Chromostereopsis: a multicomponent depth effect?

Peter Thompson, Keith May* and Robert Stone

Colours on a flat two-dimensional surface can appear to lie in different depth planes. This phenomenon, readily seen on a computer monitor, is called chromostereopsis. Typically, red objects appear closer to the observer than blue objects. Although research on chromostereopsis has a history of over one hundred years, there are still aspects of it that are not fully explained. The simplest (and earliest) explanation proposes that a combination of chromatic aberration and the displacement of the fovea from the eye's optical axis is responsible for the illusion. Recent research supports the notion that other factors need to be taken into account, for example the eccentric location of the pupils and the Stiles–Crawford effect. We describe some of our own research that suggests that in many displays at least part of any perceived depth is due to luminance differences, bright objects appearing closer than dim ones.

Keywords: chromostereopsis, colour, depth, Stiles–Crawford effect, luminance

Now that colour displays are commonplace, it is increasingly likely that the reader will have experienced a powerful visual illusion previously known only to a few vision scientists. If on a screen with a dark background there are saturated colours, reds will appear to stand out in front of blues; see *Figure 1*. This striking effect is known as chromostereopsis and it has the potential to be either an eye-catching bonus to a display or a distinct irritation to the viewer.

The history of chromostereopsis (or colour stereoscopy as it is sometimes called) goes back at least to the work of Donders in 1864[1]. The underlying cause of this effect has remained controversial to the present day but there has been no shortage of proposed explanations. Bruecke (1868)[2] proposed (and immediately rejected) the most enduring explanation of this effect, namely that the phenomenon is due to a combination of two factors, chromatic aberration and the misalignment of the visual and optical axes within the eye. The problem for Bruecke was that he could not explain why some people report that they see blue in front of red. The theory was proposed again in 1885 by Einthoven[3], though he never provided any evidence to address Bruecke's misgivings. We shall call this the 'traditional' theory of chromostereopsis. Despite Bruecke's objections this theory has gained general acceptance amongst everyone except those who actively carry out research on the phenomenon.

Perceptual Systems Research Group, Department of Psychology, University of York, York YO1 5DD, UK
*Present address: Department of Physiological Sciences, The Medical School, University of Newcastle upon Tyne, Newcastle upon Tyne NE2 4HH, UK
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THE TRADITIONAL THEORY OF CHROMOSTEREOPSIS

Einthoven[3] provided a clear and concise description of this traditional theory:

> 'The phenomenon is due to chromatic difference of magnification, for since, for example, blue rays are refracted more than red rays by the ocular media, their foci not only lie at different levels (chromatic aberration) but make different angles with the optic axis, and will thus stimulate disparate points. It follows that individuals with temporally eccentric pupils see red in front of blue, while with nasally eccentric pupils the relief is reversed.'

The first key component of this explanation is chromatic aberration in the human eye. This means simply that the optics of the eye do not bring all colours to a focus at the same point, that is, there is a shift in refractive index of the optical system with wavelength. The eye accommodates itself for the light of the greatest luminosity, i.e. for a yellow-green colour. Consequently long-wave (red) light is focused behind the retina and short-wave (violet) light is focused in front of the retina.

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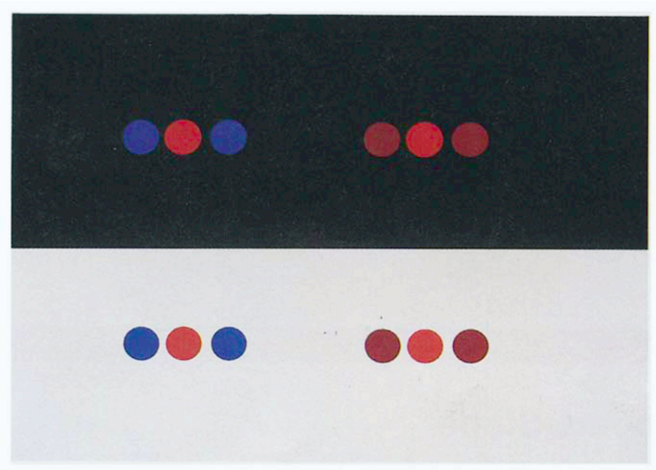

Figure 1 Demonstration of chromostereopsis: Against a black background (upper half of the figure) red will appear to stand forward in depth of blue for most viewers and bright red will stand in front of dark red. On the white background (lower half of the figure) more viewers will experience blue in front of red. Stronger effects can be obtained by reproducing this figure on a colour monitor and viewing in a dark room

The extent of this aberration may be around 2 dioptres, affecting chiefly the violet end of the spectrum (1.5 D) with a lesser effect for red light (0.5 D). This is illustrated in *Figure 2*.

The second component of the traditional explanation is the misalignment of the visual and optical axes. The eye has several axes (at least five) but we need only concern ourselves with two of them, the visual axis and the optical axis. The visual axis is easily defined; it is a line joining the 'object of regard' (i.e. what you are fixating) with the centre of the fovea. We will define the optical axis as the line, normal to the surface of the lens, along which light will pass undeviated. *Figure 3* shows the difference between these two axes schematically. The critical point to bear in mind here is that the fovea is not on the optical axis, but typically about 5 degrees on the temporal side of the retina.

Since light passing through the optical axis is undeviated (by definition), red and blue point sources located on the optical axis will give rise to blur circles that are concentric and centred on the optical axis (as in *Figure 2*). But as the fovea lies about 5 degrees to the temporal side of the optical axis in most people, a blur

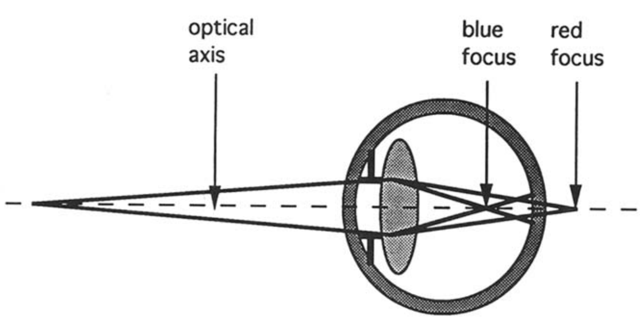

Figure 2 An object on the optical axis will be imaged on the optical axis. Red (long wavelength) light will be focused behind the retina while blue (short wavelength) light will be focused in front of the retina

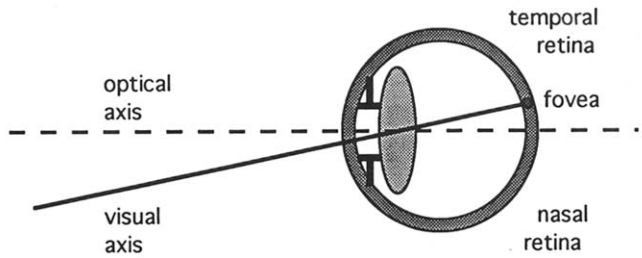

Figure 3 The fovea does not lie on the optical axis. Typically it is located about 5 degrees into the temporal retina. The line joining the point of fixation to the fovea is called the visual axis

circle centred on the fovea cannot have originated from a point on this axis. Therefore, as the fovea is used for 'looking at things', the light from a stimulus being fixated must enter the eye at an angle to the optical axis. *Figure 4* shows that, for rays entering at an angle to the optical axis, the blur circles for red and blue light are no longer concentric on the retina.

For rays angled so that they are imaged on the (temporally situated) fovea the red blur circle lies to the temporal side of the retina, the blue blur circle to the nasal side. If a stimulus is viewed with both eyes, the resulting binocular disparity is indistinguishable from the disparity caused by a genuine difference in depth and, since red is nearer to the temporal side, red is perceived to be in front of blue (see *Figure 5*). This simple explanation would be convincing were it not for the fact that Bruecke reports that some people see blue as closer than red.

Bruecke's objection: Not all people see red as closer than blue

We shall follow the usual convention of defining positive chromostereopsis as the perception of red closer than blue and negative chromostereopsis as the perception of blue closer than red. The existence of negative chromostereopsis led Bruecke to abandon the traditional explanation. However, a solution to this problem is possible: perhaps those who see blue in front of red have foveae situated on the nasal side of the

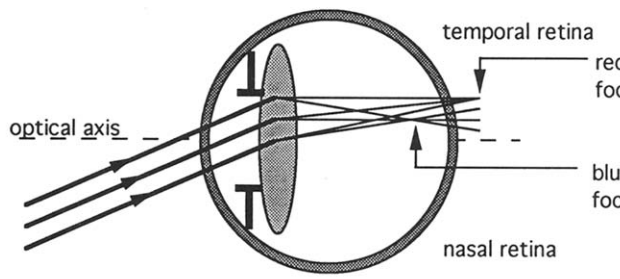

Figure 4 When light enters the eye at an angle to the optical axis, different wavelengths project onto different parts of the retina. This figure of the right eye seen from above shows (diagrammatically only) that red light will project onto a more temporal position on the retina when the object of regard is on the nasal side of the optical axis by virtue of the fact that long wavelength light is less refracted by the optics than short wavelength light

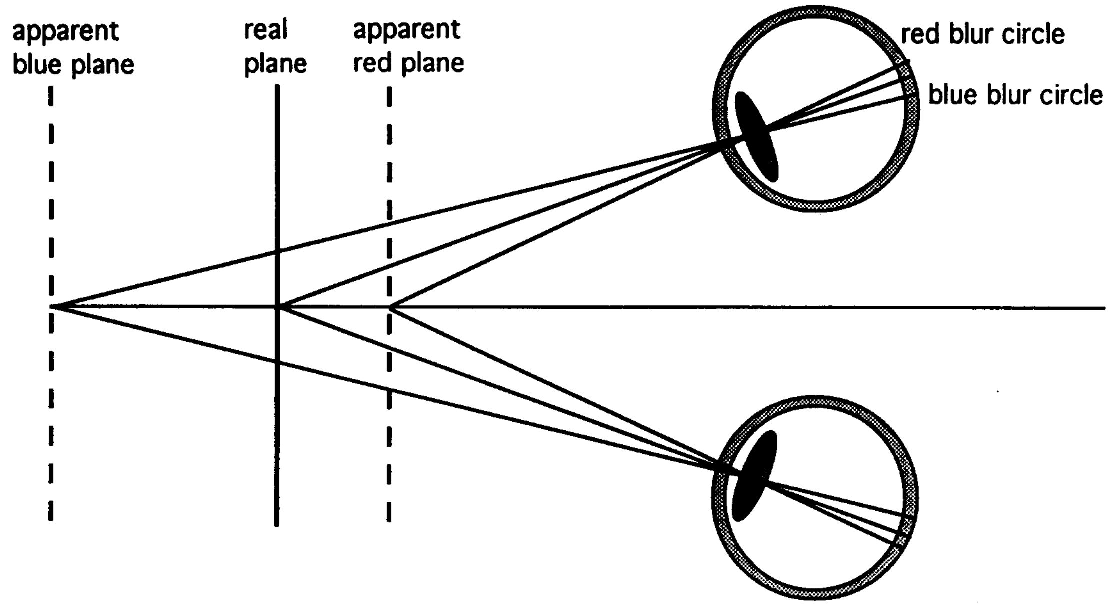

Figure 5 Following from *Figure 4*, it can be seen that objects which project to more temporal positions on the retinae will appear closer than objects that project to more nasal positions on the retinae. Hence red objects will be seen as closer than blue

optical axis or, more plausibly, such people have pupils that are positioned eccentrically. This is easily understood with reference to *Figure 6*. Shifting the pupil temporally will move the red blur circle temporally with respect to the blue blur circle (*Figure 6a*). This means that red objects will appear to be closer to the observer when the pupils are displaced temporally. On the other hand, shifting the pupil nasally will move the red blur circle nasally with respect to the blue blur circle (*Figure 6b*). This means that blue objects will appear closer to the observer when the pupils are displaced nasally.

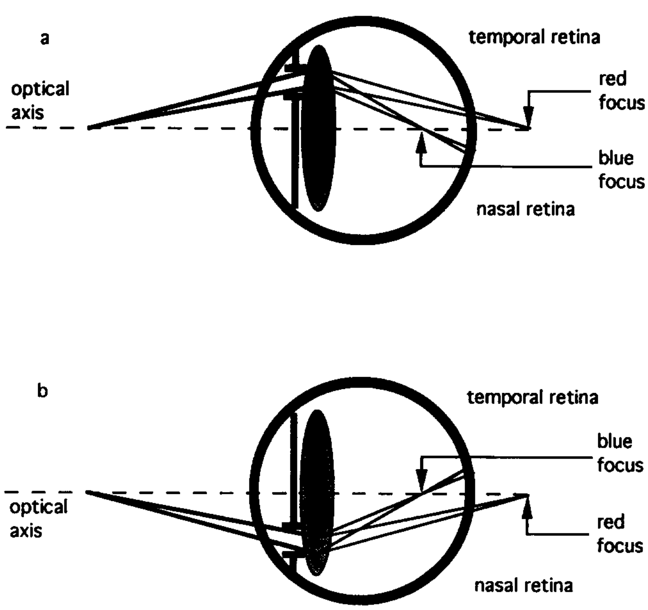

Figure 6 The effect of pupil position on blur circle position. (a) Temporally eccentric pupil in the right eye leads to red blur circle being located temporal to the blue blur circle. (b) Nasally eccentric pupil in right eye leads to red blur circle being located nasal to the blue blur circle

This discussion relies upon the assumption that some people do have eccentrically located pupils. Some evidence for this has come from Allen and Rubin[4] who suggest that there is a correlation between the direction of chromostereopsis and what they call angle kappa, the angle between the pupillary centre and the visual axis. That is, people with a pupillary centre that is situated temporal to the visual axis see red objects closer to them than blue objects. Those (rare) people who have a pupillary centre that is nasally situated (a negative kappa angle), report reduced chromostereopsis or a reversed effect in which blue appears in front of red. In this case the pupil eccentricity is working in a direction opposite to that of the misalignment of the optical and visual axes.

Since the time of Bruecke it has been known that some subjects always report negative chromostereopsis but it is also the case that some subjects report a reversal from positive to negative chromostereopsis as stimulus conditions change. For example, Kishto[5] found that 17 out of 25 subjects reliably obtained a reversal with negative chromostereopsis at low illumination and positive chromostereopsis at high illumination. Kishto's explanation (also favoured by Allen and Rubin[4]) is that the pupil may dilate eccentrically so that its effective centre moves across the optical axis as it dilates. Kishto's pattern of results would arise if the pupil centre lay on the temporal side of the optical axis at high illumination (the case considered in the previous sections) and the nasal side at low illumination.

Clearly manipulation of the viewing conditions can greatly influence the perceived depth effect. The question is whether such results can be accommodated within purely 'optical' theories. By an optical theory we mean one that seeks to explain chromostereopsis completely in terms of a binocular disparity present on the retinae.

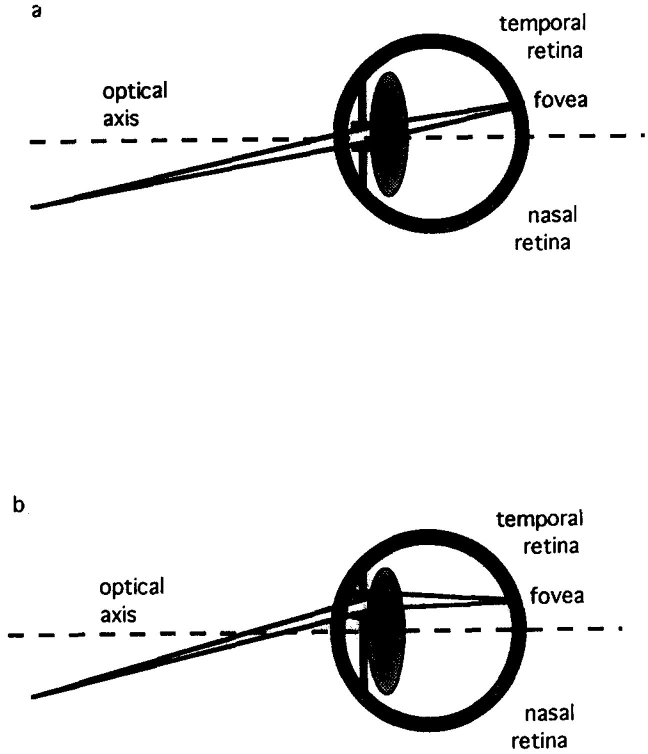

Figure 7 Moving the position of the pupil from being centred on the optical axis (a) to being centred considerably off the optical axis (b) produces a marked reduction in apparent brightness. This is known as the Stiles–Crawford effect

Modern elaborations of the traditional theory

Most recent writers on chromostereopsis have sought to extend the traditional theory to encompass some of the recent data reported. Perhaps the best example of this comes in the extremely thorough work of Vos[6,7] who presented an alternative explanation of negative chromostereopsis. He noted that the luminous efficiency varies across the pupil – a phenomenon known as the Stiles–Crawford effect. This effect deserves some elaboration. Consider the position in *Figure 7a*; a small aperture is placed in front of the eye so that only quanta travelling close to the visual axis pass through the optics and contribute to the image. In *Figure 7b* the aperture is positioned so that only light coming through the outer edge of the pupil contributes to the image. Note that if the aperture were to be moved from the centre of the pupil to the outer edge the image should not move in its position nor should its physical intensity change. However, subjects report that the light looks brighter when the light is coming through the centre of the pupil and it gets dimmer as the aperture moves out towards the edge of the pupil. Furthermore, detection thresholds for light are lowest when light enters the centre of the pupil and highest when entering the edge of the pupil. The explanation of the effect probably owes much to the shape of the cone receptor inner segments that act like a funnel to collect the incident quanta. (The Stiles–Crawford effect does not occur under scotopic light conditions when rods only are operational; rods are differently shaped from cones.)

Figure 8 shows that, as the incident light moves from the optical axis (*Figure 8a*) towards the nasal side (*Figure 8b*), the red and blue blur circles cross over; in *Figure 8a* the red blur circle lies more temporally – corresponding to the disparity that gives rise to positive chromostereopsis (red perceived closer than blue) whilst in *Figure 8b* the blue blur circle lies more temporally – corresponding to the disparity that gives rise to negative chromostereopsis (blue perceived closer than red). Vos[8] cites evidence from Dunnewold[9] that the point of maximum luminous efficiency is situated to the nasal side of the optical axis in most people. Thus the Stiles–Crawford effect tends to cause negative chromostereopsis. We now have two antagonistic effects: the temporally situated fovea that tends to cause positive chromostereopsis (Einthoven's original proposition), and the Stiles–Crawford effect that causes negative chromostereopsis in subjects whose point of maximum luminous efficiency lies to the nasal side of the optical axis. When the illumination is high the pupil is small and the Stiles–Crawford effect is reduced. This explains Kishto's finding[5] that most subjects experience positive chromostereopsis at high illumination. As the

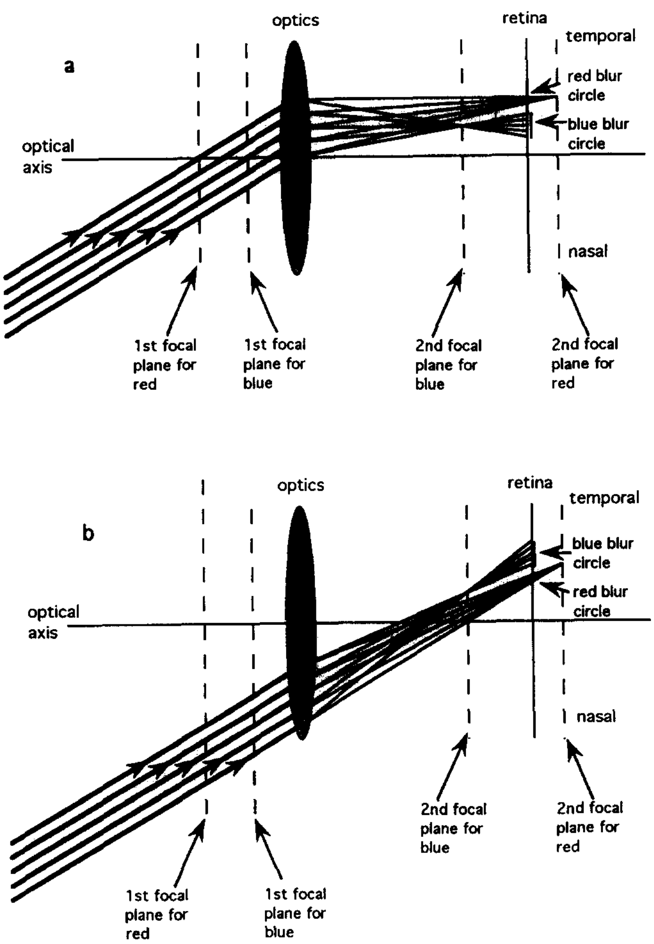

Figure 8 Vos's account of chromostereopsis appeals to the Stiles–Crawford effect as a major component of the depth effect. More detail is given in the text

illumination decreases, the pupil dilates and the magnitude of the Stiles–Crawford effect increases. At low photopic illuminations the disparity due to the Stiles–Crawford effect may become larger than that due to the eccentricity of the fovea, in which case subjects should experience negative chromostereopsis.

Vos[6] considered the Stiles–Crawford effect to be much more important in causing the reversal in chromostereopsis than eccentric dilation of the pupils. In order to substantiate this claim, he made some quantitative predictions using the eccentric dilation theory. He derived from optical theory an expression for perceived depth as a function of the interpupillary distance, assuming small pupils. This expression, which took no account of the Stiles–Crawford effect, predicted that perceived depth should vary linearly with interpupillary distance. Since the Stiles–Crawford effect is negligible with small pupils one would expect this expression to be fairly accurate. Vos tested this by varying the interpupillary distance with artificial pupils and measuring the perceived depth. He found that the predicted slope of 32 was close to the empirically derived slope of 30. Owens and Leibowitz[10] obtained similar results with small pupils.

Vos[6] then derived an expression for the perceived depth with natural (larger) pupils, again using optical theory and again not accounting for the Stiles–Crawford effect. The predictions with natural pupils proved very inaccurate. Vos noted that the magnitude of the Stiles–Crawford effect increases with pupil size and thus the prediction will be inaccurate because it does not take this into account. Further, Vos showed that if a Stiles–Crawford effect correction term is added to the equation, the predicted depth is close to the observed depth. However, the uncorrected equation that Vos used to predict depth with natural pupils assumes that the pupil is centred. Kishto's argument is that this may not be the case, and if Kishto is right, one would expect Vos's prediction for natural pupils to be inaccurate even if the Stiles–Crawford effect had played no part at all. It seems prudent to allow for the probability that both Kishto and Vos have much truth in their arguments. Clearly the position of the pupil is important (as Kishto claims) but there are several factors which determine where the *effective* pupil centre is located. One major factor will be the extent of the Stiles–Crawford effect, as Vos suggests.

Sundet[11] presented evidence that, he claimed, supports Vos's theory at the expense of Kishto's. He examined the effect of completely centric dilation with artificial pupils. If the reversal of depth with luminance is due solely to the shift in the pupil centre as it dilates, then a reversal should not be obtained with centric dilation of artificial pupils. On the other hand, Vos's account does predict a reversal of chromostereopsis with centric pupil dilation. Sundet found such a reversal and concluded that 'the hypothesis that the reversal is due to disparity changes caused by centric pupil opening must be rejected' (Ref. 11, p. 471). If we assume that the effective pupil centre is what matters then we see that Sundet is only partially correct. His results show that there must be something involved other than eccentric pupil opening, but they do not rule it out as a possible contributing factor. In fact, eccentric dilation has been demonstrated. Enoch and Hope[12] showed a nasal decentration with drug-induced dilation and Walsh[13] demonstrated that the centration of the pupil varies with natural illumination-related dilation.

Unresolved problems

Although Kishto's reversal from positive to negative chromostereopsis as luminance decreased[5] has been accounted for by Vos's theory, there may still be problems that are unresolved. In our laboratory we have investigated the effects of varying the luminance of the background and the luminances of the red and blue coloured fields independently. This could not be done by Kishto who had only crude control over luminance in his experiments. The present authors[14] have confirmed Kishto's findings in an experiment involving 190 subjects; as we reduced the luminance of coloured bars (seen against a black background) the percentage of subjects reporting positive chromostereopsis dropped from about 80% to 40%. However, in a second experiment in which the luminance of the coloured bars remained constant but the background was varied in luminance we found that while 92% of a sample of 225 subjects reported that red appeared closer than blue when the stimuli were coloured bars against a black background, 64% of these subjects reported that the blue bars looked closer when these same bars were seen against a bright background, see *Figure 1*. This strange result, which seems the opposite to that expected by optical theory, is being researched further.

IS CHROMOSTEREOPSIS DUE TO A COMBINATION OF FACTORS?

The sections above have provided a flavour of the research into chromostereopsis; the experimental results appear to demand complex models but these models have, for the most part, remained rigorously within a framework which allows only an optical explanation. That is to say, the assumption is that chromostereopsis arises because a real binocular disparity is present on the retinae. Simonet and Campbell[15,16] have challenged this assumption with a thorough investigation of chromostereopsis with a large group of subjects. They presented blue and red slits aligned one above the other, and asked subjects to view them monocularly and say whether the lower one appeared to lie directly beneath the upper slit, to the left, or to the right. If one assumes (as most researchers have) that the depth effect in chromostereopsis is a direct function of binocular disparity, then it should be possible to predict the direction of chromostereopsis from the directions of monocular disparity measured in the two eyes. Simonet and Campbell found that at high levels of illuminance, the direction of chromostereopsis was well predicted from the direction of monocular disparity, but at low levels the direction chromostereopsis and monocular disparity were uncorrelated. If correct, these results would question the assumption that the depth effect is mainly based on the binocular disparity caused by shifts in the refractive index with wavelength. However, it is possible that these results are invalid. Video recordings showed that when one eye was covered for monocular viewing, a compensatory dilation occurred in the unoccluded eye, so that monocular and binocular conditions were not strictly comparable. Simonet and Campbell argue that this may not be too important because this compensatory dilation was also found in subjects whose direction of monocular disparity was in agreement with the direction of chromostereopsis. However, only direction and not magnitude was measured – it may be that the compensatory dilation was the cause of the lack of correlation, but in subjects whose monocular and binocular conditions were in agreement, the effect was not large enough to reverse the depth effect. One solution here might be to investigate the monocular disparity effects with artificial pupils.

Research in our laboratory[17] also suggests a strong monocular component to the perception of depth in coloured displays. (We are reluctant to suggest a monocular component in chromostereopsis as this seems a contradiction in terms. Perhaps we should reserve the term chromostereopsis to cover the depth effects predicted by optical theory and introduce the possibility that there are other cues to depth in operation as well.) We have found that luminance alone can provide a potent cue to depth, that is, a bright red bar appears closer than a dark red bar seen against a black background and a bright blue bar appears closer than a dark blue bar, see *Figure 1*. Furthermore we have found that presenting red and blue objects at equiluminance on a black background appears to reduce the depth effect in most observers. (One might regard the fact that bright objects appear closer to be a special case of aerial perspective, see O'Shea *et al.*[18].) In many experiments on chromostereopsis little regard has been paid to the colour and luminance of the stimuli beyond choosing one red and one blue. (There are exceptions to this lack of rigour of course, Vos amongst them.) In such uncontrolled conditions red objects will usually enjoy considerably higher luminance than blue objects. For example, we produced a demonstration of chromostereopsis on a computer screen; we chose the brightest red and blue available and found that the red was some 50% higher in luminance. This reflects the fact that on most screens the red phosphor is more luminous than the blue. The same is true for printed material; reds are usually of a higher luminance than blues. Thus in many demonstrations of chromostereopsis at least part of the observed depth effect may be attributed to luminance or brightness differences. Our research suggests that these effects are purely monocular and thus must be considered separately from any optical theory which determines the extent of binocular disparity that is generated by coloured stimuli.

CONCLUSION

The original explanation of chromostereopsis given by Bruecke and championed by Einthoven clearly identifies the major component of the effect, chromatic aberration combined with the positioning of the fovea about 5 degrees into the temporal retina to produce a disparity that results in red objects being perceived closer than blue objects. There are problems for this simple model. Some people report the opposite effect and it is common for the depth effect to be reversed as the brightness of the display is changed. Two factors have been proposed to account for these complications: eccentric pupil dilation and the Stiles–Crawford effect. However, neither of these can be the whole explanation – the effects can persist when artificial centric pupils are used and when the pupils are too small for the Stiles–Crawford effect to be significant. We believe that both of these factors contribute independently to determine the *effective* pupil centre. The effect of this effective pupil centre may work with or against the effect of the misalignment of the visual and optical axes in determining the extent and direction of chromostereopsis.

In addition to these purely 'optical' causes of chromostereopsis we believe that perceived depth can arise as a result of powerful luminance cues to depth. Bright objects are perceived to be closer than dim objects by most people; generally in displays incorporating both red and blue objects the red objects are at a higher luminance by virtue of the fact that red is closer to the peak of the human photopic luminosity function. The result is that the perceived depth seen in chromostereopsis may often be the combination of a luminance-based depth effect and a colour-based depth effect.

For those who wish to produce a convincing chromostereoscopic depth effect we recommend that a bright red bar and a somewhat dimmer blue bar are viewed against a black background. Keep both bars in central vision and try to eliminate other cues to depth – try the effect in a completely dark room for example. Of course there may be occasions when chromostereopsis is an unwanted distraction and needs to be eliminated. For this we advise (i) reducing the luminance of the red bar somewhat and increasing the luminance of the blue to compensate; (ii) increasing background luminance and (iii) including other cues to depth into the field. This may not abolish the effect in all observers but it should lessen the effect considerably.

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