Color Management of Reflective-type LCD in Terms of Adaptation of the Human Visual System to Light Source Variation

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Abstract

In connection with the color adaptation property of the human visual system, we have explored color management of a reflective-type TFT LCD(R-LCD). Since the R-LCD works together with its ambient light as a light source, it is expected that the colorimetric color on the R-LCD must be changed if the illuminant of the ambient light is changed. However, due to the adaptation property of the human visual system, the eye does not perceive colorimetrically-corrected colors equivalently if they are on the R-LCD. In this paper, we discuss results obtained from subjective experiments, which were initiated in order to understand the perceived color differences according to light source changes. Also we show how these properties of the human visual system can be modeled and calibrated in a color management unit of a personal computer(PC), which is applicable to the R-LCD in practical usage condition.

Introduction

The development of flat panel displays has accelerated in recent years based on enormous demands of market. Especially, due to its low power consumption features,[1] the reflective-type TFT LCD(R-LCD) is expected to be used in a wide range of applications, such as lap top PC, portable phone with color i-mode service and PDA.

Since the R-LCD is seen under ambient light, the colorimetric color on the R-LCD changes if the ambient light changes. But color management of the R-LCD taken into account of the ambient light has not previously been demonstrated. In this paper, we show an approach to color management of the R-LCD based on an adaptation property of the Human Visual System to light source variations.

Corresponding Color in Terms of Ambient Light Conditions

Since an R-LCD is a reflective object, colorimetric colors on the R-LCD depend on the ambient light. However, due to the adaptation property of the human visual system,[2] the eye does not perceive colorimetrically-corrected colors equivalently even if they are on the R-LCD. In addition, the human visual system does not completely adapt to changes in the light source. Therefore, even after adaptation is complete, some color differences are perceived with a change in light source. So, due to the incomplete chromatic adaptation of the visual system, the perceived color lies between that of a colorimetric calculation(corresponding to no adaptation) and one having no change at all from variations in ambient light(corresponding to complete adaptation).

Fig.1 illustrates how to produce colors that appear similar under different ambient light. The open circle is the given reflective color stimulus for the initial ambient light. The filled circle is the colorimetric color seen under the second ambient light. After adaptation to the second ambient light is complete, the eyes perceive the color of the filled circle at the coordinates of the rectangle. However, a small error remains as shown with the arrow in Fig.1; this is the perceived color difference for the change in light source.

Since the star should be perceived as the color corresponding to the open circle, the star must be displayed instead of the filled circle in order to reduce the perceived color difference. Therefore, one key issue to represent good color on the R-LCD is to predict color coordinates of the corresponding colors (i.e. the star) and to display them on the R-LCD under particular light source. To make it possible, modeling the visual adaptation property within the R-LCD display system is required.

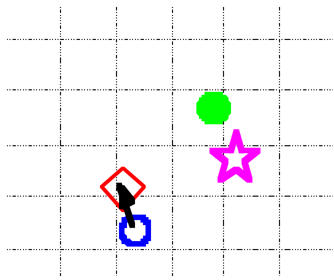


Figure 1. An example of color appearance under a different ambiant light.

Appearance of Colors on R-LCD in Terms of Adaptation of the Human Visual System to Light Source Variations

Recently, various color appearance models have been compared with the characteristics of the human visual system. However, owing to the complexity of the human visual system, no completely satisfactory result has been achieved. All the viable modern models are based on a single well-known model, the Johannes von Kries color adaptation model.[3]

In order to understand perceived color in terms of the light source, we estimated the appearance of colors on an R-LCD, using the von Kries color adaptation model and subjective experiments.

Configuration of the Experiments

Using two LCD's, we designed a subjective experiment called the pair-matching test. Fig.2 shows the experimental setup. An R-LCD with a gray mask was viewed in a light box with standard D65 or D50 illuminants. A transmissive-type LCD (T-LCD) with a gray mask was installed adjacent to the light box as a reference. Both masks were made from 20% neutral ungrained plastic, and each had a 5-cm square hole over the LCD, which was perceived as a color patch. The illuminance of the color patch potion of the R-LCD was calibrated to 600[*lx*] for both D65 and D50 illuminates.

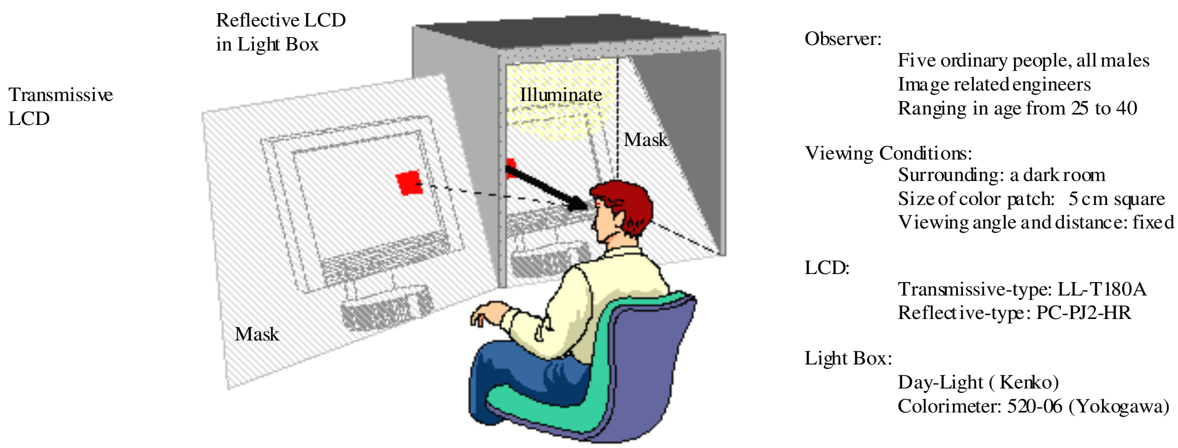


Figure 2. Configuration of the subjective experiment

This experiment used four different colors as the target color stimulus: red, green, blue, and white. The observer was required to switch their view back and forth between the two displays.

Experiment Procedure

The experimental conditions are detailed in Fig.3, which was based on a paired comparison technique. First, the observer looked at the mask on the R-LCD under a D65 illuminant for at least 3 minutes, to allow complete adaptation[(4)] (Step A in Fig.3). Next, the color red (i.e., a code value of (200,0,0)) was displayed on the R-LCD, and the observer viewed the color on the R-LCD through the 5-cm square hole in the mask. Then the observer altered the RGB code value of the T-LCD so that the color on the T-LCD matched that perceived on the R-LCD (Step B in Fig.3). The illuminant was then changed to D50 instead of D65, and the observer again focused on the R-LCD in the light box for at least 3 minutes (Step C in Fig.3). Then, the observer adjusted the color on the R-LCD so that it matched the color on the T-LCD by altering the RGB code value (Step D in Fig.3).

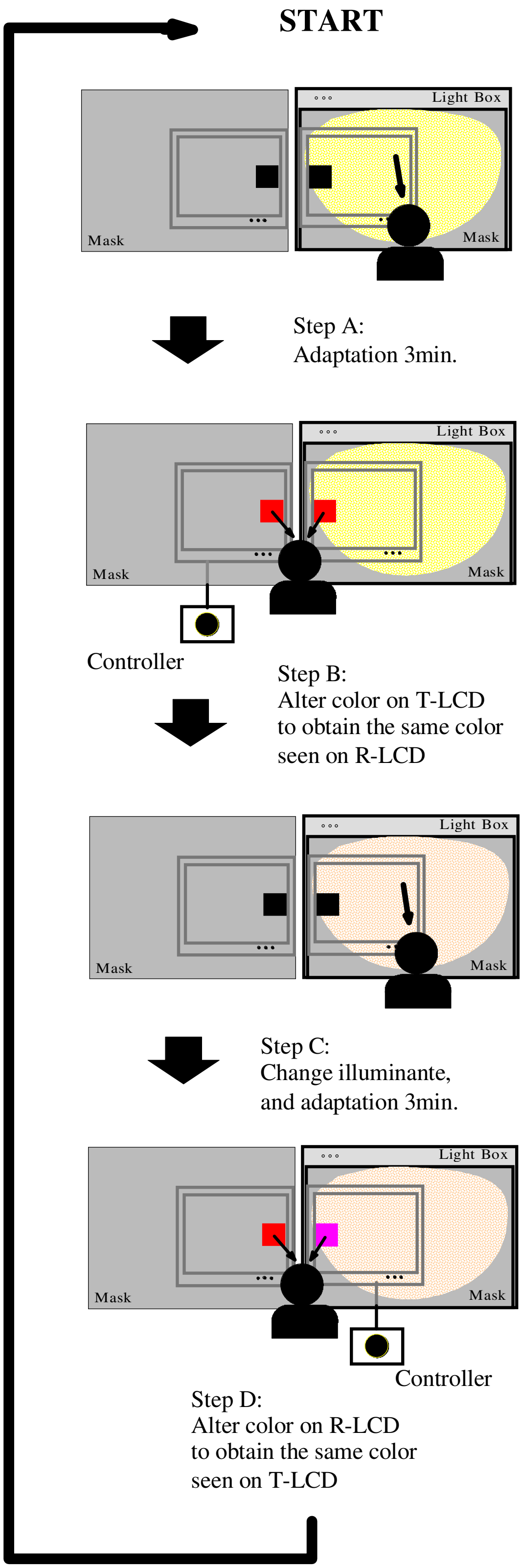


Figure 3. Flowchart of subjective experiment.

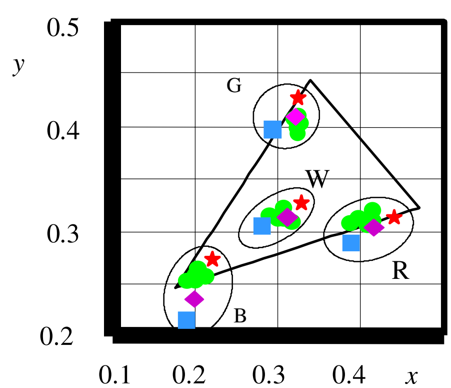
This experiment allowed us to simulate needed color correction to apply to the R-LCD to match the T-LCD. If the observer adjust R-LCD again at the step D to match the T-LCD at step B, code values on the R-LCD that will provide same color perception under different ambient light can be obtained.

If the source of illumination of the R-LCD is not changed before or after the T-LCD is aligned, the final RGB code values for the R-LCD should be approximately the same as the initial code value (i.e. (200,0,0)). As expected, when the illumination source was unchanged there were no marked differences between the initial and subsequent RGB code values for the target color patch on the R-LCD. The experiments were done carefully and proved accurate, although the sample size was not large.

Experimental Results and Discussion

The results are shown in Fig.4. The color coordinates obtained by the von Kries model are also noted. The results in Fig. 4 show that the color coordinates obtained by the von Kries model reasonably approximate the experimental results. Therefore, the von Kries model can predict the corresponding color for particular light conditions, and can be used to control a color management unit.

Since the von Kries model can be derived as a simple matrix operation, the model is expected to install into PC software easily as the corresponding color predictor.



■ Given color under D65, ★ Given color under D50, ● Experimental result under D50, ◆ Appearance of given color under D50 predicted by von Kries model, and — Range in color of R-LCD used at D50.

Figure 4. Results of subjective experiments.

Color Management of an R-LCD

One of the most critical issues in color management of an R-LCD is the color coordinate of the primary colors. Since the R-LCD works together with ambient light, the color coordinates of the red, green, and blue primary colors on the R-LCD are displaced if the illuminant of the ambient light is changed. Obviously, changes in color on R-LCD occur if ambient light changes.

Fig.5 illustrates a displacement of the primary colors. The changes shown in Fig.5 were measured when the light changed from D65 to D50 to A.

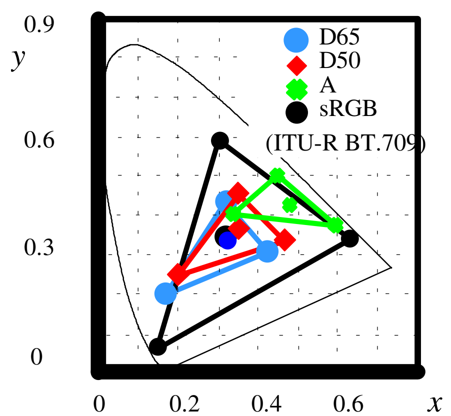


Figure 5. Displacement of the primary colors

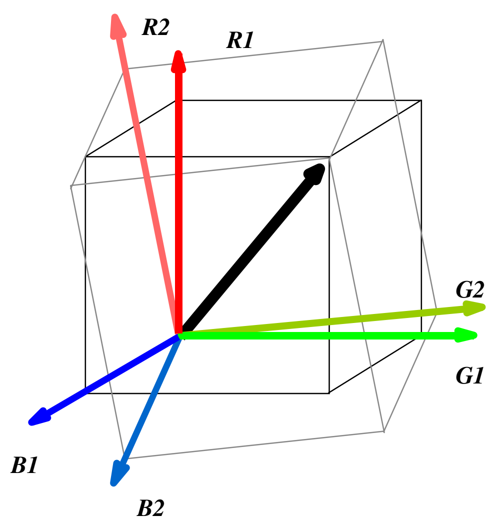


Figure 6. Perspective transform of color coordinates.

Color Compensation by Using Matrix Operation

A two-step process is required to manage color on an R-LCD: (1) compensation for the displacement of the primary colors, and (2) prediction of the corresponding color.

First, change in color due to the displacement of the primary colors is compensated by using a simple 3x3 matrix operation[5] between the digital code values of both color primaries as shown in Fig. 6. For example, a color that is expressed by a combination of one set of first color primary can be derived as another combination of a set of second color primary as follows:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_2 = \begin{pmatrix} M_1 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}_1 \quad (1)$$

where $(RGB)_1$ and $(RGB)_2$ are digital code value of the color on first and second color primaries, respectively.

As the transformation between *XYZ* tri-stimulus values and stimulus of RGB color primaries can be also expressed as 3x3 matrix, equation (1) is denoted as

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_2 = \begin{pmatrix} M_3 \end{pmatrix}^{-1} \begin{pmatrix} M_2 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}_1 \quad (2),$$

where M_2 and M_3 are

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1 = \begin{pmatrix} M_2 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad (3)$$

and

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_2 = \begin{pmatrix} M_3 \end{pmatrix}^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (4).$$

Though color coordinates of the color primary are displaced depending on its code value,[6] this displacement can be easily eliminated by using gamma correction table.

Second, as mentioned before, the von Kries model can be derived as a 3x3 matrix operation between tri-stimulus values of the color as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{predicted} = \begin{pmatrix} M_4 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{original} \quad (5)$$

The *(XYZ)predicted* values describe a color stimulus that is produced, for an observer chromatically adapted to the chromaticity of second light source, a visual match to the *(XYZ)original* stimulus viewed by an observer who is chromatically adapted to the chromaticity of first light source.

Considering equation (2) and (5), corresponding color reproduction by using the displaced primary colors is performed as

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_2 = \begin{pmatrix} M_3 \end{pmatrix}^{-1} \begin{pmatrix} M_4 \end{pmatrix} \begin{pmatrix} M_2 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}_1 \quad (6).$$

Since equation (6) can be cascaded as a simple 3x3 matrix operation, the color management of the R-LCD can be easily installed into the practical color profiles of Windows OS on a PC.[5] Using this color profile, we can reproduce the corresponding colors for specific light conditions.

Experiments

We performed subjective experiments using two laptops with R-LCD's in order to confirm how well this R-LCD color management system works in practice. The subjective experiments were initiated after adaptation to each illuminant was completed. For the experiments, each PC was viewed under a different ambient light. The color profile of each PC was calibrated using the primary colors displaced by the individual light source illuminating that PC.

Consequently, the color reproduction of the R-LCD was greatly improved, as shown in Fig.4.

Discussions

In this paper, we demonstrate color management of R-LCD in terms of adaptation of the human visual system to light source variation. Two problems are anticipated in color management on an R-LCD. First, the small color gamut of an R-LCD has to be considered. Since the primary colors are displaced markedly according to light changes, further experiments must take into account the required color gamut. Second, it must be determined how to make color-correction matrixes, such as equation (3) and (4), for a variety of light sources. The R-LCD unit would have a simple built-in sensor to use as a spectra-colorimeter of the ambient light.

In addition, further considerations about which color adaptation model should be used on an R-LCD color management have to be anticipated. Color adaptation model in terms of the Hunt effect[2] may improve practical color gamut of the R-LCD at brighter place. Since 3x3 matrix operation is a fundamental requirement within a color profile for display device, simplified Bradford model[(2)] is one of a potential models to be considered as a color adaptation model for a matrix M at equation (4).

Conclusion

This paper discussed how colors perceived on a reflective-type LCD are related to ambient light conditions. An experimental color management unit for an R-LCD based on the von Kries model has practical applications. The results obtained agree approximately with those expected.

Although the device characteristics of R-LCD's need further improvement, it is expected that R-LCD's will be used in a wide range of applications due to their low power consumption. To obtain good colors requires ambient light sensors and further experiments on the color adaptation model.

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