Design Considerations for Wide Gamut Displays

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Abstract

Conventionally, the main design parameters for the color gamut of a display are the area in chromaticity space and peak white. This suits normal-gamut 3-primary display design, but is not sufficient for designing wide gamut displays, especially if the display has more than three primaries. In this paper, we propose using the optimal color stimuli as a target for gamut design and illustrate this for displays with 3 to 6 primaries. Applying the design target to a display with an additional white primary (RGBW) [1] confirms that such a display may both have a wide gamut and high peak brightness, but also shows that saturated colors are more difficult to render. Furthermore, the analysis shows that an RGB display is attractive for color rendering and that a display with double red, green, blue, yellow and cyan primaries (see e.g. [2]) can provide a good balance between efficiency and gamut.

Introduction

Over the last decade, liquid cristal displays (LCDs) have become the predominant display technology for TVs. Despite all technical advancements, most LCDs still have a rather limited color gamut. The color gamut of the ITU Rec. 709 HDTV standard [3], which is characteristic for many conventional LCDs, covers about 33% of the visible gamut in CIE 1976 u'v' chromaticity space [4, 5]. Furthermore, this gamut is only able to reproduce about 59% of the distribution of real surface colors [6]. In terms of chromaticity, especially the area of highly saturated green, cyan, magenta and red are covered inadequately. Fortunately, the human visual system is rather forgiving, and quite natural images can be rendered using today's displays. Nevertheless, the gap between display gamut and the gamut of real colors allows for substantial improvements in image reproduction. This has resulted in an increased interest in wide gamut displays.

For 3-primary (RGB) displays, a wide color gamut (WCG) can only be achieved by increasing the primary saturation. In LCDs, this requires either color filters with a narrower pass band or a backlight spectrum with narrower peaks. Both solutions cause a loss of efficiency, which implies that more light needs to be installed to reach the same peak luminance. Replacing conventional CCFLs by ones that allow a wider gamut, for instance, results in an efficiency loss of typically $20-30\%$[7]. The losses for using narrower color filters can be even higher. Another option is to use RGB-LEDs in the backlight. This will give a wider color gamut, but is a rather expensive solution. Moreover, differential aging makes this solution sensitive to stability issues. Multi-primary displays form a promising alternative to increase the color gamut without modifying the backlight and having the adverse effect on efficiency. The added color filters typically have a broader pass-band which improves the total panel transmission. It is however important to realize that the efficiency gain is not distributed evenly over the gamut. In general, multi-primary displays have an improved efficiency for desaturated colors, while there is an efficiency loss in saturated red, green and blue due to a reduction in the total area covered per primary color [8].

Whether or not this results in an efficient wide gamut system depends on the distribution of the maximum achievable luminances over the gamut. In other words, the gamut is a 3D-volume and has to be considered as such. It is hence not only the efficiency of white that counts. There is no point in only being able to produce large luminances for a limited subset of colors, as this extra gamut space can hardly be used in rendering natural images. Furthermore, extreme peaks in the gamut increase the difference with input gamut and ask for more advanced gamut mapping [9, 10]. In RGBW systems for instance, the extreme peak around white is known to complicate the rendering of yellow [1]. This paper proposes a method to evaluate the luminance distribution of a gamut. As a part of a qualitative study, the method is applied to a selected number of wide gamut display solutions.

Methods

As pointed out, the attractiveness of a gamut is not only about the area in the chromaticity space, but also about the maximum luminance that the display can generate for each of the chromaticities. In this section, we will first introduce the gamut design target. Based on this target, a method to compare the luminance distribution of gamuts is proposed. We end this section by introducing the wide gamut displays used to illustrate the proposed method.

Gamut Design Target

To efficiently use the gamut, there should be a balance between the luminances that can be achieved at different chromaticities. Ideally, the gamut should provide a close fit to the typical content that is displayed. In this paper, we assume that for TV, the luminance distribution over colors is comparable to what is found in nature. More specifically, we assume that the colors to be rendered are typically from reflective, non-fluorescent objects. For a given illuminant, this assumption can be used to compute the maximum luminous reflectance for a color of a given chromaticity providing a practical design target. In literature, colors with this property are referred to as the optimal (object) color stimuli, MacAdam limits, or luminance factor [4, 11, 12]. The choice for our basis premise will be discussed in more detail later on.

For efficiency reasons, the display gamut is usually designed to have its maximum luminance, or *peak white*, at the targeted color temperature. To reflect this in the design target, an obvious choice is to assume that the reflective objects are illuminated by a CIE daylight illuminant of the appropriate color temperature. Typically, the preferred color temperature is between 6500 K and 11 000 K. For commercially available TV displays, color temperatures of 10 000 K are common. This is also the target in this paper used to compute the optimal color stimuli. Figure 1 shows the optimal color stimuli for a 10 000 K CIE daylight spectrum, in the CIE 1976 u'v'-chromaticity space. We will use the Yu'v'-color space throughout the paper as it has luminance as independent dimension. Since we are interested in relative luminances, this property simplifies the definition and interpretation of the gamut design. Furthermore, this space is perceptually more relevant than e.g. the CIE 1931 xyY-space. The optimal colors have been scaled

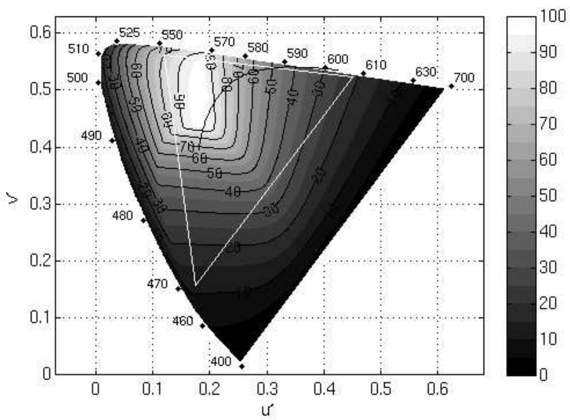

Figure 1. Optimal color stimuli for standard daylight illuminant (10 000 K).

such that a 100% reflective (white) object corresponds to a luminance factor of 100%. For other optimal color stimuli, the reflectance curve corresponds to block shaped pass or stop bands. As the pass band gets smaller for colors of increased saturation, the luminance factors drops gradually towards the boundaries of the visible colors. At the spectral locus, the luminance factor is zero due to the infinitely small pass-band of the reflectance spectrum. For yellow, however, the luminance factor stays quite high even for saturations almost up to the spectral locus. This matches with the common experience that yellow is the brightest color, even though luminance perception peaks at green.

Gamut Comparison Method

Since the luminance factor determines the ratio of maximum reflectance for object colors in nature, it provides a useful reference for evaluating display gamuts. *In this paper, a gamut is therefore considered attractive as its shape minimizes the difference with this reference.* One appealing feature of using the optimal color stimuli is that they are defined for all colors within the spectral locus. This in contrast to for instance the distribution of real surface colors measured by Pointer [6], which is also used as reference for gamut evaluation [2]. To compare a certain gamut with the optimal color stimuli, we define the following function

$$\Delta Y(u',v') = \frac{gY_{\max}(u',v') - Y_{\mathrm{ref}}(u',v')}{Y_{\mathrm{ref}}(u',v')} \times 100\%, \qquad (1)$$

expressing the percentage luminance difference of the (scaled) maximal display output $Y_{\max}$ with respect to the optimal color stimuli Y_{ref} per chromaticity. In this equation, $g \in \mathbb{R}$ is a scaling factor used to normalize the absolute display luminances and enable a comparison with the relative scale of the optimal color stimuli. When one is only interested in the shape of a single gamut, it would make sense to choose g so as to minimize the least squares difference between gamut and optimal color stimuli. In this paper, we compare the efficiency of different display solutions with the same backlight. For this reason we prefer a fixed scaling.

Before applying the above measure to a selection of wide gamut systems, let us consider, by means of example, a 3-primary system with chromaticities satisfying the ITU Rec. 709 [3] standard. The luminance contribution of each of the primaries has been selected to ensure a CIE daylight white point of 10 000 K. The gain factor g in Equation (1) is such that $\Delta Y = 0\%$ at the system's display white. Figure 2 shows the percentage luminance difference for such a system. In this figure, the triangles denote the display primaries, while the square represents display white. Since the display is only able to generate luminance for in-gamut colors, the percentage luminance difference is only defined inside the inner triangle. From the figure it is clear that the ITU Rec. 709 gamut has a shape quite comparable to that of the optimal color gamut. As we will see later on, luminance differences between 0 and -41% are reasonably small compared to the considered WCG systems and, just as important, the variations over the gamut are rather smooth. Hence the ITU Rec. 709 gamut has a luminance profile that is well suited for representing reflective colors.

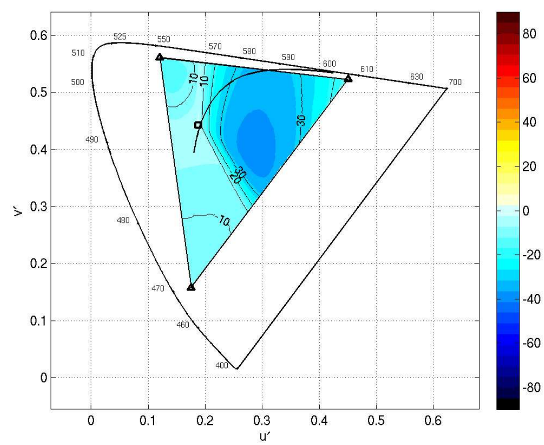

Figure 2. Percentage luminance difference (ΔY) for a display with ITU Rec. 709 primaries and a CIE daylight white point of 10 000 K. The scaling factor g in Equation (1) is such that $\Delta Y = 0\%$ for display white.

Wide Gamut Displays

In this paper, we compare the gamut shape of different display options for creating a wider gamut. Since the display primaries depend both on the choice of the backlight and the color filters, certain assumptions are needed to enable a fair comparison. The gamut of a 3-primary display can be widened by increasing the primary saturation, which is accompanied by a loss in the overall system efficiency. As a representative example of a 3-primary WCG system, we consider the system with the primaries listed in the second row of Table 1. The chromaticity of the primaries corresponds to those of a commercially available TV set. Since this system will be used as the benchmark for the other wide gamut solutions, its luminance at display white has been normalized to one. To account for the efficiency loss of the increased primary saturation, the ITU Rec. 709 gamut in Table 1, has a maximum luminance larger than 1. As a first order estimate,

Tabel 1: Primaries of the simulated display systems specified in the CIE 1976 Yu'v'-color space.

	P1	P2	P3	P4	P5	P6
ITU	0.211	0.816	0.115			
Rec.	0.451	0.121	0.175			
709	0.523	0.561	0.158			
WCG	0.221	0.691	0.089			
RGB	0.528	0.072	0.176			
	0.518	0.577	0.138			
RGB	0.166	0.518	0.066	0.750		
+	0.528	0.072	0.176	0.188		
W	0.518	0.577	0.138	0.442		
RGB	0.166	0.518	0.066	0.681		
+	0.528	0.072	0.176	0.193		
Y	0.518	0.577	0.138	0.569		
RGB	0.110	0.345	0.044	0.454	0.086	0.367
+	0.528	0.072	0.176	0.193	0.387	0.088
YMC	0.518	0.577	0.138	0.569	0.207	0.420
RGB	0.110	0.345	0.044	0.110	0.454	0.367
+	0.528	0.072	0.176	0.528	0.193	0.088
RYC	0.518	0.577	0.138	0.518	0.569	0.420

this luminance has been obtained as the sum of the maximum luminances of the wide gamut display at the ITU Rec. 709 chromaticities, resulting in an 11% efficiency difference. The precise value, however, is not important in illustrating the design target.

The second wide gamut display considered in this paper is a RGBW system. This system has been constructed by taking the same chromaticities for the R, G, and B primaries as the 3-primary wide gamut system. The luminance of primaries is scaled with the area occupied by the sub-pixels. Neglecting the presence of the thin film transistor, this scaling factor is $3/4$. Furthermore, we assume the white primary (W) to be equal to the sum of R, G, and B. As can be checked by summing the primaries in Table 1, this results in system with a 50% higher luminance at white.

Next to the RGBW system, we consider multi-primary displays with a selection of yellow (Y), cyan (C), and magenta (M) as extra color filters (such as in e.g. [2]). The primaries for these systems are constructed by following a procedure similar to the one explained above. For R, G and B, this means that the luminance is scaled with the aperture size, while the chrominance is kept the same. The primaries corresponding to the Y, M and C filters are derived by adding R and G, B and G, and R and B, respectively. This is based on the implicit assumption that the Y, M, and C color filters have the combined transmittance of the constituting primaries and the backlight remains the same.

The primaries derived in this way have a chromaticity that is still on the color triangle spanned by the R, G, B primaries. One of the interesting features of multi-primary, however, is that the extra primaries can be chosen so as to extend the chromaticity gamut from a triangle to a polygon with a larger area. To incorporate this aspect, the saturation of the Y, M and C primaries is increased by subtracting a bit of the opposite primary in the RGB triangle. For the systems in Table 1, this corresponds to $1/25$ of B and $1/5$ of the G and R for the Y, M and C color filters, respectively. Without the additional saturation, the RGBYMC display should be able to achieve a theoretical luminance gain of 50% for white. The gain for the RGBRYC is expected to be about 5% lower as M (=R+B) is replaced by R. By adding the saturation the gain of both displays reduces to about 40%. In practice, the gain is expected to be around 20%–30%, because the dyes in today's Y, M, and C filters are not as effective as those of R, G, and B.

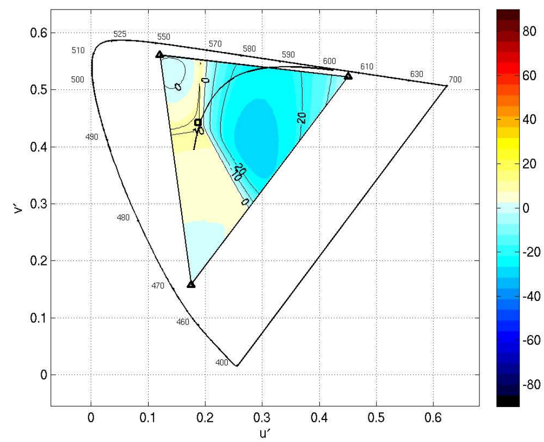

Figure 3. Percentage luminance difference (ΔY) for a display with ITU Rec. 709 primaries and a CIE daylight white point of 10000 K (1st row Table 1). The scaling factor g in Equation (1) is the same for Figure 3 to 8 and is such that $\Delta Y = 0\%$ for display white in Figure 4.

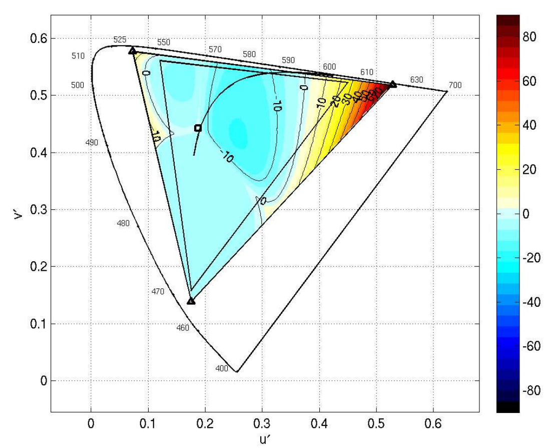

Figure 4. ΔY for a wide gamut RGB display (2nd row Table 1)

Results

To evaluate the different WCG display options presented in the previous section, the percentage luminance difference ΔY has been computed for each of the systems listed in Table 1. The outcome of these computations is presented in Figure 3 to 8. In computing the luminance difference, we have applied a fixed gain g for all gamuts. This gain ensures that $\Delta Y = 0\%$ at the white point of the 3-primary wide gamut display. In each of the figures, the ITU Rec. 709 triangle is indicated as a solid line. By comparing

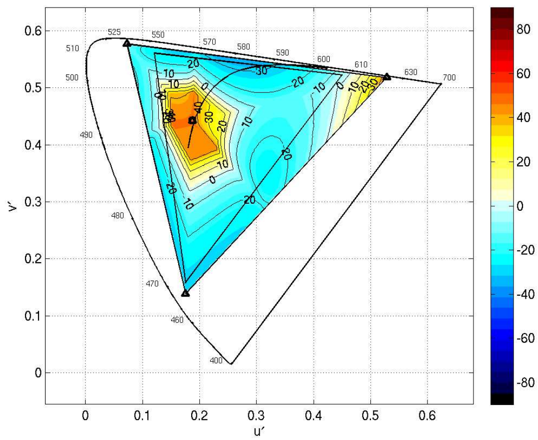

Figure 5. *ΔY for a wide gamut RGBW display (3rd row Table 1)*

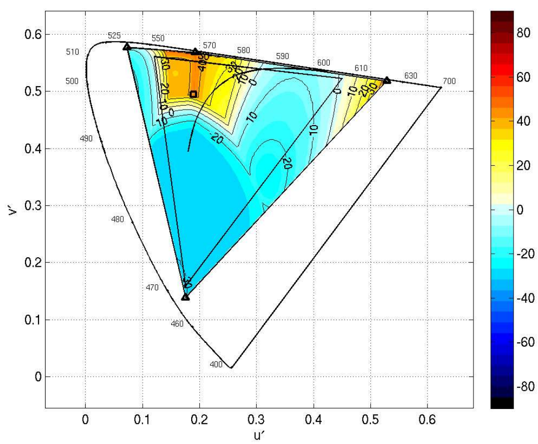

Figure 6. *ΔY for a wide gamut RGBY display ($4th$ row Table 1)*

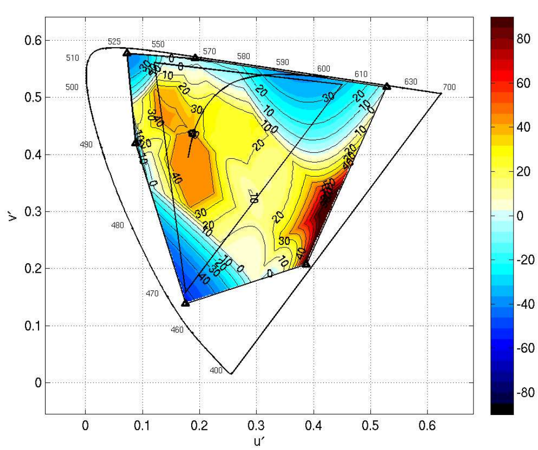

Figure 7. *ΔY for a wide gamut RGBYMC display ($4th$ row Table 1)*

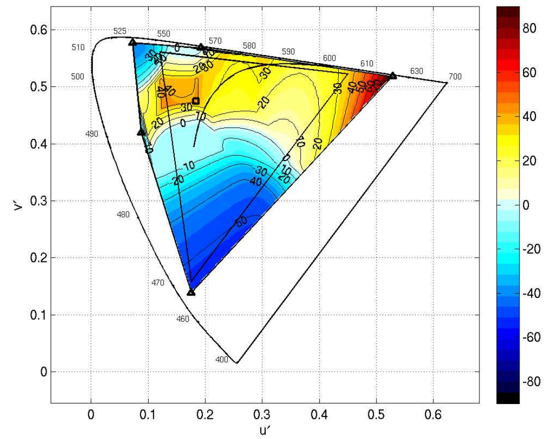

Figure 8. *ΔY for a wide gamut RGBRYC display ($5th$ row Table 1)*

Figures 3 and 4, it is clear that the wide gamut RGB display and the ITU Rec. 709 display have a luminance distribution that is quite similar in shape. The main difference between these gamuts occurs for saturated red. For these colors, the wide gamut RGB display is able to make (much) more luminance than needed for reflective objects. Because of the fixed gain g, the figures also reflect the lower efficiency of the wide gamut display.

Figure 5 shows the computed percentage luminance differences of the RGBW system. The figure confirms that an RGBW display is able to generate more brightness for white at the expense of a loss in brightness for saturated colors. The luminance gain for desaturated colors is about 50%, while for certain colors on the ITU Rec. 709 triangle it drops to about -30%. Only for very saturated red, the RGBW gamut exceeds the surface of optimal color stimuli which gives rise to a positive luminance difference. These features cause a certain imbalance in the RGBW gamut, which complicates the color rendering. In particular, the rendering of yellow with sufficient luminance will become problematic for this type of displays. When the yellow becomes too dark it will be easily perceived as brown. Because of this difficulty it might be interesting to consider the RGBY solution, where the extra white primary is replaced for a yellow primary.

The percentage luminance difference with respect to the optimal color stimuli for an RGBY display is depicted in Figure 6. The figure shows a quite substantial gain (over 40%) for colors near yellow, but there is an up to 30% loss for bluish colors. Furthermore, the white point is very yellowish (around 5000 K) and the maximum luminance drops drastically along the black body curve for increasing color temperatures. Near the desired target white point of 10 000 K the luminance loss is around 25%. Hence, even though the color rendering might be easier than for RGBW, the additional luminance in yellow cannot be exploited to full benefit. One way to increase the gamut without shifting the white point too much, could be to add more primaries.

An example of such a design is the RGBYMC display of which the percentage luminance difference is shown in Figure 7. As for the RGBW display, the luminance gain of RGBYMC is predominantly concentrated around white, while there is a significant luminance loss for saturated colors. Compared to an RGBW display, the gain for unsaturated colors is a bit lower (40% for white) but spread more evenly over a larger chromaticity area. On the other hand, the losses for saturated red, green and blue are bigger. This is due to the fact that in an RGBYMC display the saturated colors can only be produced by one out of the six sub-pixels. For yellow, magenta, and cyan colors this is only the case outside the color triangle spanned by the RGB primaries. Inside this triangle, yellow can for instance be made by having contributions from both the yellow primary and from the red and green primaries. A similar argument holds for magenta and cyan.

In practice, the luminance loss in saturated green and blue does not seem to be a problem in achieving good color rendering. This is due to the fact that very bright and saturated green and blue colors hardly occur in natural content. The frequency of occurrence of colors in typical TV and DVD content has been investigated in [13]. This study shows that the colors in natural content cluster mainly around the black body curve. The frequency of occurrence of saturated green and blue is very low. For bright colors, this distribution becomes even more extreme. The lack of luminance in saturated orange and red, however, is clearly an issue in an RGBYMC display. To alleviate this problem, one could consider to replace magenta by a second red color filter. Figure 8 depicts the percentage luminance difference for an RGBRYC display. For this display there is hardly any luminance gain at the desired white point of 10 000 K, but it has a substantial gain for all lower color temperatures along the blackbody curve. Also for yellow, orange, pink, red, and cyan, it has a substantial luminance gain compared to the optimal color stimuli. Only for saturated green, bluish magenta and blue a there is a loss in luminance, but as already indicated this is less of an issue in for natural images.

Discussion

The gamut design target in this paper is meant to evaluate the luminance distribution of different display options. It provides a way to identify chromaticity areas having an excess or shortage in luminance, which may complicate the color rendering. It is important to realize that the proposed design target is based on the assumption that the colors typically originate from reflective, non-fluorescent objects. Strictly speaking this assumption is often not satisfied. It fails for instance for computer generated creative content. Also any system gamma or color enhancement will cause a deviation from this assumption. In spite of this, one could argue the optimal colors are still a useful reference as it guarantees a certain smoothness. Large imbalances in the luminance distribution are easily detected. Furthermore it is defined for all colors in the spectral locus[1] and it reflects the common property that the brightness typically decreases with increased saturation. The optimal colors also ensure that white and yellow are most luminant. For computer graphics, which may not bear any relation with natural content, another reference might be more appropriate.

Finally it is important to stress that the proposed method provides at most an ordinal scale for ranking gamuts. Instead of generating a single-number metric, the percentage luminance difference is a 2D-map on a false-color scale. It is clearly not the intention to pass a quantitative verdict on whether a deviation from the optimal colors in certain chromaticity area is to be preferred over a similar deviation in another area. This is also impossible, as the method does neither account for the gamut mapping, of which the effectiveness of overcoming the luminance difference might vary per color, nor does it include any image statistics such as the likelihood of colors. Also the effect of the capturing and encoding of colors is not included and the choice to express the luminance difference as a percentage of the optimal color reference will introduce an increased weighting for colors close to the spectral locus. The proposed gamut design target, however, provides a simple qualitative tool to obtain a first indication of the suitability of a certain gamut in achieving natural color rendering. In addition, the method gives a first indication on which colors are likely to be most problematic in gamut mapping. Including image statistics, gamut mapping and encoding effects might facilitate a more fair comparison between colors, but is also likely to result in a more complex and case specific design target.

[1] As the primaries of an LCD are inside the spectral locus this also prevents division by zero in computing the percentage luminance difference.

Conclusions

In this paper, we proposed a target for wide gamut display design. To arrive at an efficient system, it is important to focus not only on parameters like peak white and area covered in chromaticity space, but to consider also the luminance that can be achieved for each of these colors. A gamut is a 3D-shape and should be designed as such. The luminance distribution determines to a large extend which part of the gamut can be effectively used in rendering natural images. The proposed design target is based on the assumption that the colors to be rendered typically originate from reflective, non-fluorescent objects. It therefore makes sense to define the optimal color stimuli, which describe the maximum luminance reflectance of surface colors, as a reference for the desired gamut shape. To judge how well a gamut follows this reference we define the percentage luminance difference. In a 2D-chromaticity plot, this function shows for which chromaticities the gamut is over or under designed in terms of luminance.

The proposed design target has been applied in a qualitative comparison of different wide color gamut display options. The primaries of an LCD display depend both on the choice of the backlight spectrum and color filters. As this gives a lot of freedom, certain assumptions had to made to enable the comparison. More specifically, the primaries of the considered systems have been derived from measurements of a wide gamut RGB display. Even though this will be an approximation, this approach clearly highlights the advantages and difficulties of certain choices. The analysis clearly shows that an RGBW display is indeed over designed in white, which implies that either the peak luminance can not be used to the full advantage or the rendering of saturated colors is problematic, especially in yellow. For an RGBY display the challenge is in rendering blue and compensating the too yellowish white point. The 6-primary solutions have a luminance peak that is distributed more evenly over a larger chromaticity area. The RGBYMC display however has a luminance shortage in the areas around the R, G and B primaries. Since bright saturated green and blue hardly occurs in typical input content, only the shortage in red will be a problem in practice. This issue can be resolved in the RGBRYC display by having two red primaries per pixel. Compared to a wide gamut RGB, the considered RGBRYC display has a peak white of 140%. RGBRYC is therefore a promising option for efficiently achieving a wider color gamut.

References

[1] E.H.A. Langendijk et al., Dynamic wide-color-gamut RGBW display, SID Symposium Digest, pg. 1458, (2007).

[2] S. Ueki et al., Five-primary-color 60-inch LCD with novel wide color gamut and wide viewing angle, SID Digest, pg. 927 (2009).

[3] Parameter values for the HDTV standards for production and international programme exchange, ITU-R BT.601-5, 1995.

[4] G. Wyszecki and W.S. Stiles, Color Science Concepts and Methods, Quantitative Data and Formulae, John Wiley & Son Inc., 1983.

[5] R.W.G. Hunt, The Reproduction of Color, John Wiley & Sons, 2004.

[6] M.R. Pointer, The gamut of real surface colours, Color Research and Application, pg. 145, (1980).

[7] T. Kusunoki and T. Igarashi, A high luminous cold cathode fluorescent lamp and phosphors for a WCG LCD, ECST, pg. 47, (2008).

[8] K. Hinnen et al., Multi-primary displays from a systems perspective, Int. Display Research Conference, Eurodisplay, pg. 560, (2009).

[9] J. Morovič and M.R. Luo, The fundamentals of gamut mapping: A survey, Journal of Imaging Science and Technology, pg. 283, (2000).

[10] J. Morovič, Color Gamut Mapping, John Wiley & Sons Inc., 2008.

[11] D.L. MacAdam, Maximum visual efficiency of colored materials, Journal of the Optical Society of America, pg. 361, (1953).

[12] R.S. Berns, Billmeyer and Saltzman's principles of color technology. John Wiley & Sons Inc., 2000.

[13] W.H.M. van Beek, C.N. Cordes, and N. Raman, Applied video statistics, IMID Digest, (2005).

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