Impact on the Observer Metameric Failure by Adding a White Channel to RGB-Primary Display

Jang Jin Yoo*, Junwoo Jang*, Joon Young Yang* and Soo-Young Yoon*

*** LG Display, Seoul, Korea**

Abstract

Observer metamerism, or observer metameric failure, has emerged as a significant challenge for wide color gamut displays. To address this issue, multi-primary displays have been proposed as a potential solution. However, their high manufacturing costs have hindered their commercialization in consumer products. One notable example of a successful multi-primary display is white OLED technology. In this study, we investigated how the white sub-pixel in the white OLED display affects observer metamerism. The results showed that observer metamerism decreases as the proportion of white sub-pixels increases. Additionally, adding white sub-pixels was particularly effective in improving metameric failure at narrower display spectra.

Author Keywords

observer metamerism; observer metameric failure, observer differences; observer variability; wide color gamut display; multi-primary display; white OLED

1. Objective and Background

Observer metamerism (OM) is defined as a phenomenon that occurs when two colors appear to match one observer but not another. This can happen because individual observers have different color-matching functions from the CIE standard observer, and OM could cause color mismatching and be a problem in some applications which take color accuracy critical [1].

OM has also become important in display industry as the proliferation of wide color gamut displays. To realize wide color gamut, the narrowband primary spectra should be used. To achieve the BT.2020 color gamut, display manufacturers are trying several approaches, and products using three primary laser light sources are already commercially available. While the use of these narrowband spectra has the advantage of increasing the color gamut, they are susceptible to OM [2].

Accordingly, a wide color gamut display having lower OM is in demand for color professional use. One of the solutions frequently suggested is multi-primary display which has more than 3 primary colors. There have been some multi-primary display products for other reasons than OM. For example, RGBW, RGBY LCDs etc. were in the market to offer lower power consumption or higher luminance [3]. For academic use, some multi-primary displays were developed to study wide color gamut and OM [4]. This study indicated that optimizing multi-primary display should be also considered to reduce observer metameric failure. More primaries could not always guarantee lower observer metameric failure.

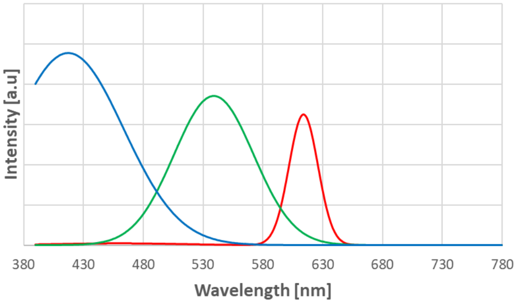
Our previous work showed the similar result as the finding [5]. We simulated a total of 14,168 virtual display spectra, and calculated OMI (observer metamerism index) referring to IEC TS 61966-13 method [6] which has been recently published by the IEC based on the CIE technical reports [7,8]. Our result indicated that the OMI is also dependent on the peak wavelength of RGB primaries even though they have the same chromaticity gamut area. Also, it was confirmed that the OMI increases as the chromaticity gamut area increases.

Meanwhile, multi-primary displays are not common now in the market due to the higher manufacturing cost and consumer price, and it is not expected the technology could be more adopted soon. However, white OLED (WOLED) having WRGB sub-pixels has been popular because this technology has advantage in productivity for large OLED panel like TV or monitor. In this paper, the WOLED's white sub-pixel as an additional channel to RGB-primary will be studied to investigate if the addition could mitigate observer metameric failure and how much the OM correlates with the white sub-pixel ratio.

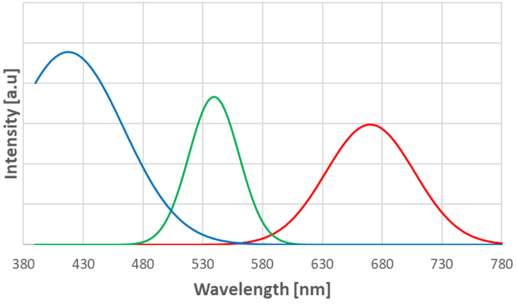
2. Method

Display Spectra

To evaluate the impact on the OM of the additional white sub-pixel, display spectra and white sub-pixel spectrum are required. We generated the hypothetical displays using the same red, green, and blue color coordinates as BT.709, DCI-P3, and BT.2020, respectively. The hypothetical displays' spectra have the form of a Gaussian function as shown in Equation (1) and Figure 1, following the method in the reference [5]. The parameter μ means the peak wavelength of a primary, while σ modulates the spectral bandwidth of the spectrum. Each hypothetical display was assumed to consist of three primaries, R, G and B, for convenience, and μ and σ of each R, G and B spectrum were derived by numerical analysis to match the target CIE 1976 $u'v'$ coordinates. Since there can be multiple combinations of μ and σ that match the target $u'v'$ coordinates, calculations were performed over a limited range of wavelengths.

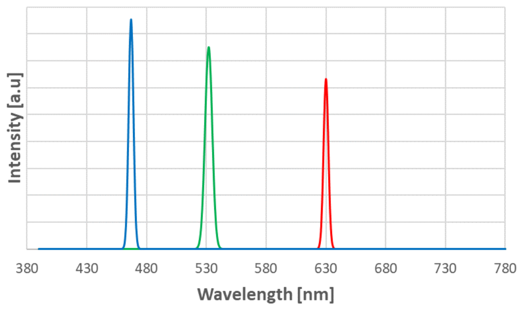


(a) BT.709 display



(b) DCI-P3 display

ISSN 0097-996X/25/5602-0990-$1.00 © 2025



(c) BT.2020 display

Figure 1. Hypothetical displays spectra

$$S_M(\lambda,\mu,\sigma)=\frac{1}{\mu\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{\lambda-\mu}{\sigma}\right)^2} \qquad (1)$$

The white sub-pixel's spectrum was also generated to have a correlated color temperature of 6500K, as shown in Figure 2. The white spectrum is based on commercially available WOLED TV products. The measured white spectrum was modified by 6500K by adjusting the ratio of red and green wavelength regions.

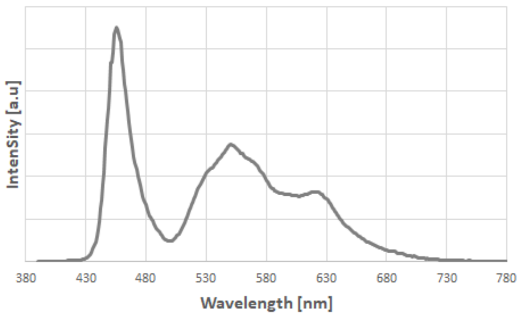


Figure 2. Hypothetical white sub-pixel spectrum.

IEC TS 61966-13

IEC TC100 recently published the 61966-13 Technical Specification (Measurement method of display colour properties depending on observers), which describes how to evaluate OM [6]. To evaluate OM, a reference color and a color matching function data set are required. The Technical Specification uses the Macbeth W, R, G, B, C, M and Y colors under a D65 light source as reference colors and a 2-degree field of view color matching functions (CMFs) calculated using the CIE model [7,8]. Except for field of view, only age is a variable in the individual CMFs. The age groups have a total of 12 individual CMFs with ages ranging from 22 to 77, evenly divided into 5-year intervals.

Figure 3 shows the flowchart of the evaluation method, first measure the spectrum of the display and conduct color matching with a reference color using individual CMF. After that, calculate the XYZ value using CIE 1931 standard observer CMF and calculate the CIE ΔE_{2000} value. And repeat these steps for individual observer and reference color. With this standard, we can get the mean, standard deviation, maximum, and minimum values of the ΔE_{2000} color difference by age for each color, as well as the overall mean, standard deviation, maximum and minimum values as results.

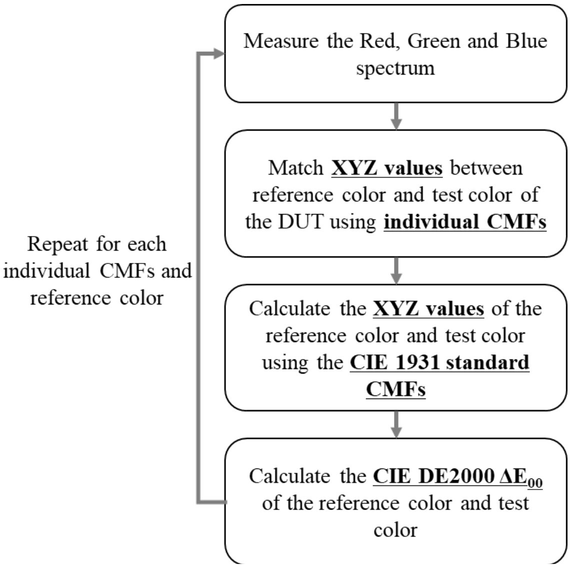


Figure 3. Flowchart of the OM evaluation method in the IEC TS 61966-13

Color matching process

In this study, we used the same IEC TS 61966-13 standard as in previous study [5,9] to evaluate OM characteristics. During this process, the spectra of the test display and the individual CMFs are used to perform color matching between the reference colors and the test display. Previous studies have shown that achromatic colors are the most susceptible to OM [5,9,10]. Thus, for this study, only the Macbeth White pattern was used.

To analyze the influence of white sub-pixels, the test display was assumed to be a color mixture of the hypothetical display spectra created in the previous clause, with varying proportions of white sub-pixels also generated. The color matching of the display with the added white sub-pixels was performed using the method of Annex D of IEC TS 61966-13 [6].

Equations (2) and (3) determine the weighting factors of red, green and blue primaries that result in the same tristimulus value as the reference color. X, Y and Z values denote tristimulus value of each primary, additional white and reference color. The w is the weighting factors of each primary.

$$\begin{bmatrix} X_{ref} \\ Y_{ref} \\ Z_{ref} \end{bmatrix} = \begin{bmatrix} X_{white} \\ Y_{white} \\ Z_{white} \end{bmatrix} + \begin{bmatrix} X_{red} & X_{green} & X_{blue} \\ Y_{red} & Y_{green} & Y_{blue} \\ Z_{red} & Z_{green} & Z_{blue} \end{bmatrix} \cdot \begin{bmatrix} w_{red} \\ w_{green} \\ w_{blue} \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} w_{red} \\ w_{green} \\ w_{blue} \end{bmatrix} = \begin{bmatrix} X_{red} & X_{green} & X_{blue} \\ Y_{red} & Y_{green} & Y_{blue} \\ Z_{red} & Z_{green} & Z_{blue} \end{bmatrix}^{-1} \cdot \begin{bmatrix} X_{ref} - X_{white} \\ Y_{ref} - Y_{white} \\ Z_{ref} - Z_{white} \end{bmatrix} \qquad (3)$$

$$\Phi_{test}(\lambda) = \Phi_W(\lambda) + \begin{bmatrix} w_{red} & w_{green} & w_{blue} \end{bmatrix} \cdot \begin{bmatrix} \Phi_R(\lambda) & \Phi_G(\lambda) & \Phi_B(\lambda) \end{bmatrix}^T \qquad (4)$$

The final test spectrum is then determined by Equation (4) using the derived weighting factors. $\Phi_{test}(\lambda)$ is the final test spectrum, and $\Phi_W(\lambda)$, $\Phi_R(\lambda)$, $\Phi_G(\lambda)$ and $\Phi_B(\lambda)$ are the spectrum of each color.

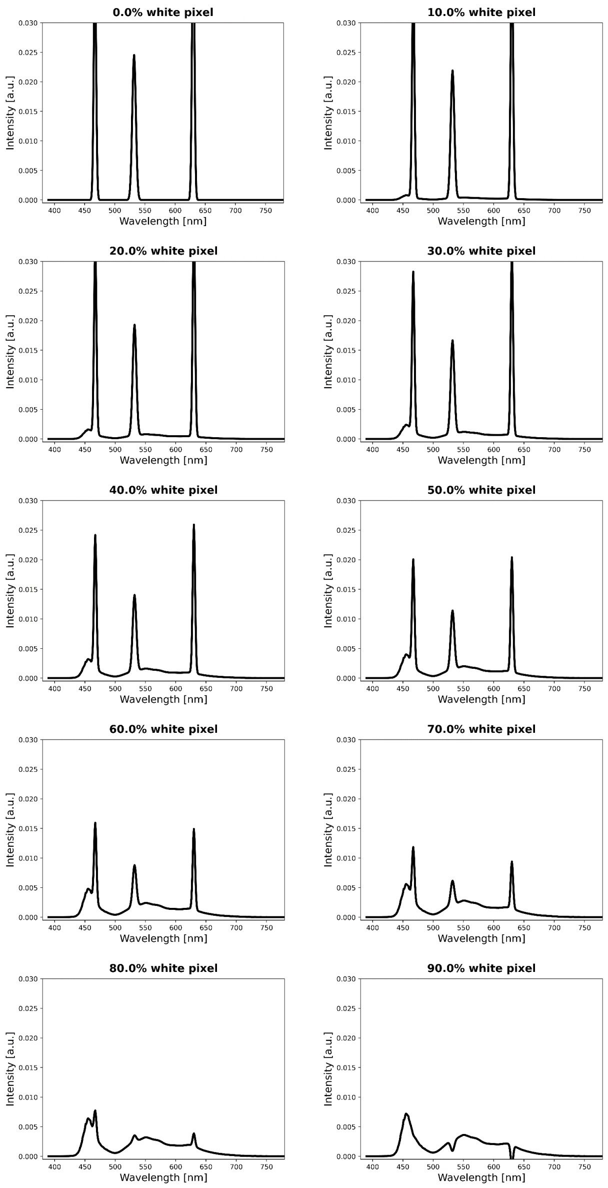


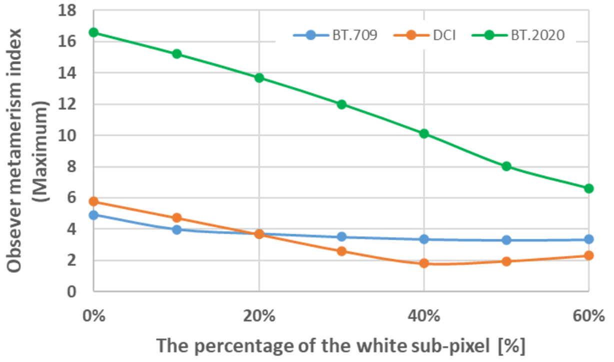
Figure 4. Final test spectra of hypothetical displays (BT.2020) with age 22 individual CMFs

Figure 4 shows the results of the final test spectra with variance of additional white sub-pixel using BT.2020 hypothetical display and age 22 individual color matching functions. The test spectrum was derived by performing color matching while varying the percentage of white sub-pixel from 0% to 90%. The percentage of white sub-pixel is the ratio of the luminance of the reference color. As can be seen in the Figure 4, as the percentage of white increases, the percentage of red, green and blue decreases. However, above 90%, the weighting factor becomes negative, which is physically impossible. Therefore, the final OMI calculations only used white percentages below 60%. It should be also noted that the XYZ values of all the hypothetical displays are matched to the same as that of the reference color of Macbeth white. And the color gamut of each hypothetical display does not change as adding the amount of white sub-pixel or luminance of white sub-pixel.

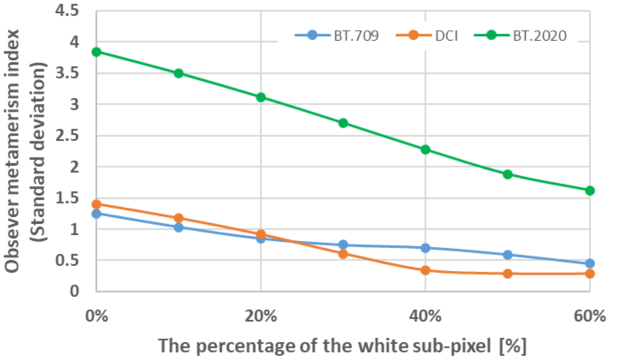
After that, the XYZ values were calculated using CIE 1931 standard observer CMFs and the ΔE_{2000} color difference was also calculated. And these steps for individual observer and reference color were repeated. With this simulation, we can get the mean, standard deviation, maximum, and minimum values of the ΔE_{2000} color difference by age for each color, as well as the overall mean, standard deviation, maximum and minimum values as results.

3. Result and Discussion

The results of calculating the OMI values of final test spectra are shown in Figure 5 below. The x-axis of the graph is the percentage of the white sub-pixel. The y-axis is the maximum value and standard deviation of OMI value over each age group. The colors in the graph represent the hypothetical displays BT.709, DCI-P3 and BT.2020, respectively.



(a) OMI (maximum)



(b) OMI (standard deviation)

Figure 5. OMI values of each hypothetical display according to the addition of white sub-pixel

As shown in the graph, we can see that OMIs decrease as the proportion of white sub-pixels increases. In particular, the worse the observer metameric failure, i.e., the narrower the display spectrum, it is clearer the observer metameric failure improves thanks to the additional white sub-pixels. For BT.2020 displays, the analysis showed a more than 2 times improvement between no additional white sub-pixels and 60% additional white sub-pixels. In general, OM is known to be susceptible in achromatic colors [9,10]. Adding white sub-pixels can improve observer metameric failure in achromatic colors, as confirmed by the results of this study.

This result indicates that adding WOLED's white spectrum makes the spectra of the displays broader which enables less sensitive to

OM. If the white spectrum is not broader than the summation of R, G and B spectra, there will not be the improvement of OMI by adding the white sub-pixel. In case of the BT.709 display, the addition effect was not bigger than other two displays with wider gamut since the spectrum of the display is already broader compared to the others.

4. Conclusion

To investigate how much the addition of white sub-pixel to RGB displays affect the improvement of observer metameric failure, the white spectrum of the WOLED was added to the spectra of three hypothetical RGB displays with the chromaticity gamut of BT.709, DCI-P3 and BT.2020. As the portion of white sub-pixel increases, the OMI values of the displays decreased, which means the improvement of observer metameric failure. Also, the BT.2020 display with narrower band showed more outstanding improvement.

While more primaries could offer wider color gamut than RGB primary, it looks difficult to see the displays with multi-primary colors in the consumer market due to the higher price and cost. So, the WOLED technology which has been successful in the TV and monitor market could be more practical solution to the observer metameric failure.

5. References

1. Fairchild MD. Color Appearance Models. Wiley & Sons; 2013:335-340.
2. Fairchild MD, Wyble DR. Mean Observer Metamerism and the Selection of Display Primaries. Color and Imaging Conference. 2007.
3. Yoshiyama K, Furukawa H, Kondo N, Nakagawa S, Yoshida Y. A New Advantage of MultiPrimaryColor Displays. SID Symposium Digest of Technical Papers. 2012 July;41:281-282. https://doi.org/10.1889/1.3500430
4. Long DL, Fairchild MD. Modeling Observer Variability and Metamerism Failure in Electronic Color Displays. Journal of Imaging Science and Technology. 2014:030402-1 - 030402-14. https://doi.org/10.2352/J.ImagingSci.Technol.2014.58.3.030402
5. Jang J, Jin Y, Yoo JJ. Analyzing Observer Metamerism Characteristics Based on the Peak Wavelengths of Primary Colors. SID Symposium Digest of Technical Papers. 2024 July;55:797–800. https://doi.org/10.1002/sdtp.17648.
6. IEC TS 61966-13:2023 | IEC Webstore [Internet]. [cited 2023 Nov 21]. Available from: https://webstore.iec.ch/publication/6776.
7. CIE 170-1:2006. Fundamental Chromaticity Diagram with Physiological Axes-Part 1.
8. CIE 170-2:2015. Fundamental Chromaticity Diagram with Physiological Axes-Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagram.
9. Jang J, Yoo JJ. Study on Observer Metamerism Characteristics of Wide Color Gamut Displays with Various RGB Primaries. International Meeting on Information Display. 2023 Aug 24.
10. Park Y. Modeling Perceptual Trade-offs for Designing HDR Displays. Theses [Internet]. 2021 Aug 9; Available from: https://scholarworks.rit.edu/theses/10956.