Research note

The Center-of-gravity Model of Chromostereopsis

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We propose the center-of-gravity model to explain chromostereopsis. This new model assumes that we perceive each color position at the center of gravity of diffusely projected color light, and that these positions gives binocular disparities to generate binocular stereopsis. This model fits the paradoxical pieces of findings on chromostereopsis better than do the previous two models.

Key words : chromostereopsis, longitudinal chromatic aberration, transverse chromatic aberration, center-of-gravity model

Introduction

Chromostereopsis is a binocular stereoscopic phenomenon that for many observers red stimuli appear to be in front of blue ones even if they are placed in the same frontoparallel surface (Figure 1). There is, however, a minority in which observers see blue in front of red (Hartridge, 1947; Howard and Rogers, 1995). Our preliminary surveys suggested that about 80% of observers see red in front of blue while about 20% see blue in front of red.

Moreover, chromostereopsis is a function of viewing distance, as suggested by Faubert (1994). We confirmed this function that the longer the viewing distance the stronger the effect. This function held true for both the majority and the minority (Yamauchi, 2004) (Figure 2).

Furthermore, it has been reported that the red-in-front-of-blue stereopsis reverses to the blue-in-front-of-red stereopsis at low illumination (Kishto, 1965; Sundet, 1972, 1976; Simonet and Campbell, 1990a). We have failed to detect this effect clearly in our casual setting. Inversely, we observed that chromostereopsis tends to be enhanced under dark adaptation, possibly depending on dilated pupils.

The longitudinal chromatic aberration model

There are two major models to explain chromostereopsis. One is the model based upon the longitudinal chromatic aberration, while the other is the one depending on the transverse chromatic aberration.

The longitudinal chromatic aberration refers to the optical phenomenon that in the eye's optic system the focus of blue light (short-wavelength light) is inevitably nearer to the lens than that of red light (long-wavelength light) even if they are projected

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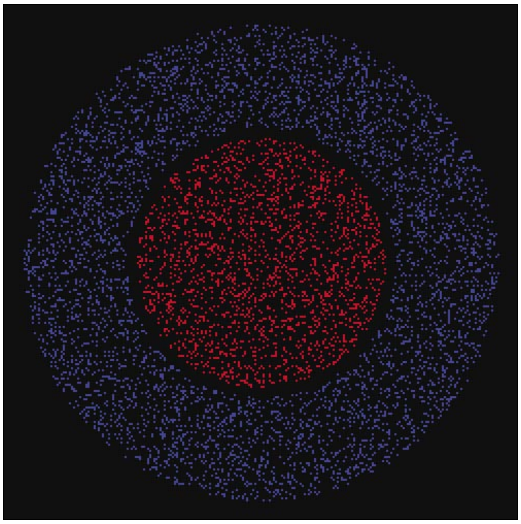

Figure 1. Chromostereopsis, a binocular stereopsis based upon the difference in color. The majority sees the circle of red random dots in front of the surrounding annulus of blue random dots. There is, however, the minority in which observers see blue in front of red. Chromostereopsis is strong when observers watch this image from more than 1 meter apart.

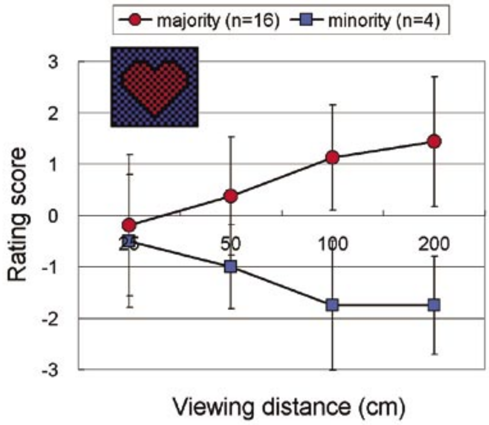

Figure 2. Chromostereopsis as a function of viewing distance (Yamauchi, 2004). Rating score 3 was given when "red appears to be in front of blue strongly" ; score 2 was given when "red appears to be in front of blue" ; score 1 was given when "red appears to be in front of blue slightly" ; score 0 means no chromostereopsis; score -1 was given when "blue appears to be in front of red slightly" ; score -2 was given when "blue appears to be in front of red"; score -3 was given when "blue appears to be in front of red strongly". The used stimulus is superimposed. The "majority" means the observers who usually see red in front of blue while the "minority" refers to those who usually see blue in front of red. For both groups, the longer the viewing distance the stronger the effect.

from the same place (Figure 3). This phenomenon depends on the difference in the refractive index, in which the index for short wavelengths is about 1.5 or 2.0 diopters greater than that for long wavelengths (Uozato, 2000). The model using the longitudinal chromatic aberration is that this foci inconsistency informs that the blue source should be farther than the red source. It is because the farther the source the nearer the focus to the lens if the refractive index is constant.

This model, however, has been discarded because chromostereopsis has to occur monocularly in this model but it actually needs binocular viewing (Howard and Rogers, 1995). Moreover, this model cannot explain why there is the minority of the blue-in-front-of-red stereopsis.

The transverse chromatic aberration model

The transverse chromatic aberration refers to the optical phenomenon that in binocular viewing blue light is projected to a more nasal part of the retina than does red light because the optical axis of the eyeball is slightly (about 5° from the visual axis: angle alpha) shifted in the outward direction from the

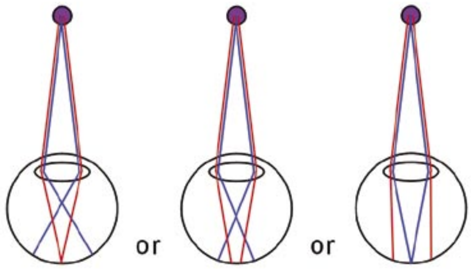

Figure 3. The longitudinal chromatic aberration. Blue has the focus nearer to the lens than red because of the difference in the refractive index depending on wavelengths of light.

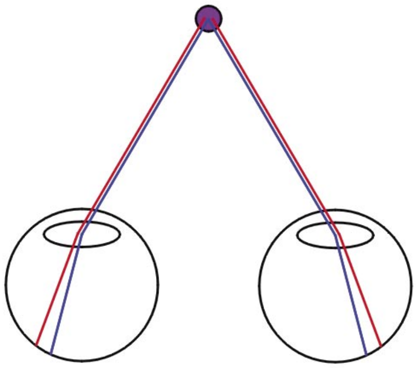

Figure 4. The transverse chromatic aberration. Blue light is projected to a more nasal part of the retina than does red light because of the difference in the refractive index depending on wavelengths of light. Note that the optical axes disagree with and are diverged from the visual axes.

visual axis (Uozato, 2000) (Figure 4). The model using the transverse chromatic aberration is that this angular difference gives binocular disparities to generate binocular stereopsis (Hartridge, 1918).

This model has widely been supported. In particular, the pinhole study has repeatedly supported it. When pinholes or artificial pupils are placed just in front of the eyeballs, chromostereopsis depends on the position of the pinholes (Terada, Yamamoto and Watanabe, 1935; Vos, 1960, 1966; Owens and Leibowitz, 1975; Simonet and Campbell, 1990b; Ye, Bradley, Thibos and Zhang, 1991). When they are placed on the temporal sides, chromostereopsis is red-in-front-of-blue (Figure 5a). On the other hand, when they are placed on the nasal sides, chromostereopsis is blue-in-front-of-red (Figure 5b). These effects have been regarded as evidence for the critical role of the transverse light projection.

This model, however, cannot fully explain why there is the minority of the blue-in-front-of-red stereopsis. If this model tries to explain this, it should be assumed that in the eyeballs of the minority the optical axis is rotated in the inward direction from the visual axis. This assumption is not plausible because it requires too much anatomical distortion.

This model cannot explain the effect of viewing distance, either. If this model tries to explain this, it should be assumed that the crystalline lens changes its orientation to make the optical axis agree with the visual axis when observers see stimuli close up. This assumption is not plausible, either, because it also requires too much anatomical transformation.

Furthermore, this model cannot explain the following phenomenon (Howard and Rogers, 1995). When the temporal half of each visual field (the nasal half of each retina) is mostly occluded, with the foveal vision being intact, blue tends to be perceived nearer than red (Figure 6a). Even the majority can see blue in front of red in this method. On the other

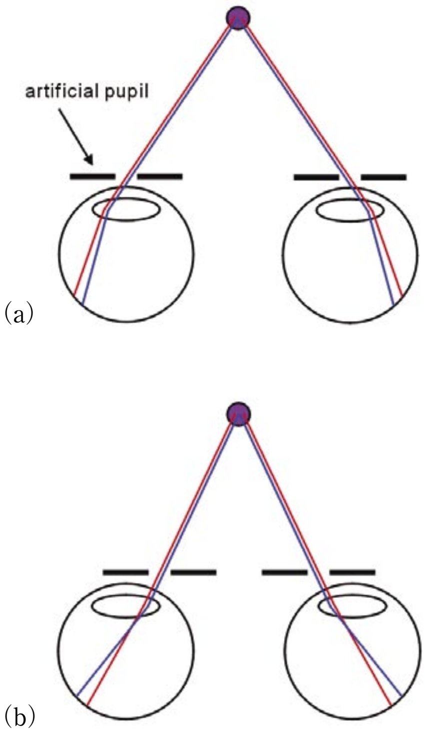

Figure 5. The effect of the position of pinholes or artificial pupils. (a) When they are placed on the temporal sides, chromostereopsis is red-in-front-of-blue. (b) When they are placed on the nasal sides, chromostereopsis is blue-in-front-of-red.

hand, when the nasal half of each visual field (the temporal half of each retina) is mostly occluded, with the foveal vision being intact, red tends to be seen nearer than blue (Figure 6b). Even the minority can see red in front of blue in this method. Since these methods do not disturb the central path of projected light, little or no changes in chromostereopsis are expected in the transverse chromatic aberration model, but this is not the case.

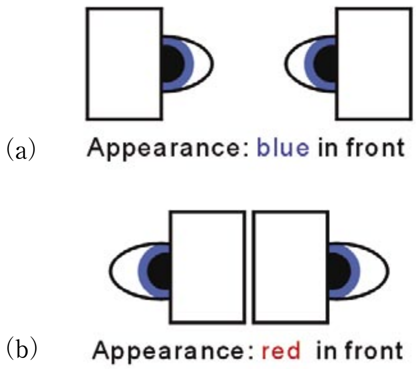

Figure 6. The effect of occlusion of half of visual fields. (a) When the temporal half of each visual field is mostly occluded, with the foveal vision being intact, blue tends to be perceived nearer than red. (b) When the nasal half of each visual field is mostly occluded, with the foveal vision being intact, red tends to be observed nearer than blue.

The center-of-gravity model

To explain these half-occlusion effects, we propose the center-of-gravity model of chromostereopsis. This model hypothesizes that the position of color is determined at the center of gravity in the range of each projected light onto the retina.

If red light is just in focus, blue light is projected diffusely. In this case, the position of the red image is in focus while the center of gravity of the diffused blue light represents the position of the blue image. On the other hand, if blue light is just in focus, red light is projected diffusely. In this case, the position of the blue image is in the focus while the center of gravity of the diffused red light represents the position of the red image.

In general, when the temporal half of each visual field (the nasal half of each retina) is mostly occluded, with the foveal vision being intact, the center of gravity of red light shifts in the nasal direction while that of blue light deviates in the temporal direction (Figure 7). These shifts give binocular disparities to generate the blue-in-front-of red stereopsis. When the nasal half of each visual field (the temporal half of the retina) is mostly occluded, the positional shifts are the reversal and the appearance is red-in-front-of-blue. The center-of-gravity model therefore can explain the phenomenon observed with half-occluded pupils.

Moreover, this model is perfectly consistent with the pinhole study (Figure 5) because the retinal position of the projected light through the pinhole equals the center of gravity of the light. Furthermore, the center-of-gravity model has an advantage to take into account the longitudinal chromatic aberration (Figure 3). However, the center-of-gravity model could also be regarded as a modified version of the transverse chromatic aberration model.

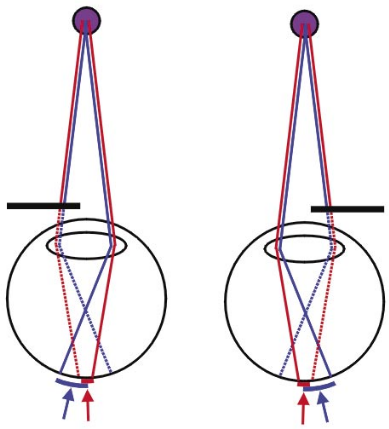

Figure 7. The center-of-gravity model. It is hypothesized that the position of color is determined at the center of gravity in the range of each projected light onto the retina. When the temporal half of each visual field (the nasal half of each retina) is mostly occluded with the foveal vision being intact, the center of gravity of red light shifts in the nasal direction while that of blue light deviates in the temporal direction. These shifts give binocular disparities to produce the blue-in-front-of-red stereopsis.

Speculation

Although the center-of-gravity model explains chromostereopsis much better than the simple longitudinal or transverse chromatic aberration models, it cannot explain the effect of viewing distance or why there are the majority and the minority. One or two independent mechanisms are then necessary to explain chromostereopsis fully.

Our speculation is that there might be individual differences in the changes in possible off-axis-viewing effects, like viewing through prism, in the optical characteristics of the overall ocular media, when observers change the viewing distance, especially when observers see into the distance. It is assumed that there are two types of off-axis-viewing effects, one being like prisms tapered in the temporal direction while the other being like prisms tapered in the nasal direction. The majority might depend on the former while the minority might reflect the latter.

There is no physiological evidence for this speculation at present because of difficulty to correctly measure the optical characteristics of ocular media in vivo. However, in our preliminary study, we observed switches in the depth order by using prisms in an ophthalmic corrective-lens set, as mentioned in Howard and Rogers (1995). This may support our speculation for the explanation of individual differences in the chromostereopsis.

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