Metric of color-space coverage for wide-gamut displays

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Abstract: Assessing the coverage of the color space of Recommendation ITU-R BT.2020 (Rec. 2020) has become increasingly important in the design of wide-gamut displays, and an appropriate metric for measuring the display gamut size is urgently needed. Display manufactures calculate the area ratios of their displays’ RGB triangles to a standard RGB triangle in the CIE 1931 \(xy\) or CIE 1976 \(u'v'\) chromaticity diagram to indicate the displays’ relative gamut size. However, they typically fail to mention which of the two diagrams the metric is based on. This paper shows that the ratios calculated in the two chromaticity diagrams are highly inconsistent, and that the Rec. 2020 area-coverage ratios for wide-gamut displays in the \(xy\) diagram are much more correlated to the Rec. 2020 volume-coverage ratios in some color-appearance spaces than the Rec. 2020 area-coverage ratios in the \(u'v'\) diagram. This paper recommends the use of the \(xy\) diagram for area-coverage ratio calculations for wide-gamut displays.

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OCIS codes: (330.1730) Colorimetry; (120.2040) Displays; (330.4060) Vision modeling.

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1. Introduction

With technological advancements in television and associated fields, the image resolution of the television system has come to play an important role in delivering an “immersive” experience to the viewer. In this light, the ultra-high definition television (UHDTV) is a next-generation television system that provides a better viewing experience than the popular high definition television (HDTV). Regarding the technicalities of UHDTV, in August 2012, the ITU-R issued Recommendation BT.2020 (Rec. 2020) specifying the video parameter values for UHDTV production and international program exchange [1]. Important features of Rec. 2020 include high pixel counts of 4K (3840 × 2160 pixels) and 8K (7680 × 4320 pixels), a
higher frame frequency of 120 Hz, and a wider color gamut than that of HDTV specified in Recommendation ITU-R BT.709 (Rec. 709) [2]. Table 1 lists the chromaticity coordinates for the red (R), green (G), and blue (B) primaries specified in Rec. 2020 and the corresponding wavelengths of monochromatic light. Rec. 2020 covers real object colors, as well as the major standard system colorimetries, and reproduces images more realistically [3–5]. Figure 1 shows the chromaticities for the RGB primary sets of standard system colorimetries: Rec. 709 (for HDTV), Adobe RGB [6] (as a de facto standard in professional color processing), and SMPTE RP 431-2:2011 [7] (for the reference digital cinema projector, informally known as DCI-P3), and Pointer’s colors [8] (representing the maximum gamut of real object colors under illuminant C). Pointer’s colors, shown in Fig. 1, are transformed to those under illuminant D65 with the CAT02 chromatic adaptation transform [9].

Table 1. Chromaticity coordinates of Rec. 2020 RGB primaries and the corresponding wavelengths of monochromatic light.

| Primary colors and reference white | Chromaticity coordinates (CIE 1931) | Corresponding wavelength (Illuminant) |
|------------------------------------|-------------------------------------|---------------------------------------|
| R                                  | 0.708 0.292                         | 630 nm                                |
| G                                  | 0.170 0.797                         | 532 nm                                |
| B                                  | 0.131 0.046                         | 467 nm                                |
| Reference white                    | 0.3127 0.3290                       | (D65)                                 |

To completely fulfill the Rec. 2020 system colorimetry, monochromatic light sources such as lasers are required for a display. Whereas liquid crystal displays (LCDs) are considered promising for UHDTV displays, and laser-backlit LCDs are expected to be available in the near future, non-monochromatic light sources may well be used from the perspective of cost and performance. The key aspects to consider are the spectral bandwidths and peak emission wavelengths in addition to color-filter crosstalk [10].

It is important to use an appropriate metric to measure the Rec. 2020 color-space coverage when designing wide-gamut displays. A popular metric for measuring the relative display gamut size is to compare the area of the triangle connecting the chromaticity points of the RGB primaries in a chromaticity diagram to that of a standard RGB, such as NTSC, Rec. 709, and (recently) Rec. 2020. Although many color scientists and some engineers believe that any reference to the area coverage in a chromaticity diagram is inappropriate because the color gamut is considered to form a solid inherently in a three-dimensional perceptual color space, most display manufacturers nevertheless adopt this pragmatic approach by defining the color gamut in areal dimensions. One serious problem with this pragmatic approach relates to the discrepancy between the area in the CIE 1931 xy chromaticity diagram and the area in the CIE 1976 u’u’v’ chromaticity diagram.
1976 $u'v'$ chromaticity diagram. Another problem is an ambiguous practice of the mixed use of two ratios: the “area ratio” ($A_{\text{display}} / A_{\text{standard}}$) of a display RGB’s triangular area ($A_{\text{display}}$) to a standard RGB triangular area ($A_{\text{standard}}$), and the “area-coverage ratio” ($A_{\text{display}} \cap A_{\text{standard}} / A_{\text{standard}}$) of the area of the common polygon between the display RGB triangle and standard RGB triangle ($A_{\text{display}} \cap A_{\text{standard}}$) to the standard RGB triangular area ($A_{\text{standard}}$). It is clear that the area-coverage ratio is effective in terms of the color-reproduction accuracy of the source content.

In this paper, we show which of the two chromaticity diagrams is appropriate as a metric for Rec. 2020 area-coverage ratio calculations for wide-gamut displays in comparison with Rec. 2020 volume-coverage ratio calculated in the perceptual spaces of some color appearance models.

2. Computing area-coverage ratios in the $xy$ and $u'v'$ diagrams

For wide-gamut television displays, a minimum requirement for the wide gamut is deemed to cover the entire Rec. 709 color space. We can easily confirm whether a display offers this wide gamut by drawing two triangles connecting the chromaticities of the display RGB primaries and Rec. 709 RGB primaries. If each display primary falls within the areas enclosed by the extended sides of the Rec. 709 RGB triangle, spectral locus, and purple boundary on a CIE chromaticity diagram, as shown in Fig. 2, any primary set encloses the Rec. 709 RGB triangle and meets the wide-gamut definition. Among myriad wide-gamut primary sets, we sampled RGB primaries as evenly as possible from each area in the nominally uniform $u'v'$ chromaticity diagram, including the RGB primaries for Rec. 709, Adobe RGB, DCI-P3, and Rec. 2020, counting 24 R primaries, 33 G primaries, 15 B primaries, and 11,880 different RGB primary sets in total. Note that the boundaries for the sample areas are not exhaustive in the definition of the wide gamut. When a non-Rec. 709 primary is chosen from the sample areas, it is possible to select the other primaries from outside their areas. In our simulation, we used the primary sets such that they fall within the sample areas (shown in Fig. 2) from the perspective of gamut-coverage balance in terms of hue [10].

![Sampled RGB primaries to cover the Rec. 709 color space: (a) the $u'v'$ diagram (with enlarged sections), and (b) the $xy$ diagram.](image)

Figure 3 compares the Rec. 2020 area-coverage ratios for the sampled RGB sets calculated in the $xy$ diagram with those in the $u'v'$ diagram. The RGB levels for each dot shown in Fig. 3 are proportional to the differences between the $u'v'$ saturation values for Rec. 709 RGB primaries and sampled RGB primaries, respectively. The dot color is black for Rec.
709 RGB primaries and light gray for Rec. 2020 RGB primaries. A greenish dot means that the green primary for the sampled RGB primary set is relatively more saturated than the other primaries, in which case the area-coverage ratios in the $xy$ diagram are mostly higher than those in the $u'v'$ diagram. A purplish dot means that the green primary is relatively less saturated than the other primaries, in which case the ratios in the $xy$ diagram are mostly lower than those in the $u'v'$ diagram. In the $xy$ diagram, the ratio for Adobe RGB (71.3%) is close to that for DCI-P3 (71.7%). By contrast, in the $u'v'$ diagram, the ratio for Adobe RGB (67.7%) is lower than that for DCI-P3 (72.8%). RGB set 1, indicated in Fig. 3(a), has the RGB primary set whose ratio in the $xy$ diagram (64.1%) is much lower than that in the $u'v'$ diagram (82.3%). RGB set 2 has the RGB primary set whose ratio in the $xy$ diagram (86.9%) is much higher than that in the $u'v'$ diagram (73.9%). It is clear that the Rec. 2020 area-coverage ratios calculated in the two diagrams are highly inconsistent.

Fig. 3. Rec. 2020 area-coverage ratios for wide-gamut RGB primary sets: (a) comparison of the ratios calculated in the $xy$ and $u'v'$ diagrams. Each dot color corresponds to the balance of the saturation for the sampled RGB primary set (see text). The chromaticity triangles of RGB set 1 and RGB set 2 are shown in (b) the $xy$ diagram, and (c) the $u'v'$ diagram.

3. Comparing area coverage with volume coverage

We now turn to the question of whether either chromaticity diagram is appropriate (and if so, which) for evaluating the Rec. 2020 color-space coverage. To confirm the validity of the area-coverage ratios in the two metrics, we compared the area-coverage ratios with the Rec. 2020 volume-coverage ratios $(V_{\text{display}} \cap V_{\text{standard}} / V_{\text{standard}})$ of the overlapped solids between the gamuts for the sampled primary sets and the Rec. 2020 gamut $(V_{\text{standard}})$ in the CIE 1976 $L^*a^*b^*$ (CIELAB), CIE 1976 $L^*u^*v^*$ (CIELUV), and CIECAM02 $JaCbC$ color spaces. Both CIELAB and CIELUV are primitive color appearance models that are standardized for a uniform color space. CIELAB is used in the colorant industry, and it has become universally applied for color specification. CIELUV accompanying the $u'v'$ diagram was once popular in the television industry, although it has since become obsolete. CIECAM02 is the latest standardized color appearance model. We used the CIECAM02 $JaCbC$ color space with the viewing condition parameters for dim surround ($c = 0.59, N_c = 0.9, F = 0.9, L_A = 16$).

To estimate the gamut of each sampled primary set, we first calculated the $xy$ chromaticity loci of the gamut boundary at the luminance factors $Y$ corresponding to the lightness values $L^*$ of 0.5, 1.5, ..., 99.5. The loci form polygons in the shape of a triangle, rectangle, or pentagon in the $xy$ space for the sampled RGB primary sets. The normalized RGB levels of
the polygon vertices can have any one of \([n \ 0 \ 0], \ [1 \ n \ 0], \ [1,1 \ n], \ [n \ 1 \ 0], \ [0 \ n \ 0], \ [0 \ 1 \ n], \ [n \ 1 \ 1], \ [0 \ n \ 1], \ [0 \ 0 \ n], \ [n \ 0 \ 1], \ [1 \ n \ 1], \ [0 \ 1 \ n]\), where \(n\) can be found within a fixed interval of \(0 < n < 1\). The \(xy\) coordinates for the polygon vertices were converted to the \(u^*v^*\) chromaticity coordinates, forming polygons with the number of the vertices of each polygon unchanged in the CIELUV color space. For the CIELAB and CIECAM02 color spaces, where the polygon edges are curved, we linearly interpolated 100 points between the neighboring \(xy\) vertices for each polygon in advance, and then converted the \(xy\) coordinates to the CIELAB \(a^*b^*\) chromaticity coordinates and the CIECAM02 \(a_c b_c\) chromaticity coordinates, respectively. Whereas the loci are aligned at regular intervals of \(L^*\) values in both the CIELAB and CIEUV color spaces, those in the CIECAM02 color space are irregularly aligned and slightly slanted, which renders the simulation highly complex. For simplicity, we set the non-constant CIECAM02 lightness values \(J\) for each locus to a constant \(J\) value for a neutral color at the corresponding \(L^*\) value. Figure 4 shows the loci representing the Rec. 2020 gamut and the RGB primaries in the CIELAB \(a^*b^*\), CIELUV \(u^*v^*\), and CIECAM02 \(a_c b_c\) chromaticity diagrams. The volume of the overlapped solid between the gamut for a sampled primary set and the Rec. 2020 gamut was approximated by the sum of the areas of the 100 intersecting loci in the CIELAB and CIEUV color spaces and the trapezoidal integration of those in the CIECAM02 color space.

Figure 4. Loci representing the Rec. 2020 gamut at \(L^*\) of 0.5, 3.5, ...99.5 (instead of increments of 1 to avoid printing too many lines) and the RGB primaries: (a) CIELAB \(a^*b^*\), (b) CIELUV \(u^*v^*\), and (c) CIECAM02 \(a_c b_c\).

Figure 5 shows the comparison between the Rec. 2020 area-coverage ratios and the Rec. 2020 volume-coverage ratios. The Rec. 2020 area-coverage ratios in the \(xy\) diagram correlates much better with the Rec. 2020 volume-coverage ratios in every color-appearance space than those in the \(u^*v^*\) diagram, even though the \(u^*v^*\) diagram is a precursor to calculating \(L^*u^*v^*\). Although these results seem counterintuitive, it should be understood that the two-dimensional areas and the three-dimensional volume do not necessarily correlate with each other. In this sense, the correlation between the ratios for the \(xy\) diagram and the color-appearance spaces would be a coincidence. By contrast, even though the \(u^*v^*\) diagram was created in an attempt to offer better perceptual uniformity on the basis of MacAdam’s color-discriminating ellipses [11], the ellipses differ in orientation, shape, and size from the ellipses of Wyszecki and Fielder [12], and the \(xy\) diagram is more perceptually uniform than the \(u^*v^*\) diagram on the basis of Goldstein’s simulation results obtained with the use of the CIE 2000 color-difference formula [13].

Furthermore, we compared the volume-coverage ratios of Pointer’s gamut \(V_{\text{display}}\big/ V_{\text{Pointer}}\) in each color-appearance space with the Rec. 2020 area-coverage ratios in the \(xy\) and \(u^*v^*\) diagrams. When designing the Rec. 2020 system colorimetry, the volume coverage of Pointer’s gamut in the CIELAB color space was considered. The details for computing the solid of Pointer’s gamut under illuminant D65 are described in [10]. Figure 6 shows this comparison. Again, the Rec. 2020 area-coverage ratios in the \(xy\) diagram correlates better with the volume-coverage ratios of Pointer’s gamut in every color-appearance space than those in the \(u^*v^*\) diagram.

Figure 5. Comparison between the Rec. 2020 area-coverage ratios and the Rec. 2020 volume-coverage ratios.

Figure 6. Comparison between the Rec. 2020 area-coverage ratios and the Rec. 2020 volume-coverage ratios.
Fig. 5. Rec. 2020 area-coverage ratio and Rec. 2020 volume-coverage ratio: (a) \(xy - L^*a^*b^*\), (b) \(xy - L^*u^*v^*\), (c) \(xy - JaCbC\), (d) \(u'v' - L^*a^*b^*\), (d) \(u'v' - L^*u^*v^*\), and (f) \(u'v' - JaCbC\).

Fig. 6. Rec. 2020 area-coverage ratio and volume-coverage ratio of Pointer’s gamut: (a) \(xy - L^*a^*b^*\), (b) \(xy - L^*u^*v^*\), (c) \(xy - JaCbC\), (d) \(u'v' - L^*a^*b^*\), (d) \(u'v' - L^*u^*v^*\), and (f) \(u'v' - JaCbC\).
4. Rec. 2020 color-space coverage balance in terms of hue

For various wide-gamut displays, it has been found that the Rec. 2020 area-coverage ratios calculated in the \( xy \) diagram and \( u'v' \) diagram are significantly different from each other, and that the former metric seems to be appropriate in comparisons with the volume-coverage ratios calculated in some color-appearance spaces. Although the area-coverage ratios in the \( xy \) diagram do not perfectly predict the volume-coverage ratio in a color appearance model, this is irrelevant because it is still unknown which existing color appearance model is the most accurate in terms of a gamut estimation [14]. Moreover, considering that calculating the volume coverage in a color-appearance space is highly complex and computationally costly in addition to the fact that some approximation is necessary in any case, the area-coverage ratio in the \( xy \) diagram is the most pragmatic approach to evaluate wide-gamut displays.

One problem is that the balance of the gamut coverage in terms of hue cannot be inferred from such a single-value criterion. In order to improve the area-coverage criterion, we propose a supplemental method to evaluate area-coverage ratios separately for cyan, magenta, and yellow regions, bounded by the lines connecting the Rec. 2020 RGB chromaticity points and the common vertex of the white point. Figure 7 shows the Rec. 2020 area-coverage ratios in the three hue regions in addition to the entire Rec. 2020 RGB triangle. Although the entire Rec. 2020 area-coverage ratio by Adobe RGB (71.3%) is just slightly lower than that by DCI-P3 (71.7%), it is possible to show that the coverage balance in terms of hue is more balanced with Adobe RGB (65.7% for cyan, 68.8% for magenta, and 76.9% for yellow) than with DCI-P3 (43.5% for cyan, 79.7% for magenta, and 86.2% for yellow).

![Fig. 7. Rec. 2020 area-coverage ratios, calculated separately for cyan, magenta, and yellow: (a) Rec. 709, (b) Adobe RGB, and (c) DCI-P3.](image)

5. Conclusion

Assessing the coverage of the Rec. 2020 color space has become increasingly important in the design of wide-gamut displays. Whereas two metrics for the area-coverage ratio in the CIE 1931 \( xy \) chromaticity diagram and the CIE 1976 \( u'v' \) chromaticity diagram have been used, they are significantly inconsistent. The area-coverage ratios in the \( xy \) diagram are much more correlated with the volume-coverage ratios in color-appearance spaces than those in the \( u'v' \) diagram. Therefore, we recommend the Rec. 2020 area-coverage ratio in the \( xy \) diagram as a pragmatic criterion for evaluating wide-gamut displays. We also propose the use of the Rec. 2020 area-coverage ratios in three hue regions to facilitate the development of well-balanced wide-gamut displays.