Reversals of the Colour–Depth Illusion Explained by Ocular Chromatic Aberration

BARRY WINN,* ARTHUR BRADLEY,† NIALL C. STRANG,‡ PAUL V. MCGRAW,‡ LARRY N. THIBOS†

Although many colour–depth phenomena are predictable from the interocular difference in monocular chromatic diplopia caused by the eye's transverse chromatic aberration (TCA), several reports in the literature suggest that other factors may also be involved. To test the adequacy of the optical model under a variety of conditions, we have determined experimentally the effects of background colour on perceived monocular chromatic diplopia and perceived depth (chromostereopsis). A Macintosh colour monitor was used to present red, blue, and green test stimuli which were viewed monocularly or binocularly (haploscopically) through 1.78 mm artificial pupils. These apertures were displaced nasally and temporally from the visual axis under controlled conditions to induce a variable degree of TCA. Monocular chromatic diplopia and binocular chromostereopsis were measured for red and blue targets, and also for red and green targets, presented on either a black background or on a background which was composed of the sum of the targets' spectral composition (e.g. red and blue presented on magenta; red and green presented on yellow). In all cases, chromatic diplopia and chromostereopsis were found experimentally to reverse in sign with this change in background. Furthermore, we found that a given coloured target could be located in different depth planes within the same display when located on different background colours. These seemingly paradoxical results could nevertheless be explained by a simple model of optical TCA without the need to postulate additional factors or mechanisms.

Chromostereopsis   Monocular chromatic diplopia   Horizontal disparity   Transverse chromatic aberration
Wavelength   Stereopsis

INTRODUCTION

Chromostereopsis is the perception of relative depth between equidistant objects of different colour when viewed binocularly. With natural pupils, most observers see red targets nearer than blue or green (Hartridge, 1918; Kishto, 1965; Sundet, 1976) but this effect is easily reversed when viewing through artificial pupils. Recent studies have provided quantitative experimental evidence to show that, as originally suggested by Einthoven (1885), interocular differences in foveal transverse chromatic aberration (TCA) provide a robust and accurate means of predicting the magnitude and direction of binocular chromostereopsis (Ye, Bradley, Thibos & Zhang, 1991, 1992). The basis of this prediction is that ocular TCA causes a polychromatic object to have multiple images which are laterally displaced across the retina. In the simpler experimental situation depicted in Fig. 1, TCA causes image doubling for two super-

imposed objects of different wavelengths, a monocular phenomenon called chromatic diplopia. If the amount of chromatic diplopia is different horizontally in the two eyes (i.e. if $\phi_r \neq \phi_l$), then a difference in binocular disparity exists between the colours and the perceptual result is chromostereopsis.

Although Einthoven's optical model for chromostereopsis has been confirmed experimentally (Ye et al., 1991, 1992) for monochromatic targets presented on black backgrounds, it is not obvious that the model can explain colour–depth phenomenon for other target configurations. For example, if TCA is held constant with fixed pupil locations, and target wavelengths are unaltered, one might expect that chromostereopsis should remain constant. However, several empirical studies have shown that colour depth effects can be reversed simply by changing the colour of the background. For example, coloured lines that appear at different depths (e.g. red in front of blue) appear to reverse their depth (blue in front of red) when the background on which they are presented is changed from black to white (Verhoff, 1928; Hartridge, 1947; Dengler & Nitschke, 1993; Thompson & Stone, 1993). Several hypotheses have been presented to explain changes in the colour–depth effect that accompany changes in background colour, e.g. border contrast

*To whom all correspondence should be addressed at: Department of Optometry, University of Bradford, West Yorkshire BD7 1DP, England.
†Department of Visual Sciences, School of Optometry, Indiana University, Bloomington, IN 47405, U.S.A.
‡Department of Vision Sciences, Glasgow Caledonian University, Cowcaddens Road, Glasgow G4 0BA, Scotland.

effects (Dengler & Nitschke, 1993), luminance changes (Thompson & Stone, 1993), cortical mechanisms (Faubert, 1994) and changes in pupil location (Kishto, 1965; Simonet & Campbell, 1990).

In light of a recent challenge to the adequacy of the TCA model to explain the effects of background colour and spatial configuration on chromostereopsis (Faubert, 1994), we have applied Einthoven's optical model to the effect of background changes on the colour reversal phenomena. The model and our experiments confirm that changes in the spectral composition of the background can reverse monocular chromatic diplopia and the colour–depth effect for purely optical reasons.

METHODS

Apparatus

A standard Macintosh colour monitor (24 × 18 cm) was used to present coloured stimuli for both monocular and binocular experiments. Each coloured target consisted of a vertically oriented rectangle ($x = 20$ mm, $y = 60$ mm) of homogeneous spectral composition viewed from a distance of 6.85 m (optical path was folded by a front surface mirror). Red, blue and green targets were generated by exciting a single phosphor and the emission spectra for each of these primary colours were measured with a Photoresearch spectro-radiometer (Photoresearch, Calif.). The coloured targets were presented either on a black background or on a background with spectral composition equal to the sum of the targets being used. That is, red and blue bars were presented on a red plus blue (magenta) background and red and green targets were presented on a red plus green (yellow) background. Spectral radiometric analysis showed typical RGB phosphor characteristics (Bradley, Zhang & Thibos, 1992) and confirmed that the magenta and yellow spectra were linear sums of the spectra of the primary colours. CIE (1931) colour co-ordinates for each of the target and background colours are presented in Table 1.

Calibration of chromatic aberration

The amount of chromatic aberration of the eye for the targets used in the experiments was estimated using the process described in detail by Bradley (1992, Fig. 3). Briefly, the radiometric spectra of the stimuli (measured at 10 nm intervals) were weighted by the CIE luminance sensitivity function (V_λ) to derive luminance spectra for each coloured target. Next, the refractive status of each wavelength in the spectrum was calculated using the Chromatic Eye model of chromatic aberration [see equation (3) in Thibos, Ye, Zhang and Bradley (1992)]. By combining these two results, both of which are functions of wavelength, we eliminated wavelength as a variable and yielding the luminance distribution of chromatic errors of focus. These distributions are illustrated in Fig. 2 for the three primary colours used in these experiments. In order to summarize each distribution by a single number, the "mean refractive error", we treated luminance as a weighting factor analogous to probability and calculated the mean refractive error as the first moment of the distribution curve. That is, we defined

$$\text{mean refractive error} = \frac{\Sigma R \cdot L(R)}{\Sigma L(R)} \quad (1)$$

where R is refractive error and $L(R)$ is the luminance of that wavelength component of the stimulus which is out of focus by amount R. Mean values calculated by this metric are shown by the abscissa values of the vertical bars in Fig. 2 and numerical values are given in Table 1. Thus, the chromatic difference of refractive error (i.e. the
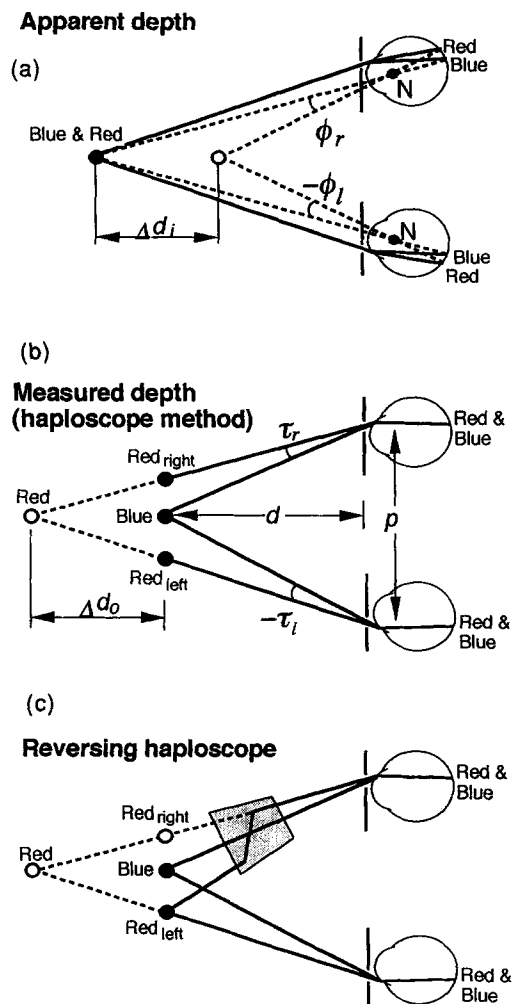

FIGURE 1. Optical model of the effect of TCA on binocular vision. ● Physical targets; ○ virtual targets. (a) Coincident red and blue objects produce separate images (a phenomenon called monocular chromatic diplopia) which subtend visual angle ϕ at the nodal point N. Interocular diferences in ϕ cause binocular disparity and the result is chromostereopsis, the perception of relative depth between equidistant objects of different colour. (b) A nulling technique for measuring the magnitude of chromatic diplopia and chromostereopsis. Haploscopic viewing of separate red and blue targets allows the subject to produce coincident retinal images by introducing an offset in the targets. The magnitude of offset angle τ in (b) is equal to the corresponding angle ϕ in (a). The physical depth Δd that would be required to make the red and blue targets appear to have the same depth may be inferred from experimental measurement of angles τ. (c) The same configuration of targets as in the conventional haploscopic arrangement in (b) may be produced with a single display by using a reversing haploscope that creates a left–right reversal of the targets for one eye.

TABLE 1. Stimulus and background parameters

Colour	CIE x	CIE y	CIE z	Mean effective wavelength (nm)	Mean refractive error of chromatic eye (D)
Red	0.626	0.323	0.032	605	0.050
Green	0.284	0.600	0.116	544	−0.245
Blue	0.152	0.067	0.781	497	−0.602
Magenta	0.298	0.152	0.550	570	−0.158
Yellow	0.443	0.482	0.075	564	−0.147

longitudinal chromatic aberration of the eye) for the targets was 0.295 D for the red–green combination, and 0.652 D for the red–blue combination.

For the Chromatic Eye model, the rate of change of TCA with pinhole displacement is equal to the chromatic difference of refractive error (Thibos, Bradley, Still, Zhang & Howarth, 1990)

$$\Delta R = \frac{TCA}{pupil\ displacement}. \qquad (2)$$

For example, the 0.652 D of mean refractive error difference for red and blue targets should cause the mean TCA to change at the rate of 0.652 rad/m, or 2.24 arc min/mm of pinhole displacement. Using the difference in the mean refractive errors for the two coloured spectra provides a useful simplification since it will determine [using equation (2)] the TCA for the central moments of the two coloured lines in the experiments. Experimental data confirm that the central moment (or gravity centre) of a distribution is a good predictor of the perceived location of line targets and psychophysically determined ocular TCA (Ye et al., 1992).

Experimental procedures

Experiments were performed on five adult observers with normal stereopsis and colour vision, two of whom had participated in similar experiments previously (Thibos et al., 1990; Ye et al., 1991, 1992). Subjects viewed the stimuli through 1.78 mm pinholes mounted on an X, Y, Z translation stage with micrometer controls. The pinholes were positioned near to the eye and the head was fixed by means of a dental bite bar. Pinhole positions were referenced to the visual axis, defined by the hypothetical line joining the fixation point to the fovea and passing through the nodal point (von Helmholtz, 1909). Operationally, the visual axis is defined as the axis of zero foveal TCA (also known as the foveal achromatic axis) and may be located by adjusting the position of the pinhole vertically and horizontally until physically aligned red and blue stimuli appeared to be aligned perceptually (Thibos et al., 1990). Pupils were dilated with two drops of tropicamide HCl (1%) which allowed controlled decentration of the pinhole pupil up to a maximum of 3 mm nasally and 3 mm temporally.

For monocular experiments, ocular TCA was induced by displacing the pinhole horizontally from the visual

axis as shown in Fig. 1. The resulting chromatic diplopia (ϕ_r in right eye, ϕ_l in left eye) was measured by a nulling technique (Thibos et al., 1990) which effectively shifts the effect from image space [Fig. 1(a)] to object space [Fig. 1(b)] where it can be measured easily. With this two-colour vernier alignment procedure the subject physically misaligns two targets (one red and the other blue or green) until they appear aligned perceptually. It has been shown previously (Ye et al., 1991) for monochromatic targets on black backgrounds that the amount of target misalignment required [angles τ_r and τ_l in Fig. 1(b)] is a direct measure of the magnitude of TCA in each eye. However, for the chromatic eye model it turns out that the rate of change of angle τ with displacement of the pinhole in Fig. 1(b) and the rate of change of angle ϕ with displacement of the pinhole in Fig. 1(a) are both equal to the chromatic difference of refraction, and hence are equal to each other (Ye et al., 1991). In the present study, we use the vernier misalignment technique to measure chromatic diplopia in object space. Vernier alignments were measured to an accuracy of 1.0 mm (i.e. 30 arc sec) with five repetitions for each pupil position.

For binocular experiments, a similar nulling technique was used to express the relative depth of
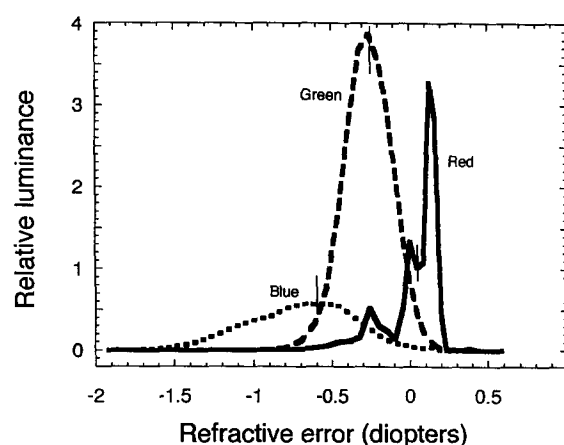

FIGURE 2. Luminance distribution of chromatic errors of focus for the three primary colours of the RGB computer display used in present experiments. Target luminance and the refractive error of the eye both vary with wavelength. Plotting these two variables against one another, with wavelength an implicit parameter, shows how much luminance is carried (ordinate) by images suffering from different amounts of longitudinal chromatic aberration (abscissa). The short vertical stroke through each curve indicates the mean refractive error of the eye for each light source.

chromostereopsis [Fig. 1(a)] as an external depth interval (Δd_o) in object space [Fig. 1(b)]. In order to present two-colour vernier targets independently to each eye, subjects viewed the screen haploscopically. The rationale of the haploscopic method is that if each vernier target is misaligned so as to null chromatic diplopia in the corresponding eye, then the situation is equivalent to having a red and a blue (or green) target physically separated in depth by amount Δd_o. For monochromatic targets presented on a black background, it has been shown previously (Ye et al., 1991) that Δd_o is related to the monocular measures of TCA according to the formula

$$\tau_l - \tau_r = \frac{p \Delta d_o}{d^2 + d \Delta d_o} \tag{3}$$

where p is the separation of the pinholes, and d is the viewing distance.

In order to implement a haploscopic arrangement with a single computer display, we developed a novel reversing haploscope device shown schematically in Fig. 1(c). The left eye viewed the display directly, but the right eye viewed the display through a front surface mirror-equivalent of a Dove inverting prism rotated so that it horizontally reversed the right eye's image without introducing any instrument chromatic aberration (inherent in a standard prism). All test stimuli were horizontally mirror-symmetric (Fig. 3) and were therefore unaffected by this horizontal reversal. Viewing such a symmetric display with this haploscope is equivalent to viewing the display binocularly. For example, if there were no ocular TCA, all parts of the stimulus will have the same horizontal disparity and hence appear at the same depth. In this haploscope, horizontal disparity was introduced into the adjustable probe stimulus by displacing its horizontal position from the axis of symmetry. For example, moving the central (probe) bar in Fig. 3(c) to the right on the display created a rightward (nasal) movement in the left eye, and a leftward (nasal) movement in the right eye. Therefore, rightward movement of the probe created bi-nasal (crossed disparity) movement and the probe appeared to advance towards the observer. The converse was true for leftward movement of the probe. Subjects adjusted the left/right position of the probe using a keyboard control until it matched the apparent depth of the targeted test stimulus. Pinholes were always displaced bi-nasally or bi-temporally by the same amount in the two eyes.

RESULTS

Experiment 1: Effect of background colour on chromatic diplopia and chromostereopsis

In previous work we have verified that binocular chromostereopsis may be predicted accurately from interocular differences in monocular chromatic diplopia through the application of equation (1) for monochromatic targets on a black background (Ye et al., 1991). Here we extend those results to include broad-spectrum

(a)

(b)

(c)

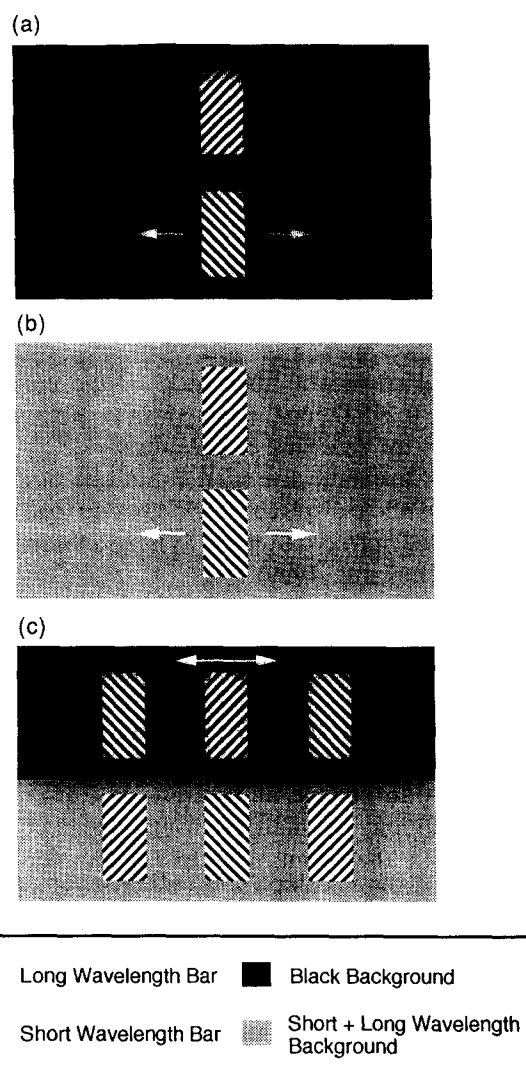| ░░ | Long Wavelength Bar | ■ | Black Background |
| ░░ | Short Wavelength Bar | ░ | Short + Long Wavelength Background |

FIGURE 3. Schematic representation of the three stimulus configurations used in this study. (a) Two coloured bars displayed on a black background. The position of the lower probe (blue or green) was adjusted by the subject to match the perceived horizontal position (monocular) or perceived depth (binocular) of the upper test bar (red). (b) The same configuration, but the background is magenta (red + blue) or yellow (red + green) instead of black. (c) The coloured probe (blue or green) is the central bar in the top half of the display. The horizontal disparity of this probe was adjusted to match the perceived depth of the flanking red bars and both the red and the blue or green bars in the bottom half of the display.

coloured targets on black or coloured backgrounds. The following target conditions were studied: blue and red targets presented on black or magenta backgrounds; and green and red targets presented on black or yellow backgrounds [Fig. 3(a, b)].

Monocular chromatic diplopia

Measurements of monocular chromatic diplopia obtained with the two-colour vernier technique are shown in Fig. 4 for the right and left eyes of two subjects. The misalignment between the red and blue vernier targets required to make them appear aligned is plotted in arc min as a function of pinhole position relative to the foveal achromatic (visual) axis. Sign convention is consistent with previous studies (Ye et al., 1991, 1992)

with positive and negative numbers on the abscissa representing temporal and nasal displacement of the pupil from the visual axis, respectively. Positive chromatic diplopia indicates that the blue (or green) probe was positioned to the left of the red bar on the monitor to achieve alignment perceptually. According to these conventions, both pinholes in Fig. 1(b) have positive displacement and the induced chromatic diplopia is positive in the right eye but negative in the left eye.

The data obtained with black backgrounds [Fig. 4(a)] are consistent with previous reports (Thibos *et al.*, 1990; Ye *et al.*, 1991) which show induced chromatic diplopia changes in an approximately linear manner with increasing decentration of the artificial pupil. The mean slope of these functions is 2.19 arc min/mm decentration which is very close to the predicted value of 2.24 arc min/mm based on the optical analysis of TCA of the Chromatic Eye model (see Methods). These results demonstrate that the simple optical model used previously to predict chromatic diplopia for monochromatic targets can also be used successfully with polychromatic targets. The magnitude of the induced diplopia was similar for right (●) and left (□) eyes with no significant inter-subject differences being present (five subjects were tested).

The important comparison is between the Fig. 4(a) (red and blue stimuli on black backgrounds) and

Fig. 4(b) (same coloured stimuli on a red + blue background). The direction of the chromatic diplopia shows a clear reversal when the background is changed from black to the sum of the spectral composition of the individual targets (magenta in this example). For example, temporal shifts of the right pinhole lead to *leftward* shifts of the probe when the background was black, but *rightward* shifts when the background was magenta. The slopes of these functions are approximately equal but opposite in sign for the two different backgrounds. This reversal of monocular chromatic diplopia predicts that chromostereopsis will also be reversed by changing the background colour. A similar reversal of chromatic diplopia was also observed for red and green targets presented on either black or yellow backgrounds. These red/green results are summarized for two observers in Fig. 6.

According to the optical model of Fig. 1, if monocular chromatic diplopia reverses when the background changes colour, then chromostereopsis must also reverse. Quantitative predictions of this reversal are shown as solid lines (black background) and dotted lines (magenta backgrounds) in Figs 5 and 6.

Chromostereopsis

Measurements of binocular chromostereopsis obtained with the two-colour haploscopic technique are
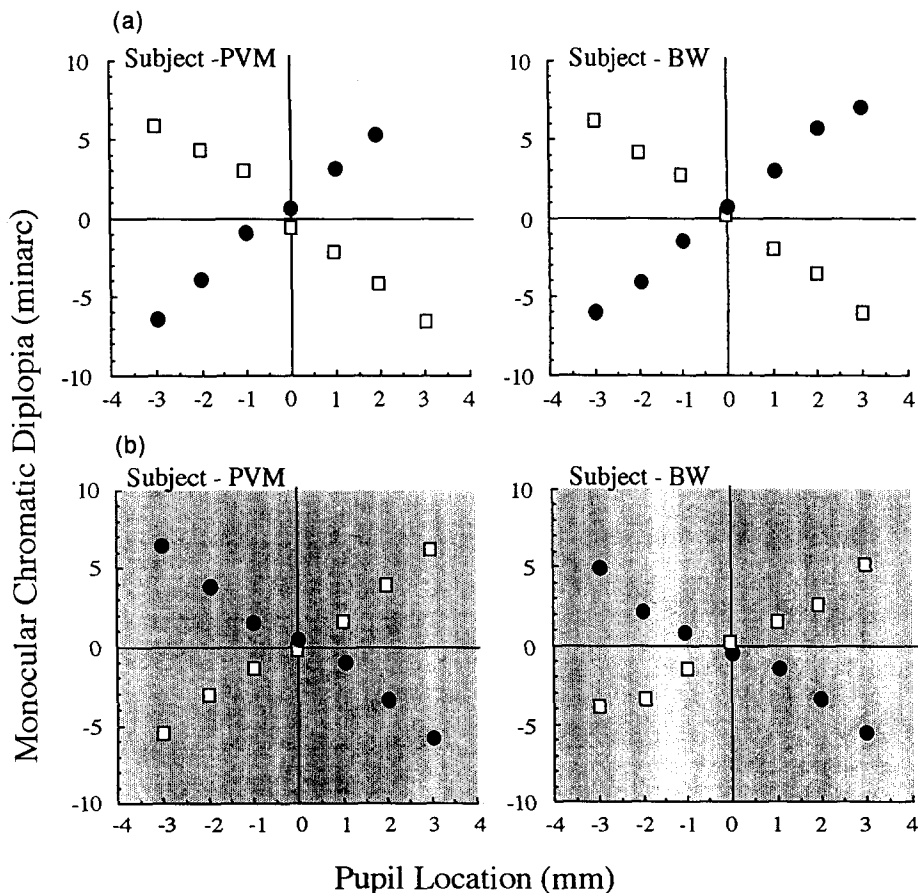

FIGURE 4. The magnitude of monocular chromatic diplopia for blue and red targets is plotted as a function of pupil locations for presentation on black (a) and magenta (b) backgrounds. ● Right eye data; □ left eye data. Note the reversal in monocular chromatic diplopia with a change in background colour.
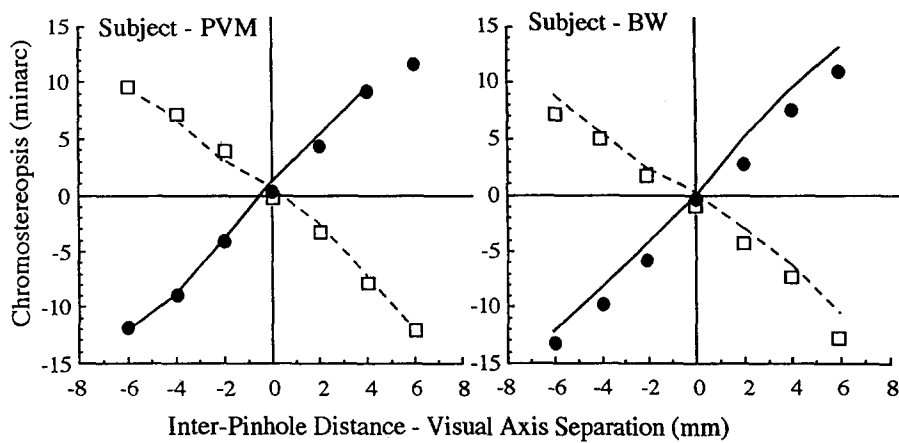
FIGURE 5. Chromostereopsis (arc min) vs pupil locations (mm). Positive chromostereopsis represents cases where the red target (605 nm) appears in front of the blue (497 nm). Data are shown for red and blue targets presented on black (●) and magenta (□) backgrounds. Predictions of the magnitude and direction of chromostereopsis calculated using the chromatic difference in monocular visual directions are indicated by the solid (black background) and dashed (magenta background) lines.

shown for two subjects in Figs 5 and 6. Figure 5 presents data for red and blue targets on black (●) or magenta (□) backgrounds. In Fig. 6 data are shown for red and green targets presented on black (●) or yellow (□) backgrounds. The horizontal axis plots the inter-ocular separation of the pinhole locations relative to the achromatic visual axis. By our sign convention, positive chromostereopsis represents the red target being perceived to lie in a depth plane nearer than the blue or green probe. To null this apparent depth with the reversing haploscope the red bar must be shifted to the left of the blue bar as shown in Fig. 1(c).

Our results show that, as expected, equal amplitude but opposite direction chromostereopsis is induced by bi-nasal and bi-temporal pupil displacements. The magnitude and direction of chromostereopsis (symbols) is predicted accurately by the difference in monocular chromatic diplopia (lines). As predicted from the monocular diplopia experiment, the direction of chromostereopsis is reversed when the stimuli are presented on a background made from the sum of the target spectra since the monocular diplopia also reversed

sign when the background changed colour. This confirms that, irrespective of background colour, chromostereopsis for isolated bars on a uniform background may be accounted for by interocular differences in monocular diplopia induced when the artificial pupils are displaced from the visual axis.

Experiment 2: Can a single colour appear in multiple depth planes?

In order to determine if a single colour could appear to lie in two separate depth planes within a single display, we arranged the apparatus so that subjects could match the depth of a blue probe on the top half of the display to the apparent depth of a red or blue target on the bottom half of the screen. The probe was always on a black background but the test targets could be on a black or magenta background. The same experiment was also performed with a green probe on a black background which was compared with red or green targets on a black or yellow background. The spatial arrangement of these stimuli for use with the reversing haploscope are shown in Fig. 3(c).
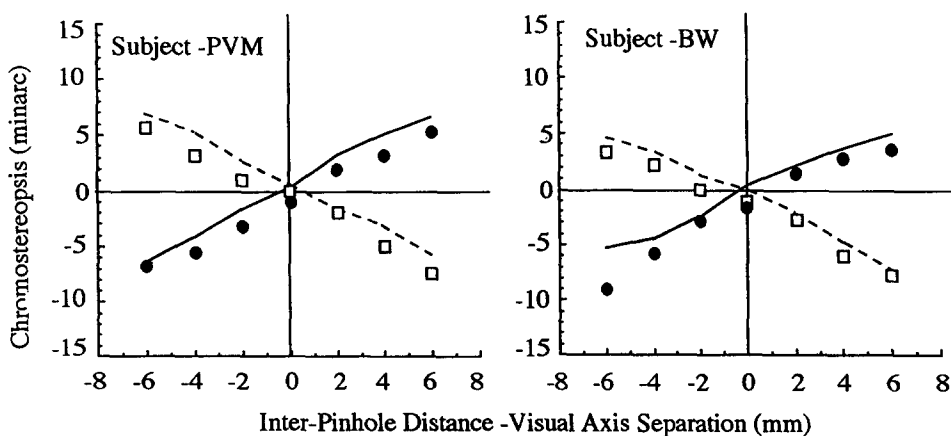

FIGURE 6. Chromostereopsis (arc min) vs pupil locations (mm). Positive chromostereopsis represents cases where the red target (605 nm) appears in front of the green (544 nm). Data are shown for red and green targets presented on black (●) and yellow (□) backgrounds. Predictions of the magnitude and direction of chromostereopsis calculated using the chromatic difference in monocular visual directions are indicated by the solid (black background) and dashed (yellow background) lines.

The results of Expt 2 are shown in Fig. 7. Figure 7(a) shows the perceived depth of the red and blue targets, as measured by the blue probe. Similarly, Fig. 7(b) shows the perceived depth of the red and green targets, as measured by the green probe. Symmetric decentration of the artificial pupils produced the predictable colour–depth effect between the blue probe and the red bars on the black background (■). This is essentially the same condition as Expt 1 (●) in Figs 5 and 6, and serves as a control. However, when the blue probe was matched to the red target on the magenta background (○), the colour–depth effect vanished. That is, the blue probe always appeared to lie in the same depth plane as the red target regardless of the separation between pinholes. On the other hand, a large colour–depth effect occurred between the blue (on black) probe and the blue on magenta test (□). That is, the blue probe and the blue target appeared to lie at different depths. It is important to note that the magnitude of this blue–blue colour depth effect was the same as the magnitude of the depth effect in the control condition (blue probe compared to red test target on black). The same result was obtained when the colour scheme was changed to red and green targets with a red probe, but because the spectral separation of red and green is less than red and blue, the effects are much smaller.

These results clearly show that, under conditions that normally produce a large colour–depth effect (e.g. binasal or bi-temporal pupil decentrations), red and blue targets can appear to lie in the same plane. Conversely, targets of the same colour and spectral composition can appear to lie in quite different depth planes.

DISCUSSION

Earlier studies have reported colour–depth reversals for broad spectrum coloured targets when the background is changed from black to white (Hartridge, 1947; Verhoff, 1928; Dengler & Nitschke, 1993; Thompson & Stone, 1993) while coloured targets are observed with

natural pupils. In order to test the ability of Einthoven's TCA model to account for such behaviour, we have performed the present experiments with controlled artificial pupils that can be adjusted with great precision. In so doing we are able to induce controlled amounts of ocular TCA and measure the resulting monocular chromatic diplopia and binocular chromostereopsis. Our experiments also differ from the previous studies in that we compared the effects of changing the background from black to the spectral sum of the targets (magenta or yellow) rather from black to white. The reason for this degression from previous studies becomes apparent when we examine the theory beyond the colour–depth reversal.

The experimental results of this study show that (1) the colour–depth effect can be reversed by changing the background colour (Figs 4–7); (2) the reversed depth effect is systematically modulated by the interocular difference in TCA (Figs 4–7); (3) the colour–depth reversal is paralleled by a reversal in monocular chromatic diplopia (Figs 4–6); (4) the depth reversal is accurately predicted by interocular differences in monocular TCA (Figs 5 and 6); (5) the chromostereopsis normally present for red and blue targets on a black background vanishes when the red target's background changes to magenta (Fig. 7); (6) two blue targets can appear to be at different depths if one of them is placed on a black and one on a magenta background (Fig. 7). Thus it appears that we have successfully replicated under controlled conditions the essential aspects of the controversial phenomenon of depth reversal.

The key to resolving these seemingly paradoxical results is to notice that all of the results can be summarized by stating that the red target on a magenta background creates the same effect as a blue target on a black background, and conversely a blue target on a magenta background creates the same effect as a red target on a black background. The same conclusion can be drawn for red and green targets on black and yellow backgrounds. The following, simple analysis of the stimuli

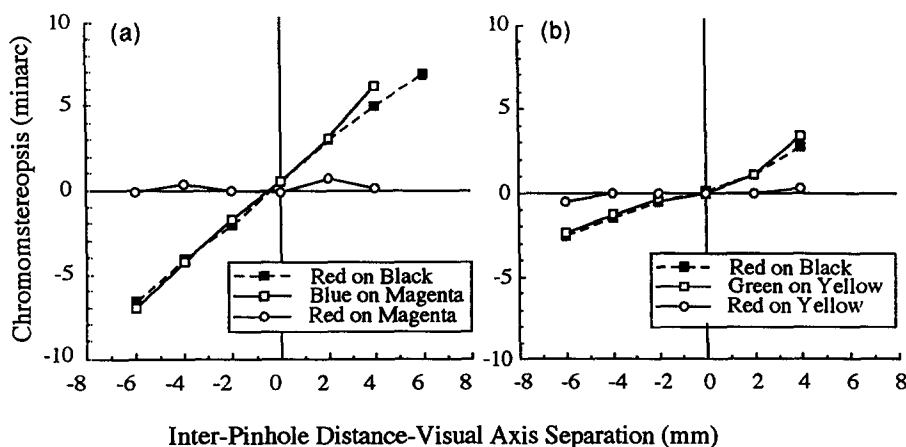Inter-Pinhole Distance-Visual Axis Separation (mm)

FIGURE 7. Chromostereopsis as a function of pupil locations for stimuli presented on a black background and a background composed of the sum of the spectral components of the long and short wavelength targets within a single display [see Fig. 3(c)]. (a) Data for red and blue targets on black and magenta backgrounds. (b) Data for red and green targets on black and yellow backgrounds. Note that red and blue targets can appear in the same depth plane and that targets of the same colour can appear in different depth planes.

used in this study confirms that these results are completely predictable and entirely consistent with the TCA model for chromostereopsis.

The explanation for the colour–depth reversal can be understood by examining the stimuli. Figure 8 shows a schematic representation of the long wavelength and short wavelength bars presented on either a black background [Fig. 8(a)] or a background which was composed of the sum of the targets spectral composition [Fig. 8(b)]. For the current study the long wavelength bar refers to red targets and the short wavelength bar refers to either the blue or the green target. Notice that although the red

bar has the same spectral composition on both the black and magenta backgrounds, it is generated in a totally different way. When presented on a black background, the red bar is produced by turning on the red gun in the centre of the screen. However, a red bar on a magenta background (which is the sum of the red and blue), is produced by turning off the blue gun in the centre of the screen. In other words, although we describe the stimulus as a red bar on a magenta background, in fact there is red everywhere on the screen and the bar corresponds to a gap in the pattern produced by the blue gun. Consequently, the retinal image of the red bar will
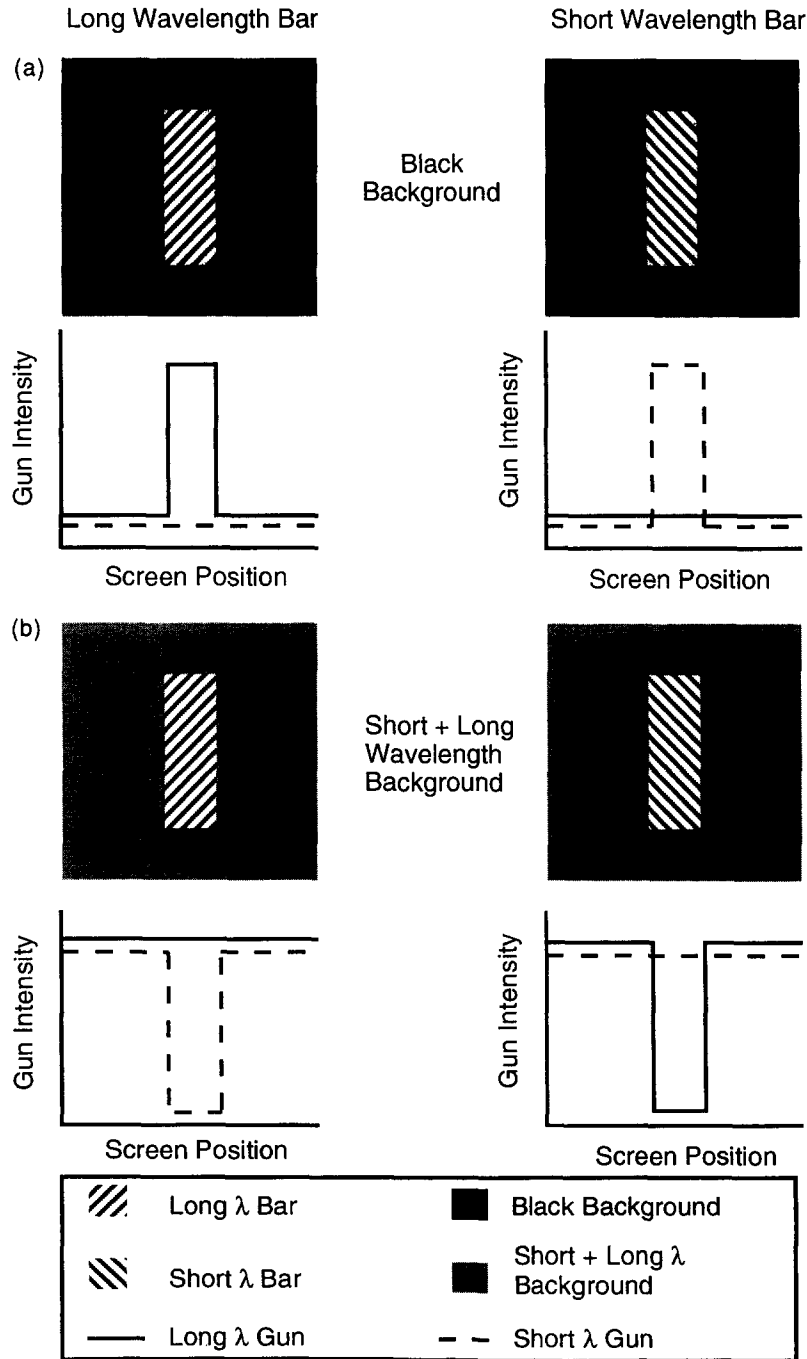

FIGURE 8. Schematic representation of the long and short wavelength targets presented on either a black (a) background or a background which was composed of the sum of the targets spectral composition (b). The model demonstrates that although targets may have the same spectral composition it is the manner in which the stimulus is generated which determines the relative chromatic shift.

be determined by the retinal location of the gap in the blue field, which will be determined by the effect of TCA on the blue short wavelength image and not the location of the long wavelength image. This is why the perceptual effects of placing the red target on a magenta background are the same as those observed with a blue target on a black background—optically speaking both are defined by the short wavelengths!

This explanation predicts all five results summarized above for backgrounds composed of the sum of the target spectra. However, all of the previous studies have changed the backgrounds from black to white. In these cases, the retinal image of say a red bar will be determined by the TCA for long wavelengths when presented on a black background and by the TCA for all other wavelengths combined when presented on a white background (Dengler & Nitschke, 1993). Our model would predict that a depth reversal would occur in these circumstances but the depth effect would most likely be attenuated because of the broad spectral distribution of the white-minus-red and white-minus-blue spectra. For example, even though the spectra of red and blue targets might be quite separate, the spectra of the white minus blue (blue line on a white background) and white minus red (red line on a white background) will contain many common wavelengths (e.g. the middle of the spectrum will be common to both targets). Since natural pupils are quite well centred on the visual axis in most subjects (Thibos, Bradley & Zhang, 1991; Simonet & Campbell, 1990; Vos, 1960), the reversed colour–depth effect may be too small to be detected by some subjects. Using our paradigm with precise control over the TCA and maintaining the spectral separation for the coloured targets on the magenta and yellow backgrounds, we were able to measure large depth reversals for all five subjects. However, we also employed the stimulus arrangement shown in Fig. 2(c) to confirm the predictions for black and white backgrounds. Results from five observers confirm that the colour–depth effects observed with bi-nasal or bi-temporal artificial pupils seen with a black background are reversed and attenuated on a white background.

We conclude that all of the seemingly paradoxical reversals in the colour–depth effect produced by changing the background colour are predicted by the Einthoven TCA model for chromostereopsis. We have also shown, quantitatively, that the model eye used so successfully to predict the perceptual effects of TCA for monochromatic targets on black backgrounds (Thibos et al., 1990; Ye et al., 1992) provides an accurate means of predicting the monocular chromatic diplopia and binocular chromostereopsis for broad spectrum coloured targets irrespective of their backgrounds. The success of Einthoven's model in these examples raises the question of whether it can provide an effective explanation for other changes in the colour–depth effect observed when making changes in the background colour and spatial configuration (Dengler & Nitsche, 1993; Thompson & Stone, 1994; Faubert, 1994; Winn, Bradley, Strang, McGraw & Thibos, 1994).

The success of the Einthoven model provides a possible direct challenge to several alternative hypotheses. For example, although interocular differences in luminance can elicit depth effects (Kumar, 1995), and brighter objects do tend to appear closer than dimmer targets, the precision with which chromostereopsis is determined by the interocular differences in monocular TCA (see Figs 4 and 5) clearly shows that interocular differences in ocular TCA are the sole determinants of chromostereopsis in our experiments. The luminance differences between the red, green, and blue targets in our experiment seem to have had no measurable effect on relative depth judgements, and the dimmer blue targets can appear behind or in front of the brighter red bars. Also, in a previous study, (Zhang, Bradley & Thibos, 1993) showed that even large interocular differences in luminance had no measurable effect on chromostereopsis. A second model, proposed by Dengler and Nitschke (1993) suggests that the colour–depth reversals observed while viewing coloured lines on white or black is due to the change in border contrast. Their border contrast model is based on interocular differences in TCA, and in principle, their model is the same as ours. It shows that depth reversals occur when switching from a black to a white background because, for example, the location of a red line on a black background is determined by the location of the red spectrum, whereas the location of the red bars on the white background is determined by the positions of the white minus red spectrum.

Finally, in some recent experiments employing random-dot patterns of two colours (red and green), Faubert (1994) has proposed some novel cortical mechanism to explain the depth changes observed when modifying the spatial and spectral characteristics of the background or surround. It is important to realize that all stereopsis, including chromostereopsis must employ some cortical mechanism. However, our data point to an ocular and not a cortical origin for colour–depth reversals. The Faubert experiments and results are similar in many ways to those of our own, and he shows (Faubert, 1994) that his data are completely dependent upon interocular differences in TCA. The unique spatial arrangement employed by Faubert prevents us from employing our simple model to explain his results. We hope to examine this issue in a future publication.

REFERENCES

Bradley, A. (1992). Glen A. Fry award lecture 1991—Perceptual manifestations of imperfect optics in the human eye: Attempts to correct for ocular chromatic aberration. *Optometry and Vision Science*, *69*, 515–521.

Bradley, A., Zhang, X. & Thibos, L. N. (1992). Failures of isoluminance caused by ocular chromatic aberrations. *Applied Optics*, *31*, 3657–3667.

Dengler, M. & Nitschke, W. (1993). Colour stereopsis: A model for depth reversals based on border contrast. *Perception & Psychophysics*, *53*, 150–156.

Einthoven, W. (1885). Stereoskopie durch Farbendifferenz. *Albrecht von Graefes Archiv fur Ophthalmologie*, *31*, 211–238.

Faubert, J. (1994) Seeing depth in colour: More than just what meets the eyes. Vision Research, 34, 1165–1186.

Hartridge, H. (1947). The visual perception of fine detail. Philosophical Translations of the Royal Society of London B, 232, 519–671.

von Helmholtz, H. (1909). Treatise on physiological optics. Translated by Southall, J. P. Washington, D.C.: Optical Society of America. (1924).

Kishto, B. N. (1965). The colour stereoscopic effect. Vision Research, 5, 313–329.

Kumar, T. (1995). Stereopsis due to luminance differences in the two eyes. Vision Research, 35, 255–262.

Simonet, P. & Campbell, M. C. W. (1990). Effect of illuminance on the directions of chromostereopsis and transverse chromatic aberration observed with natural pupils. Ophthalmic and Physiological Optics, 10, 271–279.

Sundet, J. M. (1976). Two theories of colour stereoscopy, an experimental investigation. Vision Research, 116, 469–472.

Thibos, L. N., Bradley, A. & Zhang, X. X. (1991). Effect of ocular chromatic aberration on monocular visual performance. Optometry and Vision Science, 68, 599–607.

Thibos, L. N., Ye, M., Zhang, X. & Bradley, A. (1992). The chromatic eye: A new reduced-eye model of ocular chromatic aberration in humans. Applied Optics, 31, 3594–3600.

Thibos, L. N., Bradley, A., Still, D. L., Zhang, X. & Howarth, P. A. (1990). Theory and measurement of ocular chromatic aberration. Vision Research, 30, 33–49.

Thompson, P. & Stone, R. (1993). Chromostereopsis: The relative contributions of colour and luminance to perceived depth. Perception (Suppl.), 22, 9–10.

Verhoeff, F. H. (1928). An optical illusion due to chromatic aberration. American Journal of Ophthalmology, 11, 898–900.

Vos, J. J. (1966). The colour stereoscopic effect. Vision Research, 6, 105–107.

Winn, B., Bradley, A., Strang, N. C., McGraw, P. V. & Thibos, L. N. (1994). Chromostereopsis and monocular chromatic diplopia in complex visual stimuli. Investigative Ophthalmology and Visual Science (Suppl.), 35, 2169.

Ye, M., Bradley, A., Thibos, L. N. & Zhang, X. (1991). Interocular differences in transverse chromatic aberration determine chromostereopsis for small pupils. Vision Research, 31, 1787–1796.

Ye, M., Bradley, A., Thibos, L. N. & Zhang, X. (1992). The effect of pupil size on chromostereopsis and chromatic diplopia: Interaction between the Stiles–Crawford effect and chromatic aberrations. Vision Research, 32, 2121–2128.

Zhang, X. X., Bradley, A. & Thibos, L. N. (1993). Experimental determination of the chromatic difference of magnification of the human eye and the location of the anterior nodal point. Journal of the Optical Society of America A, 10, 213–220.