharff and Geisler (1992) used an equivalent-contrast metric derived on signal-detection-theoretic grounds in order to compare stereoscopic performance with luminance-defined and colour-defined stimuli. They found using this metric that two out of their three subjects could perform a depth-discrimination task equally well at isoluminance as at other ratios of red-to-green luminance. They concluded from this result that chromatic information and luminance information are processed with equal efficiencies for the purposes of stereopsis, and that any differences in performance observed in other studies were merely due to the reduced effective contrast of the stimuli caused inevitably by the overlap in spectral sensitivities of the L and M cones.

At first reading, the conclusions of this study appear to be at odds with those of Scharff and Geisler (1992), but this is not necessarily the case. A comparison of the luminance and chromatic contrast thresholds for depth identification determined in this study, using the equivalent-contrast metric employed by Scharff and Geisler (1992), showed that our chromatic thresholds were actually *lower* than the equivalent luminance thresholds by 3.3 and 4.4 dB for DS and FK respectively. This result certainly implies that the efficiency of colour depth identification is no worse, and in fact appears even better, than the efficiency for luminance depth identification in our study, when the comparison is made on the basis of the information present at the level of the photoreceptors. However, in this study our primary goal was a comparison between the contrast requirements for detection and depth identification, because such a comparison enabled us to determine whether there was evidence for labelled lines in chromatic stereopsis. The equivalent-contrast metric used by Scharff and Geisler (1992), precisely because it is photoreceptor based, cannot by definition predict any differences in performance found between processes that might be mediated by different post-receptoral mechanisms. Our data suggest that the superiority of chromatic stereopsis measured using the equivalent-contrast metric found here is a consequence of the counterbalancing of two effects: one a very significant superiority in detection of chromatic over luminance contrast when measured using the equivalent-contrast model (see Geisler, 1989), and two, the significant gap between detection and depth identification found in the chromatic, but not the luminance, case.

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*Note that this explanation ignores the influence of chromatic aberration.

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APPENDIX

Data Used to Predict Contrast Thresholds for Depth Identification, with Examples

In this appendix we present the data that were used to make the predictions of the contrast thresholds for depth identification, together with some example psychometric functions.

If the probability of correctly identifying the stereoscopic depth of a stimulus is dependent *only* upon the probabilities of it being detected in each eye then the simultaneous-detection model should be able to predict not only the contrast thresholds for depth identification, but also the shape of the psychometric function. It is clear from Fig. A1 and Table A1 that the shape of the psychometric function is not predicted accurately by the model. The examples shown are the monocular-detection psychometric functions for each subject (upper panels) together with the prediction obtained from these functions (lower panels). Plotted with the prediction are the data and fitted psychometric function for the depth-identification task. Note that in each case these data are for best depth-identification performance (over the "coarse" disparity range) obtained with luminance contrast. The chief point to note is that, while the contrast threshold for depth identification is within the range of the model's prediction (i.e. slightly lower than the prediction), the slope is considerably shallower. This has generally been the case in previous applications of the model (see Simmons, 1992).

There are a number of possible reasons for this discrepancy between model and data. First, if there is a difference between the contrast sensitivities to crossed and uncrossed disparities the psychometric function will be "spread out" when these data are combined. Second, it is noticeable that the fit is better for the upper portion of the psychometric function. Possibly the effects of binocular neural summation (see main text) are more apparent at lower contrast levels where the monocular stimulus is just below detection threshold. Third, there are more sources of extraneous noise in the depth task than the

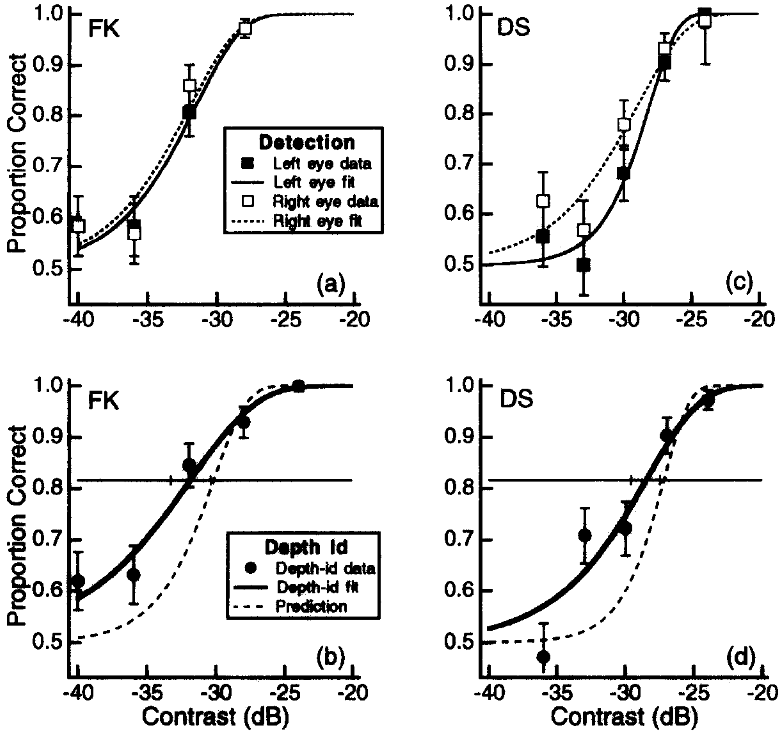

FIGURE A1. Example psychometric functions from the detection and depth-identification experiments. Only luminance contrast data are presented. (a) Proportion-correct data plotted as a function of luminance contrast in dB for monocular detection in the left (solid squares) and right (open squares) eyes for an eccentricity of 20 arc min. The error bars are standard errors based on the assumption that the data were sampled from a binomial distribution. The solid and dashed lines are the maximum-likelihood fits of Weibull–Quick functions to the left- and right-eye data respectively. (b) The depth-identification data (solid circles) obtained at a disparity of 40 arc min, again with binomial error bars. The thick solid line is the best-fitting Weibull–Quick function to the data. The dashed line is the prediction obtained (with no free parameters) from the monocular-detection data. The thin solid horizontal line indicates the threshold performance level. The short vertical bars along this line indicate the 95% confidence limits on the threshold as computed by bootstrap analysis of the data (see text). Similar data are shown for DS in (c) and (d), except that the depth-identification data were obtained at a disparity of 30 arc min.

TABLE A1. Monocular detection data are presented with threshold (α, in dB of attenuation from a contrast of unity) and slope (β) parameters

	Monocular detection data				Prediction		Depth identification data			
Condition	α_L (dB)	β_L	α_R (dB)	β_R	$\alpha_{pred.}$ (dB)	$\beta_{pred.}$	$\alpha_{act.}$ (dB)	95% conf. limits	$\beta_{act.}$	95% conf. limits
FK Luminance	31.6	2.6	32.0	2.5	30.2	3.6	31.9	U: 33.3 L: 30.5	1.8	U: 2.4 L: 1.2
FK Colour	28.7	2.2	30.2	2.2	27.6	3.0	25.4	U: 26.9 L: 24.2	1.6	U: 2.3 L: 1.1
DS Luminance	28.1	4.2	29.0	2.4	27.2	4.7	28.5	U: 29.6 L: 27.4	2.2	U: 3.3 L: 1.6
DS Colour	27.9	1.8	26.5	2.3	25.1	2.9	20.3	U: 21.6 L: 18.9	1.6	U: 2.3 L: 1.0

Also shown are the predicted psychometric function parameters and those actually obtained (peak performance over the "coarse" disparity range), together with 95% confidence limits (upper, U, and lower, L) on the parameters.

detection task. Specifically there is more of a need for accurate and stable fixation in the depth task, and consequently the number of mistakes made might be higher.

These reasons, however, are not enough to invalidate the model. As stated in the main text, this model only serves as a lower bound on performance in a similar way to that provided by binocular probability summation when the task is binocular contrast detection. Also, given that the task is one of correct depth identification, it is important that both crossed *and* uncrossed disparities can be correctly detected at the measured threshold.* Experiments are underway in which we use a paradigm that allows correct depth identifications to be more easily distinguished from response biases.

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*Note that the use of a threshold criterion of 81.6% rather than 75% is important here. A performance of 75% correct could be obtained by correctly identifying, say, all of the crossed disparities, but displaying random performance on the uncrossed.