Perceptual Color Attributes-Correlated 2D Color Gamut Volume Representation and Its Analysis

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Abstract

2D color gamut volume representation of high dynamic range displays is proposed, which is highly correlated with perceptual color attributes. Most of the color volume metrics can approximately measure the reproducible volume range of colors but the measured single volume score and the 3D graphical representation are still not straightforward to understand or compare color characteristics of displays. Therefore, by employing a new 2D representation of 3D color gamut volume, the volume information of a display is intuitively visualized and hence it provides easy way to visually compare color performance of displays. Based on this representation, understanding perceptual color dimensions such as 'Vividness' and 'Depth' becomes straightforward.

Author Keywords

Color reproduction, high dynamic range, color gamut volume, color gamut wings, color vividness, color depth.

1. Introduction

Color reproduction capability is one of the most important feature for delivering realistic images on a screen. Therefore, when it comes to metrologies for characterizing color performance of displays, there are so many measurement, evaluation and analysis items, for example, white light output (WLO), color light output (CLO), white point accuracy, color gamut and color gamut volume and so on [1, 2]. Among them, color gamut and color gamut volume (CGV) are the most important and representative measures for representing color reproduction capability on screen. Considering color gamut which measures how many colors a display can render, we only need to measure the three primary colors (red, green and blue), three multi-chromatic colors (cyan, magenta and yellow), black and white. We can plot the range on International Commission on Illumination (CIE) 1931 chromaticity diagram, which represent how much vivid colors a display can show on display screen. First, optical characteristics (the units of the tristimulus values, XYZ) of the displayed patterns on screen are measured, second, the optical information (XYZ) is converted to chromaticity (*xy* and *Y*) and finally the chromaticity coordinates values (*x* and *y*) are pointed on a two dimensional (2D) CIE 1931 chromaticity diagram. In this process, however, the 2D representation does not consider how bright those colors are, that is the large *Y*. Because gamut area is more specifically a range of reproducible chromaticities without considering a lightness of colors, therefore, an appropriate color appearance model has been required. Since the original SDR content was mastered with standard 100 cd/m^2 (nits) brightness, there was no problem in the era of only standard dynamic range (SDR). However, most of the recent displays can be likely set to a higher level than this, that is, the high dynamic range (HDR) display world has come as HDR content has been getting a much higher peak brightness than that of SDR [2, 3]. Many conventional SDR displays cannot show brightest highlight image areas of HDR content at the levels since recent HDR content is mastered with peak light levels from over 1,000 nits to 4,000 nits and sometimes over 10K nits.

Figure 1. Comparison between (left) SDR and (right) HDR color and luminance range; the brighter colors a content has, the more realistic viewing experience.

Along with the development and widespread use of the HDR wide color gamut displays, there have been proposed many HDR color capability metrologies and representations [4-6]. CGV is the coming together of the entire range from the color gamut to the luminance range as an integrated fashion. It determines both which colors are displayed and how luminous, meaning it governs both intensity and saturation, brightness, and the range of color. Thus, the three dimensional (3D) CGV are both dependent on the 2D chromaticity and brightness of colors, while 2D chromaticity gamut means the essential nature of a color regardless of luminance. Simultaneously, to develop the metrologies for HDR color performances, many academic and industry professionals have been working for display standardizations such as International Electrotechnical Commission (IEC) and International Committee for Display Metrology (ICDM) [1].

There have been various researches in relation to the color gamut volume measurement, evaluation, representation method such as color gamut rings (CGR) [4, 5]. The 2D volume representation, CGR, is designed to intuitively show that the addition of non-primary optical color channels to red, green and blue trichromatic component which can affect in a significant decrease in the chroma at higher lightness levels. For the purpose, the representation makes it possible to quantitatively comprehend the CGV without rendering volumetric 3D shapes in a certain color space. However, the CGR's visualizing and quantifying method still has non-intuitiveness to compare CGVs of different displays or contribution to the volume of a single hue in CGV. Specifically, the representation is sometimes not trivial to understand the color characteristics of displays for general people who are not in the related industries. Therefore, in this paper, a straightforward 2D representation of HDR displays' CGV is presented. The representation, Color Gamut Wings (CGW) is to sample the outermost line of the color volume according to the hue and plot it in 2-D space. This method makes it possible to compare the color volume of a certain display with any standard volume space and to compare the color volumes between displays. This representation method is also suitable for understanding the perceptual attributes of displays using 'Vividness' and 'Depth' of colors proposed by R. S. Berns [7].

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2. Perceptual Color Attributes for Communicating Different Colors

For any color representation, tools is required to intuitively understand or tell the characteristics of color and communicate their attributes. In this paper, CIELAB-based perceptual terms proposed by R. S. Berns are introduced to describe color performance of different two displays. CIELAB has three axes: L^*, a^* and b^*. L^* is a function of the luminance factor only for considering lightness independently from chromaticness (a^*, b^*). Luminance mimics human vision in a general sense, with achromatic and chromatic stimuli making distinct visual differences in the perception of spatial and temporal color. The psychophysics of over-threshold color tolerance are further supported if the tolerance ellipsoid minimizes the interaction between lightness and chromaticness [8]. Creating a visual example using CIELAB reveals that varying chroma and hue while maintaining constant lightness produces a color perception rarely seen in everyday experience. R. S. Berns conducted a research to create a CIELAB-based coordinate embodying Hering's concept [9]. This was achieved by defining three new coordinates for CIELAB: Vividness (V^*), Depth (D^*) and Clearity (T^*), where subscript (*ab*) is omitted. Vividness is the degree of departure of the color from a neutral black color and Depth represents the degree of departure of the color from a neutral white color. Clearity which is an attribute of color used to indicate the degree of departure of the color from its background color is not dealt with in this paper.

Changes in concentration for mixtures of colorants result in changes in both chroma and lightness. Directly illuminated three-dimensional colored objects change in both chroma and lightness between direct illumination and either shadow or highlight. vividness, V^*, and depth D^*. Each represents a Euclidean distance from a color defined by L^* and L^* to C^* of 0 and either $L^* = 0$ for vividness or $L^* = 100$ for depth as formulated in Eq. (1).

$$
\begin{aligned}
V^* &= \sqrt{(L^*)^2 + (a^*)^2 + (b^*)^2} = \sqrt{(L^*)^2 + (C^*)^2} \\
D^* &= \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \\
&= \sqrt{(100 - L^*)^2 + (C^*)^2}
\end{aligned}
\qquad \text{Eq. (1)}
$$

As indicated in Fig. 2, these dimensions were rotations in the L^*-C^*plane and were more meaningful to a colorist since these perceptions were highly correlated with colorant amounts. Artists use similar terminology. Certainly, the correlations with colorant intensity, shadows, and highlights are promising. The clearly defined color terms of vividness and depth could improve communication between visualizations of display characteristics. Increasing a color's vividness corresponds to a 'cleaner' or 'brighter' color while decreasing vividness makes the color 'duller'. On the other hand, increasing depth corresponds to a 'stronger' color while conversely decreasing depth makes the color 'weaker' and 'paler'.

3. Color Gamut Wings

CIELAB CGV metrics provide a single unit value that describes the size of a display's color volume and hence it is a useful value for simply understanding and comparing the color capability of a display. To obtain the CGV, the device-independent sampling of the display gamut is achieved by uniformly spanning the range of code value input to the display and measuring the resulting colors. The code values to be measured are defined by uniformly sampling the six faces of the *RGB* input color space.

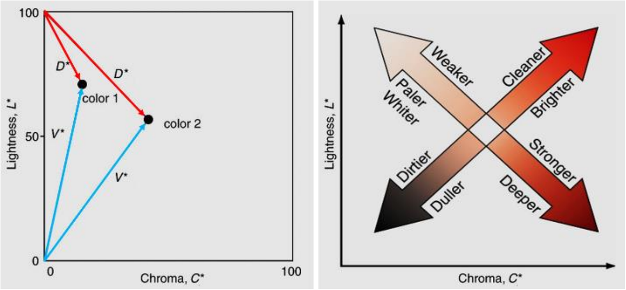

Figure 2. Vividness, V^* and depth, D^* and their perceptual difference for different colors, (left) direction and magnitude of the two vectors define each attribute (V^* and D^*) of two colors, (right) perceptual effect of different color attributes on the L^*-C^* plane, Figures are from [7].

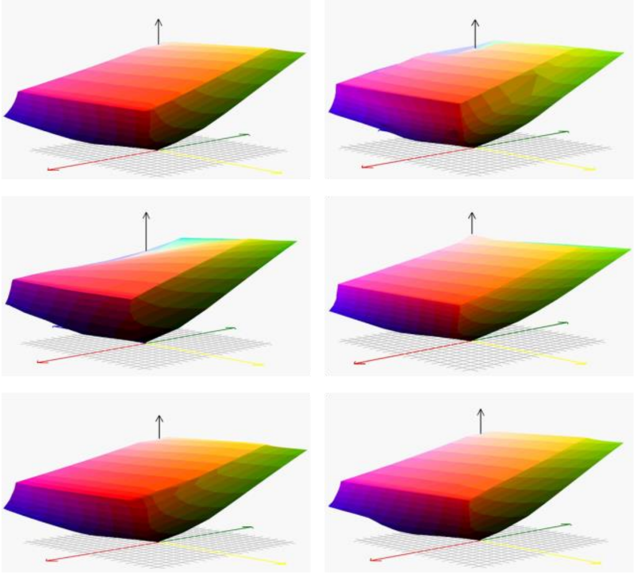

Figure 3. Estimated color gamut volume of different six type of displays. The volume shapes look like different but how much they are different when comparing two of them from different displays?

It was empirically determined that good CGV accuracy could be achieved using an 11×11 lattice of colors per *RGB* cube face (total 602 colors) [10-12]. In CIELAB color space, L^* representing the lightness is a normalized value by the maximum L^* (100). To illustrate gamut wings, the gamut volume boundaries in the $L^*a^*b^*$ color space need to be first obtained at 100 different lightness values, that is L^* values ranging from 0.5 to 99.5 with an interval of 1. The first step is to move the measured values of the display to a device independent color space. This allows unbiased comparison between displays that have different or similar white points. After measuring 602 test patterns on screen and transforming the color space, the tessellation of arbitrary points into contiguous hulls can be a problematic mathematical procedure in the presence of the concave surfaces common in gamut hulls [10]. In Fig. 3, six color volume measurement result and their representation of very different six type of displays are presented. The volume shapes look like different but how could we know that how much they are different when comparing two of them from different displays?

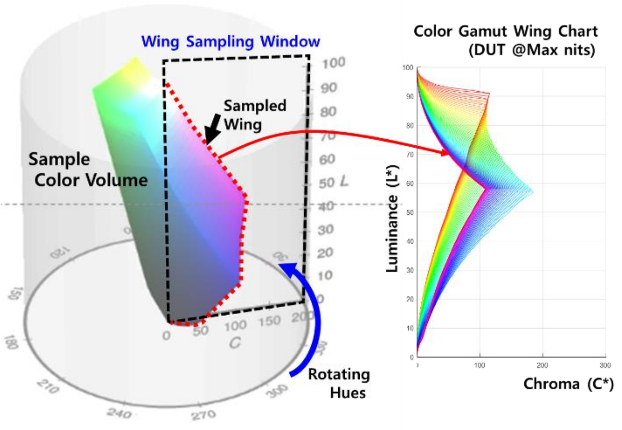

Figure 4. Illustration of the way to obtain wings of color volume surface and its representation, (left) sampling method of color volume wings from a given CGV, (right) a case when the wing sampling rate is 6, that is, 60 wings are shown for the given CGVs.

With an obtained CGV, hue wings of the color volume surface can be captured and illustrated on 2D plane [11, 12]. Fig. 4 conceptually shows how the wings can be obtained from a given CGV. As shown in Fig. 4 (left), it is assumed that there is a wing sampling window when the CGV is on the LCH space. This sampling window samples the surface of the color volume at a given hue angle. If the wing sampling window is fixed and the surface is sampled for all hue values while rotating the volume 360 degrees, a vector space of 360x100 size can be obtained. The number of sampling wings is an option and each wing has its hue color in Fig. 4 (left). When they are plotted in 2D space, it provides intuitive visibility and readable representation as shown in the Fig. 4 (right).

4. Analysis Colors on CGW

CGW can be expressed for one specific display for a test and can provide a comparison style to intuitively compare the color characteristics between a standard color volume and a display under test (DUT) or between DUTs as well. Fig. 5 shows an measurement and the representation result of CGW for comparison between (left field) a multi-chromatic WRGB self - emissive display and (right field) a RGB additive self -emissive display. By just seeing the shape of wings, it is easy to comprehend the volume ranges for each colors (hue) along the lightness level. Specifically, CGW representation fits well for comparison of two different displays of having different WLO and CLO characteristics. As illustrated in Fig. 6, let us consider WLO and CLO measurement results of the two above (displays the additive RGB display and a multi-chromatic WRGB display with 'White Boosting'), respectively. The white luminance output of the RGB additive display hardly changes depending on APL, and the general formula “sum of Red, Green and Blue light outputs equals the White light output” is established concretely. The ratio (‘WLO/CLO’) plot says, however, that the white luminance output of the multi-chromatic (with an additional white sub-pixel) display becomes closer to the sum of CLO (Red, Green and Blue light outputs) as the APL becomes greater, but still not the same. Additionally, it is almost doubled at a low APL test measurement.

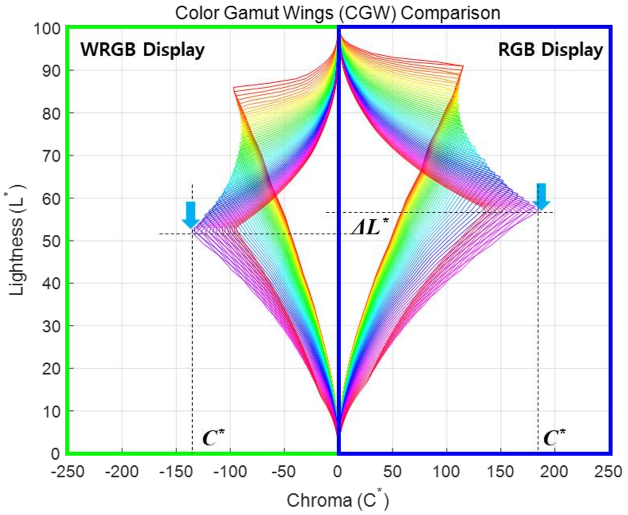

Figure 5. CGW comparison between (left, green field) a WRGB additive OLED display and (right, blue field) a multi-chromatic RGB OLED display, each color of wing represents hue of evenly sampled colors.

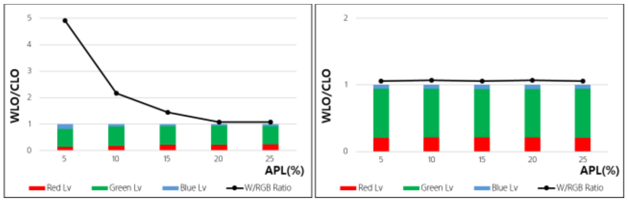

Figure 6. CLO and WLO measurement results for two different displays shown in Fig. 5, (left) WRGB multi-chromatic display and (right) RGB additive display.

This means that multi-chromatic display uses high luminance output of white pixel than those of colors as the APL decreases. As presented CGW plots in the Fig. 5, the ‘White Boosting’ effect for color gamut volume can be intuitively understandable. Arrows are indicating that the color volume of the multi-chromatic display is condensed along the L^* axis. In Fig 4, we can easily understand how the ‘White Boosting’ affects perception of the reproduced color [13-14]. The colors of multi-chromatic displays with ‘White Boosting’ may stronger and deeper but not brighter and cleaner than additive RGB displays. Moreover, the luminance difference (ΔL^*) for the same hue at each most largest chroma (C^*) as indicated arrows in Fig.5 is also recognizable in this proposed representation.

Additionally, we can compare which display can reproduce more vivid and deep colors by comparing the Vividness and Depth as below Fig. 7 and Table 2. To employ the metrics of Vividness and Depth on the CGW chart, they are measured based on the vertex (point with the largest chroma) for all color wings [10, 12]. In Fig. 7, The horizontal axis represents each hue (360 degrees) and each graph represents the Vividness and Depth values (in log scale) measured based on the maximum chroma point in the CGW for each wings. As shown in Fig. 5, max chroma is a good reference to compare the color performance. For the same hue wing, the lightness difference between two displays can be compared.

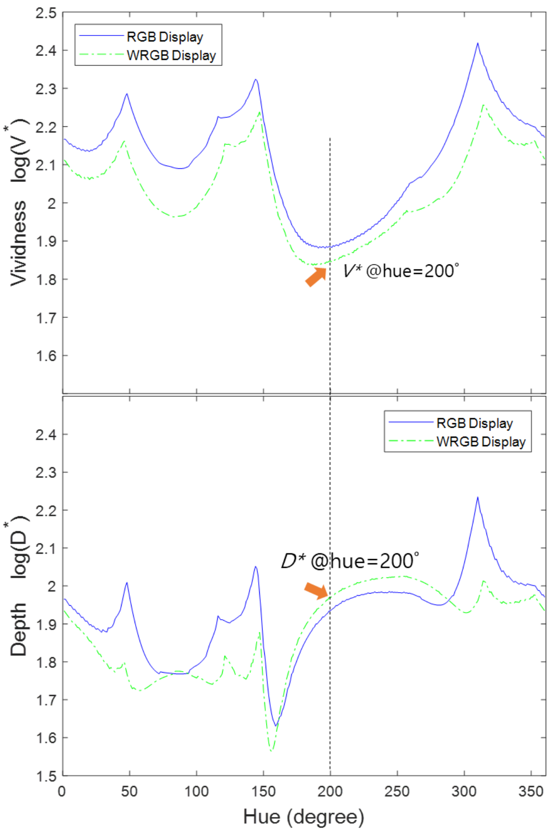

Figure 7. Vividness, *V** and depth, *D** of two different sub-pixel structured displays shown in Fig. 5, (top) Vividness and (bottom) Depth for each CGW for all hues. The arrows in orange shown in each figure indicate Vividness and Depth for the sample hue (200˚).

Table 2. Mean and variance of Vividness and Depth

(Log scale)		RGB Display	WRGB Display
Vividness	Mean	**2.120**	2.032
	Variance	**0.019**	0.013
Depth	Mean	**1.924**	1.879
	Variance	**0.012**	0.013

We can learn that the Vividness and Depth of the RGB display for most of hues are larger than those of the WRGB type. Simple statistical analysis presented in Table 2 indicates that the Vividness and depth of the RGB display are higher than the WRGB display by 22% and 11% respectively. The fact that both perceptual terms of one display are larger than those of another is possible when the color volume of one display is much wider than that of another.

5. Conclusion

This paper presented the color volume wings which is an intuitively readable and comparable 2D representation method for high dynamic range displays' color gamut volume. Most of the recent color volume metrologies approximately measure the 3D volume and the score effectively but their volume representations are not enough for intuitively understanding color characteristics of displays. By employing the proposed 'Color Gamut Wings (CGW)', we proposed easy way to compare the color attributes of a display with any standard volume space such as DCI-P3 or a method for easily comparing the color volume between two different types of displays on a 2D representation.

6. References

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