PERGAMON

Vision Research 39 (1999) 2127–2141

Vision Research

On the apparent collapse of stereopsis in random-dot-stereograms at isoluminance

Frederick A.A. Kingdom [a],*, David R. Simmons [b], Stéphane Rainville [a]

[a] *McGill Vision Research Unit, 687 Pine Avenue West Room H4-14, Montréal, Québec H3A 1A1, Canada*
[b] *Department of Vision Sciences, Glasgow Caledonian University, City Campus, Cowcaddens Road, Glasgow G4 0BA, UK*

Received 18 September 1997; received in revised form 25 June 1998

Abstract

We have investigated the apparent collapse of stereopsis obtained with random-dot-stereograms at isoluminance. Contrast thresholds for both depth and form discrimination of targets in random-dot- and figural stereograms were measured at a number of disparities, using both isoluminant and isochromatic stimuli. All contrast thresholds for stereoscopic tasks were normalised to contrast thresholds for detecting the appropriate stimulus. We found that at isoluminance contrast thresholds for depth judgements were no higher for random-dot compared to figural stereograms, even when normalised to the same thresholds obtained with isochromatic stimuli. On the other hand contrast thresholds for three-dimensional form judgements were much higher than those for depth judgements in isoluminant, compared to isochromatic random-dot-stereograms. This specific impairment of stereoscopic form (as opposed to depth) processing at isoluminance was confirmed in a further experiment in which subjects were required to judge the presence and orientation of depth corrugations in a disparity-modulated random-dot-stereogram. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Stereopsis; Random-dot-stereograms; Colour vision; Isoluminance; Surface perception

1. Introduction

Lu and Fender's (1972) classic demonstration of the collapse of stereopsis in isoluminant random-dot-stereograms began a controversy which remains unresolved today. Two issues underlie the controversy. The first is whether their demonstration shows that stereopsis is completely colour blind, or instead merely less efficient when utilising chromatic compared to luminance information. If, for the moment, we accept that colour vision is capable of supporting stereopsis at isoluminance (evidence reviewed below), the second issue is whether isoluminant random-dot-stereograms constitute a special case of stereopsis at isoluminance. In a random-dot-stereogram the depth target is only visible in the cyclopean view, whereas in a figural stereogram, such as one consisting of a simple bar target, the target is visible monocularly (Julesz, 1971). Evidence reviewed in the second part of the introduction suggests that stereopsis in isoluminant random-dot-stereograms might be especially impaired compared to isoluminant figural stereograms. The purpose of this communication is to confirm whether or not this is the case, and if so why.

1.1. Is stereopsis colour blind?

The two extreme positions on this question are perhaps best represented by Livingstone and Hubel (1987), and Scharff and Geisler (1992). Livingstone and Hubel (1987) claimed that with both random-dot and figural red–green stereograms, one can always find a red/green luminance ratio at which stereoscopic depth perception is impossible, so long as one is careful to remove any potential luminance artifacts[1]. Scharff and Geisler (1992) on the other hand, using data collected with random-dot-stereograms, argued that the apparent loss in stereoscopic depth perception at isoluminance does

---

* Corresponding author. Fax: + 1-514-8431691; e-mail: fred@jiffy.vision.mcgill.ca.

[1] This point of view was confirmed more recently by Livingstone (1996).

PII: S0042-6989(98)00257-0

not represent a total loss of depth perception. On the contrary, they suggest, the loss is entirely due to a lack of effective contrast in the stimulus. The marked overlap in spectral sensitivity of L (long-wavelength-sensitive), and M (medium-wavelength-sensitive) cones means that a post-receptoral, cone-subtractive, $L-M$ chromatic mechanism would be much more weakly stimulated by an isoluminant random-dot-stereogram than a cone-additive, $L+M$ luminance mechanism would be by an isochromatic stereogram. Using an equivalent-contrast metric derived from an ideal observer model, they showed that stereoscopic performance for some of their subjects was as good with red–green isoluminant patterns as with isochromatic patterns.

Between these two positions lie a number of studies which mainly employ figural stereograms, and which claim that colour vision can support stereopsis, but less efficiently than luminance-based vision (Comerford, 1974; Gregory, 1977; de Weert, 1979; Simmons & Kingdom, 1994, 1995, 1997; Kingdom & Simmons, 1996). In particular Simmons and Kingdom (1997), on the basis of stereo-depth measurements made with Gabor patterns containing various combinations of colour and luminance contrast, concluded that contrast thresholds for stereopsis were subserved by *independent* chromatic and luminance stereopsis mechanisms.

1.2. Are random-dot-stereograms a special case of stereopsis at isoluminance?

Given the evidence that colour vision can support stereopsis at least to some degree, we now consider whether isoluminant random-dot-stereograms constitute a special case of isoluminant stereograms. Two of the studies mentioned above which showed that stereopsis was possible with isoluminant figural stereograms, namely Gregory (1977) and de Weert (1979), failed to demonstrate stereopsis with isoluminant random-dot-stereograms. This led de Weert (1979) to speculate that while colour could support stereoscopic depth perception under certain conditions, it was unable to support the cooperative mechanisms necessary for perceiving depth in random-dot-stereograms. In a later experiment however, and the most comprehensive study to date on stereopsis with isoluminant random-dot-stereograms, de Weert and Sazda (1983) came to a different conclusion. They found that stereoscopic depth perception *was* possible with isoluminant random-dot-stereograms when forced-choice methods were employed, irrespective of whether the task was to identify the depth or the form of the target. However de Weert and Sazda (1983) used random-dot-stereograms whose elements had hard edges, and luminance artifacts from chromatic aberration could have been present. Furthermore, Rogers and Howard (1995) have argued that the small size of the random-dot-stereograms used by de Weert and Sazda (3 × 3°), together with the high contrast border of the stimulus, could have helped subjects detect depth via convergence. Despite these problems the conclusion drawn by de Weert and Sazda (1983) is worth noting: 'There is no fundamental difference in the contribution of colour to stereopsis in figural stimuli and in random dot stereograms at isoluminance' (p560).

Other reasons besides the correspondence problem have been suggested for why stereo-depth perception in isoluminant random-dot-stereograms might be particularly impaired. Simmons and Kingdom (1995) and Kingdom and Simmons (1996) have suggested the impairment could be due to an absence of a second-order chromatic stereopsis mechanism. A second-order stereopsis mechanism is one sensitive to the disparity of contrast modulations rather than luminance modulations (e.g. the envelope, rather than the carrier, of a Gabor pattern). Such a mechanism has been isolated for isochromatic (luminance-only) stimuli (Wilcox & Hess, 1996), but appears almost completely absent for isoluminant chromatic stimuli (Simmons & Kingdom, 1995; Kingdom & Simmons, 1996). According to Simmons and Kingdom (1995), stereopsis in random-dot-stereograms might in part be subserved by such a second-order mechanism, especially at large disparities where the quarter-cycle-limit would be exceeded for many of the spatial frequencies in the stimulus. At large disparities, contrast variations at a relatively coarse scale could arise by chance in the stimulus, and might constitute the only reliable signals for stereo-depth. A recent study by Kovács and Fehér (1997) supports this hypothesis. An absence of a second-order chromatic stereopsis mechanism might therefore result in difficulty in perceiving depth in isoluminant random-dot-stereograms, especially at large disparities.

To summarise, the literature on stereopsis with isoluminant random-dot-stereograms allows the following positions to be taken: (1) Stereopsis is essentially colour-blind, and any residual depth perception at isoluminance is artifactual (Livingstone & Hubel, 1987; Livingstone, 1996); (2) stereopsis at isoluminance is possible, and is only impaired because of a lack of effective contrast in the stimuli: chromatic stereopsis mechanisms are not themselves deficient (Scharff & Geisler, 1992); (3) stereopsis at isoluminance is possible in figural stereograms, but not in random-dot-stereograms because the latter are unable to activate the cooperative mechanisms necessary to elicit stereopsis (de Weert, 1979; but see de Weert and Sazda (1983), for counter-evidence showing stereopsis with isoluminant random-dot-stereograms); (4) stereopsis is possible in both figural and random-dot stereograms, but is more impaired in random-dot-stereograms because of an absence of a second-order (contrast-envelope-sensitive) chromatic stereopsis mechanism (Simmons & Kingdom, 1995; Kingdom & Simmons, 1996).

The purpose of this communication is to determine what underlies the apparent loss of stereopsis in random-dot-stereograms at isoluminance. The experiments described here use a technique previously employed by ourselves to assess chromatic stereopsis with Gabor patches, (Simmons & Kingdom, 1994, 1995, 1997; Kingdom & Simmons, 1996), namely to measure the *contrast threshold* for making a stereopsis judgement at a given disparity. This method has two advantages over conventional methods of measuring stereoscopic performance, such as $D_{\min}$ (the minimum detectable disparity, or stereoacuity) and $D_{\max}$ (the maximum detectable disparity) for the study of chromatic stereopsis. First, it allows us to measure stereoscopic performance throughout the disparity range using a forced-choice procedure: $D_{\min}$ and $D_{\max}$ only deal with the extreme of detectable disparities. Second, it offers a means of equating chromatic and luminance stereopsis performance, by normalising the contrast threshold for making the stereo judgement to that for *detecting* the stimulus.

2. Methods

2.1. Subjects

Two of the authors acted as subjects (FK, SR), and one undergraduate volunteer (AW). FK and AW were emmetropic, while SR wore his normal optical correction. All were experienced psychophysical observers. AW was completely naive as to the purpose of the experiments.

2.2. Stimuli

2.2.1. Generation

The stimuli were generated using the VSG2/3F videographics card (Cambridge Research Systems) hosted by a Gateway 2000 P5 computer, and displayed on a BARCO Calibrator monitor.

2.2.2. Calibration and contrast resolution

The VSG2/3F can display images with 256 intensity levels per gun, selected from 12-bit (4096 levels) linearised CLUTs (colour look-up-tables). Each gun on the monitor was calibrated using the Optical system (Cambridge Research Systems), which generates the 12-bit gamma-corrected CLUTs. The 12-bit CLUTs provided a contrast resolution of about 0.05% (see Kingdom & Whittle, 1996), which is sufficient for measuring contrast thresholds. Whatever the contrast of the stimulus, it was always displayed with the full 8-bits, the intensities of which were suitably selected from the 12-bit CLUTs.

2.2.3. Random-dot-stereograms

Random-dot-stereograms (Fig. 1a) were constructed from filtered noise. Prior to filtering, each stereo-half measured 10.7 × 10.7°, and consisted of elements 6 × 6 arc min whose pixel intensity levels were drawn randomly from the 256 available, i.e. they had a flat luminance distribution. In the standard condition the target was a vertically centred square subtending 5.35 × 5.35°, horizontally offset in each stereo-half-pair by an amount which determined the required disparity. Random-dot-stereograms with rectangular targets were also employed, details of which are given below. To minimise any high spatial frequency luminance artifacts introduced by chromatic aberration, each stereo-pair was filtered by spatial convolution with a two-dimensional isotropic Gaussian filter, whose output was renormalised to maintain stimulus contrast. The spatial point-spread-function of the Gaussian filter was

$$h(r, \sigma) = \exp(-r^2/2\sigma^2)$$

where r is radial distance, or $\sqrt{(x^2 + y^2)}$, and σ is the space constant of the filter. σ was set to 0.15° for all conditions, except for the experiments dealing with the

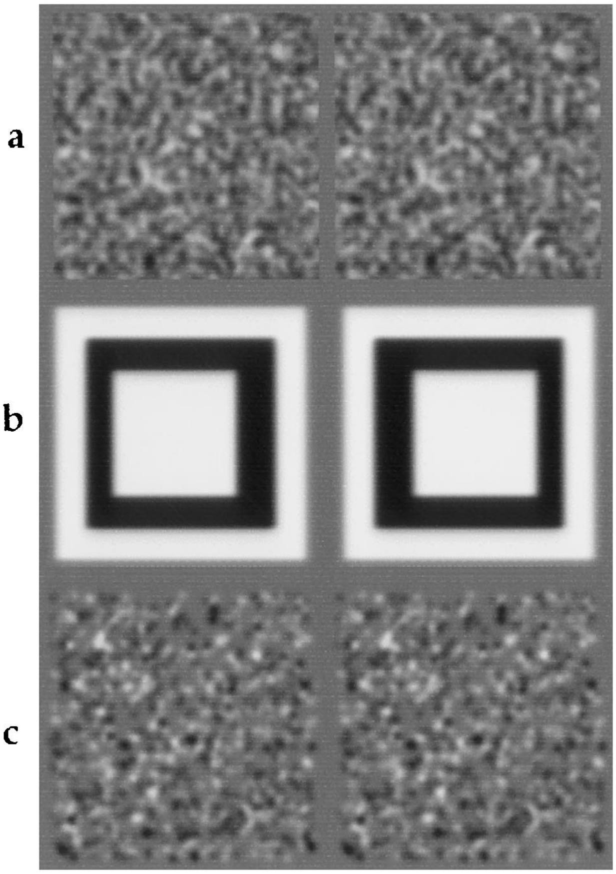

Fig. 1. Stereo-pairs of the three types of stereogram used in this study. Top (a) rectangular target random-dot-stereogram. Middle (b) figural stereogram. Bottom (c) disparity-modulated random-dot-stereogram, with left oblique corrugation.

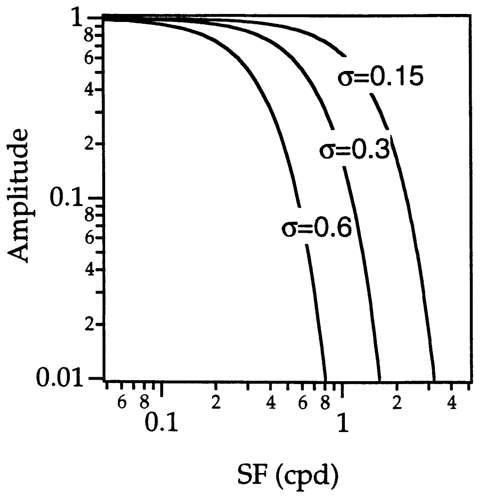

Fig. 2. Normalised amplitude spectra of the three Gaussian filters used to lowpass filter the figural and random-dot stereograms. The σ value gives the standard deviation in degrees of each filter. The $\sigma = 0.15°$ filter is the standard filter used for all the experiments except Experiment 3 which investigated the effects of Gaussian blur.

effect of Gaussian blur, in which σ values of 0.3 and 0.6° were also used. The normalised amplitude spectrum of the two-dimensional Gaussian function is

$$H(f_r, \sigma) = \exp(-2\pi^2\sigma^2 f_r^2)$$

where f_r is radial spatial frequency. Fig. 2 plots the amplitude spectra of the three filters employed. As can be seen the $\sigma = 0.15°$ filter (the standard condition) attenuates all spatial frequencies higher than 3.0 cpd to less than 1% of their original contrast. Scharff and Geisler (1992) showed that a filter similar to this one also removed frequencies above 3.0 cpd (using the same 1% criterion), and effectively eliminated the effects of chromatic aberration in their random-dot-stereograms.

Both isoluminant red–green and isochromatic yellow–black random–dot-stereograms were employed. For the yellow–black stimuli, the red and green phosphor modulations were in phase, whereas for the red–green stimuli they were out of phase. Out-of-phase modulation was achieved by inverting one of the two (red or green) CLUTs. The background of the stimuli was a uniform yellow with an $R/(R+G)$ value equal to that of the random-dot-stereogram. The contrast of the random-dot-stereogram was defined as the r.m.s (root mean square) contrast of either the red or green modulation. The mean luminance of all the stimuli employed in the experiments described here was 8.0 cd/m^2. The chromaticity coordinates of the red and green phosphors were ($x = 0.623$, $y = 0.340$) and ($x = 0.278$, $y = 0.584$), respectively.

Before a given experimental session eight random-dot-stereograms were freshly generated and stored off-screen in the VSG's video-graphics memory. On a given trial one of the random-dot-stereograms was selected and displayed on the monitor with either crossed or uncrossed disparity, the latter achieved by a simple reversal of the two stereo-half-pairs. The CLUTS were also subject to random inversion. In a given red–green stereogram this meant that a red blob in one stimulus presentation could become a green blob in another (and for a yellow–black stereogram a bright yellow blob could become a dark yellow blob), thus effectively doubling the number of random-dot-stereograms employed from eight to 16.

2.2.4. *Figural stereograms*

An example of a figural stereogram is shown in Fig. 1b. Its outer dimensions were the same as the random-dot-stereograms (10.7 × 10.7°). It consisted of an outer annulus 1.34° in width, an inner surround, and a central square target subtending 5.35 × 5.35° (except in one condition when the target was a rectangle—see below). The annulus and target were both the same colour or luminance polarity, while the inner surround was of opposite colour or luminance polarity. The figural stereograms were also filtered with a Gaussian with the standard condition σ of 0.15°. As with the random-dot-stereograms the background outside the annulus was set to a uniform yellow with an $R/(R+G)$ value equal to that of the stimulus itself. Contrast was defined as Michelson contrast. As with the random-dot-stereograms, on each trial the CLUTs were subject to random inversion. Thus, for example, in the case of the red–green figural stereogram, the annulus and target might be red and inner surround green on one stimulus presentation, and vice versa on another.

2.2.5. *Disparity-modulated stereograms*

Fig. 1c shows an example stimulus. It consisted of 1000 Gaussian blob micropatterns, each positioned randomly within the 10.7 × 10.7° extent of the stimulus. The disparity of each micropattern was chosen to produce a sinusoidal modulation of disparity with a spatial frequency of 0.075 cpd, which produced about one cycle of disparity modulation. The orientation of the disparity grating was either at −45° (left oblique) or +45° (right oblique). The phase of disparity modulation was always randomised. The pixel intensity profile of each micropattern was defined as:

$$s(r, \sigma) = 127 \pm 127 * \exp(-r^2/2\sigma^2)$$

where r is radial distance, σ is the space constant at 0.15°, and the ± symbol indicating that two types of Gaussian micropatterns, an increment and a decrement, were generated in video memory. When the two types of micropattern were displayed, half were red and half green in the case of the red–green stimulus, half bright yellow and half dark yellow in the case of the yellow–black stimulus.

Because the disparities of the Gaussian micropatterns varied continuously over a narrow range, it was necessary to define their positions in the two stereo-half-pairs with sub-pixel accuracy, as follows. Template micropatterns were first generated off-screen in video memory. Each template was computed by discretely sampling a two-dimensional Gaussian function whose position could be varied smoothly over a continuum of spatial positions. The centre of the Gaussian in each template was offset from the centre of the template with sub-pixel precision by an amount which determined its disparity. For each disparity, two templates were produced, one for each stereo-half, with the two Gaussians offset from the template centre by $\pm$ half the disparity. Thus the number of templates was equal to twice the number of disparities. When the position of a micropattern on the display had been randomly selected and its required disparity computed, the appropriate template pair was selected and copied into position in the two stereo-half-pairs. When the Gaussians fell on top of each other, their amplitudes but not DC levels were added.

2.3. Stereo presentation

The two stereo-halves of each stimulus were presented on either side of the monitor screen separated by 55 arc min. They were combined optically by a modified 8-mirror Wheatstone stereoscope. All mirrors were cemented into position except for the two front mirrors whose position along the line of sight of the subject could be adjusted until fusion was accomplished.

2.4. Procedure

Contrast thresholds for performing all tasks were measured using a 2-IFC (two interval forced-choice) procedure. Before each session the subject was required to adapt to a blank yellow screen at the appropriate $R/(R+G)$ ratio for 1 min. On each trial two stimuli were presented which differed along a particular dimension (e.g. front vs. back for the depth task, left oblique vs. right oblique for the orientation task) and the subject was required to detect the interval with the requisite feature. In pooling data for both crossed and uncrossed disparities, we assume that these are being detected with roughly equally efficiency. For the detection task, one of the intervals contained a blank, and the subject had to choose the interval with the stimulus. A tone accompanied each stimulus presentation (including the blank intervals) to indicate the presence of the stimuli. A different tone indicated an incorrect decision. Stimulus exposure duration was 500 ms with abrupt onset and offset. A standard two-up, one-down staircase procedure was employed (Levitt, 1971) to obtain the contrast threshold. This procedure gives the threshold for the 70.7% correct performance level. The staircase was terminated after twelve reversals and the contrast threshold calculated as the geometric mean contrast over the previous ten reversals. At least three thresholds were measured for each condition, and unless otherwise stated the data points shown in the figures give the geometric means and geometric standard errors of these measurements.

3. Experiments and results

3.1. Experiment 1: depth discrimination for random-dot and figural stereograms

In this experiment we compared the ability of subjects to perform a front versus back depth discrimination task for both random-dot and figural stereograms, at a disparity of 15 arc min for SR and FK, and 30 arc min for AW. We first obtained the approximate isoluminant point by requiring subjects to adjust the $R/(R+G)$ ratio of a random-dot-stereogram with an r.m.s. contrast of 8.33%, until the perception of depth was minimised. This procedure also enabled us to check whether the dramatic loss of stereoscopic depth perception noted in traditional demonstrations was also found for our stimuli. For our random-dot-stereograms, the sharply defined target seen when the random-dot-stereogram was defined with a high or low $R/(R+G)$ value disappeared at an $R/(R+G)$ around 0.5 for all subjects. The mean of ten settings was calculated using this procedure, and this was used to determine the particular set of $R/(R+G)$ values employed in the experiments, with the majority of values chosen close to isoluminance. We then measured both contrast thresholds for depth discrimination (front vs. back) and contrast thresholds for simple detection[2], for both figural and random-dot stereograms at a range of $R/(R+G)$ values. The $R/(R+G)$ values producing the highest contrast thresholds for depth discrimination were, for the figural and random-dot stereograms respectively: SR, 0.5 and 0.48; FK, 0.48 and 0.49; AW, 0.49 and 0.49. These were taken to be the isoluminant

---

[2] Note that detection thresholds used were those for binocular detection, rather than simultaneous monocular detection (SMD) as used in our previous studies of stereopsis at isoluminance (Simmons & Kingdom, 1994, 1995, 1997; Kingdom & Simmons, 1996). This change was justified because the detection thresholds were being used for normalisation only and not for a comparison of contrast thresholds for detection and stereopsis. Any resulting differences between normalised isochromatic and isoluminant contrast thresholds for stereopsis would be due to differences in binocular summation between the two stimulus classes. According to Simmons and Kingdom (1998) these differences should amount to no more than a factor of $\sqrt{2}$ and very probably less than that.

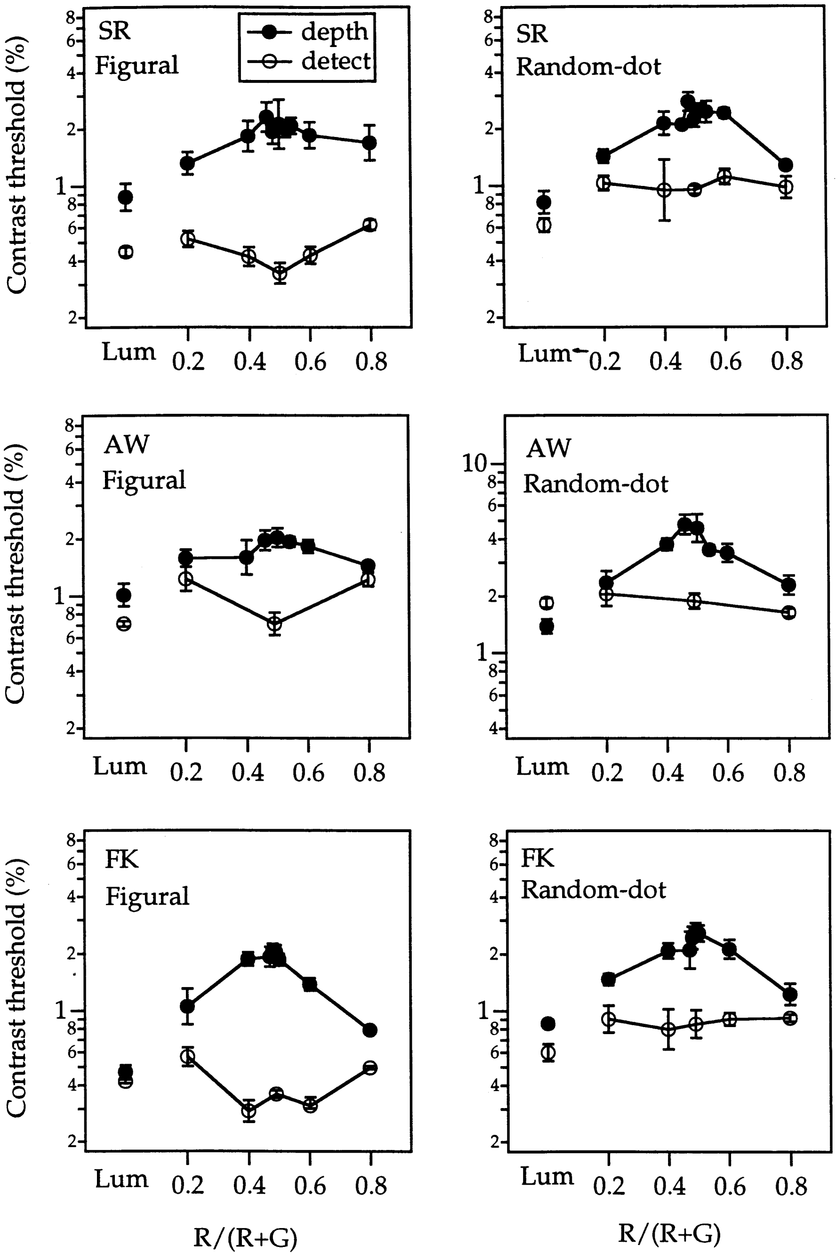

Fig. 3. Contrast thresholds for depth discrimination (●) and detection (○) of both figural (left) and random-dot (right) stereograms, as a function of $R/(R+G)$. Contrast thresholds for the isochromatic stereograms are presented as single data points on the left of each graph and labelled as Lum on the abscissa.

$R/(R+G)$ values. Finally we measured contrast thresholds for both depth discrimination and detection for isochromatic yellow–black stereograms at an $R/(R+G)$ value of 0.5.

The data for this first experiment are shown in Fig. 3. Each graph shows contrast thresholds for both depth discrimination (●) and detection (○) for red–green stereograms as a function of $R/(R+G)$. Data for the isochromatic yellow–black stimuli are shown as isolated points on the left side of each graph. As Fig. 3 shows, depth discrimination thresholds for both figural and random-dot red–green stereograms are highest around an $R/(R+G)$ value of about 0.5.

In order to directly compare the isoluminant and isochromatic conditions, depth discrimination contrast thresholds for these conditions were normalised by dividing them by their detection thresholds at the isoluminant $R/(R+G)$ value. The results are shown in Fig. 4. For both figural and random-dot stereograms, detection-normalised contrast thresholds are higher for the isoluminant compared to isochromatic conditions. However, of primary interest here is the comparison between the figural and random-dot stereogram data. The detection-normalised ratios of isoluminant to

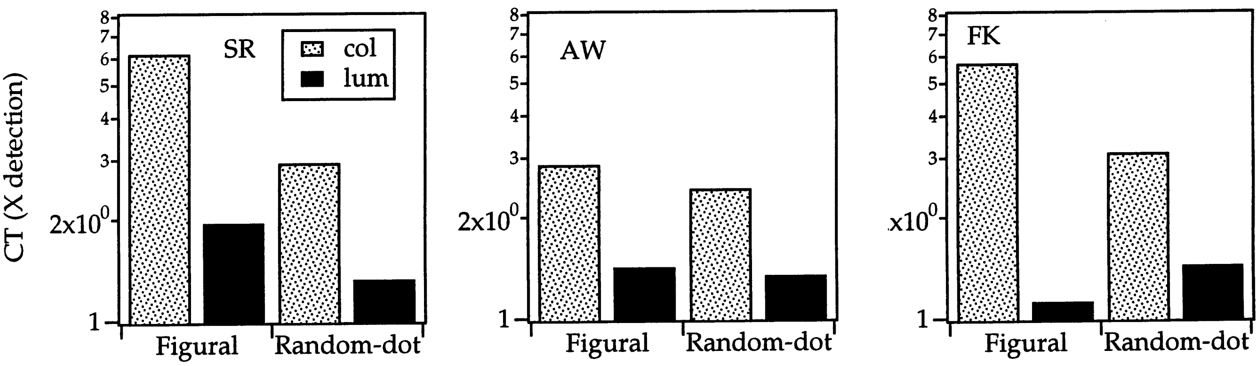

Fig. 4. Comparison of the isoluminant (col) and isochromatic (lum) conditions from Fig. 3. Depth discrimination contrast thresholds for the isoluminant conditions were obtained by fitting Gaussian functions to the plots in Fig. 3 and estimating the peak. Both the isoluminant and isochromatic thresholds were normalised by dividing by their respective detection thresholds.

isochromatic thresholds are, for the figural and random-dot stereograms, respectively: SR, 3.2 and 2.2; AW, 2.0 and 1.8; FK, 5.1 and 2.2. In other words, for these stimuli, contrast thresholds for depth discrimination with isoluminant random-dot-stereograms were no higher than with isoluminant figural stereograms (in fact they were slightly lower), when compared to performance with isochromatic stimuli. To determine whether this was a general finding, we measured depth discrimination thresholds at a number of disparities for two subjects, FK and AW. The results are shown in Fig. 5. As the figure shows, the size of the gap between the detection-normalised isoluminant and isochromatic thresholds is similar for the figural and random-dot stimuli at all disparities. Averaged across disparity, the detection-normalised ratios of isoluminant to isochromatic thresholds are, for the figural and random-dot stereograms, respectively: AW, 1.76 and 1.72; FK, 3.2 and 2.52.

3.2. Experiment 2: depth versus form discrimination in random-dot-stereograms

In this experiment we consider whether depth and form judgements in random-dot-stereograms show a similar pattern of performance depending on whether the random-dot-stereograms are isoluminant or isochromatic. This experiment is only relevant for random-dot-stereograms, because the forms of targets in figural stereograms are, by definition, visible monocularly and therefore cannot be used to test stereo-form processing (though we do use a figural stereogram in this experiment as a control for form processing per se, as described below). In order to make a valid comparison between depth and form judgements in our random-dot-stereograms, we used the same stimulus set for both. The random-dot stimulus was identical to that employed in the previous experiment, except that the target was now a rectangle rather than a square. The rectangle had a 2:1 aspect ratio, with its longer side the same length of the square used in the previous experiment. It could appear in one of two orientations, horizontal or vertical. If horizontal it could appear immediately above or immediately below the mid-point of the stereogram. If vertical, it could appear immediately to the left, or immediately to the right of the mid-point. The target could also be in crossed (front) or uncrossed (back) disparity. In the *depth* discrimination task, the subject's task was to decide in which interval the target appeared in front. For this task both the position and orientation of the rectangle were randomised on each stimulus presentation. In the *form* discrimination task, the subject had to identify the interval in which the target was horizontal, and for this task both the position and disparity of the target were randomised on each stimulus presentation. The reason for having the two alternative positions of the target was to eliminate the possibility of subjects identifying the form of the target by noting whether or not a single point within the notional square region containing the rectangular targets was in stereo-depth[3].

Performance as a function of the $R/(R+G)$ value is shown in Fig. 6. Detection thresholds for the square-target random-dot-stereograms obtained in the first experiment are also shown, assuming they would be no different for the rectangular-target stimuli employed here. As the figure shows, while form discrimination thresholds are invariably higher than depth discrimination thresholds, they appear to be especially so around

---

[3] Note that simply randomising the position of the rectangle within the square region would not be sufficient to eliminate this single-point depth cue. If the position of the rectangular targets were simply randomised, a subject would perform above chance if he/she adopted the strategy that a point perceived in depth, say, a quarter of the way along the top edge of the square indicated a vertical rectangle, whereas the absence of such a point in depth indicated a horizontal rectangle. However, for the situation used here in which the rectangular targets were constrained to be in one of the four positions as described above, such a strategy would result in only chance performance.

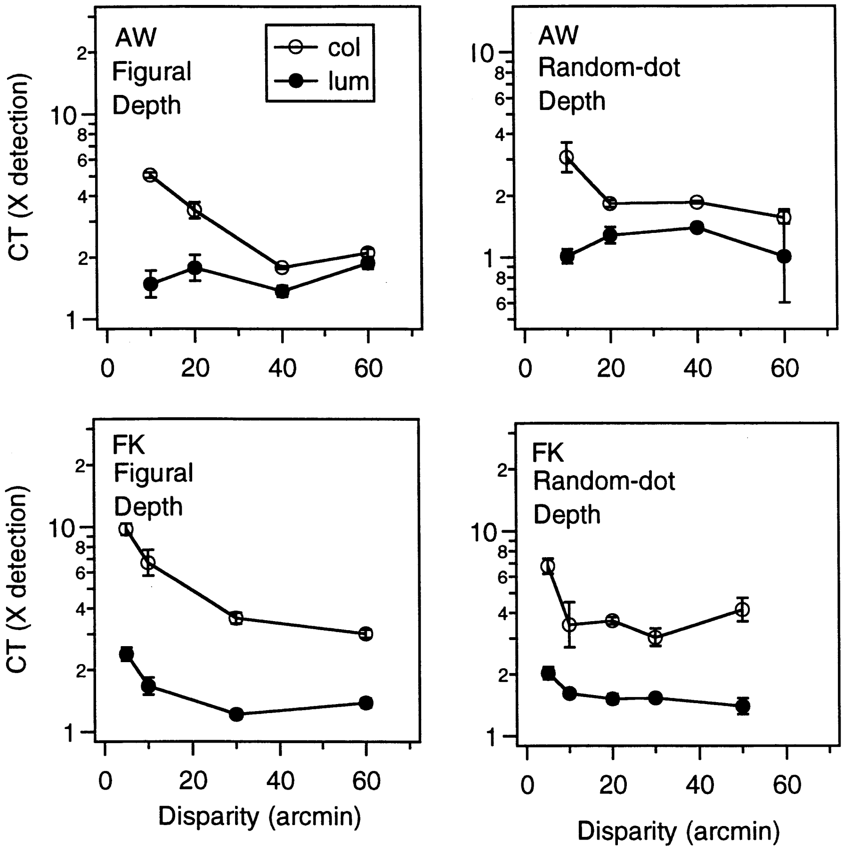

Fig. 5. Contrast thresholds for depth discrimination as a function of disparity for figural (left) and random-dot (right) stereograms. Data for both isoluminant (col) and isochromatic (lum) are shown. All thresholds are normalised to dectection.

isoluminance. Fig. 7 shows the isoluminant and isochromatic data. For the random-dot-stereogram data in Fig. 7, the ratio of the detection-normalised isoluminant to isochromatic thresholds are for the depth and form tasks, respectively: SR, 1.79 and 5.51; AW, 4.6 and 7.0; FK, 2.45 and 7.81. There would thus appear to be an interaction between the type of task (depth or form) and the stimulus dimension (colour or luminance), and we refer to this as the dimension-by-task interaction. On the right of each histogram in Fig. 7 are the results from a control experiment in which subjects were required to judge the form (horizontal or vertical) of a rectangular target version of the figural stereogram shown in Fig. 1b. This was a simple control to eliminate a highly unlikely, but nevertheless conceivable, cause of the apparent deficit in stereo-from processing in our isoluminant random-dot-stereograms. In this control experiment the orientation of the rectangle was visible monocularly as well as binocularly, and thus tested for a deficit at isoluminance in form processing per se, as opposed to stereoscopic (i.e. cyclopean) form processing. As Fig. 7 shows, performance for this control is slightly better for the isoluminant compared with isochromatic stimuli, thus eliminating the simple form explanation.

Fig. 8 shows that the dimension-by-task interaction generalises to other disparities for all three subjects. Detection-normalised thresholds for the depth task (left hand plots) are slightly higher with the rectangular-target compared to the square-target random-dot-stereograms used previously (right hand plots in Fig. 5), and this is likely due to the positional uncertainty of the rectangular targets. Between about 10 and 50 arc min, the ratio of detection-normalised isoluminant to isochromatic thresholds is greater for the form (right hand plots) than depth (left hand plots) task in all subjects. Outside this disparity range the dimension-by-task interaction is not evident, and this is most likely due to performance being close to, or at, D_{min} and D_{max}. It is not clear why the interaction should disappear as performance approaches D_{min} for the chromatic stimuli (evidenced by the relatively high detection-normalised thresholds for the 10 arc min isoluminant condition for SR and FK, and the inability to obtain any threshold at isoluminance for AW at this disparity). As performance approaches D_{max} the lack of a dimension-by-task interaction is best explained by noting the subjective reports of all three subjects. At 60 arc min for SR and FK, and above 40 arc min for AW, the subjects reported identifying the target in the form task

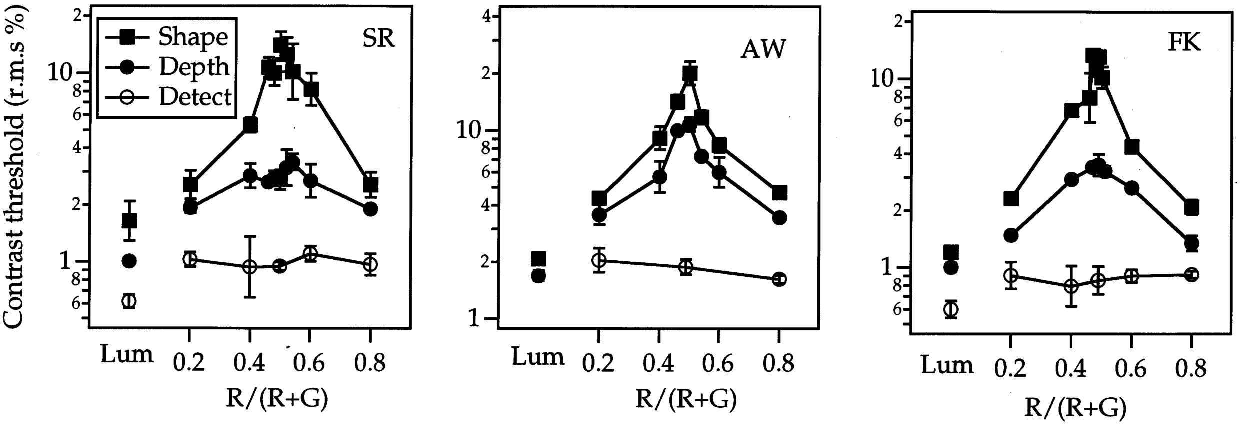

Fig. 6. Stereo-form, stereo-depth and detection thresholds for random-dot-stereograms with rectangular targets, as a function of the $R/(R+G)$ ratio. Thresholds for the isochromatic stimuli are presented as single data points on the left of each graph and labelled Lum on the abscissa.

in terms of the orientation of the unfused region in the middle of the stimulus. To obtain a quantitative estimate of the dimension-by-task interaction for this set of data we consider just the data that lies within the disparity range which appears to be the optimal disparity range for all three subjects, namely 20–40 arc min. Averaged across disparity the ratios of the detection-normalised isoluminant to isochromatic contrast thresholds are, for the depth and form tasks, respectively: SR, 1.6 and 3.4; AW, 2.3 and 6.6; FK, 3.3 and 8.5.

These results point to a selective deficit in the processing of stereoscopic form in isoluminant random-dot-stereograms. Why might this be? Two reasons suggest themselves. First is the relative insensitivity of the chromatic system to high spatial frequencies (Granger & Hurtley, 1973; Mullen, 1985). The detection of the relatively sharp changes in disparity at the edges of the rectangular target may well be important for determining its form, and this probably involves stereopsis mechanisms tuned to relatively high spatial frequencies (Smallman & MacLeod, 1994). Chromatic insensitivity to high spatial frequencies may be reflected in the absence of such mechanisms. We will refer to this as the spatial frequency explanation. Second, the visual system might encounter difficulty in interpolating local chromatic depth information in order to generate a stereo-defined surface. We will refer to this as the surface interpolation explanation. The remaining experiments aim to test between these two explanations.

3.3. Experiment 3: effect of Gaussian blur

To test for the spatial frequency explanation, we compared depth and form contrast thresholds for random-dot-stereograms filtered by Gaussian kernels with three space constants: the standard $\sigma = 0.15°$, and additionally $\sigma = 0.3$ and 0.6° (see Fig. 2). If the deficiency of the chromatic system for encoding stereoscopic form were due to its relative insensitivity to high spatial frequencies, then we should be able to simulate the effect in the isochromatic stimuli by simply removing high spatial frequencies. We would therefore expect an increase in the ratio of form/depth discrimination thresholds with isochromatic stimuli as σ increases. On the other hand we would not expect such an increase for the isoluminant stimuli, because the high spatial frequencies removed by filtering are already attenuated by the visual system. We tested both these predictions. Target disparities were set at 15, 30 and 60 arc min, respectively for the $\sigma = 0.15$, 0.3 and 0.6° filters, as a best estimate method of taking into account the known size-disparity relationship in stereopsis (Smallman & MacLeod, 1994). The results are shown in Fig. 9. For the isochromatic stimuli, there is a slight increase in the form/depth ratio as σ increases, which gives some support to the spatial frequency hypothesis. However, in SR and FK's data there is also an increase in the form/depth ratio in the isoluminant condition as σ increases, which we argued earlier we would not expect. For AW, stereo-form thresholds could only be obtained for the $\sigma = 0.3$ condition within the limits of monitor contrast. The results of this experiment therefore are somewhat equivocal. While they do not rule out a contribution of spatial frequency to the chromatic deficit in stereoscopic form discrimination, they also suggest that this is unlikely to be the sole explanation for the findings. The results of this experiment also confirm that the dimension-by-task interaction previously observed for the $\sigma = 0.15°$ filter condition is maintained at higher filter space constants. The gap between the detection-normalised form and depth thresholds is significantly larger for the isoluminant compared to isochromatic data for all subjects. Subject AW in particular was unable to perform the form task at isoluminance (within the monitor contrast limits)

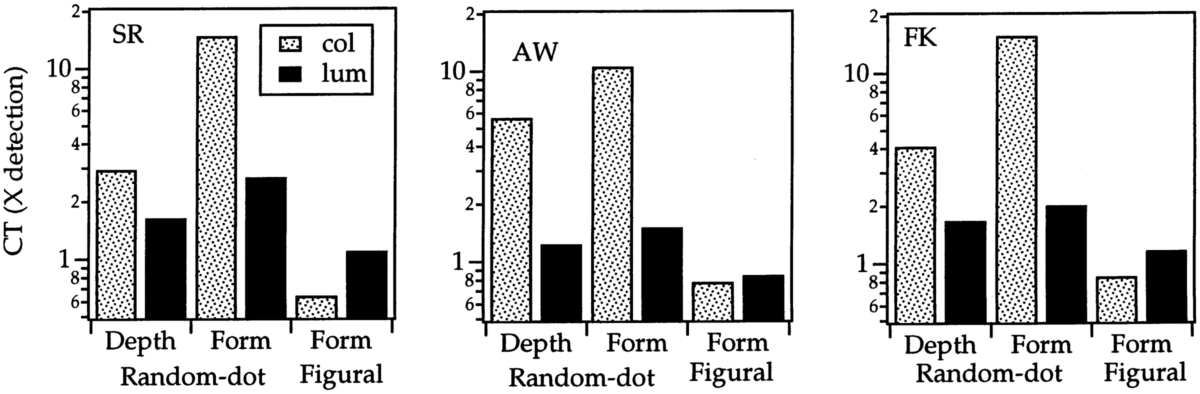

Fig. 7. Comparison of isoluminant (col) and isochromatic (lum) thresholds from Fig. 6. All thresholds have been normalised to detection. On the right of each graph are shown normalised thresholds for performing a form judgement with a figural stereogram containing a rectangular target.

except with the $\sigma = 30$ arc min condition, even though she was easily able to perform the depth task at isoluminance at all σ values, as well as both depth and form tasks with the isochromatic stimuli.

3.4. Experiment 4: modulation detection and orientation discrimination in disparity modulated random-dot-stereograms

To test more directly for the surface interpolation explanation of the dimension–by–task interaction we measured performance with the disparity modulated stereogram illustrated in Fig. 1c. Each stereogram was constructed from Gaussian blob micropatterns positioned randomly with the stimulus, each given a disparity appropriate for producing a sinusoidally modulated surface oriented left or right oblique (see Section 2 for more details). Subjects must presumably interpolate local disparity information in order to detect the presence and form of the corrugations in this stimulus, and this was ensured by randomising the phase of disparity modulation for each stimulus presentation. If the visual system had a special deficit in deriving a surface representation from chromatic disparity information, we should expect particular difficulties with these stimuli. Moreover, because the spatial frequency of disparity modulation was relatively low at 0.075 cpd, no sharp-edge disparity information was present, and therefore the task was less likely to be subject to the confounding effects of chromatic/luminance contrast spatial frequency tested in the previous experiment[4]. The test stereograms had an amplitude of disparity modulation of 15 arc min, i.e. a peak-to-trough difference of 30 arc min, a value chosen to lie approximately at the optimum disparity revealed by the data presented in Fig. 8. We used oblique orientations of disparity modulation because of the known difference in sensitivity to horizontal and vertical disparity modulations (Rogers & Graham, 1983). Contrast thresholds for three tasks were measured. In the first, modulation-detection task, the subject had to decide in which interval the stereogram possessed disparity modulation, the comparison interval containing an unmodulated stereogram. In the second, orientation-discrimination task, the subject had to decide in which interval the orientation of the stereogram was left oblique, the comparison interval containing a right oblique stereogram. Finally we measured contrast thresholds for detecting the stimuli. The modulation-detection and orientation-discrimination tasks should not be thought of as necessarily congruent with the depth and form tasks used earlier with the rectangular-target random-dot-stereograms. We used two types of task to test for the generality of any measured differences between the isoluminant and isochromatic disparity-modulated random-dot-stereograms.

The results are shown in Fig. 10. The figure shows a large ratio of detection-normalised isoluminant to isochromatic contrast thresholds for both SR and FK. For AW we were unable to obtain contrast thresholds for either the modulation-detection or orientation-discrimination stimuli at isoluminance within the limits of the monitor, even after repeated trials using a range of different disparities and disparity modulation spatial frequencies. AW simply could not see any depth corrugations in the isoluminant stimuli under any conditions. For the two subjects who were able to obtain thresholds in the isoluminant condition, the (geometric) mean ratio of the detection-normalised isoluminant to isochromatic thresholds was 6.7 for the modulation-detection and 7.4 for the orientation-discrimination task. As with the ratios for the form task using rectangular-target random-dot-stereograms, these ratios are much higher than for discriminating depth in either the square-target or rectangular-target random-dot-stereograms. These results therefore reinforce the idea that subjects are specifically impaired at interpolating

---

[4] Assuming, of course, that the size-disparity correlation hypothesis is correct (Smallman & MacLeod, 1994).

local disparity information in order to generate a stereoscopically defined surface at isoluminance. In the case of isoluminant disparity-modulated stimuli, this impairment results in particular difficulty in both detecting the stimulus corrugations as well as identifying their orientation.

4. Discussion

This study has produced two main findings. First, more contrast relative to detection is required to judge the depth (front vs. back) of targets in isoluminant random-dot-stereograms compared to isochromatic random-dot-stereograms, but the difference in contrast requirements is no greater than is found with figural stereograms. Second, the difference in contrast requirements between isoluminant and isochromatic random-dot-stereograms is greater when the judgement is about stereoscopic form than when it is about stereoscopic depth. It would appear that when the visual system is required to interpolate local disparity information to provide stereoscopic form information, colour vision is especially deficient. In terms of the classic demonstration by Lu and Fender (1972) showing the apparent collapse of stereopsis at isoluminance in random-dot-

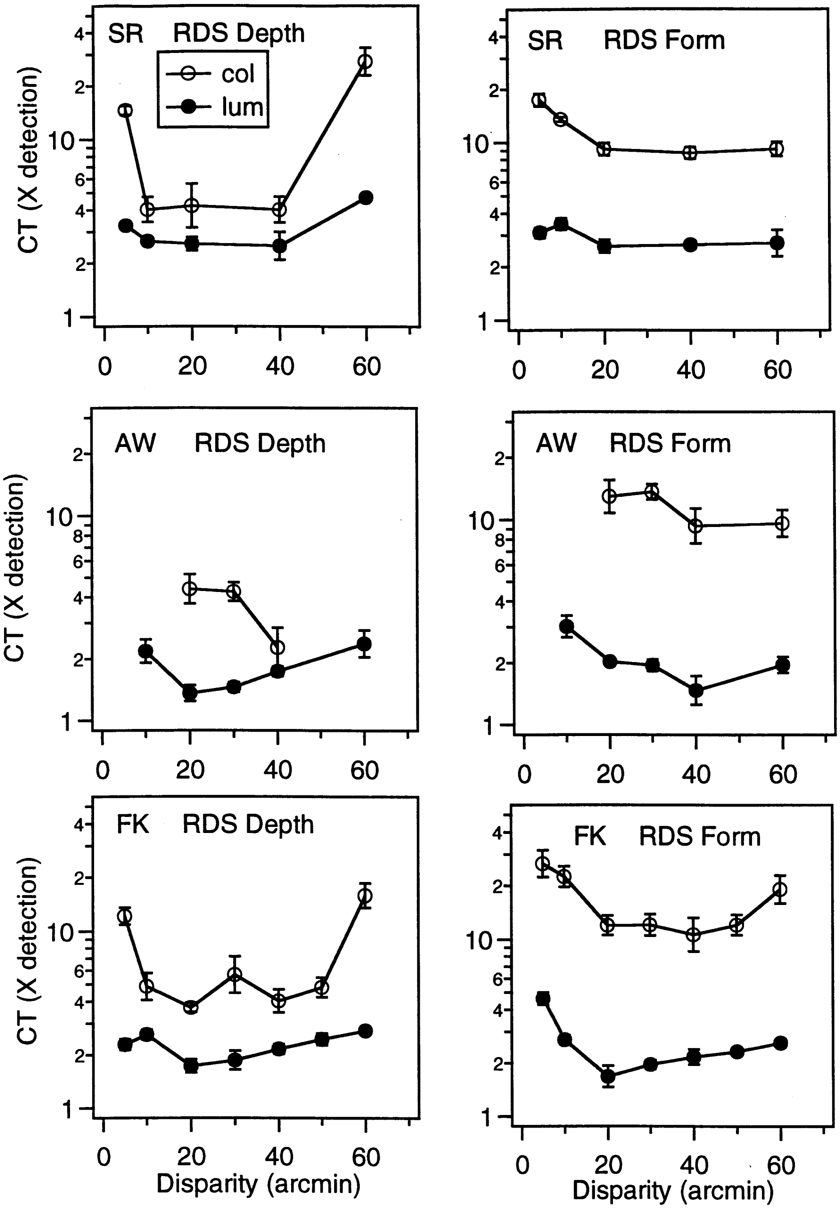

Fig. 8. Stereo-form and stereo-depth thresholds as a function of disparity, for both isoluminant (col) and isochromatic (lum) random-dot-stereograms. All thresholds have been normalised to detection. The missing data points in AW's isoluminant data are conditions where it was impossible to obtain thresholds within the contrast range of the monitor.

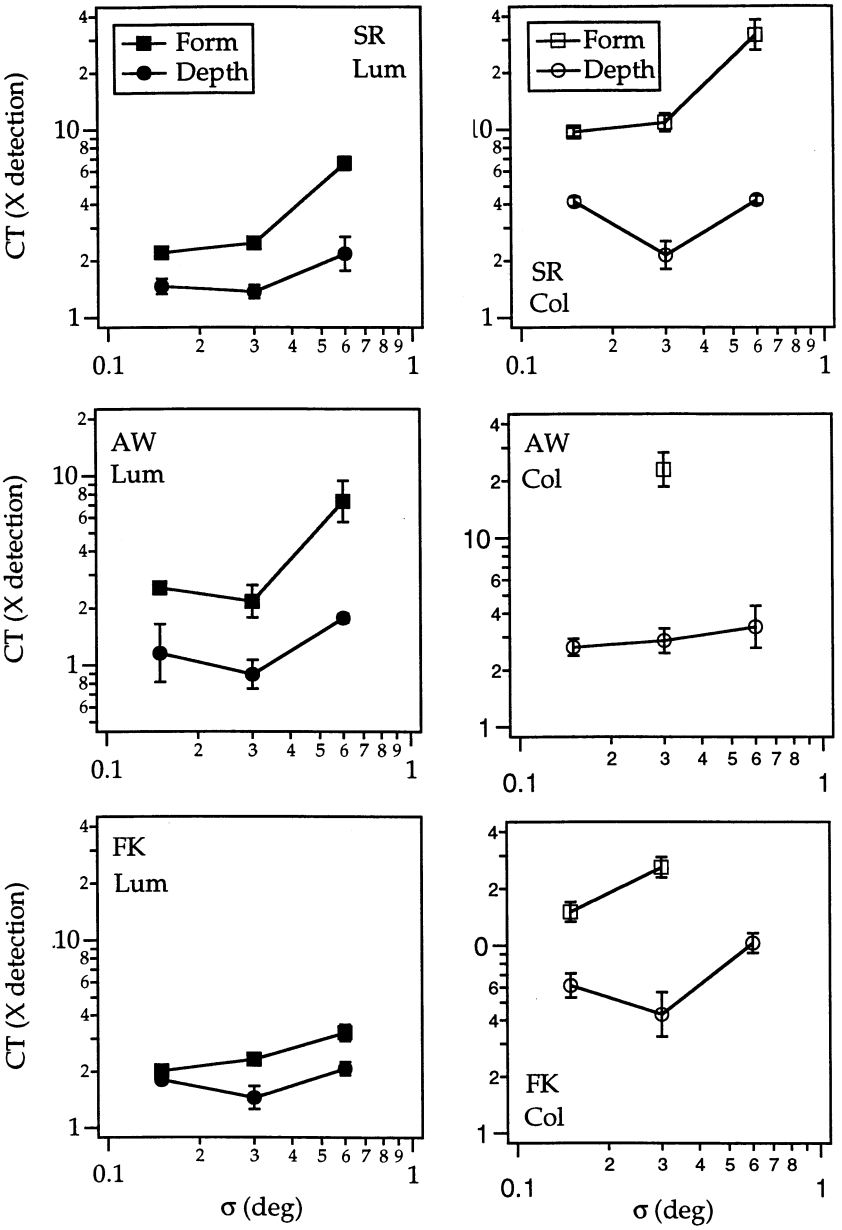

Fig. 9. Stereo-form (■) and stereo-depth (●) contrast thresholds as a function of Gaussian blur σ, for both isochromatic (● and ■) and isoluminant (○ and ■) random-dot-stereograms. The disparity of the stimuli also covaried with σ, respectively 15, 30 and 60 arc min for σ's of 0.15, 3.0 and 6.0°. Thresholds are normalised to detection. Missing data points in AW's and FK's isoluminant data are conditions where it was impossible to obtain thresholds within the contrast range of the monitor.

stereograms, our results suggest that this effect is primarily due to a deficit in processing stereoscopic form, rather than stereoscopic depth. Moreover, our results with disparity-modulated random-dot-stereograms suggest that this deficit is due to an inability to interpolate local disparity information to produce stereoscopic surfaces.

4.1. Depth discrimination in figural and random-dot-stereograms

Our choice of figural stereogram was admittedly arbitrary. For the stimuli we chose, the ratio of isoluminant to isochromatic detection-normalised depth-discrimination thresholds ranged between 1.8 and 5.1 with an average of about 2.8. If one compares these results with our random-dot-stereograms, which yielded ratios ranging from 1.8 to 2.5 with an average of 2.1, it is clear that stereoscopic depth judgements using isoluminant random-dot-stereograms are not especially impaired when compared with figural stereograms. If we restrict ourselves to depth discrimination therefore, we are in accord with de Weert and Sazda's (1983) conclusion that there is no fundamental difference between random-dot and figural stereograms at isoluminance. The small superiority in the detection-normalised isoluminant to isochromatic ratios for the random-dot compared to figural stereograms most likely reflects the different spatial frequency composition of the two classes of stimuli. The figural stereograms contain relatively more power in the low spatial frequencies compared to the random-dot stimuli, and because the chromatic CSF is low-pass (Granger & Hurtley, 1973; Mullen, 1985) we would expect the isoluminant figural strimuli to have lower contrast detection thresholds (see Fig. 3). This has the effect of driving up the gap between detection and depth discrimination in the isoluminant figural, but not random-dot stereograms.

4.2. A chromatic deficit in the processing of stereo-form

Our results suggest a specific impairment in stereoscopic form tasks using isoluminant random-dot-stereograms. One can legitimately argue that flat-plane random-dot-stereograms are not however the best stimuli to reveal this deficit. In principle it was possible for our subjects to solve the rectangular-target form task by noting the depth of just two points within the central square region of the stimulus, thus requiring only a minimal amount of spatial interpolation. Our motivation however was to examine stereoscopic form processing using stimuli similar to those of previous investigators who showed a particularly compelling loss of depth in isoluminant random-dot-stereograms (Lu & Fender, 1972; Gregory, 1977; de Weert, 1979; Livingstone & Hubel, 1987; Livingstone, 1996). We found that with the rectangular target random-dot-stereograms, the ratio of (detection-normalised) isoluminant to isochromatic thresholds was higher for the form than the depth task across a range of disparities and degrees of stimulus blurring, and for all three subjects tested. This is consistent with the idea that subjects solved the form task by extracting a global form property of the stimulus, and that this task proved particularly difficult at isoluminance.

Why a specific impairment in stereoscopic form perception at isoluminance? The effect of blurring the rectangular-target random-dot-stereograms demonstrated that the relative insensitivity of the chromatic system to high spatial frequencies may have been a contributing factor, though unlikely to account for all the impairment. However, the results with the disparity-modulated random-dot-stereograms unequivocally point to a special difficulty for colour vision in interpolating local disparity information to generate a stereoscopically-defined surface. In particular our naive subject AW, who was able to perform nearly all other tasks, found it impossible to detect the corrugations in the disparity-modulated random-dot-stereograms at isoluminance within the limitations imposed by the equipment. Our suggestion of a specific impairment of colour vision in interpolating local disparity information also accords with the observation that in the flat-plane random-dot-stereograms, it is the *surface* of the target which appears to disappear at isoluminance.

Is there any hint of this special stereoscopic form deficit in previous studies? In de Weert and Sazda's (1983) study, the form task involved subjects identifying the position of a quadrant missing from the target square. Performance dropped from 85 to about 60% when going from 20% luminance contrast to isoluminance. On the other hand with the depth task, in which the depth of a central square (front vs. back) had to be identified, performance dropped from 100 to about 90%. Unfortunately it is difficult to draw any firm conclusions from these results, because an apparent difference between the form and depth discrimination task is confounded by the ceiling effect in the depth discrimination data. Nevertheless de Weert and Sazda's (1983) results are not inconsistent with ours. We will shortly examine why colour vision might be especially deficient in generating stereoscopic surfaces, but first we consider two other possible explanations for the results.

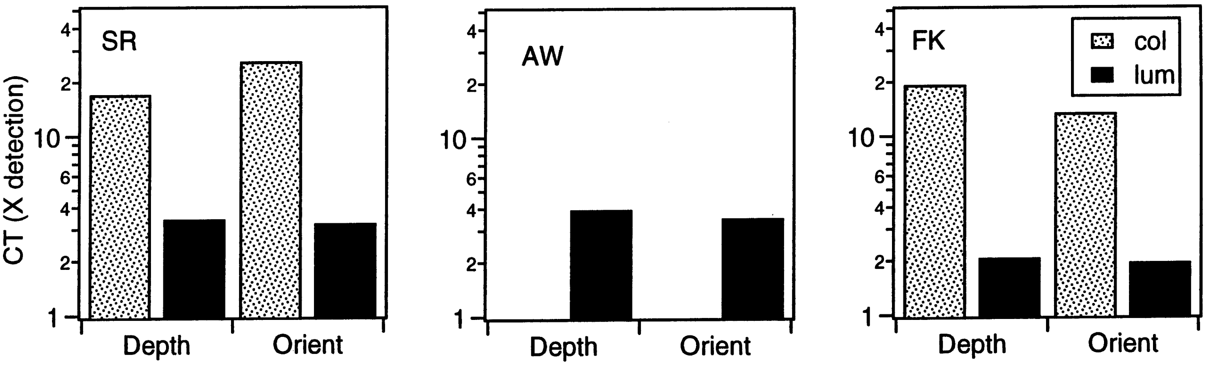

Fig. 10. Detection-normalised contrast thresholds for detecting the modulation (depth) and orientation (orient) of the disparity-modulated random-dot stereogram illustrated in Fig. 1c. AW's isoluminant data is missing because she was unable to obtain any thresholds within the contrast range of the monitor for these conditions.

4.3. Chromatic aberration

Could chromatic aberration account for our findings? We minimised the potential confounding effects of chromatic aberration by removing all spatial frequencies above about 3.0 cpd from our stimuli (see Section 2). The main experimental evidence which argues against chromatic aberration for our findings is that if our ostensibly isoluminant stimuli were acting as low-contrast luminance stimuli we would not expect the dimension–by–task interactions we observed in Experiment 2, which employed identical stimuli for both depth and form tasks. We would instead expect the relative performance of the form and depth tasks to be the same for both isoluminant and isochromatic stimuli. For this reason we find it difficult to see how chromatic aberration could account for our results.

4.4. Absence of a 2nd-order mechanism

In the introduction we suggested that poor stereopsis in isoluminant random-dot-stereograms might be due to an absence of a second-order chromatic stereopsis mechanism (Kingdom & Simmons, 1996; Simmons & Kingdom, 1995). However the results of this study suggest otherwise. An absence of a second-order mechanism would be expected to produce a special deficit in *depth* discrimination in isoluminant random-dot-stereograms, yet we showed that depth judgements were no worse in isoluminant random-dot compared to figural stereograms. Moreover, recent studies using luminance-defined disparity-modulated stimuli have shown that second-order stereopsis mechanisms are not involved in generating stereoscopic surfaces (Ziegler & Hess, 1998), whereas first-order mechanisms (i.e. those sensitive to local luminance contrasts) appear to be critical (Hess, Kingdom & Ziegler, 1997; Kingdom, Ziegler & Hess, 1997). We conclude therefore that an absence of a 2nd-order chromatic stereopsis mechanism is unlikely to be the reason for specific impairment we have observed in stereoscopic form processing at isoluminance.

4.5. Positional uncertainty or a sparseness of neurones?

We now consider two possible physiological reasons for the impairment in stereoscopic form processing at isoluminance. The first is that chromatic stereopsis mechanisms are noisier than their luminance counterparts, providing less precise information about the position of targets in depth. The second is that a smaller proportion of the neurones which detect contrasts are sensitive to disparity in the chromatic compared to the luminance pathways. Both possibilities could give rise to the two main findings with isoluminant stereograms, namely the greater contrast requirements of chromatic stereopsis and the particular difficulties in generating a stereoscopic surface. The generation of stereoscopic surfaces may involve cooperative processes operating between neighbouring disparity-tuned neurones (Nelson, 1975; Marr & Poggio, 1976; Mayhew & Frisby, 1980), and these in turn might require a neurophysiological substrate of densely packed disparity tuned neurones operating with relatively high precision.

If sparseness in chromatic stereopsis mechanisms is the ultimate culprit, then this could originate in a number of ways. Chromatic stereopsis mechanisms could be sparse throughout the visual field. On the other hand they might be concentrated heavily in foveal vision, with their numbers falling off so rapidly with eccentricity that the efficiency of chromatic stereopsis processing falls off even faster than detection (Mullen, 1991; Mullen & Kingdom, 1996). If this were the case, stereoscopic surfaces would be difficult to generate at isoluminance because they would invariably cover regions where chromatic stereopsis mechanisms were virtually absent. However, depth judgements would be relatively unimpaired, as the signals from the foveal chromatic stereopsis mechanisms would be sufficient for the task. Experiments are currently being conducted to determine which, if any, of the above reasons is the cause of the pattern of results found here.

5. Conclusion

We have shown evidence that the apparent collapse of stereopsis in isoluminant random-dot-stereograms results from a specific impairment in the generation of stereoscopically defined surfaces at isoluminance. Whether this is because chromatic stereopsis mechanisms are (a) uncertain in their position-in-depth coding; (b) sparse across the visual field; or (c) present only in central vision, is currently being investigated.

Acknowledgements

This research was supported by a grant from the MRC (Canada), #MT11554, given to FK, and an NSERC (Canada) PGS B Fellowship to SR.

References

Comerford, J. P. (1974). Stereopsis with chromatic contours. *Vision Research*, *14*, 975–982.

Granger, E. M., & Hurtley, J. C. (1973). Visual chromaticity-modulation transfer function. *Journal of the Optical Society of America*, *63*, 1173–1174.

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

Hess, R. F., Kingdom, F. A. A. & Ziegler, L. R. (1997). On the relationship between the spatial channels for luminance and disparity processing. *Vision Research*, (in press).

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

Kingdom, F. A. A., & Simmons, D. R. (1996). Stereoacuity and colour contrast. *Vision Research*, *36*, 1311–1319.

Kingdom, F. A. A., & Whittle, P. (1996). Contrast discrimination at high contrasts reveals the influence of local light adaptation on contrast processing. *Vision Research*, *36*, 817–829.

Kingdom, F. A. A., Ziegler, L. R. & Hess, R. F. (1997). Spatial scale facilitates stereoscopic segmentation. *Vision Research*, (submitted).

Kovács, I., & Fehér, A. (1997). Non-Fourier information in bandpass noise patterns. *Vision Research*, *37*, 1167–1175.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, *49*, 467–477.

Livingstone, M. S. (1996). Differences between stereopsis, interocular correlation, and binocularity. *Vision Research*, *36*, 1127–1140.

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.

Marr, D., & Poggio, T. (1976). Cooperative computation of stereo disparity. *Science*, *194*, 283–287.

Mayhew, J. E. W., & Frisby, J. P. (1980). The computation of binocular edges. *Perception*, *9*, 69–86.

Nelson, J. I. (1975). Globality and stereoscopic fusion in binocular vision. *Journal of Theoretical Biology*, *49*, 1–88.

Mullen, K. T. (1985). The contrast sensitivity of human colour vision to red–green and blue–yellow gratings. *Journal of Physiology*, *359*, 381–409.

Mullen, K. T. (1991). Color vision as a post-receptoral specialization of the central visual field. *Vision Research*, *31*, 119–130.

Mullen, K. T., & Kingdom, F. A. A. (1996). Losses in peripheral colour sensitivity predicted from hit and miss post-receptoral connections. *Vision Research*, *36*, 1995–2000.

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

Rogers, B. J., & Howard, I. P. (1995). *Binocular vision and stereopsis*. New York: Oxford University.

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., & Kingdom, F. A. A. (1994). Contrast thresholds for stereoscopic depth discrimination 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.

Simmons, D. T., & Kingdom, F. A. A. (1997). On the independence of chromatic and achromatic stereopsis mechanisms. *Vision Research*, *37*, 1271–1280.

Simmons, D. T., & Kingdom, F. A. A. (1998). On the binocular summation of chromatic contrast. *Vision Research*, *38*, 1063–1071.

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.

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

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

Wilcox, L. M., & Hess, R. F. (1996). Is the site of non-linear filtering in stereopsis before or after binocular combination? *Vision Research*, *36*, 391–399.

Ziegler, L. R. & Hess, R. F. (1998). Stereoscopic depth but not shape from second-order stimuli. *Vision Research* (in press).