

Spectral Definition of Standard Color Space Primaries for Display

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Abstract

To calibrate a display, a standard color gamut is defined by the target chromaticity coordinates of RGB primaries in CIE 1931 color space, e.g. DCI-P3 and Rec.709. Due to lack of spectral information of such standard target gamut primaries, transformation of target color gamut from CIE 1931 color space to another color space associated with a different observer (defined by a different set of CMFs) is not possible. In this paper, we introduce a novel method for transforming target primary colors from CIE 1931 color space into a new target color space with improved color appearance consistency for typical observers. Our approach represents each primary with a simple spectral definition across the visible range. Results demonstrate that this spectral definition significantly reduces inter-observer variation, thereby offering a practical solution to cross-observer display color space transformation.

Introduction

The development of novel display technologies with varieties of emission spectrum have increased the potential for an observer to perceive mismatched appearance of a single scene on multiple calibrated displays [1][2]. The color of a display is impacted by the spectral distribution of the display signal and the observer color matching functions (CMFs). The CIE 1931 standard observer CMFs, which have been widely used in display industry, have shown limitations to achieve perceptual consistency in modern displays with narrow spectral primaries. That is, two displays showing colors with same CIE 1931 tristimulus values yet their spectral power distributions are distinct, a color mismatch can be observed. This necessitates the need for calibrating a display with a set of CMFs that better represents average observers to achieve color appearance consistency across display technologies [3].

Consistency of appearance across display devices is enabled by characterization and calibration process, through which a display color gamut is characterized by measuring the panel properties and then mapping into a set of standard target color spaces, such as to Rec.709 [4], DCI-P3 [5], Adobe RGB [6], or Rec.2020 [7]. The transition to modern colorimetric observers, such as CIE 2015 2° CMFs, exposes a critical gap in display calibration. There is neither standard reference that defines the primary coordinates in any color space other than CIE 1931, nor spectral definition of standard target primaries in literature for color transformation between color spaces. This ambiguity, compounded by the diverse and technology dependent spectral power distributions (SPDs) of commercial displays, makes it impossible to map such standard target colors directly from the CIE 1931 color space to another color space associated with a different set of observer CMFs. To define spectral characteristics of such standard color gamut primaries, the main objective of this work is to develop the theoretical ground for spectral properties of a display based on the premise of minimizing inter-observer variability for the percept of a color.

Method

Optimal Color Stimuli

An optimal color stimulus refers to a theoretical spectrum of an additive or subtractive color reproduction that defines the boundary of the system, governed by the spectral characteristics of optimal color primaries [8]. Optimal color stimuli are object colors that lie on the surface of the object-color solid which set the boundary of all possible object colors [9]. An optimal color can be described by its spectral reflectance function in a simple form that takes only zero or unity values throughout the visible spectrum range [10][11]. The step function – in two forms – can be used to represent an optimal color stimulus,

$$E(\lambda) = \begin{cases} 1, & \lambda_1 \leq \lambda \leq \lambda_2 \\ 0, & \text{others} \end{cases} \quad (1)$$

where $E(\lambda)$ denotes the spectral reflectance function of a stimulus, λ denotes the variable of the spectral wavelength, and λ_1, λ_2 are the transition wavelengths in the visible range. The other form is a simple flip of zero and unity values of Eq. (1) across the spectrum and can be mathematically defined as:

$$E(\lambda) = \begin{cases} 0, & \lambda_1 \leq \lambda \leq \lambda_2 \\ 1, & \text{others.} \end{cases} \quad (2)$$

These two function types are illustrated in Fig.1 respectively.

Emissive Color Stimuli

In this paper, we apply the definition of optimal color for emissive stimuli, i.e. display colors, to represent their relative spectral power distribution (SPD) where its SPD is normalized to its peak value. Consequently, this study focuses exclusively on color chromaticity, while the luminance dimension is disregarded.

Given a spectral function, the color tristimulus values of such an emissive signal is defined as,

$$\rho_i = \int_{\lambda_{min}}^{\lambda_{max}} E(\lambda) p_i(\lambda) d\lambda, \quad i \in \{X, Y, Z\} \quad (3)$$

where $E(\lambda)$ is spectral power distribution of a display stimulus under the same definition as in Eqs (1) and (2), and $p_i(\lambda)$ is the color matching functions of an observer (i denotes the color channel) throughout the visible spectrum range of λ_{min} and λ_{max} [12]. In this study, the following values will be used: $\lambda_{min} = 390$ nm and $\lambda_{max} = 760$ nm. Given the tristimulus XYZ values, it is straightforward to calculate its chromaticity values as $x = \frac{X}{X+Y+Z}, y = \frac{Y}{X+Y+Z}$.

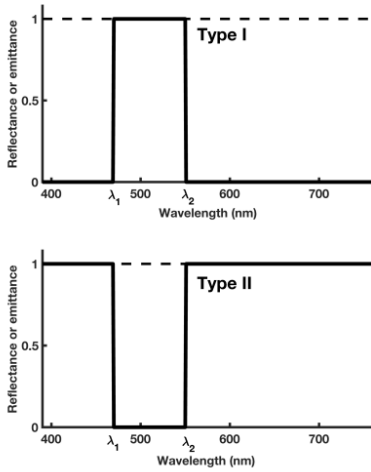


Figure 1. Two types of step function used to represent the spectral reflectance or emittance distribution of optimal color stimuli. The top and bottom curves show the spectral function of Eq. (1) and Eq. (2) respectively.

Following the definition, varying the parameters of λ_1 and λ_2 throughout the visible spectrum generates the complete set of all possible emissive stimuli. From these spectral stimuli, all corresponding chromaticity coordinates within the spectral locus can be computed, as depicted in Fig. 2. The colors of Type I and Type II are complementary and therefore, cover the entirety of the chromaticity diagram. In addition, each point in the color space is associated with its corresponding optimal spectral stimulus function of either Type I or II. Special cases of color stimuli under the definition of Eq. (1), when $\lambda_1 = \lambda_2$, form the spectral locus of the chromaticity diagram and that of Eq. (2) makes the equal energy (EE) white point with xy chromaticity value of (1/3, 1/3).

For a given target spectral stimulus, such as D65 or EE white, an additive color reproduction system with broadband spectral distribution can reproduce colors with minimized observer metamerism. A theoretical display with optimal color primaries of simple and broader option of spectrum for each primary satisfies the condition of minimized inter-observer variability, thus can be used for the spectral definition of standard color space primaries in a display system.

Spectral Definition of Display Primaries

Display color gamut refers to the range of colors a display can produce and is determined by its RGB primaries. A display standard color space, such as Rec.709, DCI-P3, Adobe RGB, is defined by target chromaticity coordinates of RGB primaries in CIE 1931 color space. Yet, the standards do not provide spectral definition of the target RGB primaries, and thus it is not possible to transform the standard color gamut to a different observer other than CIE 1931 standard observer. In this paper, we seek spectral functions in the form of the same spectral definition of optimal colors that return the exact chromaticity values of RGB primaries of standard color spaces.

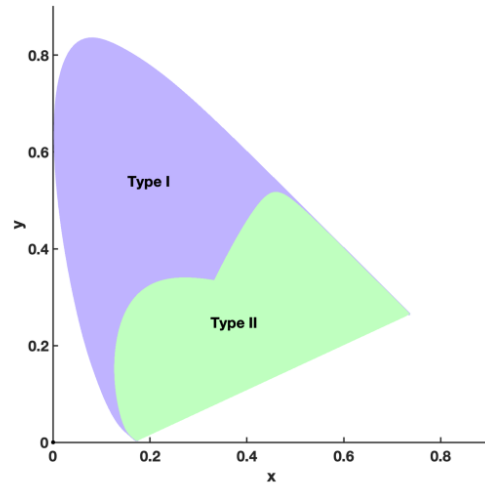


Figure 2. The color coverage of all possible spectral stimuli under the definition of Type I (in purple) and Type II (in green) illustrated in the xy chromaticity diagram respectively.

Let $E(\lambda)$ represent the spectral curve of a standard primary in the form of step function (the spectral shape is determined by the transition wavelengths of λ_1, λ_2) whose target chromaticity values are $[x, y]$ and $p_i(\lambda)$ for the color matching functions of the CIE 1931 standard observer as in Eq. (3). It is useful to recast the continuous formulation in Eq. (3) in the discrete domain by using matrix-vector representation where spectra are represented as sampled vectors. In this study, the visible spectrum is sampled between 390 nm and 760 nm with the sampling step of 1 nm, thus a spectrum is a 1×371 vector.

Converting into discrete domain, Eq. (3) is rewritten as

$$\underline{\rho} = \underline{E} \underline{p} \quad (4)$$

where the vector \underline{E} denotes the spectrum of a standard primary. \underline{p} represents the CIE 1931 color matching function, and $\underline{\rho}$ is a 1×3 denotes the color response values with chromaticity values of $[x, y]$.

For a standard color gamut, only the 2-D chromaticity values matter for defining the color boundary and thus its intensity values can be ignored in this problem. For the right side of Eq. (4), the only variables are the transition wavelengths, λ_1, λ_2 .

The mathematical problem of Eq. (4) can be reformed as,

$$\begin{bmatrix} x \\ y \end{bmatrix} = f\left(\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix}\right). \quad (5)$$

In Eq. (5), the chromaticity coordinates $[x, y]$ is a function of two variables $[\lambda_1, \lambda_2]$, hence, is a deterministic problem with an exact solution with two unknown variables and corresponding equations. This formulation and problem solution apply to basically all standard RGB color spaces, e.g. Rec.709, DCI-P3, Adobe RGB. For the special case of Rec.2020 [7], its primaries have the monochromatic solution where $\lambda_1 = \lambda_2$ and are equal to 630 nm, 532 nm, 467 nm for red, green, and blue primaries respectively.

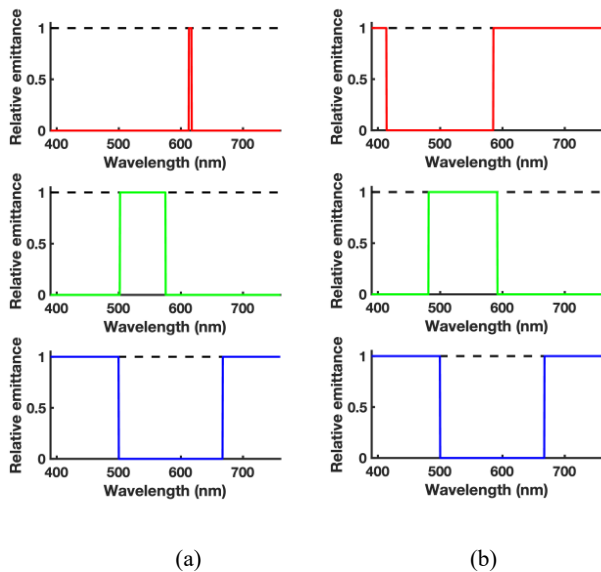


Figure 3. The spectral distribution of the RGB standard primaries of (a) DCI-P3 and (b) sRGB displays.

Given the spectral definition of target primary colors, it is straightforward to transform the primary spectra into a new color space using Eq. (3) to derive the color coordinates of the color gamut targets in the new color space. Hence, we have achieved the goal of color transformation for color gamut across observers.

Results

Optimal Spectral Display

By solving for Eq. (5), we can obtain the spectral curves of RGB primaries for different color gamuts. The spectral distribution of the RGB primaries of DCI-P3 and sRGB color spaces derived from Eq. (5) are shown in Figs 3a and 3b respectively. Note, the terms of Rec.709 and sRGB are used interchangeably in this paper as they share the same gamut and RGB primary definitions. For DCI-P3 primaries in Fig. 3a, it can be seen that red and green primaries are in the function form of Type I while blue primary is in Type II as blue primary of DCI-P3 has color values which fall into the cyan region of Fig. 2. The red primary has a very narrow spectral shape due to its closeness of chromaticity values to the spectral locus. Out of surprise, we see that the blue spectrum contains distribution not only in the short wavelength but also contains emission in the long wavelength end. Also, the spectrum distribution of RGB primaries do not have any overlap across the visible spectrum. In Fig. 3b, comparing to DCI-P3, the red and green primary functions give much wider spectral ranges than those in DCI-P3. Its red primary falls into Type II with small portion of signal from the short wavelength (blue end).

We term a display with such spectral definition of RGB primaries as ‘optimal spectral display’. The spectral functions of the proposal are imaginary stimuli in the sense that no actual display can give spectral emission with transition as sharp as in the step function. However, they are of significant interest serving as an ideal display since they are independent of unit variation or display technology. For example, OLED and LCD displays both can reproduce DCI-P3 color gamut, yet these two technologies produce

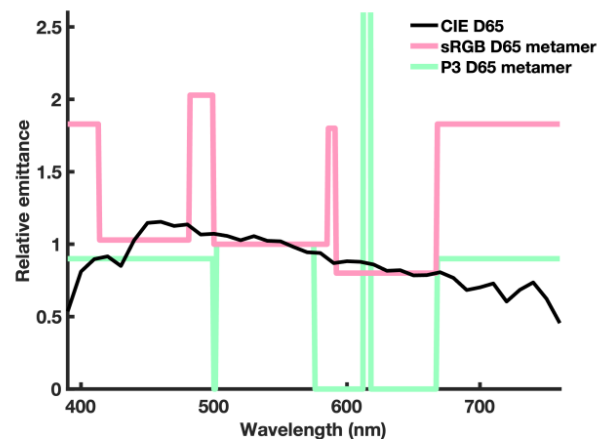


Figure 4. The D65 metamers of the optimal spectral displays of sRGB and DCI-P3 gamuts compared to the standard D65 illuminant.

very different spectral distribution of its primaries. It is not sensible to select a golden unit from either technology to represent as a typical unit of DCI-P3 color gamut. In the next subsection, we will also show the ‘optimal’ properties of our spectral display proposal.

Observer Variability across Age and FOV

When a display shows a color, it generates the emissive signal by a combination of light intensities of red, green and blue primaries. For displaying a D65 white point, it lights a color signal which gives the same chromaticity values of D65, but a different spectral distribution compared to D65 standard illuminant. We say that the display white spectrum is a metamer to D65 illuminant and this phenomenon is a fundamental mechanism for color displays.

For the optimal spectral displays defined as in Fig. 3, its relative spectral distributions of D65 metamer are shown in Fig. 4. The spectral distributions are normalized at the wavelength of 555 nm. The D65 metamer of the sRGB display has non-zero values across the spectrum and those bumps are overlapping regions of RGB primary spectra. As for the D65 metamer of the DCI-P3 display, it has a larger magnitude in the red region for its shape red primary spectral shape.

To assess the observer variations of different displays, we follow the evaluation method proposed in [13]. Here, the evaluation is made with respect to two variables: the field-of-view (2° and 10°) and ages (20/40/60 years-old), in total six conditions. The color matching functions across conditions are transformed from CIE 2006 physiologically relevant observers [14]. The performance of the proposed optimal spectral displays is evaluated against the typical displays of sRGB and DCI-P3 color gamuts, as shown in Fig. 5. The blue polygon in the top figure represents the color values of the D65 metamer of the sRGB optimal spectral display under different ages and FOVs, while the black polygon represents the results of a typical LCD display with sRGB color gamut. The bottom plot in Fig. 5 shows the performance of P3 displays, including the DCI-P3 optimal spectral display, an OLED display, and an LCD display. It is clear that the optimal spectral display gives much smaller polygon compared to other display for both sRGB and DCI-P3 gamuts, which indicates significantly better observer consistency across FOVs and ages.

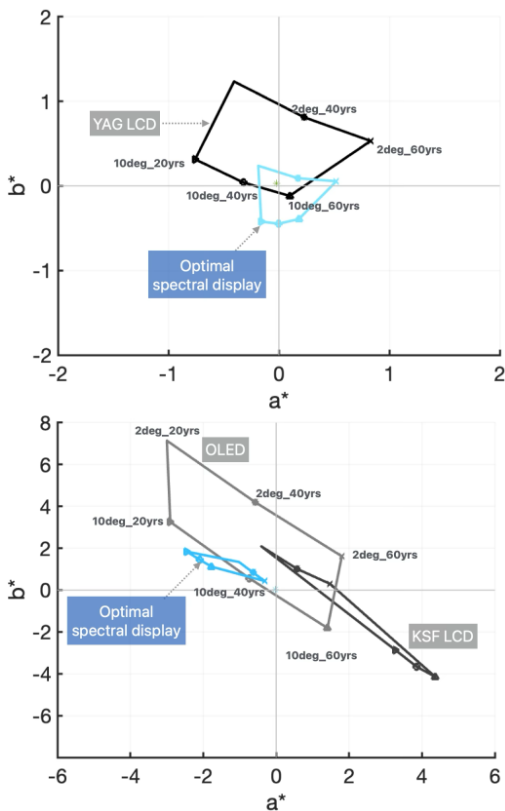


Figure 5. The variability of white point perception of sRGB (top) and DCI-P3 (bottom) displays with observers across different ages and FOVs.

Also, comparing the overall polygon area between sRGB and P3 displays, we can see that sRGB displays give much tighter boundaries and thus shows more stable color reproduction across different observer conditions than DCI-P3 displays. It confirms with the known effect in display industry that displays with wider color gamut – generally relate to narrower spectral distribution of RGB primaries – have more severe observer inconsistency than those with broader spectral distributions [1].

White Appearance Consistency

To assess the white appearance inconsistency due to different display technologies, we will evaluate the white perception difference across DCI-P3 displays by the individual observers from Stiles and Burch data set [15].

Figure 6 shows the D65 metamers of the proposed optimal spectral display, an OLED display, and an LCD display. All these displays give an exact D65 white point reading of [0.3127, 0.329] in CIE-xy chromaticity values. From the figure, we see that the D65 spectrum of the optimal spectral display gives the broad spectrum compared to the other two displays.

To evaluate the white color difference, we compute the color difference between the standard D65 illuminant and a D65 metamer of a test display perceived by an individual, and then average color difference among observers. Figure 7 shows the results of three test displays in terms of $\Delta u'v'$. The average and the standard deviation of the test displays shown from left to right are 0.0012 ± 0.0007 , 0.0047 ± 0.0024 , 0.0048 ± 0.0024 . The optimal spectral display gives the best white appearance consistency.

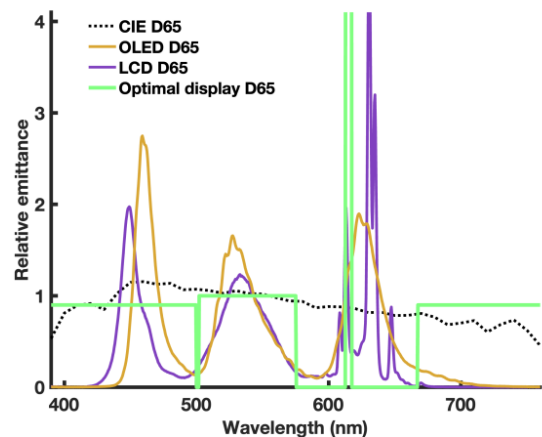


Figure 6. The spectral distributions of CIE D65 illuminant and its D65 metamers of OLED, LCD and our proposed optimal spectral displays.

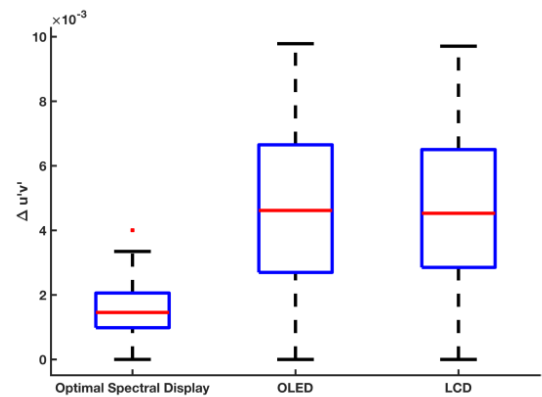


Figure 7. The color delta of D65 metamers perceived by individual observers from the Stiles and Burch's data set.

Conclusion

In this paper, we develop a simple method to generate the optimal spectral representation of the RGB primaries of a standard color gamut which is originally defined with 2-D chromaticity coordinates in the CIE 1931 color space. Given the RGB primary spectra, it is straightforward to obtain the new chromaticity coordinates of the gamut in a new color space. Hence, this study provides a useful method to transform 2-D color coordinates of gamut to any desired color space, not bounded to CIE 1931.

Experiment results show that the optimal spectral definition of standard RGB primaries, so-called 'optimal spectral display', gives significantly improved observer variation when displaying colors compared to real LCD and OLED testing displays.

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