

**Interocular Differences in Transverse Chromatic Aberration Determine
Chromostereopsis for Small Pupils**

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Abstract

Chromostereopsis has been attributed previously to interocular differences in foveal transverse chromatic aberration (TCA). We tested this hypothesis by measuring chromostereopsis as a function of the separation of small artificial pupils. We also measured the monocular transverse chromatic aberration under the same conditions. Our results show that chromostereopsis with small pupils can be precisely accounted for by the interocular difference in monocular transverse chromatic aberration. This relationship is closely predicted by a simple water eye model.

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Introduction

Equidistant objects of different color often appear to lie at different distances, with red objects generally appearing closer than blue on a black background (Verhoeff, 1928; Hartridge, 1947; Kishto, 1965). This phenomenon, originally reported by Goethe in 1810 (Sundet, 1978), is generally referred to as chromatic stereoscopy (Bennett and Rabbetts, 1984; Hartridge, 1918), color stereoscopy (Kishto, 1965; Loewenstein and Donald, 1941; Sundet, 1972; Vos, 1960) or chromostereopsis (Allen and Rubin, 1981; Bode, 1986; Owens and Leibowitz, 1975; Simonet and Campbell, 1989; Simonet and Campbell, 1990). Chromostereopsis is more pronounced for objects with widely different spectral composition and is largest when comparing targets illuminated with short wavelengths to those illuminated by long wavelengths (Bennett, et al., 1984; Hartridge, 1947). Interestingly, not all subjects observe this effect (Verhoeff, 1928), and some tend to see a reverse effect of blue objects in front of red (Einthoven, 1885; Kishto, 1965). Also, there are several reports that the magnitude and the direction of this depth effect can change with changes in illumination. For example, subjects who report red to be in front of blue at photopic light levels often report the reverse at mesopic or scotopic light levels (Kishto, 1965; Sundet, 1972; Simonet and Campbell, 1990).

The earliest theoretical explanation for chromostereopsis by Donders in 1868 (Allen, et al., 1981; Sundet, 1978) credited the phenomenon to the greater accommodative effort required for focusing on red as opposed to blue. Subsequently, Einthoven (1885) attributed chromostereopsis to interocular differences in transverse chromatic aberration (TCA) of the human eye. Einthoven's hypothesis gained support from subsequent experimental observations that changes in location of small artificial pupils can change the magnitude of chromostereopsis (Kishto, 1965; Owens, et al., 1975; Vos, 1960). The reasoning is that pupil displacement changes the amount of monocular TCA and thus the location of differently colored retinal images (Ivanoff, 1953; Thibos, et al., 1990). Under

binocular conditions, interocular differences in pupil locations will produce interocular differences in the relative image position for different wavelengths. In short, pupil displacement induces TCA which creates binocular disparity and hence differences in perceived depth.

Although Einthoven's hypothesis is qualitatively consistent with some of the published experimental data, evidently no quantitative attempt has been made to confirm that monocular chromatic aberration can fully account for chromostereopsis. Also, this theory appears to be inconsistent with some of the experimental data. For example, changes in chromostereopsis with changes in pupil size (Kishto, 1965; Owens, et al., 1975; Sundet, 1972; Vos, 1960; Ye, Zhang, Bradley and Thibos, 1989; Simonet, et al., 1990) cannot be predicted from a simple geometrical optics model. Several alternative hypotheses have been introduced, most notably by Vos (1960), who argues that shifts in chromostereopsis with pupil size are due to decentration of the peak of the Stiles-Crawford effect. More recently, Simonet and Campbell (1990) showed that, at the target luminance level of 50 cd/m^2 , the direction of binocular chromostereopsis for natural pupils failed to agree with the direction of monocular TCA in four of six subjects.

In the present paper, we examine the quantitative predictions of Einthoven's model and show that, at least for small pupils, interocular differences in induced TCA at the fovea provide a robust and highly accurate means of predicting binocular chromostereopsis. Also, chromostereopsis can be closely predicted by a simple optical model of the binocular visual system consisting of two water eyes and two pinholes.

Methods

I. Experimental methods

Apparatus

Monocular and binocular experiments were both conducted with the same apparatus. Subjects viewed two vertical black rods which subtended 15 by 115 min of arc at a viewing distance of 105 cm, measured from a pinhole placed close to the subject's eye. These two rods were separately installed on two optical benches, one rod above the another. The upper rod was fixed and the position of the lower one could be adjusted laterally with 0.01 mm accuracy and longitudinally with 0.5 mm accuracy. A calibrated pair of interference filters were used to transilluminate the top and bottom halves of a glass diffusing screen with red (622 nm) and blue (433 nm) light respectively. The glass screen was positioned behind the rods, such that the top and bottom black rods were seen against red and blue backgrounds, each subtending 250 by 115 min of arc. To maximize vernier acuity, the maximum achievable target luminances were used (red target was 95 cd/m² and the blue target was 12 cd/m²). Two 0.7 mm pinholes were installed close to the eye and their horizontal positions were controlled independently to 0.1 mm accuracy with machinist's micrometers.

Experimental procedures

Five young adults with normal stereopsis and color vision participated in these experiments. Two of them were highly practiced observers. Subjects viewed the vertical rods through pinholes set as close as possible to the subject's eyes (typically less than 8 mm from the cornea) and fixed relative to the head by means of a dental bite bar. The subject's pupils were dilated with one or two drops of 1% tropicamide which produced a range of pupil sizes from 7.5 to 8.5 mm. The pinhole positions were referenced to the

visual axis that joins the fixation object to the fovea passing through the nodal point (von Helmholtz, 1909), which can be operationally defined as the axis of zero foveal TCA (Thibos, et al., 1990). The visual axis of each eye was determined separately by adjusting the pinhole horizontally until both physically aligned and equidistant rods appeared aligned.

Monocular vernier experiment

This experiment measured induced TCA separately for each eye. The method was the same two-color vernier alignment technique described by Thibos, et al. (1990). Both rods were positioned at the same distance (105 cm), and a method of adjustment procedure was used for the subject to align the rod in the blue field directly under the rod in the red field. Data were collected for pinhole positions spanning the entire horizontal extent of the dilated natural pupil. Three alignments were made for each condition. These tests were performed with the untested eye occluded. The amount of physical misalignment necessary to achieve perceptual alignment was recorded for each position of the pinhole and the mean misalignment was interpreted as the amount of induced TCA in the object space of the eye+pinhole optical system.

Binocular stereoscopic experiment

The purpose of this experiment was to measure perceived depth between objects illuminated with long and short wavelength light. Both rods were laterally aligned (i.e. zero vernier offset) and the subject viewed the target binocularly through two pinholes. In the main experiment, the pinholes were initially aligned on the right and left visual axes. They were then moved symmetrically either both nasally or both temporally from the visual axes. In an additional control experiment, the initial pinhole positions were both displaced by 1 mm either to the right or to the left of the visual axes. In these experiments, the subject adjusted the longitudinal distance of the rod in the blue field until it appeared to lie in the same plane as the rod in the red field. Three alignments were made for each

condition. The physical depth between rods necessary to eliminate the perceptual depth between rods was recorded for the full range of pinhole separations and the mean depth was interpreted as the magnitude of chromostereopsis in object space.

II. Basis for predictions

TCA is described by the angular separation of the chief rays for different wavelengths (Thibos, et al., 1990). The magnitude of TCA produced by manipulating the pinhole location is defined as induced TCA and is directly proportional to the misalignment of the pupil relative to the visual axis (Thibos, Bradley, Still, Zhang and Howarth, 1990). As shown in Fig. 1, TCA induced by displacement of an artificial pupil may be specified either in the image space (τ') or the object space (τ). The amount of induced TCA depends on angle of incidence of the chief ray, which can be varied by changing pinhole location. When the pinhole is displaced from the visual axis, the blue chief ray (short wavelength) is more refracted than the red chief ray (long wavelength). Therefore, the induced TCA results in a chromatic difference of position in the retinal images (Fig. 1a). However, our experimental measurements of induced TCA are determined in object space. This is achieved by the two-color vernier- alignment technique described by Thibos et al. (1990). In order to make images with different wavelengths superimpose, the objects must be physically separated by amount τ (Fig. 1b). For convenience of calculation, we adopted the sign convention that TCA in object space is positive when the angle is clockwise from the blue ray to the red ray. Using a simple water-eye model and ray tracing, the variation of induced TCA with pupil displacement can be very closely predicted (Thibos, et al., 1990). In the paraxial region, where the pinhole is near the visual axis, induced TCA is proportional to pinhole displacement with the constant of proportionality equal to the chromatic difference of refraction of the model (Thibos, et al., 1990).

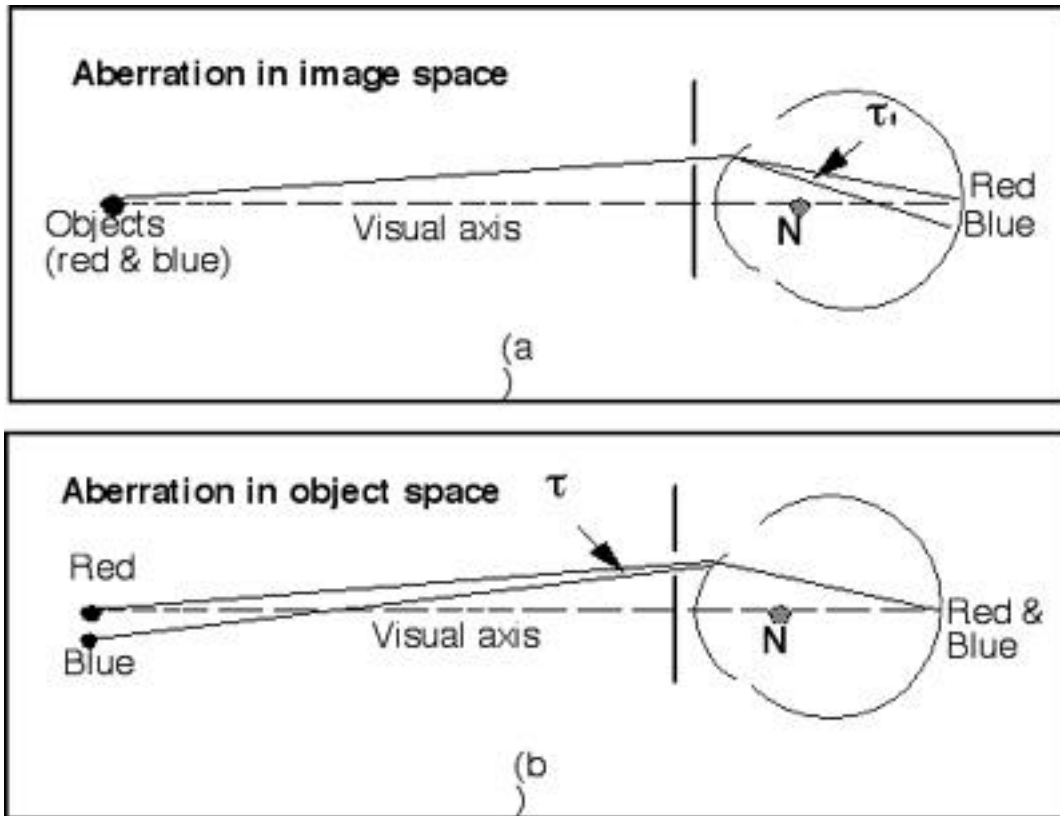


Fig. 1. Schematic of the water-eye model which assumes that the red light is in focus on the retina. The illustrated rays pass through the center of the pinhole limiting aperture and are referred to as "chief rays" in the text. (a) The relationship between TCA and the pupil position in image space for the model eye. Point N is both the nodal point and the center of the refracting surface. Angle τ' is TCA in image space. (b) TCA (τ) in object space. Black circles indicate the positions of the red and blue objects. In order to superimpose two color images, these objects must be separated because of TCA.

In the binocular case, the chromatic difference of position in the retinal images may produce the binocular disparity giving rise to chromostereopsis. If chromostereopsis is only determined by TCA, the interocular difference in foveal TCA should predict the binocular disparity. To generate this prediction, we can build a simple model binocular system by combining two water eyes and two pinholes as shown in Fig. 2. In Fig. 2a, the filled circle represents an object emitting long (red) and short (blue) wavelengths. If we assume the blue images fall on the fovea, then the red images fall temporal to the fovea when both pinholes are displaced temporally. Therefore, the red images will fall on non-corresponding points of the retina and the red object (open circle) will appear in front of the blue.

Our scheme for experimentally measuring chromostereopsis is illustrated in Fig. 2b. The amount of chromostereopsis is indicated by d_0 , the longitudinal separation between red and blue targets which appear to be at the same depth. By Einthoven's theory, the amount of binocular chromostereopsis (d_0) is related to the interocular difference of monocular TCA ($\tau_r - \tau_l$) by the geometry of Fig. 2b. Thus, the explicit hypothesis we sought to test was that the following equation holds:

$$\tau_r - \tau_l = \frac{2B}{d^2 + d} \frac{d_0}{d_0} \quad (1)$$

where $2B$ is the inter-pinhole distance, d is the viewing distance, and the angles τ induced TCA are specified in radians.

A link between the measured amount of chromostereopsis identified in Fig. 2b and the apparent depth shown in Fig. 2a may be established by appealing to the optical properties of the water-eye model. For this model, the rate of change of the external angle τ with displacement of the pinhole is approximately equal to the chromatic difference of refraction (Thibos et al., 1990). Similarly, the rate of change of the visual angle ϕ with pinhole displacement is also equal to the chromatic difference of refraction (Thibos, Bradley and Zhang; 1990). It therefore follows that to first approximation, $\tau = \phi$ and thus measured and apparent depth are equal. This result holds only in the paraxial region, however, and for larger displacements of the pupil this equality breaks down. For example, apparent depth is expected to be 18% smaller than measured chromostereopsis when the pinholes are displaced 3.5 mm from the visual axes.

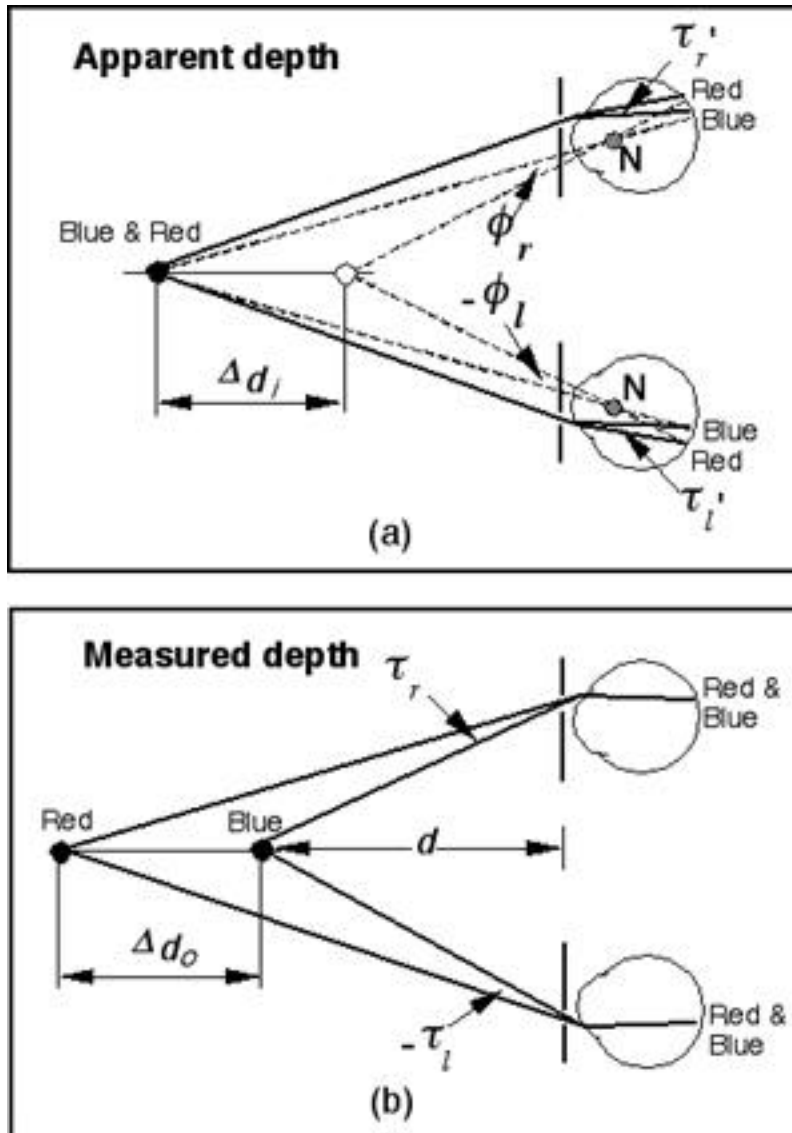


Fig. 2. Schematic of the model binocular system consisting of two water eyes. Filled dots represent the positions of the blue and red objects. (a) The relationship between binocular disparity and induced TCA in image space. Distance Δd_i is perceived depth when red and blue objects lie at the same distance. Angles τ_r' and τ_l' is induced TCA of the right eye and left eye in image space. Angles ϕ_r and $-\phi_l$ are subtended by the displaced red and blue images when referenced to the nodal points (N). Difference of these two angles [$\phi_r - (-\phi_l)$] is defined binocular disparity. (b) The relationship between chromostereopsis and induced TCA in object space. Distance Δd_o is measured longitudinal separation of two rods which appear at the same distance and d is the viewing distance. Angles τ_r and $-\tau_l$ are the object space induced TCA of the right eye and left eye, respectively. Difference of these two angles [$\tau_r - (-\tau_l)$] is the predicted chromostereopsis.

Results

Monocular transverse chromatic aberration

Induced TCA for the right and left eyes of four subjects are shown in the four panels of Fig. 3. The TCA is plotted as a function of pinhole position relative to the visual axis. Positive and negative numbers on the abscissa represent temporal and nasal displacements from the visual axis, respectively. Positive TCA in Fig. 3 indicates that the rod in the blue field was positioned to the left of the rod in the red field in order that they appeared aligned. Triangles and squares show the mean data for the right and left eyes. The maximum standard error for these mean data was less than 0.6 min of arc which is less than the symbol size. As expected from previous experiments (Thibos, et al., 1990), when the pinholes were decentered, TCA increased approximately linearly. The right eye and left eyes had the same amount of TCA and there were no large difference between individuals. Slopes of the least-squared regression line fit to the pooled data are 4.9 min/mm for the right eye (R-squared 0.978) and -4.9 min/mm for the left eye (R-squared 0.967). These values are slightly greater than obtained previously (4.4 min/mm) using the same methods (Thibos, et al., 1990) and also greater than theoretical prediction (lines in Fig. 3) for the water eye (4.0 min/mm).

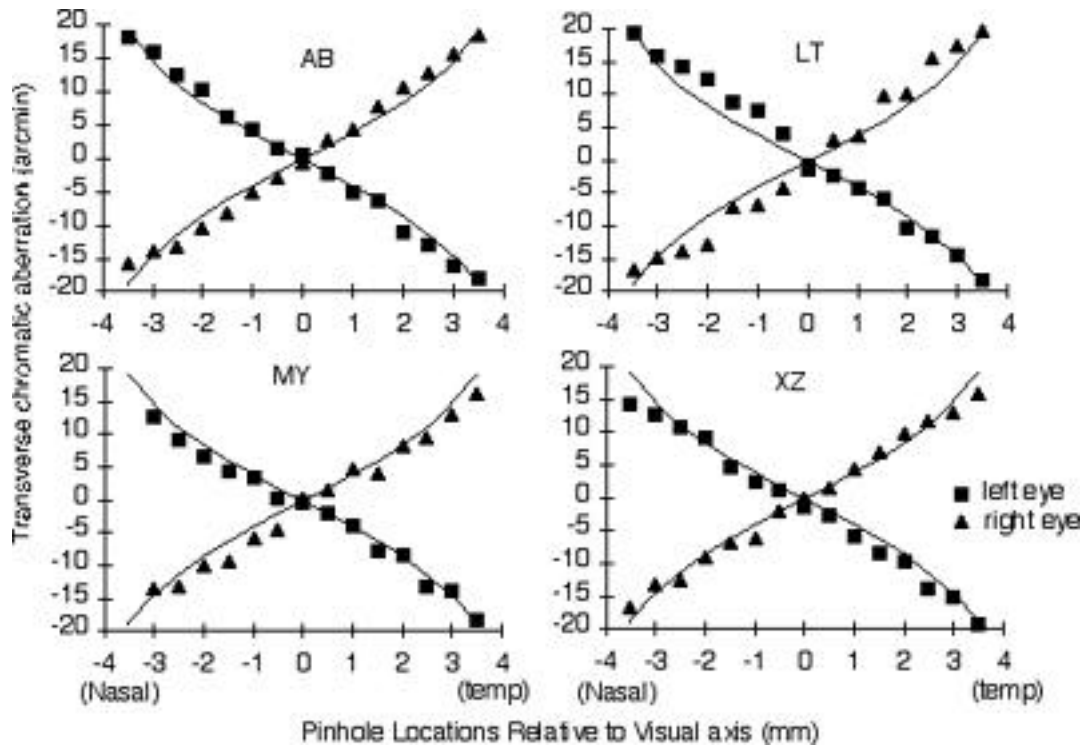


Fig. 3. Induced TCA (min of arc) is plotted a function of the pinhole location (mm). Positive TCA represents the blue ($\lambda = 433$ nm) rod located left of the red ($\lambda = 622$ nm). Positive pinhole locations are temporal and negative locations are nasal with respect to the visual axis. Squares and triangles show data of the left and right eyes, respectively. Lines are predictions of the water-eye model.

Chromostereopsis

Our main experimental results are a quantification of the following observation. When a pair of aligned, black rods set against a bipartite, two colored background are viewed through symmetrically displaced pinholes, they appear to lie at different distances. This difference in apparent distance is greatest when the pinholes are maximally displaced. In order to make the rods appear at the same distance, the subject must separate these two rods longitudinally. From this separation, angular chromostereopsis can be calculated by the right side of formula (1) and the results are shown by the symbols in Fig. 4 as a function of pinhole separations. On the lower abscissa, pinhole separation (inter-pinhole distance) has been normalized by subtracting the horizontal separation of the right and left eye visual axes. The upper horizontal axis plots the monocular pinhole position relative to

the visual axes. Positive chromostereopsis represents the case when subjects set the rod in the red field behind the rod in the blue field in order to make both rods appear equidistant (a sign convention originated by Hartridge, 1947). Positive chromostereopsis always occurs with bi-temporal pinholes. Our results show that chromostereopsis increases approximately linearly with displacements of the pinholes and that bi-nasal and bi-temporal displacements produce equal and opposite chromostereopsis. Because of our operational definition of the visual axis, chromostereopsis is absent when both pinholes are on the visual axes.

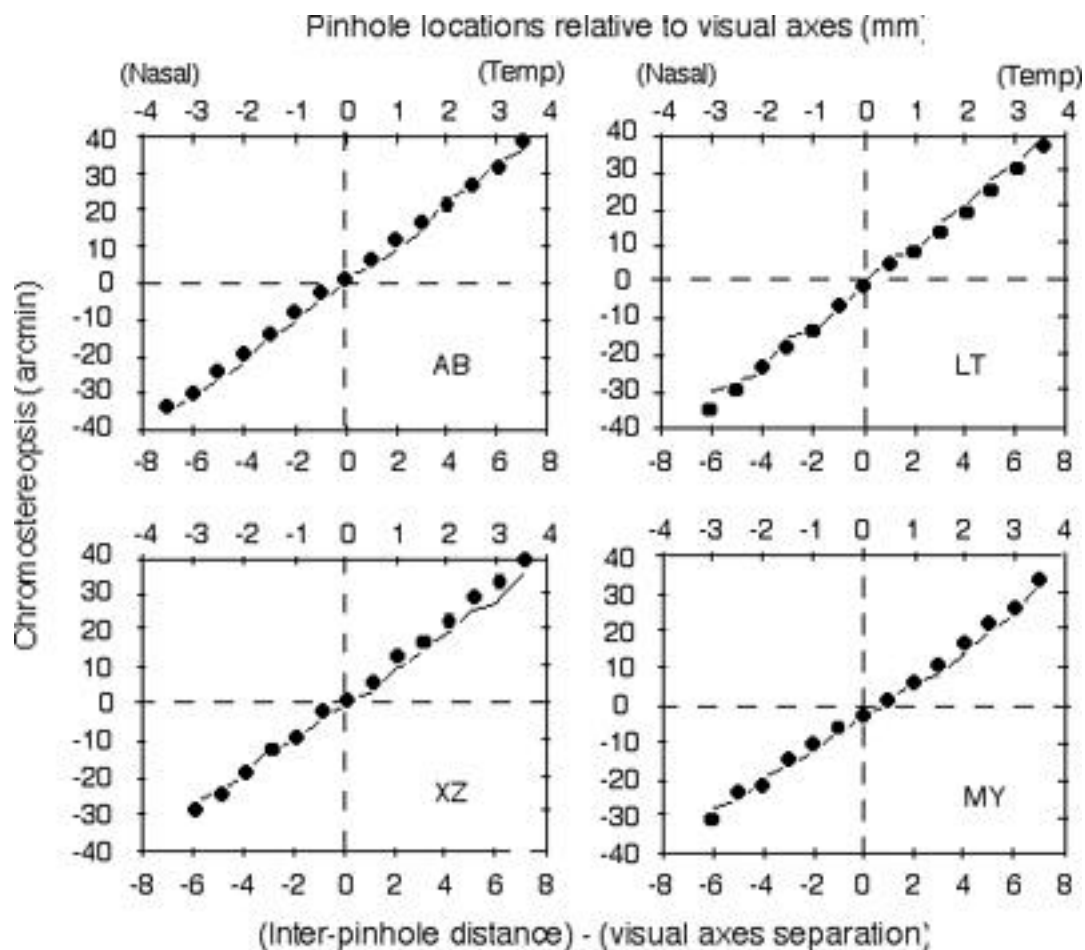


Fig. 4. Chromostereopsis is plotted as a function of pinhole location. The upper abscissa represents the right and left pinhole locations relative to the visual axes. The lower abscissa represents the difference between the inter-pinholes distance and separation of the visual axes. Positive chromostereopsis means the rod in the red field is set behind the blue. Symbols are data from the binocular experiment and lines are predictions from monocular TCA data shown in Fig. 3.

If chromostereopsis is due to chromatic difference of monocular visual direction, then the results in the Fig. 3 should predict the chromostereopsis data of Fig. 4. For example, displacing the pinholes temporally 2 mm from visual axes in each eye for subject AB will introduce approximately 10 min TCA for the right eye and - 10 min TCA for the left eye. Then, the interocular difference in visual direction is 20 min. This prediction has been calculated for all four subjects and is shown by the solid lines in Fig. 4 which are with reference to the upper abscissa in Fig. 4 which is the monocular displacement of a pinhole from the visual axis of each eye. The quantitative agreement between the binocular results and the prediction of chromostereopsis obtained from each subjects' monocular TCA data is very good (Table 1).

| Subject | Chromostereopsis | | Prediction by TCA data | | Prediction by model |
|---------|------------------|-----------|------------------------|-----------|---------------------|
| | Slope (min/mm) | R-squared | Slope (min/mm) | R-squared | Slope (min/mm) |
| AB | 4.94 ± 0.10 | 0.998 | 4.79 ± 0.09 | 0.998 | 4.0 |
| LT | 5.30 ± 0.20 | 0.993 | 5.47 ± 0.33 | 0.982 | |
| MY | 4.23 ± 0.10 | 0.997 | 4.33 ± 0.11 | 0.997 | |
| XZ | 4.96 ± 0.15 | 0.995 | 4.48 ± 0.18 | 0.992 | |
| Average | 4.86 | | 4.77 | | |

Table 1. Comparison of the effect of inter-pinhole separations on experimentally determined chromostereopsis, chromostereopsis predictions from monocular TCA measurements, and the model binocular system. Slopes (+/- 1SEM) for the central 3 mm portion of the pupil are from linear fits to the chromostereopsis data and predictions shown in Fig. 4.

To compare these results with predictions from the water-eye model, data from all four subjects are pooled within the shaded area in Fig. 5. Calculations of chromostereopsis by the model binocular system for symmetric displacements of both pinholes from the visual axes are shown in Fig. 5 by the line. The average slope of linear fits for four subjects' mean data in the central 3 mm is 4.9 min/mm and the slope of central linear portion of theoretical curve is about 4.0 min/mm. Therefore, compared to real visual systems, the model binocular system has slightly less (82%) chromostereopsis. Slope data from all four subjects are given in Table 1.

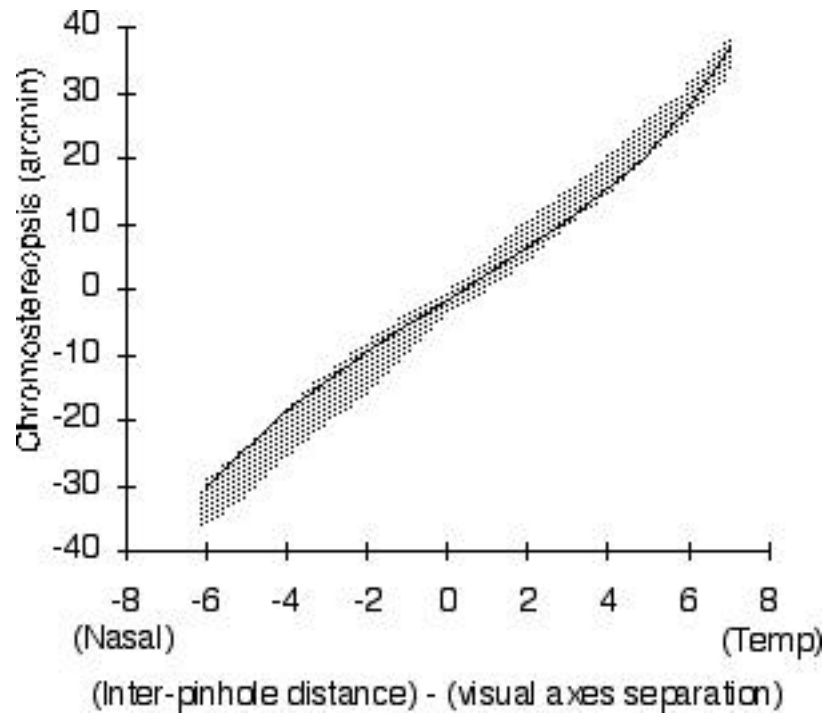


Fig. 5. Comparison The predicted chromostereopsis (line) of our model eye system is compared to data from four subjects as a function of pinhole location with respect to the visual axis. The shaded area shows the range of results for four subjects.

Additional test of the model

Both the predictions and experimental data described in Fig. 4 were obtained for a binocular visual system with two pinholes displaced symmetrically (bi-nasally or bi-temporally) from the visual axes. Clearly this is a special case, and it is important to examine the generality of this model for predicting chromostereopsis under a wide range of pupil locations. In the symmetric case, the two eyes had approximately the same amount of induced TCA, but of opposite sign. In the asymmetric case the two eyes could have different amounts of induced TCA. According to the model, chromostereopsis is determined solely by the interocular difference of TCA. For example, no chromostereopsis would be expected if the right and left eye pinholes were both displaced to the right or left of the visual axes by 1 mm, because each eye should have exactly the same monocular TCA and their difference is therefore zero. In other words, when the right and left eye

pinholes are both displaced by the same amount in the same direction, a pair of blue or red images fall on corresponding points on the retina, thus binocular disparity and apparent depth is zero.

| Subject | Reference points | | | | | |
|---------|-------------------|-----------|-------------------|-----------|-------------------|-----------|
| | Visual axes | | Right 1 mm | | Left 1 mm | |
| | Slope / Intercept | R-squared | Slope / Intercept | R-squared | Slope / Intercept | R-squared |
| AB | 5.1 / -0.9 | 0.999 | 5.1 / +1.8 | 0.998 | 5.0 / +0.4 | 0.996 |
| MW | 4.7 / +2.3 | 0.993 | 4.8 / +1.9 | 0.987 | 4.6 / +2.2 | 0.992 |
| MY | 4.8 / +3.1 | 0.990 | 4.9 / +3.1 | 0.983 | 5.0 / +4.0 | 0.993 |
| XZ | 5.0 / -0.3 | 0.994 | 5.1 / -0.3 | 0.992 | 5.0 / -0.3 | 0.994 |
| Average | 4.9 / +1.05 | | 5.0 / +1.63 | | 4.9 / +1.58 | |

Table 2. Comparison of chromostereopsis for different conditions. Slopes (arcmin/mm) and intercepts (arcmin) are from linear fits to all chromostereopsis data for each condition (see text for details).

In order to test the generality of the model, we have repeated the binocular experiment, but using pinholes that start out asymmetrically displaced from the visual axes. Initially both pinholes were set either to the right or to the left by 1 mm with respect to the visual axes. At these two starting positions, both eyes have a substantial amount of induced TCA, but it is of equal magnitude and equal sign in the two eyes (Fig. 3). Pinholes were then displaced bi-nasally or bi-temporally from these new reference locations. Results are shown in Fig. 6 for four subjects. In Fig. 6, values on the abscissa represent the separation of the pinholes relative to the visual axes and are equal to the difference between the inter-pinhole distance and the separation of the visual axes. Zero represents pinhole separations that are equal to the visual axes separation, e.g. on visual axes (squares), both 1 mm to the right of the visual axes (circles), or both 1 mm to the left of the visual axes (triangles). The slopes (arcmin/mm) and intercepts (arcmin) of the least-squared regression line fit to the experiment data are shown in Table 2. The slopes and intercepts of these functions are very similar for each subject. The non-zero intercepts observed in two subjects probably result from small errors in determining the visual axis location. The results clearly show that binocular disparity depends only on the inter-

pinhole distance, not the absolute position of the pinholes. This confirms that it is the interocular difference in induced TCA, not its absolute amount, that determines chromostereopsis. These results imply that small head movements did not contribute any variation of chromostereopsis when the interpupillary distance was kept constant.

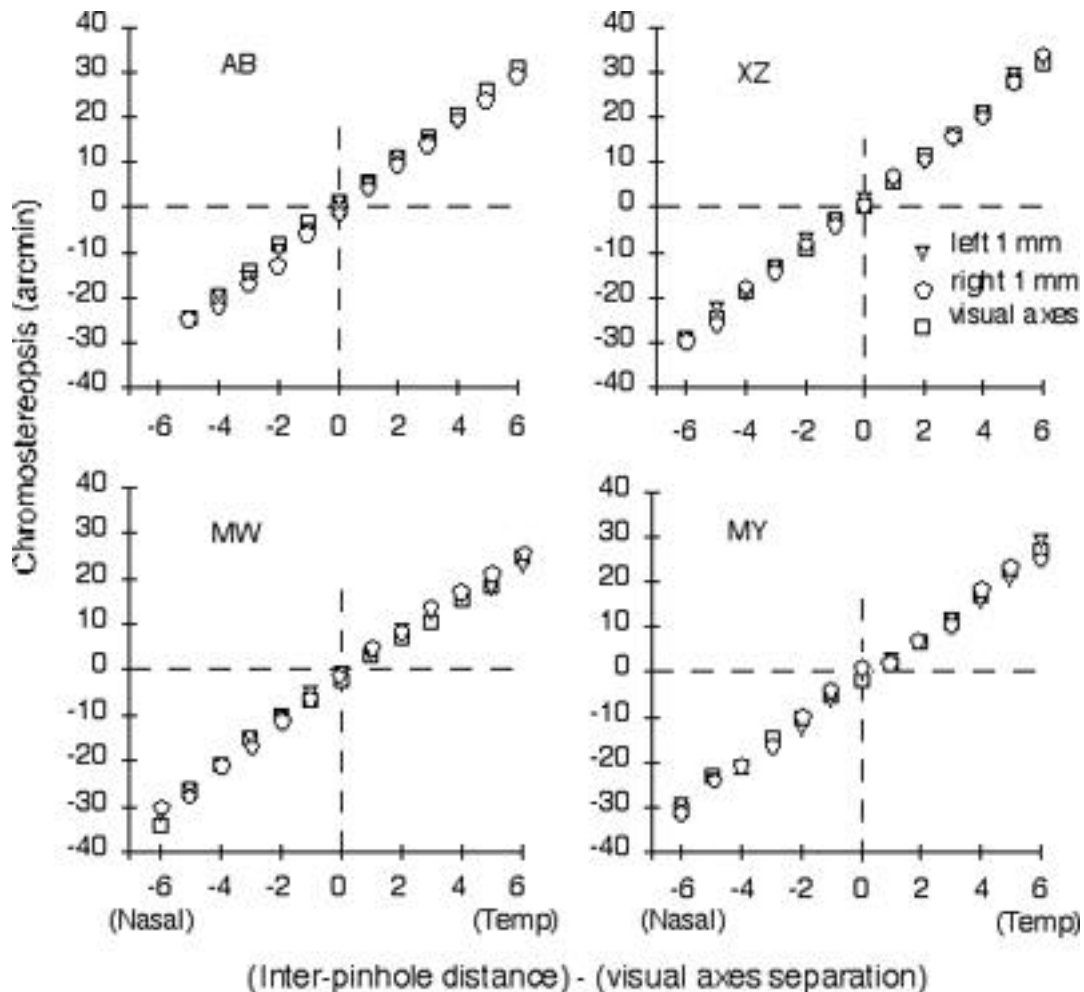


Fig. 6. The relationship between chromostereopsis and inter-pinhole distance. Positive values on the abscissa indicate that both pinholes are moved nasally with respect to the reference point. Three reference points were used: visual axes (squares), right 1 mm (circles) and left 1 mm (triangles) from the visual axis (see text for details).

Discussion

For over a century, chromostereopsis has been described as an illusion of depth resulting from interocular differences in visual direction caused by monocular transverse chromatic aberration (Einhoven, 1885). In the present paper we have reported the first quantitative test of this hypothesis and have found that for small, decentered artificial

pupils, chromostereopsis can be accurately accounted for by the measured monocular TCA. There are no large differences in chromostereopsis between individuals when pinhole positions are carefully controlled. Furthermore, the major features of chromostereopsis can be predicted quantitatively by a simple binocular optical model composed of two water eyes. However, this binocular model predicts slightly less (by approximately 18%) chromostereopsis than measured for real eyes. This small under estimation is also true for monocular TCA measurements (Thibos, et al., 1990), which suggests that the water medium of the reduced eye has less chromatic dispersion than the ocular media of the human eye.

Earlier experiments showed that interpupillary distance is important for chromostereopsis (Kishto, 1965; Owens, et al., 1975; Vos, 1960) and two of those studies provided sufficient information about stimulus wavelengths, small aperture separations, and the viewing distance to allow quantitative comparison with predictions based on the water eye (Fig. 7). Their measurements were achieved by symmetrically displacing small apertures relative to the center of the natural pupils. However, as we have shown, absolute separation of these apertures is not the important factor. Instead, chromostereopsis is determined by the separation of apertures minus the separation of the visual axes. Accordingly, we subtracted the aperture separation that produced zero chromostereopsis (i.e. the visual axis separation), and the replotted data from both studies are well matched by the theoretical prediction (Fig. 7). The slope of the least-squares regression line fit to Vos' data is -4.7 (min/mm), and fit to Owens and Leibowitz's data is -3.0 (min/mm), reflecting the narrower spectral difference used by these authors. The slope of the theoretical prediction for Vos' data is about -4.3 (min/mm) and for Owens and Leibowitz's data is about -2.9 (min/mm). Thus the same model which accounts for our experimental data also accounts for the previous by published measurements of chromostereopsis.

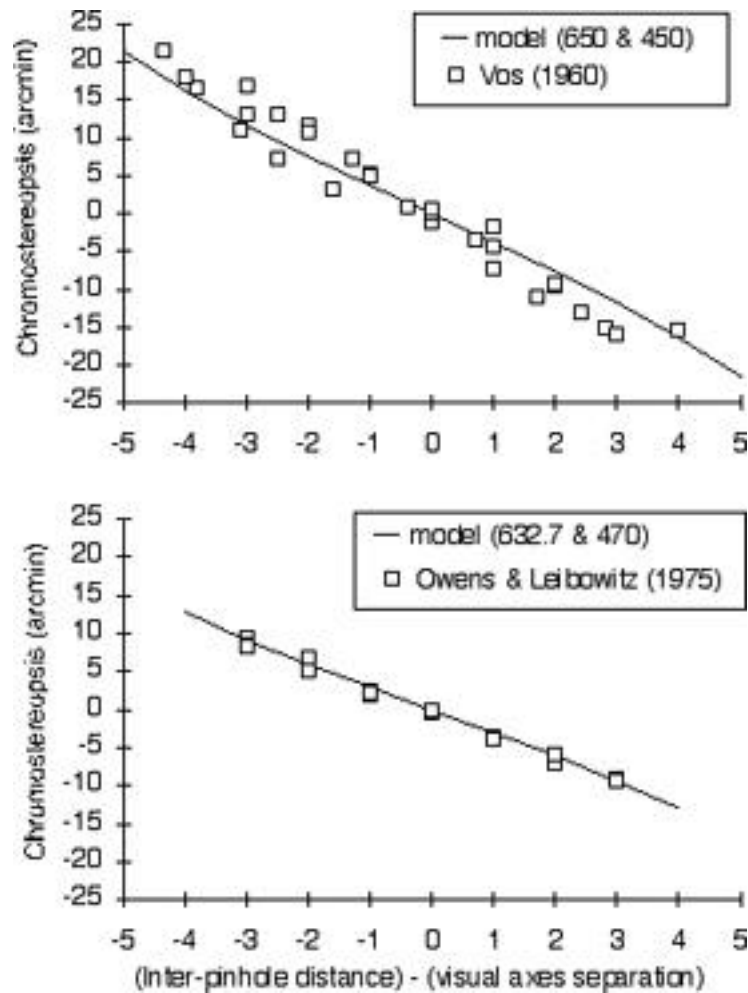


Fig. 7. Application of proposed model to published results. The abscissa represents differences between inter-pinhole distance and the separation of the visual axes. Symbols are the experiment data from Vos (1960) and Owens & Leibowitz (1975). Lines are predictions from the water eye binocular system.

Some have argued that chromostereopsis is due to the accommodation reflex (Donders, 1886; Karkowski and Lloyd, 1951). Because of longitudinal chromatic aberration, equidistant sources of different color can not simultaneously be in focus on the retina. In fact, the eye must produce more refractive power to focus long-wavelength light on the retina than to bring short-wavelength light in focus. Since the amount of contraction of the ciliary muscle is related to the magnitude of refractive power of the eye, it is hypothesized that proprioceptive impulses from the ciliary muscles convey information

about relative depth, with the effect that a long-wavelength source seems to be nearer than a short-wavelength source (Donders, 1886; Karkowski, et al., 1951). However, our use of small pinholes effectively eliminated the differential accommodative demand introduced by longitudinal chromatic aberration because depth of focus is equal to 1.7 diopters for a 1 mm pupil (Campbell, 1957). Therefore, neither the large amounts of chromostereopsis, nor the dependence of chromostereopsis on pinhole positions can be accounted for by the accommodation reflex theory.

With natural pupils, Simonet and Campbell (1990) found no correlation between TCA and chromostereopsis for target luminances of 50 cd/m². However, using artificial pupils, our results (Fig.4) show a high correlation between induced TCA and chromostereopsis at similar target luminances (95 cd/m² for the red target and 12 cd/m² for the blue target). There are two significant differences between their study and ours that could account for their failure to confirm Einthoven's hypothesis. First, because these authors used natural pupils, both the size and position of the natural pupil may have differed slightly in the monocular TCA and binocular chromostereopsis experiments. Also, because the natural pupils are generally closely aligned with the visual axis (Thibos, et al., 1990; Simonet and Campbell, 1990), their experiment only examined very small magnitudes of TCA and chromostereopsis (for example, only ten of sixty eyes observed any detectable TCA). Because of the near- or sub-threshold TCA and chromostereopsis, experimental variance probably reduced the correlation between these two manifestations of chromatic aberration. Therefore, we suggest the discrepancy between their two different results are probably due to the range of pupil displacements being tested and uncontrolled changes in pupil size and position.

Although our formulation of Einthoven's theory can accurately predict chromostereopsis for small pupils, it is inconsistent with a variety of chromostereopsis phenomena associated with large pupils. For example, when the pupil changes size due to

luminance change, some people see chromostereopsis reversed (Simonet and Campbell, 1990; Kishto, 1965; Sundet, 1972). Vos (1960) also found chromostereopsis for natural pupils disagreed with data for small artificial pupils with equal separations. Chromostereopsis decreases as pupil size increases (Ye, et al., 1989) which Vos (1960) suggested might be accounted for by the change of the luminous efficiency over the pupil as described by the Stiles-Crawford effect. When the pupil gets larger, the differences in luminous efficiency across the pupil become progressively more pronounced which, he argued, caused a gradual shift of the visual direction from the retinal location of the chief ray to the points of maximum brightness (Stiles and Crawford, 1933).

Our formal model developed from Einthoven's theory allows a quantitative prediction of chromostereopsis for different binocular optical instruments, e.g. microscopes. Binocular microscopes usually have less than 2 mm exit pupils (Mattas, Townsend and Leibowitz, 1978). Therefore, if the interpupillary distance of the microscope is set slightly different to the observers' visual axes separation, a color depth illusion will be generated. A 1 mm difference will produce approximately 5 min of arc disparity for blue (433 nm) and red (622 nm) objects. Also, if the exit pupil of the microscope is displaced from the visual axis of the human eye, the monocular transverse chromatic aberration will produce reduced image quality (van Meeteren and Dunnewold, 1983; Thibos, 1987) and reduced contrast sensitivity (Green, 1967). Therefore, chromostereopsis may be one of several related problems for designing optical instruments.

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