Methods to Assess the Relative Number of Discernible Colors for Displays

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Abstract

The quantitative description of the size of a display gamut is crucial for designing the wide-gamut display of high saturation primaries. Three methods are proposed for the calculation of the number of discernible colors in a display gamut volume. The methods are demonstrated with a comparison of two mobile phone displays, one based on AMOLED technology and the other based on LCD technology. The AMOLED has 60-80% more discernible colors than the LCD display. Not only is the result relatively invariant to the computational method but it is also similar when the analysis is carried out in CIELAB space or CIECAM02 space.

Introduction

There have been many attempts to answer the question of how many distinct colors there are, with widely varying answers, though usually in the range 2-10 million [1-2]. Recently, Morovic *et al.*, put forward arguments for the question of how many colors there are is unanswerable though even they conceded that there are at least 1.7 million colors [3].

Nevertheless, estimates of the number of discernible colors that can be displayed on an imaging device are still valuable as a way of quantitatively comparing the performance of difference devices or different technologies. The quantitative description of the size of a display gamut is crucial for designing the wide-gamut display of high saturation primaries. Display gamuts are often compared in terms of gamut areas and gamut volumes. However, the number of discernible colors that a gamut can display is another useful metric. Hill *et al.* compared different color spaces based on a uniform quantization of them using the CIELAB and CIE94 color-difference formula [4]. This led to an estimate of the number of discernible colors in each space on the basis of a threshold for color difference of 1 unit. Wen (2006) then described a method to count the number of discernible colors in a display gamut using the CIE94 color-difference equation [5]. The method showed that there were 199,491 discernible colors for the ITU-R BT.709 standard display. Two LED displays – one using three primaries and one using four primaries – were considered and were shown to have gamut volumes that were 1.76 and 1.98 times larger than the rec. 709 standard display; however, the number of discernible colors was 1.38 and 1.49 times greater respectively

This paper describes three methods to count the number of discernible colors in a display. One of the methods is based on a uniform quantization of the gamut volume similar to the methods employed by Hill *et al.* [2] and Wen [5]. The other two methods are based on dense packing of spheres and dodecahedra. The purpose of the work is not to arrive at a definite answer for the number of discernible colors; we accept the arguments of Morovic *et al.* [3] and appreciate that the number of discernible colors will depend upon a great many factors. Rather, we seek a method to quantitatively compare the gamut volumes of different displays based on an estimate of the number of discernible colors under some reasonably justified assumptions and conditions.

Experimental

Two contemporary mobile-phone displays (see Table 1) were considered in this study; one was an AMOLED display and the other was an LCD display.

Table 1: Basic parameters for AMOLED and LCD displays.

Basic Parameters	AMOLED	LCD
Size (inch)	5.1	5.2
Display Mode	Super AMOLED	True HD-IPS + LCD
Pixel Resolution	1080 × 1920	1080 × 1920
Colour Resolution	16M	16M

Color stimuli were measured using a Minolta CS1000 spectroradiometer in a dark environment under two different conditions. In the first condition the stimulus filled the whole display (so-called full-field condition) and in the second condition the stimulus was presented as a centered patch occupying 4% of the screen area with a grey (RGB = 103) surround (so-called box condition). In order to quantify the gamut volumes the CIE luminance (cd/m^2) and chromaticity coordinates were measured for 26 color patches (white, black, red, green, blue, cyan, magenta, yellow and 6 additional levels for each of the primaries).

Gamut areas and gamut volumes were calculated for the two displays under the two conditions. The gamut areas were calculated in the CIE xy chromaticity space. The gamut volumes were calculated in four different color spaces; luminance and xy; CIELAB, luminance and uv, and CIECAM02 (a modern color-appearance space) [6].

Three methods were employed for the estimation of the number of discernible colors in CIELAB and CIECAM02 space.

In the *grid* method a regular grid was constructed in the color space with the grid intersections each representing a discernible color. The spacing of the grid was set to 1 CIELAB unit (when carried out in CIELAB color space). The convex hull of the gamut was then placed in the grid and the number of colors within the grid was counted (see Figure 1).

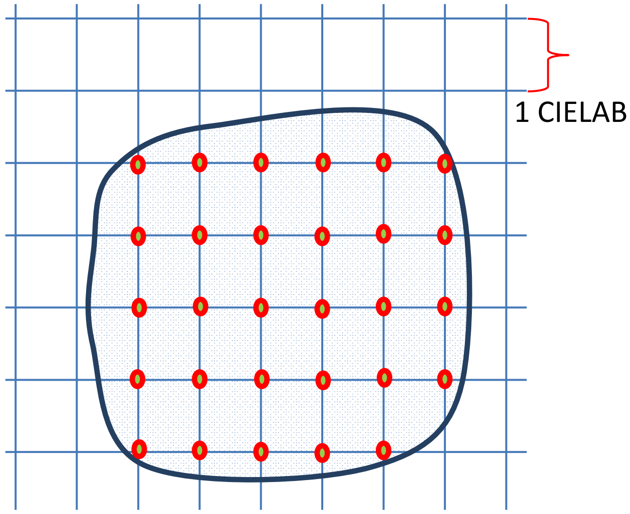

Figure 1. *Schematic diagram to illustrate the CIELAB grid method. A grid of points is constructed that are spaced 1 CIELAB unit apart. The number of points that are inside the display gamut (shown by the curved line above) are calculated. The example is shown in 2-D but, of course, the calculation is carried out in 3-D.*

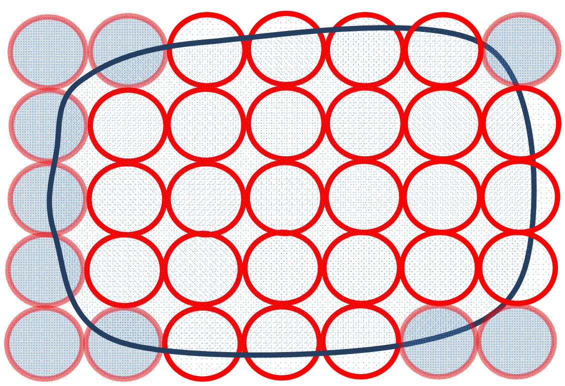

Figure 2. *Schematic diagram to illustrate the sphere method. The number of spheres of diameter 1 CIELAB unit within the gamut volume is calculated. The example is shown in 2-D but, of course, the calculation is carried out in 3-D.*

In the *sphere* method the number of dense-packed spheres (with diameter of 1 CIELAB unit) that can fit in the device gamut volume are calculated (see Figure 2). The number is arrived at by knowledge that the average sphere packing density is $\pi/(18)^{0.5} = 0.74048$ and that the volume of a sphere $v = (4/3)\pi(d/2)^3$ where d is the diameter of the sphere. If the gamut volume is V then the volume occupied by the spheres inside the gamut is $0.74048V$ and the number of spheres $= 0.74048V/[(4/3)\pi(d/2)^3]$.

In the *dodecahedron* method the number of dense-packed dodecahedra (with distance between the centers of two adjacent dodecahedra of 1 CIELAB unit) that can fit in the device gamut volume are calculated. A dodecahedron is a polyhedron with 12 flat faces (Figure 3) and that packs with density of 1. The calculation is therefore similar to the calculation in the sphere method but is simpler. The volume of a dodecahedron $v = a^3(15 + 5^{0.5}7)/4$ where a = length of a one of the sides in the polyhedron. If the gamut volume is V then the number of dodecahedra $= 4V/(a^3(15 + 5^{0.5}7))$.

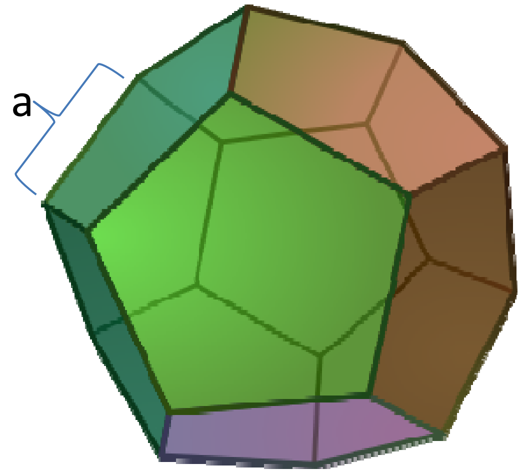

Figure 3. *Schematic diagram to illustrate the dodecahedron method. The dodecahedron is a 12-faced polyhedron. The length of the side a used in the calculation is illustrated in the diagram.*

Why have we used three different methods to count the number of discernible colors? The reason for this is that each has it its own merits and it is not easy to definitively state that one method is better than another. Although they will likely each give slightly different answers for the number of discernible colors, the ratio of the numbers for the two displays calculated by each of the three methods should give a robust view on which display can show the greater number of discernible colors.

Results

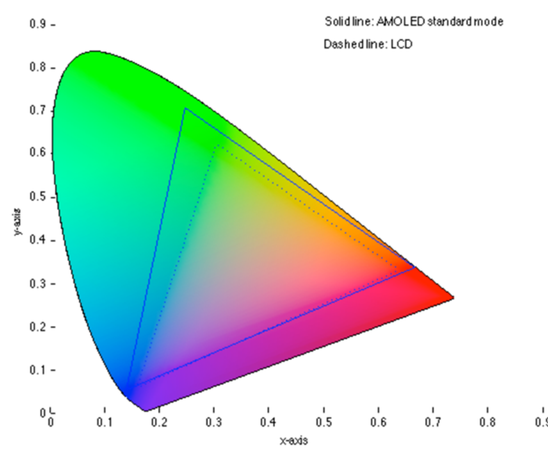

Figure 4. *Chromaticity diagram showing the gamuts of the AMOLED (solid line) and LCD (dashed line) displays.*

Figure 4 shows the gamut areas of the two displays in the CIE chromaticity diagram. The areas of the AMOLED and LCD are 41.1% and 33.6% of the full CIE color gamut respectively.

Table 2 illustrates the display gamut areas and volumes for the different color spaces for the box measurement condition.

Table 3 shows the corresponding results for the full-field measurement condition. The gamut area of the AMOLED display is 35% larger than for the LCD display. The gamut volume is 15-80% larger than for the LCD display depending upon the color space that is used and the measurement condition. Note that the calculation of volume in the CIECAM02 space is not presented for the full-field measurement condition. This is because there is no surround available.

Table 2: Color areas and volumes for the box measurement condition.

Color Space	AMOLED	LCD	AMOLED advantage
xy area	0.1560	0.1151	35.5%
Lvxy volume	47.79	32.21	48.4%
CIELAB volume	1,398,108	889,759	57.1%
Luv volume	1,938,925	1,408,634	37.6%
CIECAM02 volume	2,303,206	1,461,527	57.6%

Table 3: Color areas and volumes for the full-field measurement condition.

Color Space	AMOLED	LCD	AMOLED advantage
xy area	0.1562	0.1154	35.4%
Lvxy volume	41.25	36.04	14.5%
CIELAB volume	1,500,564	846,582	77.2%
Luv volume	2,140,264	1,315,542	62.7%

Tables 4 and 5 show the number of discernible colors for the two displays under the box and full-field measurement conditions respectively in CIELAB color space. For the box measurement condition the number of discernible colors is 59% greater using the grid method for the AMOLED display when compared with the LCD display and 57% greater using the sphere and dodecahedra methods. For the full-field measurement condition the number of discernible colors is 79% greater using the grid method for the AMOLED display when compared with the LCD display and 77% greater using the sphere and dodecahedra methods.

Table 4: Summary of the calculations of number of discernible colors in CIELAB space (box condition).

	AMOLED	LCD	AMOLED advantage
grid	1,375,680	864,920	59.1%
sphere	1,977,222	1,258,308	57.1%
dodecahredron	2,015,185	1,282,468	57.1%

Table 5: Summary of the calculations of number of discernible colors in CIELAB space (full-field condition).

	AMOLED	LCD	AMOLED advantage
grid	1,484,731	829,212	79.1%
sphere	2,122,117	1,197,247	77.2%
dodecahredron	2,162,862	1,220,234	77.2%

Table 6 shows the number of discernible colors for the two displays under the box measurement condition in CIECAM02 color space. The number of discernible colors is 63% greater using the grid method for the AMOLED display when compared with the LCD display and 58% greater using the sphere and dodecahedra methods.

The relative results using the three methods for counting the number of discernible colors are approximately the same and this is encouraging given that then the computational algorithm for the grid method is very different than for the other two methods.

Table 6: Number of discernible colors in CIECAM02 space using the three methods.

	AMOLED	LCD	AMOLED advantage
grid	2,088,391	1,277,568	63.5%
sphere	3,257,223	2,066,910	57.6%
dodecahredron	3,319,762	2,106,595	57.6%

Conclusions

Three methods are proposed for the calculation of the number of discernible colors in a display gamut volume. One of the methods is based on a uniform grid and similar to some previously published methods; the other two methods are based on dense packing of spheres and dodecahedra. The methods are demonstrated with a comparison of two mobile phone displays, one based on AMOLED technology and the other based on LCD technology. Interestingly, despite the fact that the grid method is computationally very different from the other two methods, all three methods give very similar results for the relative number of discernible colors. The AMOLED consistently has 60-80% more discernible colors than the LCD display. Not only is the result relatively invariant to the computational method but it is also similar when the analysis is carried out in CIELAB space or CIECAM02 space.

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Author Biography

Yuan Li received her PhD from the University of Leeds (2012). Since then she has worked in the School of Design at University of Leeds. Her current research interests are psychophysical analysis, whiteness, color assessment in dentistry and image quality.