Experimental Evaluation of Chromostereopsis with Varying Center Wavelength and FWHM of Spectral Power Distribution

Masaru Tsuchida, Kunio Kashino, and Junji Yamato

NTT Communication Science Laboratories, Atsugi, Japan
{tsuchida.masaru,kashino.kunio,yamato.junji}@lab.ntt.co.jp

Abstract. This paper experimentally shows how the center wavelength and spectral power distribution (SPD) of displayed color is related to chromostereopsis. Chromostereopsis – a visual illusion whereby the impression of depth is conveyed in two-dimensional color images – can be applied to glassless binocular stereopsis by controlling color saturation even when a commercial liquid crystal display (LCD) is used to display a two-dimensional image. We conducted evaluations of stereoscopic visual effects among monochrome images using an LCD panel and three monochrome backlights whose SPD had a single peak. The center wavelength and full width at half maximum (FWHM) of the SPD for the backlight were varied. The experimental results show that chromostereopsis does not occur strongly when the FWHM of a backlight is larger than 100 nm. We also suggest that the impression of the depth for monochrome images depends on the center wavelength and FWHM of the color, which indicates chromostereopsis can be expressed by the chromatic aberration.

Keywords: Chromostereopsis, stereoscopic display, color saturation, wavelength, spectral power distribution.

1 Introduction

1.1 Background

Chromostereopsis has been well known from over a hundred year ago as a visual illusion whereby the impression of depth is conveyed in two-dimensional (2-D) color images [1-3]. For example, when red and blue color images are displayed on the same image display monitor, the majority of observers perceive the red image to be placed in front of the blue one. Figure 1 shows an example of red-blue images. Although it depends on color gamut of display monitor, red areas strongly appear to be in front of blue ones. This effect is thought to be caused by transverse chromatic aberration in eyes [3-7] because it becomes weak in monocular observation. This indicates that chromostereopsis can be applied to stereoscopic displays. If the chromatic aberration model is correct, the spectral power distribution (SPD) of primary colors for display monitors should have a strong effect on chromostereopsis.

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Fig. 1. Example of red-blue images

Liquid crystal displays (LCDs) are widely used for displaying 2-D color images these days, and it may be possible to display three-dimensional (3-D) images on LCD by exploiting the principle of chromostereopsis. However, the effect of stereopsis is not very strong in LCD for general use. One of the reasons is that the saturation of the primary colors on general LCDs is not high enough for binocular stereopsis based on chromostereopsis.

Wide color gamut display monitors (e.g., LCDs using red-green-blue LED backlight or multi-primary color display monitors [8-11]) are also on the market, mainly for professional use. The saturation of primary colors in these displays is higher than that in general LCDs, which enables us to enhance the power of color expression. In addition, the effect of binocular stereopsis is stronger than in general LCDs. This advantage can provide a new power of expression to creators in various fields, such as advertising, art and game design. For example, a part of a displayed image can be located in front or back of a part of another image in 3-D space. A method for enhancing of depth perception using chromostereopsis has been presented, but it is not applicable to 3-D image displays [12].

As described above, the hue and saturation of images are cited as factors in chromostereopsis. On the other hand, chromostereopsis is explained by the model based on the transverse chromatic aberration [3-7]. This suggests that the center wavelength and the full width at half maximum (FWHM) of the SPD for the light from displayed images strongly affects chromostereopsis. However, there have been few discussions or experiments dealing with these physical factors in past researches.

1.2 Motivation

Our final goal is to achieve natural stereoscopic display on a 2-D display monitor by exploiting the relationship between chromostereopsis and physical factors. To archive the goal, the relationship mentioned above such as the center wavelength, SPD, and FWHM of the SPD shall be revealed. In this paper, as a first step to archive the goal, we discuss and examine monochrome light whose SPD have a single peak.

1.3 Overview

In section 2 of this paper, we discuss chromostereopsis in terms of validation experiments. In section 3, we describe experimental results with varying wavelength and FWHM of LCD's primary colors for confirming chromostereopsis can be expressed by a model based on the chromatic aberration and how the SPD affects depth perception. In particular, a monochrome backlight for each primary color was generated from an xenon lamp and a narrow band-pass filter. Several band-pass filters with the same center wavelength, but with different FWHM were prepared and were switched in turn. Before starting the evaluation experiments, we measured the primary colors of a general LCD and a wide color gamut one to confirm their chromaticity and SPD. These results are used to determine the center wavelength and FWHM of the band-pass filters in the next experiments. Finally, we summarize the paper and about future works in Sec.4.

2 The Basis of Validation Experiments Using Commercial LCDs

In this section, we describe the difference between general and wide color gamut LCDs. We have measured primary colors and SPD of both LCDs and have determined the center wavelength of SPD of monochrome light used in experiments described in the next section.

Figures 2 shows a chromaticity diagram representing the color gamut of primary colors of a general LCD (using white-LED backlight) and a wide color gamut LCD (using red-green-blue LED backlight). The color gamut of the general LCD plotted on the chromaticity diagram is much narrower than that of Adobe-RGB color space and

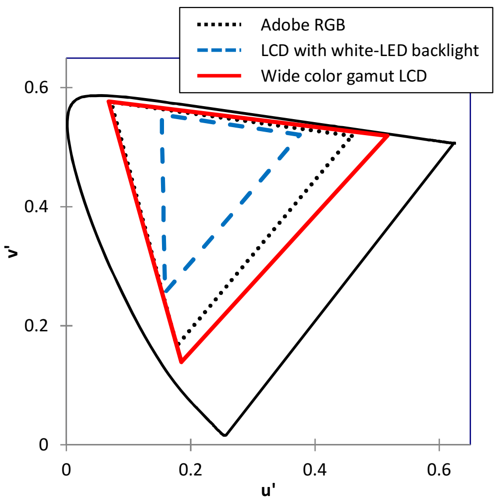

Fig. 2. Chromaticity diagram representing color gamut of LCD

the wide color gamut LCD. And the chromaticity diagram shows that the saturation of blue and red of the wide color gamut LCD is higher than that of the adobe RGB color space. The chromatic characteristics of an LCD are determined by the SPD for the backlight and by the spectral transmittance of color filters on the liquid crystal panel.

Figure 3 shows SPDs of each primary color for the LCD with white LEDs. As for blue, although there is a peak of the SPD at 450 nm and its FWMH is 20 nm, the SPD overlaps in wide range between blue and green. The center wavelength of green and red are 550 and 600 nm, and their FWHMs are approximately 40 and 60 nm. However, a large overlap of SPDs between green and red also exists, which makes the color gamut narrow.

Figure 4 shows SPDs of each primary color for the LCD with red-green-blue LED backlight. The center wavelengths and FWHMs are 440 and 25 nm for blue, 510 and 40 nm for green, and 630 and 15 nm for red. Few overlaps exist among the SPDs of each primary color. As a result, the color gamut is enlarged.

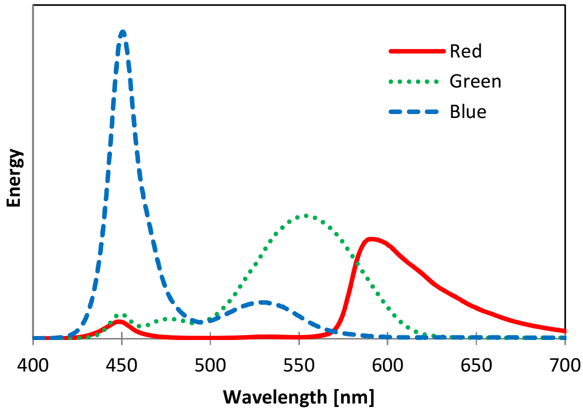

Fig. 3. SPDs of primary colors of the LCD with white-LED backlight

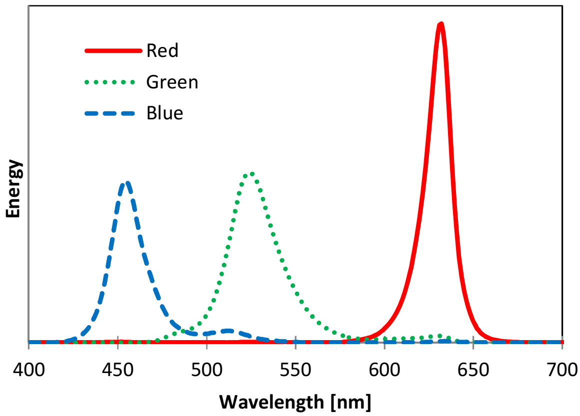

Fig. 4. SPDs of primary colors of the wide color gamut LCD

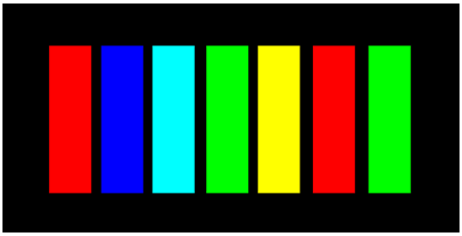

Fig. 5. Color chart for confirming effect of the chromostereopsis

Figure 5 shows a color chart for displaying on both types of LCDs. The depth of each color patch is intergraded from red (front side) to blue (back side) when the LCD with red-green-blue-LED backlight was used. On the other hand, all color patches displayed on the LCD with white-LED backlight seemed to be located at the same depth.

From the measurements and considerations above, we have determined the center wavelength as follows: 440 nm for blue, 510 nm for green, and 630 nm for red, and FWHMs of the narrow band-pass filter (interference filter) as follows: 10, 20, 40, and 100 nm.

3 Experiments with Varying Center Wavelength and FWHM of Primary Colors

3.1 Experimental Setup

In this section, we describe the display system used in our experiments as shown in Fig. 6. The system consists of an LCD panel with a red-green-blue filter array (the number of pixels is 1980 x 1200; the panel size is 24 inches), band-pass filters, and three xenon lamps. Inside the housing of one of the xenon lamps, there is a filter turret on which eight filters can be attached, and backlight is selected from the eight-band

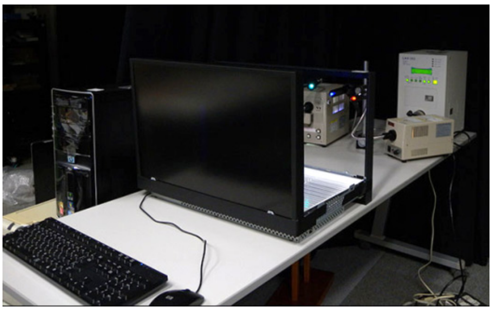

Fig. 6. Experimental system

Fig. 7. Filter turret and band-pass filters in the xenon lamp system

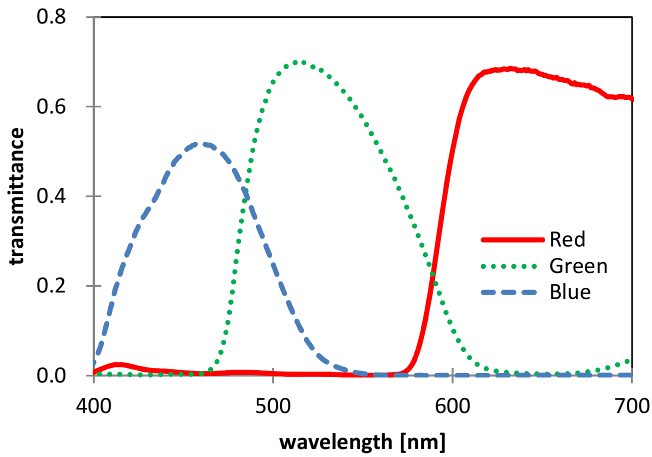

Fig. 8. Spectral transmittance of color filters on LCD panel

monochrome lights (Fig.7). Figure 8 shows the spectral transmittance of the color filters of the LCD panel. FWHMs of the spectral transmittance of blue and green filters are approximately 100 nm. This graph shows that the transmittance of green overlaps part of the range of red and part of the range of green. Light from the lamp house passes through a glass fiber guide and is emitted from a rod lens, which can make brightness uniform on the LCD panel.

3.2 Evaluating the Relationship between the Impression of Depth by Binocular Stereopsis and FWHM of SPD of Primary Colors

We conducted experiments in which we varied the center wavelength and FWHM of the SPD for primary colors to determine whether to show that chromostereopsis could be expressed using chromatic aberration. A dark room was used for the experiments because chromostereopsis tends to be enhanced under dark adaptation. The impression of depth was evaluated by comparing red-gray, green-gray, blue-gray, and red-green-blue images by changing the narrow band-pass filters with different FWHM for red and blue. The distance between the observer and LCD panel was approximately 50 cm.

A light that passed through a band-pass filter and a glass optical fiber was used as an LCD backlight. The band-pass filter whose FWHM was 10 nm was installed in front of a rod lens. Band-pass filters whose FWHMs were 20, 40, and 100 nm were attached to the filter turret as shown in Fig. 7 and were switched in turn. The color image for the 10 nm FWHM was compared with color images for the 20, 40, and 100 nm FWHMs to confirm how the impression of depth changed. A gray image was used as a reference depth plane.

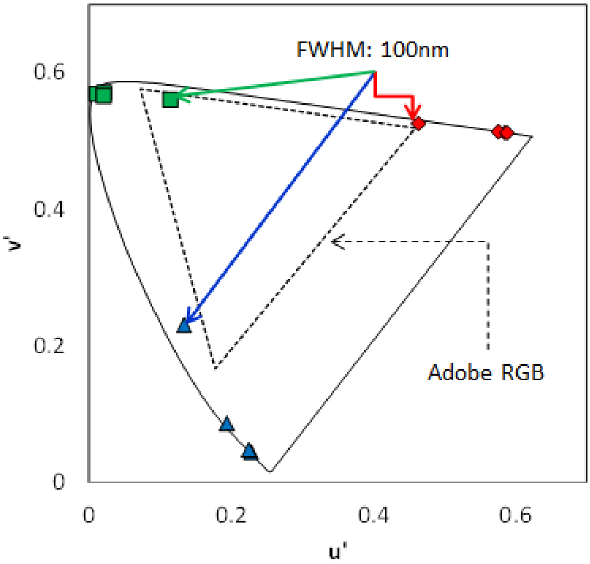

Fig. 9. Chromaticity values with FWHM of displayed colors varied

Figures 9 shows a chromaticity diagram on which u'-v' values of each color are plotted. This diagram shows the areas covered by the three primaries whose FWHMs are 100 nm are smaller than that of Adobe RGB. In this experiment, each primary color has an SPD with a single peak and relatively small overlap between each primary color compared to the LCD with the white-LED backlight introduced in Sec. 2. For images with the same center wavelength, the impression of depth weakened by comparing with the color image for the 10 nm FWHM with that for the larger FWHMs. In addition, the color image for the 100 nm FWHM seemed to be located on almost the same depth plane as the gray image. This phenomenon occurred in red, green, and blue images. The green images seemed to be located on almost the same depth plane even when the band-pass filter was changed to another filter at the same center wavelength but with different FWHM.

From these results, we suggest that the blur caused by chromatic aberration on the retina becomes larger as the FWHM of the SPD for the displayed color is increased (see Fig.10). This makes binocular parallax smaller and thereby weakens the impression of depth. For example, in the case when the SPDs of primary colors are broad and have large overlap between each primary color such as the LCD with the white-LED backlight introduced in Sec. 2, the binocular parallax becomes small.

Finally, we compared eight images with a 30 nm FWHM and center wavelengths of 450, 480, 510, 540, 570, 600, 630, or 660 nm to confirm the impression of depth. The image with longer wavelengths was perceived as located in front of that with shorter wavelengths in order of indicated above.

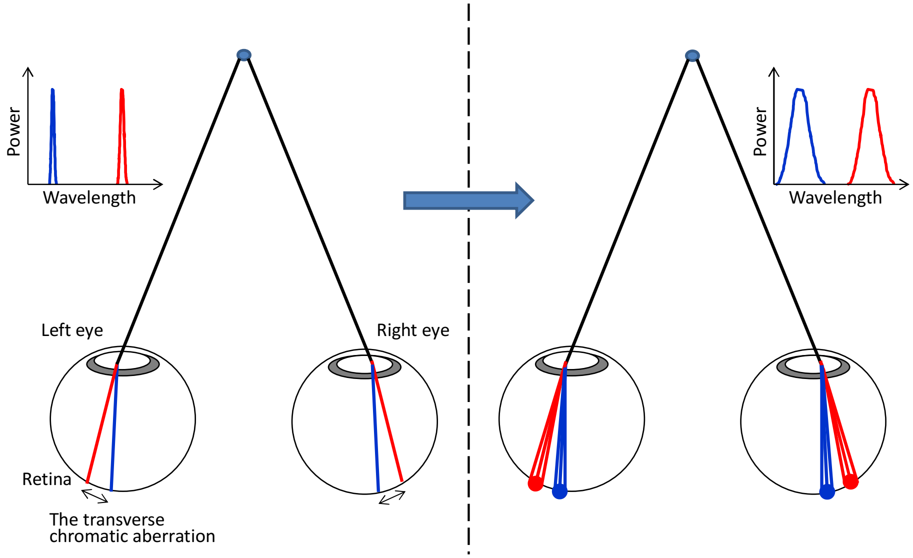

Fig. 10. Relationship between FWHM of SPD and binocular parallax

4 Conclusion

In this paper, we have discussed the relationship of center wavelength and SPD of displayed color to chromostereopsis. The experimental results have shown that the impression of the depth of monochrome images depends on the center wavelength and FWHM of the displayed color, indicating that chromostereopsis can be expressed by a chromatic aberration model.

For future works, experiments for evaluating the SPD's effects on depth perception, in which the different center wavelength, FWHM of primary color, and brightness of background, are required. In addition, the SPD of a displayed color with multiple peaks should be compared with a color whose SPD has a single peak. Even when the color whose SPD consists of a summation of several SPDs with a single peak whose FWHM is small, the same chromaticity value can be obtained from a color whose SPD has a single peak.

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