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Chromostereopsis and stereograms

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Abstract

Aim: **To explore the effect that colour has on fusion range. An illusion of depth can be created by colour (chromostereopsis). To most observers chromostereopsis is the perception that a red stimulus is in front of a blue stimulus when it originates from the same fronto-parallel surface, and is due to chromatic aberration. Chromostereopsis cues can complement or conflict with disparity cues in a stereogram. This may result in an increase or decrease in an observer's binocular control over the stereogram. In this study, fusional range was used as a measure of binocular control.**

Methods: **A group of students aged 18–22 years ($n = 30$) participated in a repeated measures design experiment. Three stereograms, viewed on a synoptophore, consisted of a 'control' stereogram with disparity cues only, a stereogram with 'complementing' chromostereopsis cues and a stereogram with 'conflicting' chromostereopsis cues. The participants' positive and negative fusion ranges were recorded for each stereogram and were analysed separately to account for any possible shift in total fusion range.**

Results: **There was a statistically significant difference between the three stereograms. Where 'complementing' chromostereopsis cues are present the positive and total fusion ranges increased, whilst 'conflicting' chromostereopsis cues caused a decrease in the positive and total fusion ranges.**

Conclusion: **Chromostereopsis does have an effect on the binocular control of a stereogram and may have applications to orthoptic exercises.**

Introduction

Chromostereopsis (or colour stereoscopy) is a phenomenon in which colour acts as a depth cue. To most observers a red stimulus appears to be in front of a blue stimulus when it originates from the same fronto-parallel surface. Theories have been around for over a hundred years linking the effect of longitudinal chromatic aberration (LCA) and the binocular disparity caused by transverse chromatic aberration (TCA).

Einthoven, writing in 1885, is credited with the first qualitative explanation of chromostereopsis: '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 (LCA) but make different angles with the optic axis, and will thus stimulate disparate points (TCA)'.[1] Chromatic aberration (CA) within the human eye is caused by dispersion of different wavelengths of light. The emmetropic human eye is maximally sensitive to wavelengths of 555 nm under photopic conditions. LCA is experienced along the optical axis as illustrated in Fig. 1. The eye has to accommodate to bring long-wavelength light (perceived as red) from behind the retina into focus. Accommodation is relaxed to allow short-wavelength light (perceived as blue) to focus on the retina. Differences in accommodation exerted to bring colours into focus provide feedback to the visual system. It was hypothesised that proprioceptive impulses from the ciliary muscle could be interpreted as relative depth cues creating chromostereopsis.[2] Depth cues are also created by binocular disparity in chromostereopsis due to TCA where pupil alignment causes colour foci to 'make different angles with the optic axis'.[1] TCA produces coloured blur circles on the retina, so that red blur circles lie temporally in relation to the blue blur circle in each eye. These act as binocular disparity cues at corresponding points in each retina ('colour diplopia'). Projections of the red disparate points appear to originate from a nearer apparent depth plane (Fig. 2). Ye *et al.*[2] strongly suggested binocular disparity (TCA) alone creates chromostereopsis. They found chromostereopsis was still demonstrated using a pin hole which eliminated accommodative demand (LCA).

The visual axis usually falls temporally on the retina of each eye, at an angle of about 5° to the optical axis (Fig. 1). Natural pupils are generally aligned with the visual axis.[2]. Einthoven[1] commented, 'It follows that individuals with temporally eccentric pupils see red in front of blue, while with nasally eccentric pupils the relief is reversed'; this is supported by the findings of Winn *et al.*[3] This is called 'negative chromostereopsis', where the usual effect of chromostereopsis is reversed: blue is perceived closer than red. Allen and Rubin[4] found that subjects with negative angle kappa had reduced or negative chromostereopsis. Having a negative angle kappa means pupillary centres are displaced nasally to the visual axis and is relatively rare. This may explain why only a minority of observers experience negative chromostereopsis.[5]

Guibal[6] demonstrated that the sense of near was increased with the addition of the colour red but that chromostereopsis cues did not override geometric depth

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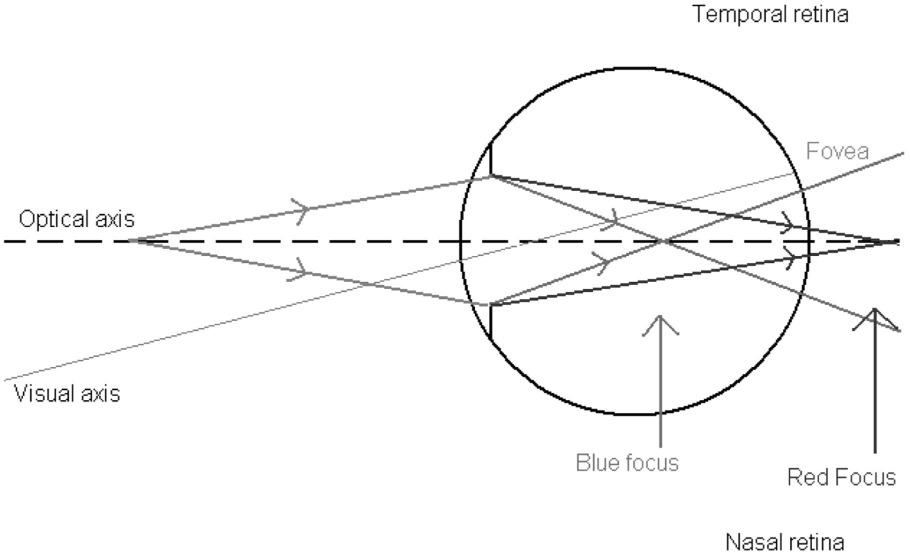

Fig. 1. The chromatic aberration within the eye and the angle of the visual axis in relation to the optical axis.

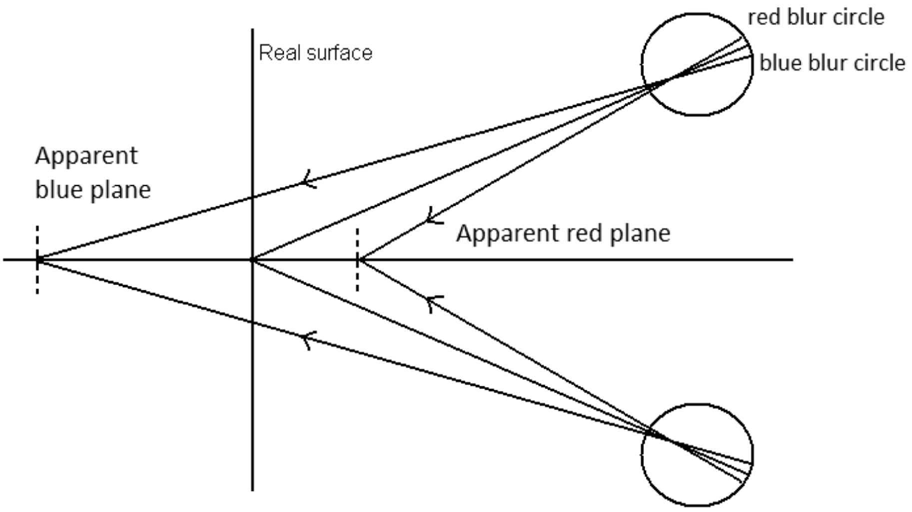

Fig. 2. Apparent depth planes perceived due to transverse chromatic aberration causing binocular disparities between coloured blur circles.

cues. In the current experiment, chromostereopsis was an additional depth cue to those created by disparity. The addition of a chromatic depth cue to a stereogram may complement or conflict with the disparity cues in a stereogram. Our hypothesis is that complementing chromostereopsis cues would improve binocular control of a stereogram, whereas conflicting chromostereopsis cues would reduce binocular control. In this study, fusional range is used as a measure of binocular function/control. An increase in binocular control, demonstrated by an increased or extended fusional range or amplitude, may suggest improved perception of the stereogram. Reduced ease in perceiving the stereogram would result in decreased fusional amplitude.

Methods

A repeated measures design was used so that three conditions were tested on each participant. Each participant viewed three stereograms on the synoptophore, which were created by pairs of synoptophore slides. The first pair of slides (Fig. 3) formed the 'control' slides, to produce the control stereogram. Each slide consisted of two black circles: a larger, outer one and a smaller, inner

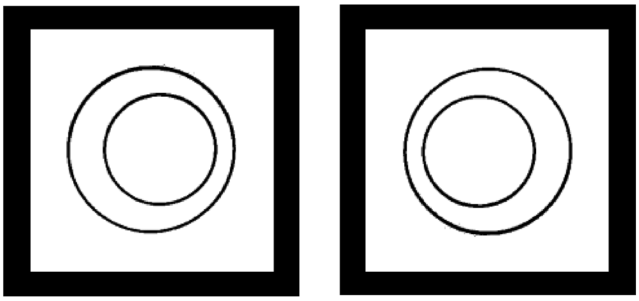

Fig. 3. The control set of synoptophore slides.

Table 1. Averages and standard deviations (SD) for total, positive and negative fusion ranges with different stereograms

	Average total fusion range (°)	SD for total fusion range (°)	Average positive fusion range (°)	SD for positive fusion range (°)	Average negative fusion range (°)	SD for negative fusion range (°)
Control stereogram	31.73	14.32	25.77	13.50	−5.97	1.85
Complementing stereogram	35.33	13.19	29.77	13.08	−5.57	1.76
Conflicting stereogram	29.53	13.59	23.90	12.88	−5.63	2.47

one. The inner circle from each slide was displaced towards the participant so that fusion of the disparity cues produced the appearance of a protruding inner circle when viewed through the synoptophore. These slides were similar to existing slides D1 and D2 produced commercially by Clement Clarke. The next pair of slides were the 'complementing' slides and formed the complementing stereogram. Cues of chromostereopsis complemented disparity cues because the inner circle was red and the outer circle was blue. The final pair of slides were named the 'conflicting' slides and formed the conflicting stereogram. The cues of chromostereopsis conflicted with disparity cues as the inner circle was blue and the outer circle was red.

The order of viewing was determined by an assigned random order and an equal number of participants experienced each order. The pairs of slides were placed in occlusive packets labelled 'A', 'B' and 'C' in an attempt to avoid the examiner knowing the order. Thirty students aged 17–22 years were used. Participants were emmetropic or wore refractive correction, with monocular visual acuities 0.1 logMAR units or better with each eye. A cover test was carried out at 1/3 m and 6 m ; deviations were not measured. Twenty-four participants were exophoric, 5 were esophoric and 1 was orthophoric. All participants demonstrated stereo-acuity of 100 seconds of arc or better on the Frisby stereo-acuity test. An Ishihara colour vision test demonstrated no protan or deutan colour vision defects in any participant. Signed consent was obtained from the participants.

Procedure

The amplitudes of both positive and negative fusion ranges were recorded once for each participant with each of the three stereograms viewed on the synoptophore. This was carried out by starting with locked synoptophore arms with all measurements at zero. Then the fusion dial was turned so as to slowly move the two images at equal speed away from the centre (zero) and therefore away from each other. The participant was instructed to report the 'end point', which was the point at which they could no longer fuse the two images and noticed diplopia. The end point was recorded to the closest degree on the fusion dial. After each end point was reached the synoptophore arms and fusion dial were returned back to zero.

Statistical analysis

One-factor ANOVA was carried out to determine any difference in results between the three stereograms. The positive fusion range was analysed separately to the negative fusion range. Order effects and presence of heterophoria were considered.

Results

ANOVA of total fusion ranges for the three stereograms showed a statistically significant effect ($F(2,47) = 4.998$, $p < 0.015$). There were no order effects.

Table 1 shows the averages and standard total deviations for total fusional range and its component parts (positive and negative fusional ranges) under the three conditions. Fig. 4 visualises these data. There was an increase in average positive fusion range with complementing chromostereopsis cues and a decrease with conflicting cues compared with the average positive range attained with the control. ANOVA of the three sets of data showed a statistically significant effect for positive fusion range also ($F(2,46) = 5.693$, $p < 0.01$). ANOVA showed there was no statistically significant effect for negative fusion range ($F(2,52) = 0.768$, $p > 0.45$).

Discusssion

Our hypothesis was that additional complementing chromostereopsis cues would improve an observer's binocular control of a stereogram. Statistical analysis of the total positive fusion range supports this hypothesis. The total fusion range increased with complementing chromostereopsis cues and decreased with conflicting cues. Breaking the results down into their components shows that the effect on total fusion ranges is due entirely to a significant effect on the positive fusional range. Statistical analysis of the negative fusion range shows chromostereopsis has no effect.

The reason why chromostereopsis does not affect negative fusion range is, as yet, unexplained. It would be interesting to compare the results of a similar experiment with the synoptophore slides' inner circle displaced away from the participant instead of towards them to see whether the same interaction is found between total and component fusion ranges.

We attempted to make the examiner blind to the order of conditions by storing the slides in occlusive labelled bags, but this could have been a potential source of examiner bias. Using an assistant to place the slides into the synoptophore could avoid any bias. Other elements of the experiment that could be improved upon were: regulating the speed of tube vergence, improving the accuracy of recording the break point, removing ceiling effects on the positive fusional range, monitoring pupils, establishing individual preference for positive or negative chromostereopsis, screening for eccentric pupils and screening for negative angle kappa (Allen and Rubin[4] found this is associated with negative chromostereopsis). Due to the small sample size of esophoric and orthophoric patients in this study, sufficient analysis of the effect of heterophoria on chromostereopsis was not

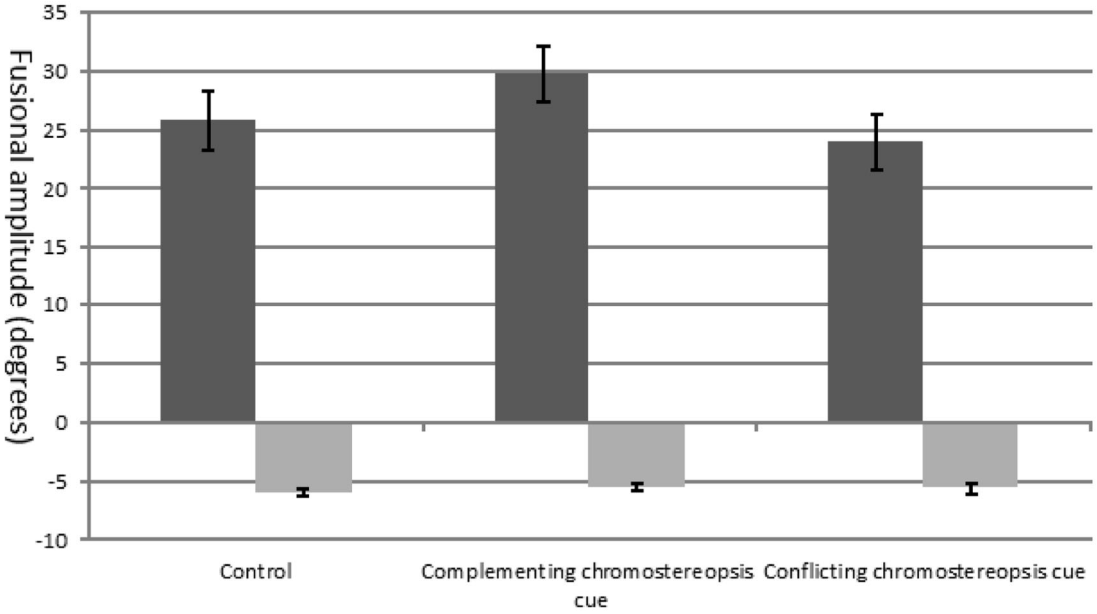

Fig. 4. The average total, positive and negative fusion ranges with different stereograms, including error bars.

possible. It is also possible that different refractive errors may have an effect on chromostereopsis if inducing a prismatic effect. Lenses that are chromatically uncorrected and with base-out prisms of at least 5^{Δ} increase chromostereopsis, whilst base-in prisms of 5^{Δ} or more induce negative chromostereopsis.[4] These optical enhancements could be used to control chromostereopsis and investigate further its influence on binocularity.

Conclusion

Chromostereopsis does have an effect on the binocular control of a stereogram. Applications of these findings can be made to stereograms used as orthoptic exercises. Giving patients a similar stereogram to that used in this experiment with chromostereopsis cues that complement the desired perception of the stereogram may help them to perceive the three-dimensional illusion more easily. Conflicting cues may challenge the patient further.

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The authors declare they have no competing interests.

Investigation of participants was in accord with the guidelines of the Declaration of Helsinki.

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