# Single display gamut size metric

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***Abstract*** — To measure the relative gamut sizes of wide-gamut displays, it is herein proposed that the CIE 1931 *xy* chromaticity diagram be used rather than the nominally perceptually uniform CIE 1976 *u′v′* chromaticity diagram. High correlations were found between the area-coverage ratios in the *xy* diagram and the volume-coverage ratios in the CIE 1976 $L^*a^*b^*$ color space for major standard wide-gamut color spaces. It is also demonstrated herein that performing planimetry in the uniform *u′v′* diagram does not yield accurate relative display gamut sizes, even though the large sizes obtained using the *u′v′* diagram are often reported regardless of the fact that its uniformity is valid only when the luminance factor is constant. The single display gamut size metric using the *xy* diagram will facilitate the unbiased development of wide-gamut displays.

***Keywords*** — *chromaticity diagram, display gamut size, planimetry, ultra-high definition television (UHDTV), Recommendation ITU-R BT.2020 (Rec. 2020), wide-gamut displays.*

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## 1 Introduction

Since the introduction of the wide gamut system colorimetry[1] for ultra-high definition television (UHDTV) specified in Recommendation ITU-R BT.2020 (Rec. 2020),[2] the development of direct-view wide-gamut displays has become a high priority, although it is a major challenge. Rec. 2020 covers the color spaces of the major standard system colorimetries: Recommendation ITU-R BT.709 (Rec. 709)[3] (for high-definition television), Adobe RGB[4] (as a de facto standard in professional color processing), and SMPTE Recommended Practice 431-2:2011[5] (i.e., the DCI-P3 standard for the reference digital cinema projector). Figure 1 shows the chromaticities of the red, green, and blue (RGB) primary sets in the CIE 1931 *xy* and CIE 1976 *u′v′* chromaticity diagrams. The RGB chromaticity points are connected by straight lines, forming an “RGB triangle” for each color space. The Rec. 2020 RGB triangles in the two diagrams are each divided into three regions colored in cyan, magenta, and yellow, where the straight borderlines connect the RGB chromaticity points with the reference white point (D65). Note that the Adobe RGB red and green primaries are identical to the Rec. 709 red primary and (obsolete) NTSC 1953 green primary, respectively, while the Adobe RGB and DCI-P3 blue primaries are identical to the Rec. 709 blue primary.

Although liquid crystal displays (LCDs) are considered promising as UHDTV displays and laser-backlit LCDs attain the Rec. 2020 color space,[6] non-monochromatic light sources may also be used due to their cost and performance benefits.[7] Many displays that support the Rec. 2020 color space are commercially available, although their gamut coverages vary. It has been reported that quantum-dot-based LCDs can achieve more than 90% area coverage of the Rec. 2020 color space in both the *xy* and *u′v′* diagrams.[8] On the other hand, most such displays approximately achieve the Adobe RGB or DCI-P3 color space, which covers around only 70% area of the Rec. 2020 color space.

In the development of wide-gamut displays of varying gamut sizes, gamut size measurement has become increasingly important, and an appropriate metric is urgently needed. A popular metric involves comparing the area of the RGB triangle in the *xy* or *u′v′* chromaticity diagram to the area of the RGB triangle of a standard RGB color space, such as NTSC, Adobe RGB, DCI-P3, or (recently) Rec. 2020. The *u′v′* diagram, which is a projective transformation of the *xy* diagram, yields perceptually more uniform color spacing and has become popular for use in planimetry. From the point of view of color science, any reference to area coverage in a chromaticity diagram is inappropriate because a color gamut inherently forms a solid in a three-dimensional perceptual color space due to the trichromatic nature of human vision, in which a color is represented in cylindrical coordinates (chroma, hue, and lightness) or Cartesian coordinates (two opponent color dimensions and lightness). Nevertheless, display manufacturers define relative display gamut sizes in areal dimensions because planimetry is simple in terms of calculation and historically has yielded continuous metrics. However, there is a major problem with this pragmatic approach that is related to the discrepancy between the areas in the *xy* and *u′v′* chromaticity diagrams. In reality, manufacturers tend to use the larger of the two resulting gamut sizes. Another problem is the ambiguous practice of using two different ratios: the “area-size ratio” ($A_{\mathrm{display}}$ /

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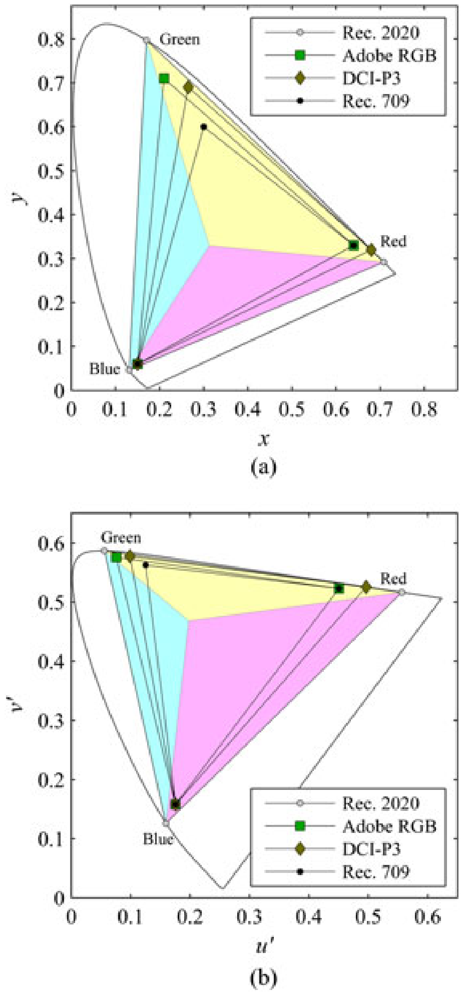


**FIGURE 1** — Chromaticities of RGB primary sets of standard Rec. 709, Adobe RGB, and DCI-P3 color spaces in (a) CIE 1931 *xy* and (b) CIE 1976 *u′v′* chromaticity diagrams. Each Rec. 2020 RGB triangle is divided into three regions colored in cyan, magenta, and yellow, where straight borderlines connect RGB chromaticity points with reference white point (D65).

$A_{\mathrm{standard}} \times 100\%$), which is the ratio of a display's RGB triangle area ($A_{\mathrm{display}}$) to the standard RGB triangle area ($A_{\mathrm{standard}}$), and the "area-coverage ratio" ($A_{\mathrm{display}} \cap A_{\mathrm{standard}}$ / $A_{\mathrm{standard}} \times 100\%$), which is the ratio of the area in which the display and standard RGB triangles overlap ($A_{\mathrm{display}} \cap A_{\mathrm{standard}}$) to $A_{\mathrm{standard}}$. If a primary is outside of the target color space, the area-size ratio becomes larger than the area-coverage ratio and can be more than 100%, while the area-coverage ratio is limited up to 100%.

Regarding the target color space, Rec. 2020 is the most suitable in that its RGB color space covers the major standard color spaces and most real object colors, and it is also the standard gamut for UHDTV. From the point of view of source color reproduction accuracy, the coverage ratio (rather than the size ratio) is valid. Regarding planimetry using the two different chromaticity diagrams, Masaoka and Nishida[9] used a heuristic approach to compare the Rec. 2020 area-coverage ratios in the *xy* and *u′v′* diagrams to the Rec. 2020 volume-coverage ratios in the CIELAB, CIELUV, and CIECAM02 (the latest standardized color appearance model)[10] color spaces. They proposed using the *xy* diagram rather than the perceptually uniform *u′v′* diagram to determine the gamut metric, as their simulation results revealed a higher correlation between the Rec. 2020 area-coverage ratios in the *xy* diagram and the Rec. 2020 volume-coverage ratios in each of the color appearance spaces. Nevertheless, the Adobe RGB and DCI-P3 color spaces will remain important target gamuts for other applications and devices, such as computer monitors, mobile displays, and organic light-emitting diode devices. For these wide-gamut color spaces, a metric consistently using the area-coverage ratio would be reasonable because each color space is assumed to have already been standardized as a sufficiently wide space, in which case it is preferable to reproduce the source color accurately in the sufficiently wide space rather than to stretch the source gamut roughly toward the outside from the standard space. If it is important to take into account the gamut outside of the Adobe RGB or DCI-P3 space, the Rec. 2020 area-coverage ratio would be more reasonable to use than the Adobe RGB area-size or DCI-P3 area-size ratio.

In this paper, the area-coverage ratios in the *xy* and *u′v′* diagrams are compared with the volume-coverage ratios in the CIELAB color space by using Adobe RGB and DCI-P3 as well as Rec. 2020 as the target color spaces and a number of RGB primary sets sampled for wide-gamut displays. Then, the chromaticity diagrams are discussed in terms of their suitabilities as single metrics for planimetry.

## 2 Simulation

### 2.1 Sampling wide-gamut RGB primaries

The minimum requirement for a wide gamut is that it must cover the entire Rec. 709 color space.[11] It is easy to verify whether a display offers a sufficiently wide gamut by drawing two RGB triangles: one for the display and one for the Rec. 709 color space. If each display primary is within the area enclosed by the extended sides of the Rec. 709 RGB triangle, the spectral locus, and the purple boundary in a CIE chromaticity diagram, as shown in Fig. 2, any RGB primary set can enclose the Rec. 709 RGB triangle. The RGB primaries were sampled as evenly as possible from each area in the uniform *u′v′* diagram. A total of 24 red, 33 green, and 15 blue primaries were sampled (including the RGB primaries for Rec. 2020, Adobe RGB, DCI-P3, and Rec. 709), yielding 11,880 different RGB primary sets in total.[9] Note that the boundaries of the sample areas are not exhaustive in the definition of the wide gamut. When a non-Rec.-709 primary is chosen from one of the sample areas, it is possible to select the other one or two primaries from outside of the sample areas. In the simulation, however, only primary sets that fell entirely within the sample areas were used in order to ensure hue balance in the gamut coverage.[7]

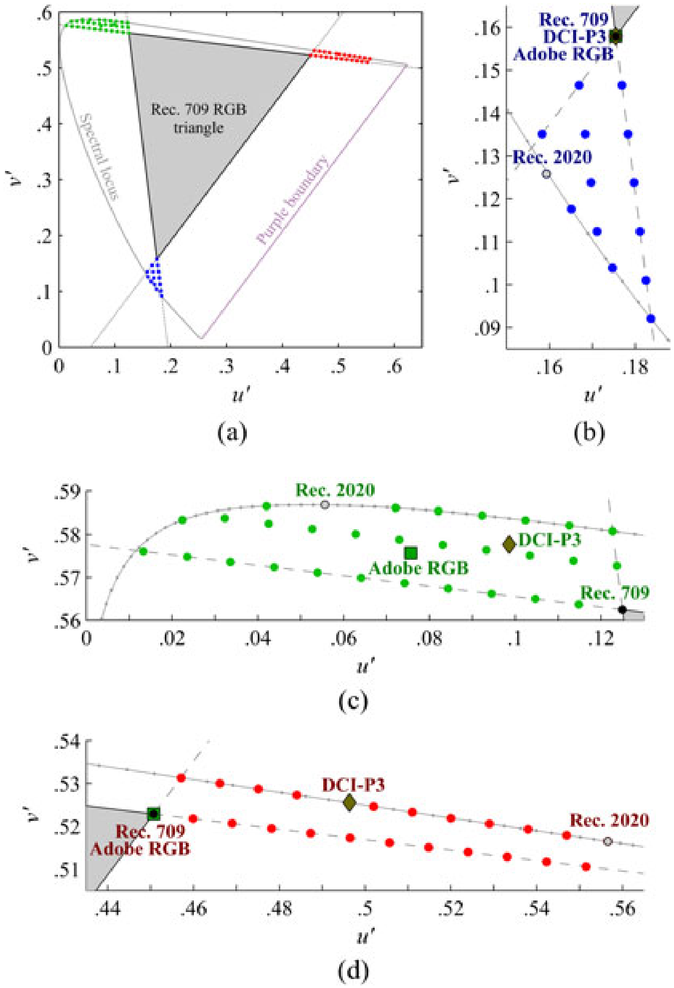


**FIGURE 2** — RGB primaries sampled to cover Rec. 709 color space in (a) CIE 1931 *xy* chromaticity diagram and enlarged sections containing sampled (b) blue, (c) green, and (d) red primaries. Gray circle, green square, brown diamond, and black circle markers denote Rec. 2020, Adobe RGB, DCI-P3, and Rec. 709 RGB primary sets, respectively, as in Fig. 1 legend.

## 2.2 Gamut-coverage computation

To determine the area-coverage ratios ($A_{\mathrm{RGB}} \cap A_{\mathrm{standard}}$ / $A_{\mathrm{standard}} \times 100\%$), the coordinates of the overlap polygons and their areas were computed by using the Sutherland–Hodgman algorithm[12] and the shoelace formula,[13] respectively. The volume-coverage ratio ($V_{\mathrm{RGB}} \cap V_{\mathrm{standard}}$ / $V_{\mathrm{standard}} \times 100\%$) is the ratio of the volume of the solid region in which the sampled primary set and Rec. 2020 gamuts overlap ($V_{\mathrm{RGB}} \cap V_{\mathrm{standard}}$) to the volume of the standard gamut ($V_{\mathrm{standard}}$) in a color appearance space. To estimate the gamut volume for each sampled RGB primary set, 100 gamut boundary polygons in the $xyY$ space were first obtained at the luminance factors $Y$ corresponding to lightness values $L^*$ of 0.5, 1.5, …, and 99.5. The normalized RGB levels of each vertex of each polygon may have any of the following sets of values: [$n$ 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], or [1 0 $n$], where $0 \le n \le 1$. Each polygon has three, four, or five vertices. To analyze the CIELAB space, where the polygon edges are curved, 100 points between each pair of adjacent $xy$ vertices were interpolated in advance for each polygon and were then converted into CIELAB $a^*b^*$ coordinates. Figure 3 shows contour plots of the Rec. 2020, Adobe RGB, DCI-P3, and Rec. 709 gamuts in the CIELAB $a^*b^*$ diagram. To calculate the volume-coverage ratios, the coordinates of the vertices of the overlap area and its size at each lightness value were computed by the Sutherland–Hodgman algorithm and the shoelace formula, respectively, and the volume was approximated by the sum of the areas of the 100 constant-lightness loci.

## 2.3 Results

Figure 4 shows a comparison of the gamut-coverage ratios in the $u'v'$ and $xy$ diagrams, the $xy$ diagram and the CIELAB space, and the $u'v'$ diagram and the CIELAB space for Rec. 2020, Adobe RGB, and DCI-P3. The RGB levels for each dot color are proportional to the differences between the $u'v'$ saturation values for the Rec. 709 RGB primaries and the sampled RGB primaries. For example, the green dots indicate that the green primaries for the sampled RGB primary sets are relatively

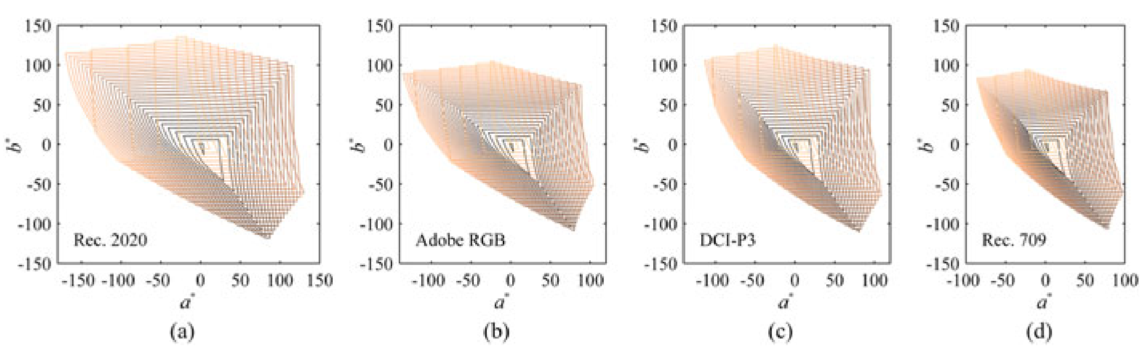


**FIGURE 3** — Gamut contour plots for (a) Rec. 2020, (b) Adobe RGB, (c) DCI-P3, and (d) Rec. 709 in $a^*b^*$ diagram obtained using $L^* = 0.5$, 3.5, …, and 99.5 (instead of increments of one lightness value to improve legibility).

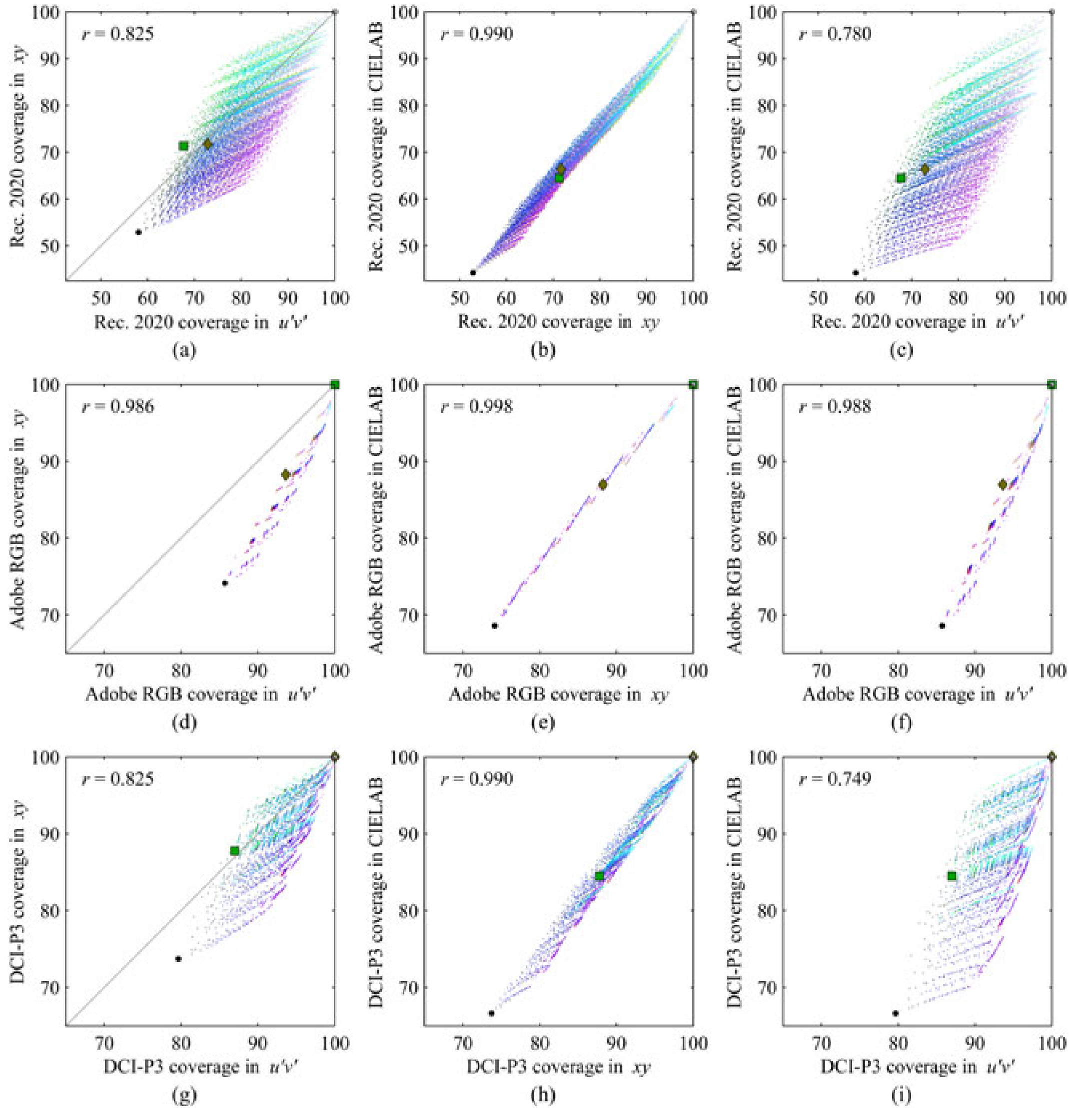


**FIGURE 4** — Comparison of coverage ratios in *xy* and *u′v′* diagrams, *xy* diagram and CIELAB space, and *u′v′* diagram and CIELAB space for (a)–(c) Rec. 2020, (d)–(f) Adobe RGB, and (g)–(i) DCI-P3 for sampled RGB primary sets. Gray circle, green square, brown diamond, and black circle markers denote Rec. 2020, Adobe RGB, DCI-P3, and Rec. 709 RGB primary sets, respectively, as in Fig. 1 legend.

saturated, whereas the magenta dots indicate that the red and blue primaries are relatively saturated.

## 3 Discussion

Figures 4(a) and 4(g) clearly show that the gamut-coverage ratios calculated using the $xy$ and $u'v'$ diagrams are inconsistent. The Rec. 2020 and DCI-P3 area-coverage ratios are mostly larger in the $u'v'$ diagram than in the $xy$ diagram with saturated red and blue primaries. The low correlations between the area-coverage ratios in the two diagrams result from the overestimate of the magenta area in the $u'v'$ diagram. Figure 5 presents a bar graph of the Rec. 2020 cyan, magenta, and yellow coverage ratios for Rec. 2020, Adobe RGB, DCI-

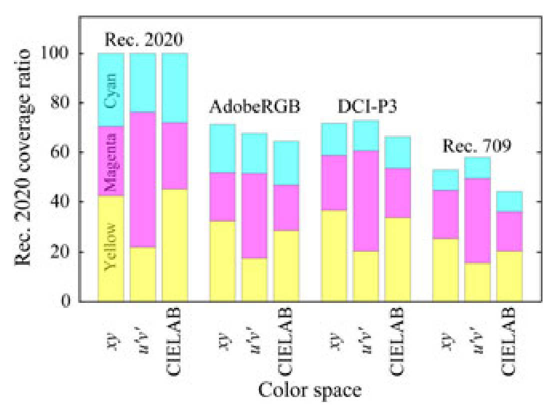


**FIGURE 5** — Bar graph of Rec. 2020 cyan, magenta, and yellow coverage ratios for Rec. 2020, Adobe RGB, DCI-P3, and Rec. 709 in *xy* and *u′v′* diagrams and CIELAB space.

P3, and Rec. 709 in the $xy$ and $u'v'$ diagrams and the CIELAB space. Each bar is divided into cyan, magenta, and yellow regions corresponding to the divisions shown in Fig. 1. Figure 4 (d) shows the Adobe RGB area-coverage ratios are always larger in the $u'v'$ diagram than in the $xy$ diagram. The high correlation between the Adobe RGB area-coverage ratios in the two diagrams results from the fact that the magenta area coverage is constant for the sampled RGB sets. The larger area-coverage ratios in the $u'v'$ diagram that target standard wide gamuts might explain the trend of performing planimetry in the $u'v'$ diagram in the display industry.

The volume-coverage ratios are more closely correlated with the area-coverage ratios in the $xy$ diagram than with those in the $u'v'$ diagram. Higher correlations between the Rec. 2020 volume-coverage ratios and the area-coverage ratios in the $xy$ diagram than between the same volume-coverage ratios and the area-coverage ratios in the $u'v'$ diagram were also observed in the CIELUV $L^*u^*v^*$ space ($r = 0.985$ for $xy$, $r = 0.849$ for $u'v'$) and CIECAM02 $Ja_Cb_C$ space ($r = 0.969$ for $xy$, $r = 0.805$ for $u'v'$).[9] Furthermore, higher correlations were also found between the Rec. 2020 area-coverage ratios in the $xy$ diagram and the volume-coverage ratios of Pointer's gamut[14] in the CIELAB ($r = 0.925$ for $xy$, $r = 0.669$ for $u'v'$), CIELUV ($r = 0.934$ for $xy$, $r = 0.735$ for $u'v'$), and CIECAM02 ($r = 0.913$ for $xy$, $r = 0.675$ for $u'v'$) color appearance spaces.[9] Pointer's gamut represents the maximum gamut of real object colors with smaller gamut than the Rec. 2020 gamut that has larger high-lightness regions, especially in saturated green. This result validates the use of planimetry in the $xy$ diagram in a practical sense in terms of visual importance of display gamut in TV applications, nevertheless the area-coverage in the $xy$ diagram encloses the enlarged unnaturally saturated green area.

The usability of the $xy$ diagram for this purpose does not imply that the $xy$ diagram is perceptually more uniform than the $u'v'$ diagram. The non-uniformly enlarged yellow and green regions in the $xy$ diagram coincidently enhance its suitability as a metric. When comparing different colors with the same luminance levels, the uniform $u'v'$ diagram may work well because of its nominal uniformity. However, it is incorrect to conclude that the $u'v'$ diagram can be used in planimetry to measure display gamuts based on its uniformity that is valid only when the luminance factor is constant.

## 4 Conclusion

Planimetric display gamut size measurements performed using the $xy$ and $u'v'$ chromaticity diagrams are inconsistent. Based on the high correlation between the area-coverage ratios in the $xy$ diagram and the volume-coverage ratios in color appearance spaces, it is recommended that the $xy$ diagram be used as a single metric for measuring relative display gamut sizes. The perceptual uniformity of the $u'v'$ chromaticity diagram is innately valid only when the luminance factor is constant, and it cannot be assumed that the $u'v'$ diagram is usable for the measurements based on its uniformity. It is expected that using the $xy$ diagram as a single metric will facilitate the unbiased development of wide-gamut displays.

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