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Chromostereopsis

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Synonyms

Color stereoscopic effect; Color stereoscopy; Depth in color

Definition

Chromostereopsis refers to a phenomenon of binocular stereopsis that depends on binocular disparity due to the difference in color [1–4]. For example, red and blue on the same surface can appear to lie in different depth planes.

Overview

When the background is black (Fig. 1), the majority of observers see red objects closer to them than blue ones (red-in-front-of-blue observers), while a minority of observers see the reversal (blue-in-front-of-red observers) and the rest do not experience the phenomenon. On the other hand, when the background is white (Fig. 2), the perceived depth order is reversed, and the effect is weaker than when the background is black.

Goethe [5] may deserve to be the first person who proposed the notion of advancing color (red) versus receding color (blue), but he did not notice the binocular aspect of chromostereopsis. According to Thompson et al.'s review [6], the history of chromostereopsis goes back at least to the work of Donders in 1864 [7], while Vos' review [4] suggested that Donders first reported this effect in 1868, followed by Bruecke [8] in the same year. According to Dengler and Nitschke's review [9], however, Brewster [10] reported in 1851 that owing to the chromatic aberration of the lens, short-wavelength colors are seen stereoscopically as more distant.

Both Donders and Bruecke attributed chromostereopsis to accommodative feeling, which was translated to the perception of distance [4]. Blue or short-wavelength light has a larger refractive index than the red or long-wavelength one. This makes the color rays run in a different way as shown in Fig. 3. This is called "longitudinal chromatic aberration" [3]. This idea suggests that red should be closer than blue even if both colors are placed in the same depth plane because a closer object comes into focus at the posterior part. Moreover, this idea suggests that chromostereopsis should be seen monocularly. Yet, these two suggestions are not the cases, and this idea is not regarded as a plausible explanation of chromostereopsis [3, 11].

It was Bruecke [8] in 1868 who found the binocular nature of the phenomenon [4]. The optical axis of an eyeball is slightly (about 5° = angle gamma or angle alpha) shifted in the outward direction from the visual axis. Red light is thus projected to a more temporal part of the retina than does blue light (Fig. 4) because of the difference in refractive index of both colors. This physiological optics is called "transverse chromatic aberration" [3]. This idea suggests that red should be perceived in front of blue through

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Fig. 1 Chromostereopsis. For the majority of observers, the *inset* made up of *red* random dots appears to be in front of the surround consisting of *blue* ones. For a minority, the *inset* appears to be behind the surround. The rest do not experience the phenomenon. Chromostereopsis is strong when observers see the image at a distance

Fig. 2 When the background is *white*, the effect is reversed and it is weaker than when the background is *black*. Those who see *red* in front of *blue* in Fig. 1 see *blue* in front in this image, while those who see *blue* in front of *red* in Fig. 1 see *red* in front in this image

binocular stereopsis based upon the binocular disparities of both colors. More specifically, a closer object projects to a more temporal part in the retina and so does red light. This suggestion, however, made Bruecke immediately reject his hypothesis because some of his observers reported red receding with respect to blue.

According to Vos [4], Einthoven discovered in 1885 that chromostereopsis is enhanced or reversed by using a simple method as shown in Fig. 5 [11, 12]. Covering the temporal parts of both pupils forces observers to see blue in front of red (upper image of Fig. 5). On the other hand, covering the nasal parts of both pupils makes observers see red in front of blue (lower image of Fig. 5). This method was also demonstrated by Kishto [13]. He cited Kohler's article [14] in 1962, which did not mention any other literature, though.

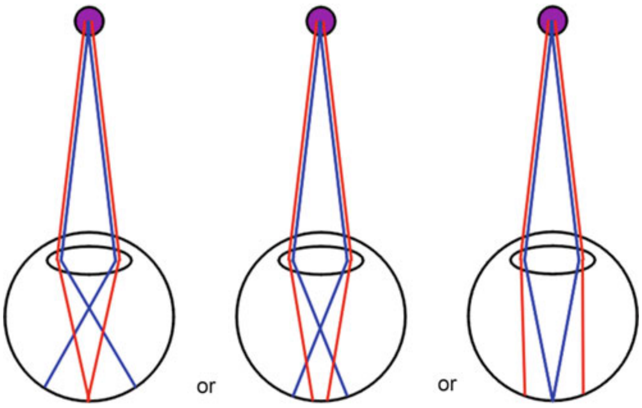

Fig. 3 The longitudinal chromatic aberration. *Blue* has the focus nearer to the lens than *red* because of the difference in the refractive index depending on color

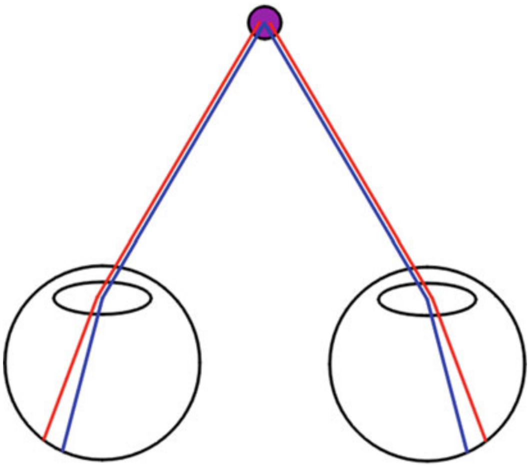

Fig. 4 The transverse chromatic aberration. *Red* light is projected to a more temporal part of the retina than does *blue* light because of the difference in the refractive index depending on color. Note that the optical axes are slightly (about 5°) diverged from the visual axes

Subsequently, Einthoven's covering method was simplified to the method using artificial pupils. Nasally placed artificial pupils gave blue in front of red (upper image of Fig. 6), while temporally placed ones rendered red in front of blue (lower image of Fig. 6) [15–23]. Vos [4, 16, 18] attributed chromostereopsis to interactions between each individual pupil decentralization (angle gamma) and the Stiles-Crawford effect. The Stiles-Crawford effect is a phenomenon that the rays entering the eye through the peripheral regions of the pupil are less efficient than those through the central region [24]. This two-factor model, which Vos [4] called the "generalized Bruecke-Einthoven explanation," has been widely accepted, while a few authors did not approve it [25].

Many studies suggested that pupil size affects chromostereopsis [19, 21–23], which supports the generalized Bruecke-Einthoven explanation. Simonet and Campbell [26], however, did not find any consistent relationship between pupil size and chromostereopsis.

Einthoven's original finding was explained by the center-of-gravity model (Fig. 7) [27]. 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. For example, when the temporal half is occluded, the center of gravity of red light shifts in the relatively nasal direction, while that of blue light deviates in the temporal direction (upper image of Fig. 7). These shifts give binocular disparities to produce the blue-in-front-of-red stereopsis. When the

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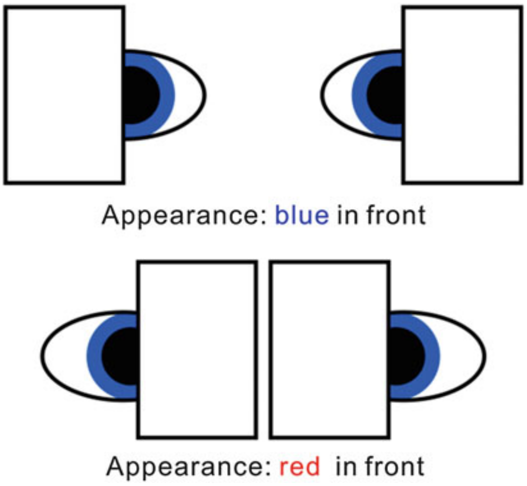

Fig. 5 Einthoven's covering method. *Blue* in front of *red* is generated or enhanced by covering the temporal parts of both pupils (*upper image*), while *red* in front of *blue* is produced or enhanced by covering the nasal parts of both pupils (*lower image*)

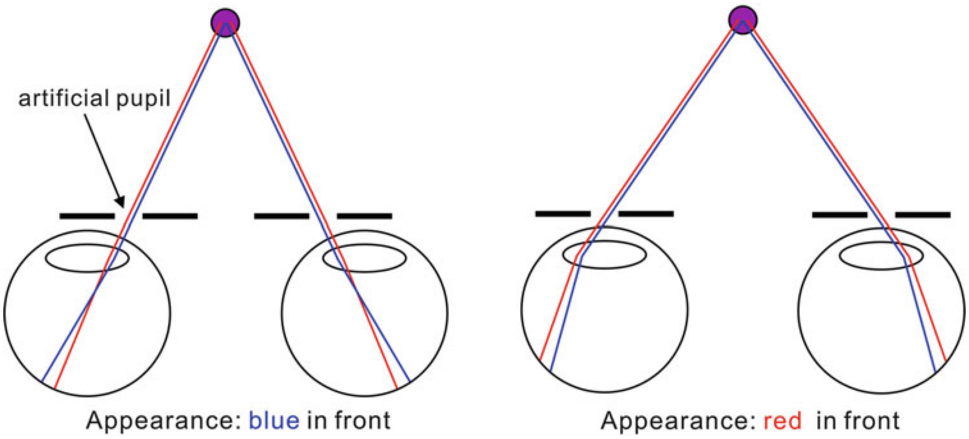

Fig. 6 When artificial pupils are placed nasally, observers see *blue* in front of *red*. On the other hand, when artificial pupils are placed temporally, observers see *red* in front of *blue*

nasal half is occluded, the center of gravity of red light shifts in the relatively temporal direction, while that of blue light deviates in the nasal direction (lower image of Fig. 7). These shifts give binocular disparities to produce the red-in-front-of-blue stereopsis.

In 1965, Kishto reported a tendency that red appears to be in front of blue at high levels of illumination, while blue appears to be in front of red at low levels of illumination, i.e., 17 of 25 observers (68 %) reported so [13]. This finding was influential and drew much attention [3], though it was questioned by some studies [9, 26]. For example, Simonet and Campbell [26] reported a reversal in the direction of the chromostereopsis for 16 of 30 observers (53 %) when the ambient illumination was increased, but six of them (38 %) reported a change toward the blue-in-front-of-red chromostereopsis. Moreover, at low illuminance, there was lack of correlation between the direction of chromostereopsis and transverse chromatic aberration, which may indicate that there may be a supplementary binocular factor in chromostereopsis [26].

In 1928, Verhoeff reported that the perceived depth order between red and blue is reversed by changing the background from black to white (Fig. 2) [9, 28–30]. One account is that red surrounded by white lacks

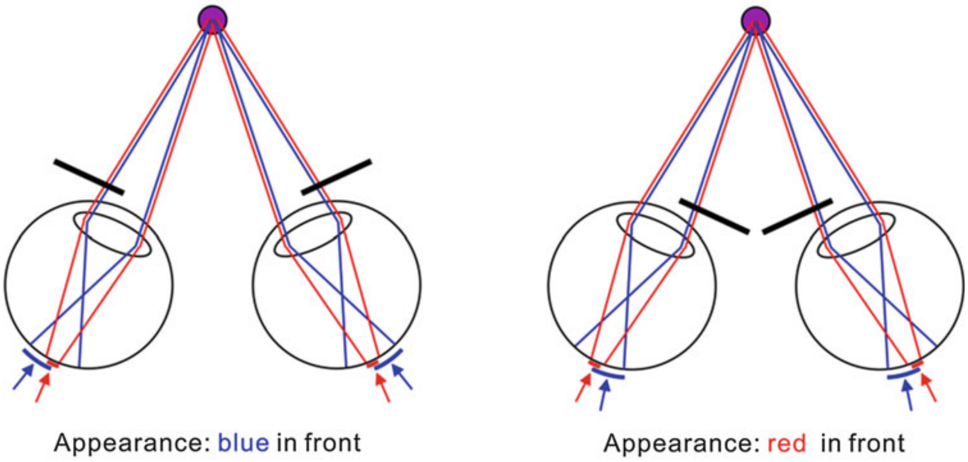

Fig. 7 The center-of-gravity model. This model takes longitudinal chromatic aberration into account, in which the perceived position of a color is judged to be at the center of gravity of its diffused light

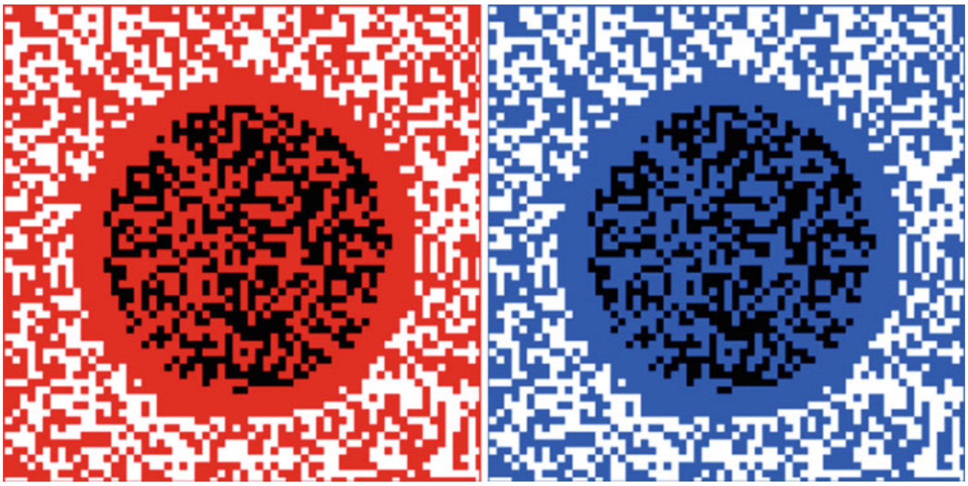

Fig. 8 Images suggested by Hartridge [32]. *Red*-in-front-of-*blue* observers see the *black inset* in front of the *white* surround in the *left image*, and they see the *inset* behind the surround in the *right image*. *Blue*-in-front-of-*red* observers see the reversal. Observe these images at a distance

blue, while blue surrounded by white lacks red, suggesting that there are virtually blue and red edges, respectively [28]. According to Faubert [31], Hartridge described in his 1950s textbook [32] that “when both black and white pattern lie on a uniformly coloured background a stereoscopic effect is frequently noticed” (Fig. 8).

With respect to this luminance-dependent reversal, Faubert [31, 33] proposed a new demonstration of chromostereopsis in which colors are bordered with each other (Fig. 9) and pointed out the critical role of luminance profiles caused by transverse chromatic aberration in subsequent binocular stereopsis. The luminance-profile-dependent binocular stereopsis is thought to correspond to the one which Gregory and Heard showed in 1983 as shown in Fig. 10 [34, 35], though Faubert did not mention it. If the luminance order is reversed between the two colors, the apparent depth is reversed as shown in Fig. 11. When two colors are isoluminant, two depth planes are simultaneously observed (rivaldepth) with luster where two colors meet (Fig. 12) [31]. In addition, actually a century ago, Einthoven [11] had pointed out the role of luminance profiles caused by transverse chromatic aberration, but he had assumed the perception of

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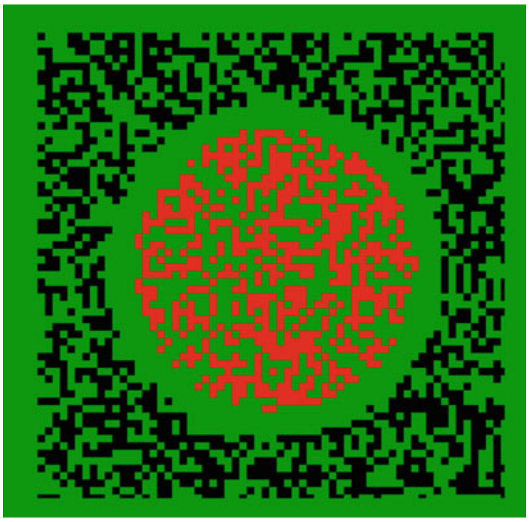

Fig. 9 Chromostereopsis when the background is not achromatic. Luminance of *red* is highest, followed by *green* in this image. Those who see *red* in front of *blue* in Fig. 1 see the *inset* in front of the surround; those who see *blue* in front of *red* in Fig. 1 see the *inset* behind the surround. Observe this image at a distance. Einthoven's covering method (Fig. 5) also works

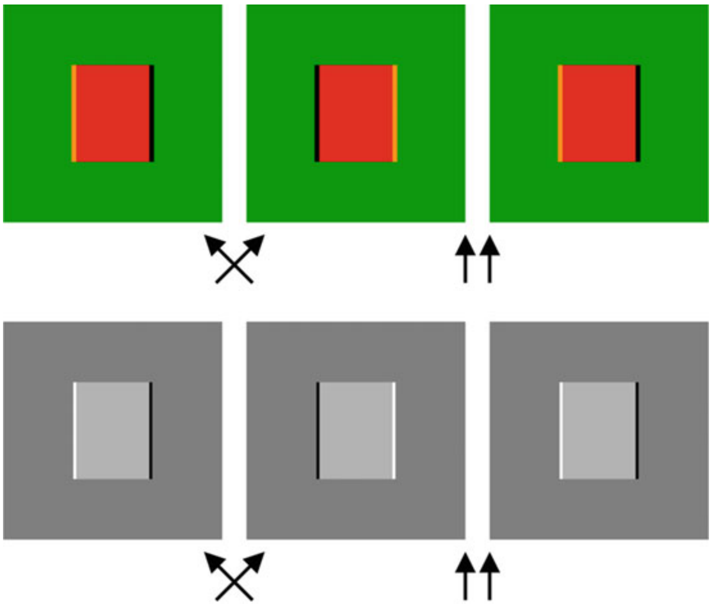

Fig. 10 Faubert's luminance-profile-based idea [31]. Color fringes or luminance profiles of a *red* object in front of *green* such as that in Fig. 9 produced by transverse chromatic aberration are depicted. It is supposed that mirror images are rendered to each eye. This binocular disparity generates a special type of binocular stereopsis which depends on luminance contrast polarity of the object's edges [34, 35]. This stereogram demonstrates *red*-in-front-of-*green* appearance when cross-fusers use the *left* and *middle* panels or uncross-fusers see the *middle* and *right* ones. The perceived depth is determined by the luminance profiles shown in the *lower row*. Note that *red* or *light-gray* rectangles do not give binocular disparity with respect to the frames; both fringes of each rectangle promote to make binocular stereopsis

convex or concave objects depending on where illuminated light comes from and made a monocular explanation like the crater illusion (Fig. 13).

Faubert's luminance-profile-based model [31, 33] can be extended to explain the luminance-dependent reversal (Fig. 14). Suppose that white consists of red, green, and blue. Given transverse chromatic aberration when the background is black, and suppose that red appears to shift in one direction, blue

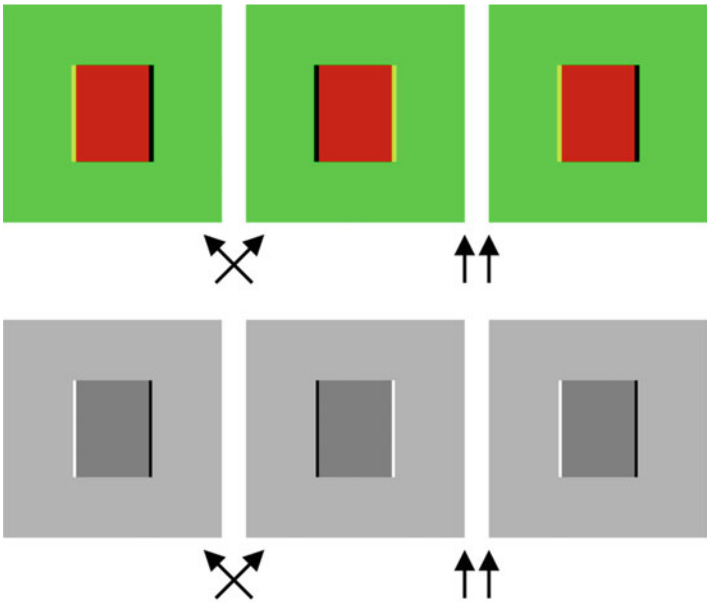

Fig. 11 If the luminance order of the two colors in Fig. 10 is exchanged, the apparent depth is reversed. This stereogram demonstrates *red*-behind-*green* appearance when cross-fusers use the *left* and *middle* panels or uncross-fusers see the *middle* and *right* ones

appears to shift in the opposite direction (upper panel of Fig. 14), and green does not change the apparent position. Then, when the background is white, red appears to slightly shift in the opposite direction, with yellow leading to and magenta (color mixture of red and blue) following red. On the other hand, blue appears to slightly shift in the same direction as that of red when the background is black, with cyan (color mixture of blue and green) leading to and magenta following blue (lower panel of Fig. 14). Figure 15 shows the pictorial explanation of how transverse chromatic aberration induces the positional shifts of colors.

It was reported that the effect of chromostereopsis is large when observers see the image at a distance [13, 27, 31], whether observers are of the red-in-front-of-blue type or the blue-in-front-of-red type [27]. This issue remains open. In addition, there is no literature to suggest any involvement of myopia or hyperopia in chromostereopsis.

The majority of observers see red in front of blue with the black background in a light environment. How many people see blue in front of red? In Luckiesh [15], 11 % (1 of 9 observers) did so. The proportion was 4 % (1 of 25 observers) in Kishto [13], 30 % (9 of 30 observers) in Simonet and Campbell [26], 7 % or 14 % (1 or 2 of 14 observers) in Dengler and Nitschke [9], 20 % (4 of 20 observers) in Kitaoka et al. [27], and 21 % (16 of 75 observers) in Kitaoka [37].

Color anomaly people also see chromostereopsis. Kishto [13] examined three color anomaly observers, one being a strong protanope, one being a mild deuteranope, and the third having too poor color discrimination to read any of Ishihara plates. They all saw red in front of blue with the black background in a light environment.

It is thought that some part of the effect is due to luminance differences or contrast differences (Fig. 16), with bright objects appearing closer than dim ones [6] or high-contrast objects appearing closer than low-contrast ones [38]. Saturation also affects chromostereopsis [11, 13]. Desaturation decreased the depth effect, though desaturation is inevitably accompanied by changes in luminance, contrast, or spectrum.

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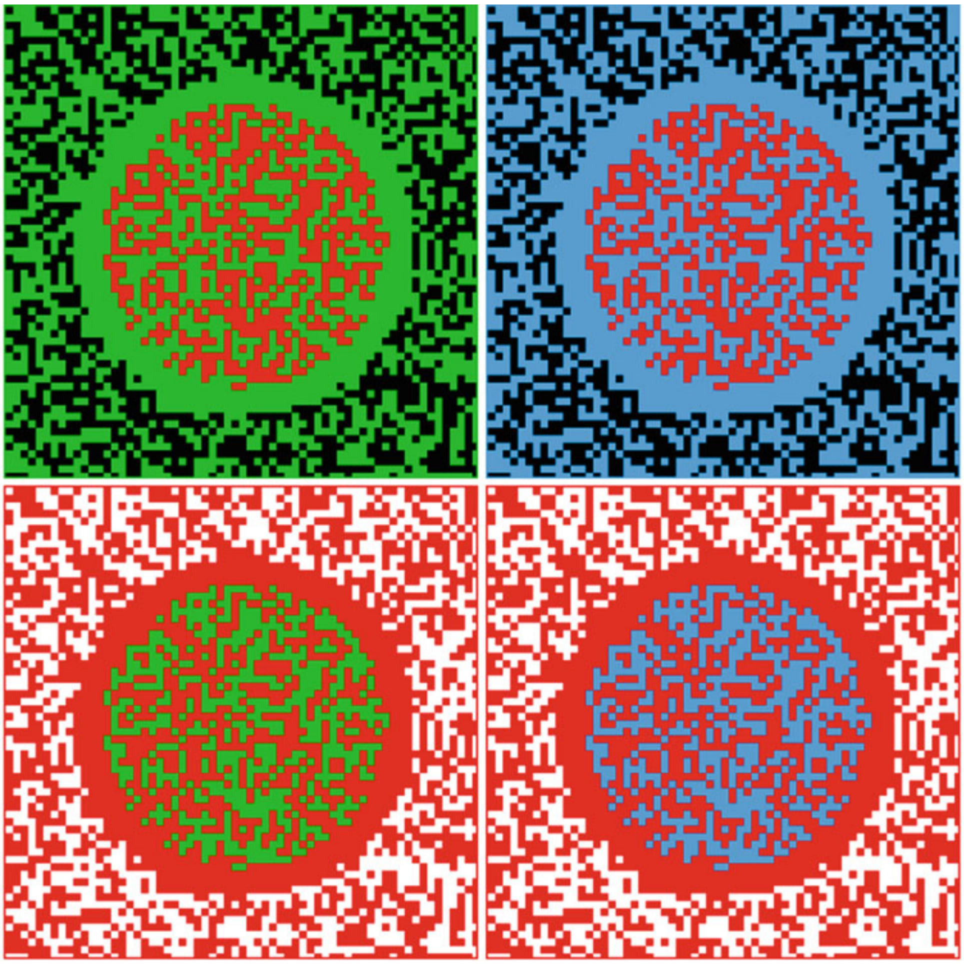

Fig. 12 Isoluminant colors make observers perceive rivaldepth with luster. Note that precise isoluminance is realized depending on displays and individuals

Moreover, if an image consists of the inset and surround, there seems to be a tendency that the inset appears to be behind the surround (Fig. 17). This phenomenon seems to be observed with achromatic images, too (Fig. 18).

Neural correlates of chromostereopsis were investigated using visually evoked potentials [39]. Results demonstrate that the depth illusion obtained from contrast of color implicates similar cortical areas as classic binocular depth perception.

Summary

It is summarized that chromostereopsis is a phenomenon of binocular stereopsis based upon binocular disparity produced by some interaction between optic properties of color rays and further neural processing. Chromostereopsis is a ubiquitous phenomenon and has a considerable pile of observations gained in its long research history.

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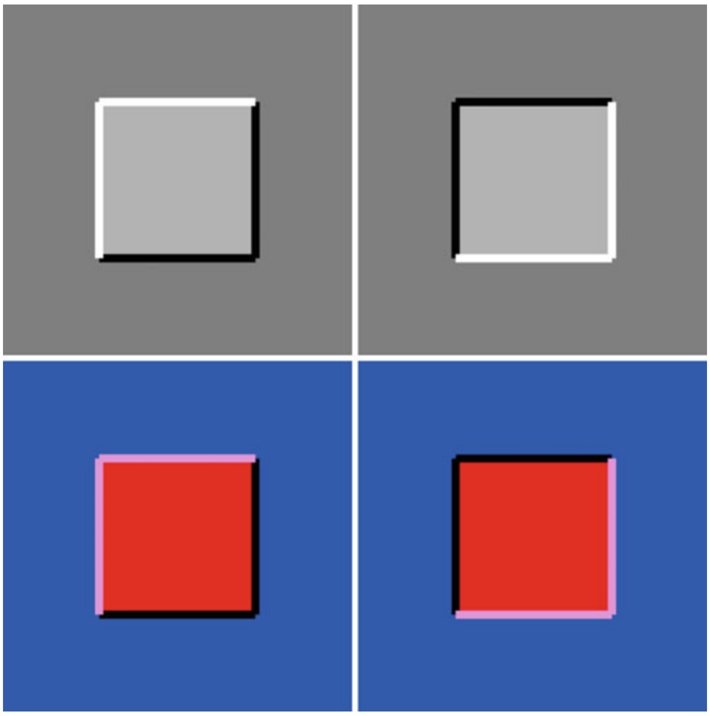

Fig. 13 Idea of the crater illusion. The central *square* appears to be in front of the background in the *upper left panel*, while that appears to be behind the background in the *upper right panel*. This depth effect depends on the positions of highlighted or shadowed edges [36]. The basic idea of Einthoven [11] is demonstrated in the *lower panels*

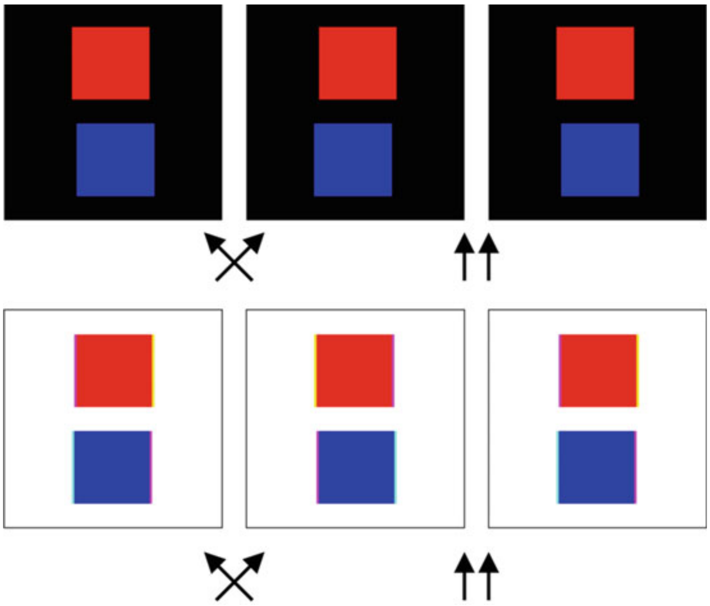

Fig. 14 Faubert's model can be extended to explain the color reversal. If *red* and *blue* objects are vertically aligned with the *black* background but appear to be shifted in position by transverse chromatic aberration as shown in the *upper panel*, the expected shifts with the *white* background are reversed as shown in the *lower panel*. This idea accounts for the luminance-dependent reversal (Fig. 2). Note that this stereogram demonstrates *red*-in-front-of-*blue* appearance when cross-fusers use the *left* and *middle* panels or uncross-fusers see the *middle* and *right* ones

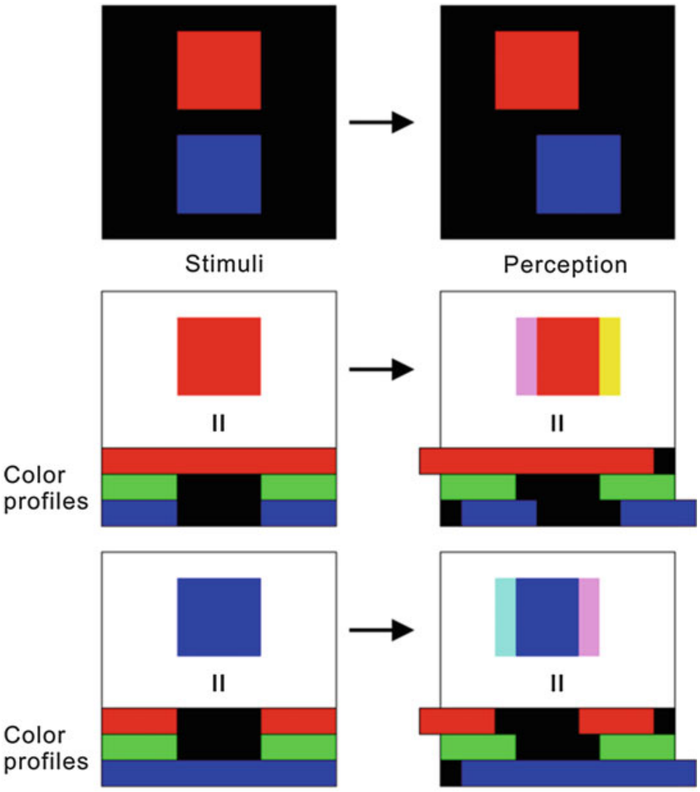

Fig. 15 If transverse chromatic aberration moves *red* to the *left* and *blue* to the *right* (*uppermost row*) and does not change the position of *green*, *red* surrounded by *white* appears to shift rightward (*middle row*), while *blue* surrounded by *white* appears to shift leftward (*lowermost row*). Thus, apparent position shifts of the two colors are reversed depending on whether the background is *black* or *white*. Note that the *left* column shows the physical position of the two colors, and the *right* column demonstrates apparent positions of the two colors with color fringes produced by color mixture of shifted component colors

Fig. 16 The *inset* appears to be in front of the surround. High-luminance and/or high-contrast objects appear to be closer than low-luminance and/or low-contrast ones

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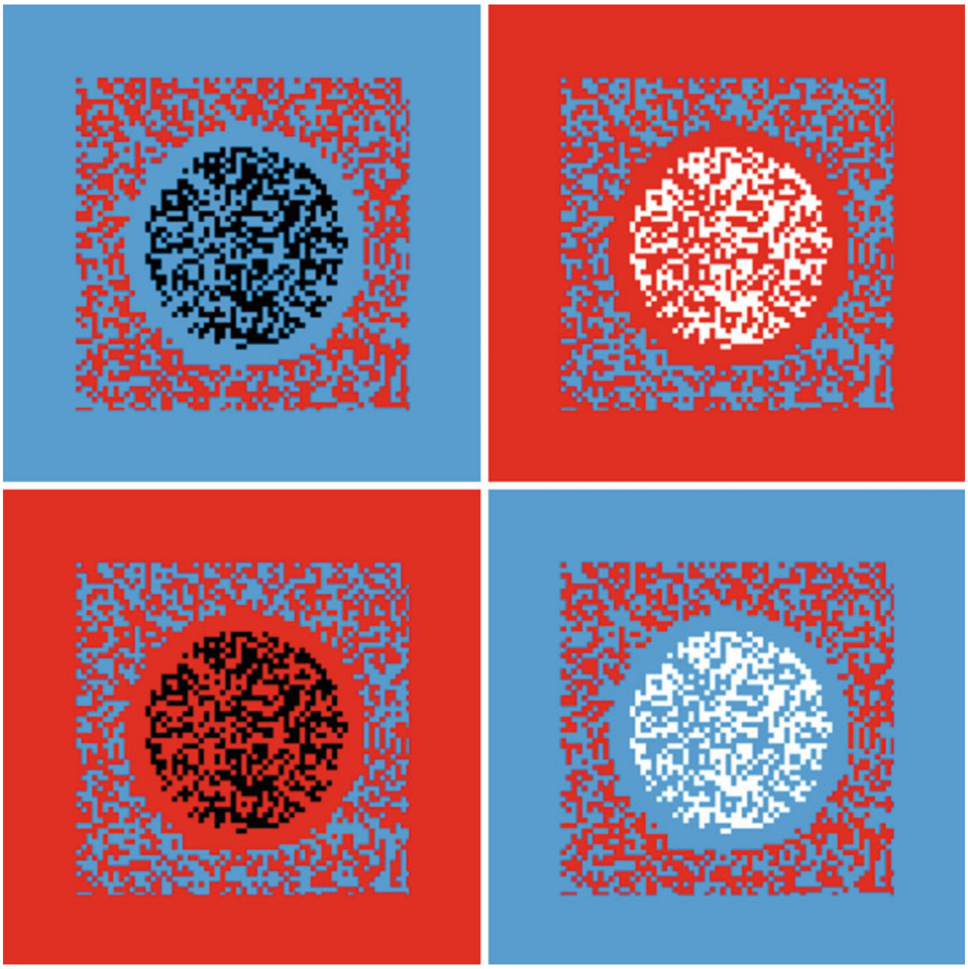

Fig. 17 Images showing a tendency that the *inset* appears to be behind the surround

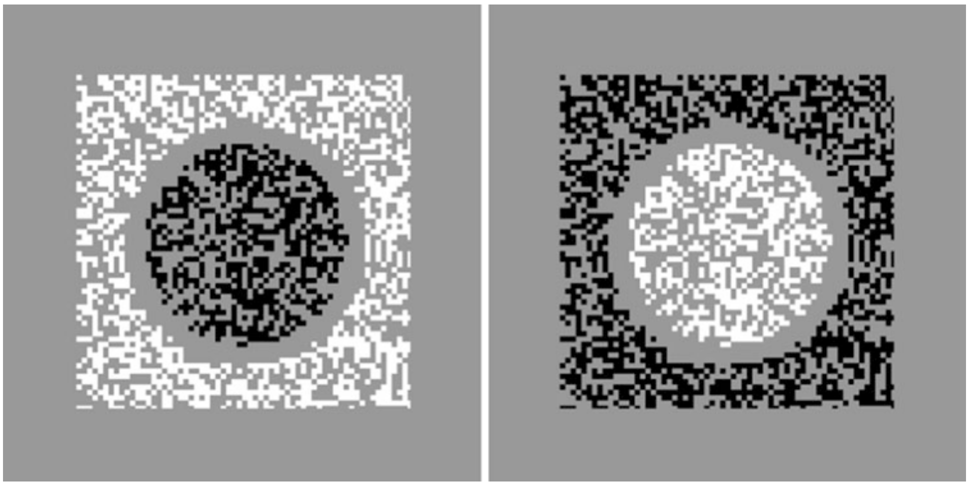

Fig. 18 Achromatic images also show the tendency that the *inset* appears to be behind the surround

Cross-References

► Stereo and Anaglyph Images

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