

Improving Color Reproduction Accuracy and Color Gamut of Mobile Displays

Kirchner, E.^{a*}, Ivo van der Lans^a, Esther Perales^b, Francisco Martínez-Verdú^b

^aColor Research, Sassenheim, THE NETHERLANDS

^bUniversity of Alicante, Alicante, SPAIN

*Eric.Kirchner@akzonobel.com

ABSTRACT

We recently developed the generic MDCIM model to improve color reproduction accuracy, specifically for mobile displays. It combines both a device-specific display characterization model and a method to account for the effect of ambient illuminance. The Mobile Display Characterization and Illumination Model (MDCIM) was applied on displays representing both main technologies for mobile displays: LCD and OLED.

We organized psychophysical tests with seven observers under four different ambient illuminance levels, ranging from 600 to 3000 lx. Observers rated color reproduction accuracy of color patches on the display, as compared to physical RAL samples. For an Apple iPad Air 2 tablet computer (LCD display), we find that MDCIM considerably improves color reproduction accuracy at all ambient illuminance levels. Observers clearly prefer the new method over using conventional techniques based on sRGB color space. For example, the percentage of satisfactory color matches at 3000 lx increases from 0 to 60 %. For a Samsung Galaxy S4 (OLED) display we find similar improvements. For example, at 1000 lx ambient illuminance the percentage of reasonable color matches increases from 20 % to 80 % by using the MDCIM model. We show that the MDCIM model can be applied for many modern mobile displays, as for instance at medium term the QD technology, using only publicly available technical specifications.

KEYWORDS: Color Imaging, Digital Color Reproduction, Displays, Mobiles, Visual Psychophysics

1. INTRODUCTION

We recently developed a new generic model to improve color reproduction accuracy, specifically for mobile displays [1][2]. This MDCIM (Mobile Display Characterization and Illumination Model) combines two approaches: (i) it provides a device-specific display characterization model, in order to account for the specific properties of a particular display, and (ii) it takes into account the effect of ambient illuminance. We evaluated the accuracy of the MDCIM model for two very different types of displays, based on LCD and OLED technology. Taken together, these technologies represent current mobile displays on smartphones and tablet computers.

2. MODEL DETAILS

The sRGB color space is the default device-independent color space, and is based on the Gain-Offset-Gamma model from Berns *et al.* [3][4]. In Refs. [1][2] the mathematical-physical derivation of the MDCIM model is shown, and we will not repeat it here. We only remark here that in the derivation of the commonly used sRGB color space [4], assumptions were made on display specifications and on viewing conditions that may have been applicable to television sets and computer screens in the late 1990s, when sRGB was defined, but that do not apply for current mobile displays, or for instance following the current recommendations for the ITU-R BT.2020 specifications for UHD TV. Refs. [1][2] show how all parameter values in the MDCIM model can be calculated from a few technical specifications of a display: the CIE 1931 chromaticity values (x , y) and maximum luminance Y_{max} of the three color channels, and the fit parameters g and d_0 of the Tone Rendering Curves measured on the

display. For a more extensive presentation of the MDCIM model, including aspects such as accounting for ambient illuminance, adaptation, white-point and CIECAM02 model, we refer to our previous publications [1][2].

3. PSYCHOPHYSICAL TESTS

For this evaluation, we organized psychophysical tests with seven observers under ambient illuminance levels varying from 600 to 3000 lx. The observers rated the color reproduction accuracy of color patches on the display as compared to physical samples. We used 35 colors from the RAL840HR collection from the German Institute for Quality Assurance and Labeling (RAL). We selected low gloss samples, well distributed over color space.

For all samples, we measured spectral reflectance with a multi-angle spectrophotometer (BYK-mac from BYK-Gardner), with 10 nm spectral resolution. To minimize the influence of gloss, we used data corresponding to the 110° aspecular angle. This data was converted into RGB-images, using either the sRGB encoding space or the MDCIM model described in the previous section. For cases where resulting colors are out-of-gamut, we used a simple gamut mapping algorithm as described in our previous articles [1][2].

Seven observers compared two different images on the mobile display with every physical sample. Observers had to indicate which of the two images showed the best color match. There was no way in which observers could know which image was calculated using which method (sRGB encoding space or MDCIM model), and this was also randomized for each sample. Finally, observers were asked to rate the color difference between image and physical sample on a scale from 0 to 5, according to descriptions listed in Table 1.

Table 1. Visual scores and descriptions used in the psychophysical tests.

Score	Description	Score	Description
0	No / hardly any difference	3	Difference visible, doubtful match
1	Small, negligible difference	4	Difference clearly visible; not correct match
2	Difference visible but still reasonable	5	Large difference; very bad match

4. RESULTS

For the LCD display of an Apple iPad Air 2 tablet computer, Table 2 shows that the MDCIM model considerably improves color reproduction accuracy at 600, 1500 and 3000 lx. The majority of observations prefer the color match generated by the MDCIM model over those created with conventional sRGB encoding space. This majority is 66 % at 1500 lx ambient lighting, and even reaches 87 % and 98 % at 3000 and 600 lx. This indicates that the MDCIM model produces a large improvement in color reproduction accuracy on the iPad Air 2. Only at 1000 lx ambient lighting, the MDCIM model is found to not lead to an improvement (but also not leading to worse color reproduction accuracy). Very similar results are obtained for the Samsung Galaxy S4, with OLED technology. This mobile phone (and its successors) has the capability of color management, by letting the user choose between different display modes. We have tested two of them here, Movie Mode and Standard Mode. In both modes, the MDCIM model brings substantial improvement. Unlike for the iPad Air 2, improvement is also found at 1000 lx ambient illuminance.

Table 2. Preference of observers for images based on the MDCIM model over conventional images based on sRGB encoding color space.

Illuminance Level (lx)	Apple iPad Air 2 (LCD)	Samsung Galaxy S4 (OLED) Movie Mode	Samsung Galaxy S4 (OLED) Standard Mode
600	98 %	83 %	91 %
1000	50 %	75 %	70 %
1500	66 %	88 %	77 %
3000	87 %	95 %	97 %

The results summarized in Table 3 show that not only the color reproduction accuracy improves when using the MDCIM model, but also the percentage of satisfactory color matches increases. For the Apple iPad Air 2, the conventional sRGB encoding space leads to an average color accuracy of 3.6, which is somewhere between a doubtful and a not correct match according to the descriptions (Table 1).

The percentage of “satisfactory” color matches increases dramatically. For example, for 3000 lx ambient illuminance the increase is from 0 to 60 %. For the OLED display of a Samsung Galaxy S4 smartphone we obtain similarly large improvements. For example, at 1000 lx ambient illuminance the perceived color match between displayed color and physical RAL sample is considered to be at least “reasonable” by an average of 20 % of the observers when using conventional techniques. Using the MDCIM model, this percentage increases to 80 %.

Table 3. Average visual score for color reproduction accuracy, obtained for images based on sRGB encoding color space and on the MDCIM model, for the Apple iPad Air 2 and the Samsung galaxy S4 display.

Illuminance Level (lx)	Apple iPad Air 2 (LCD)		Samsung Galaxy S4 (OLED) Movie Mode		Samsung Galaxy S4 (OLED) Standard Mode	
	sRGB	MDCIM	sRGB	MDCIM	sRGB	MDCIM
600	4.6	2.6	3.5	2.4	3.5	2.1
1000	3.6	3.6	3.5	2.3	3.1	2.4
1500	3.6	3.0	4.1	2.2	3.5	2.2
3000	4.4	2.9	4.4	2.6	4.4	2.6

5. IMPLICATIONS FOR DISPLAY GAMUTS

The theoretical limits of colors that arise from light reflection are represented by the object-color solid [7] [8]. In this way, we obtain the limits of the MacAdam-Rösch color solid encoded by illuminant D65 and standard observer CIE-1931 XYZ. These limits are shown as solid lines in Figure 1. In Figure 1a, the dashed line shows the range of colors that, according to the MDCIM model for 1500 lx ambient illuminance, can be represented on an iPad Air 2 display without becoming out-of-gamut, i.e. without any of the R , G and B values falling outside the 0-255 range for eight-bit color representation. The graph shows that for object colors with $L^* = 50$ many green and yellow colors are out-of-gamut.

For object colors with different value for L^* , the MacAdam-Rösch limits change and also the color gamut of the display changes. Figure 1b shows that under 1500 lx ambient illuminance, only a very small part of the theoretically possible object colors with $L^* = 90$ can be reproduced accurately on an iPad Air 2 display. Many bright red, yellow and blue colors are out-of-gamut. Figure 1c shows how the range of colors that can accurately be visualized on an iPad Air 2 shrinks even further when ambient illuminance becomes 3000 lx. The display is simply incapable of matching both brightness and colors with even only small saturation. Corresponding results for the Samsung Galaxy S4 display are shown in Figure 1d.

6. CONCLUSIONS

The results obtained in this work show that color reproduction accuracy of mobile displays can be greatly improved by using the MDCIM model instead of the conventional device-independent sRGB color space. The model is generic, and only requires accurate data on a number of parameters: chromaticity values (x , y) and maximum luminance values Y_{max} for the three color channels, and the gamma value g and threshold value d_0 for each channel. All other parameters in the model are directly calculated from these values as demonstrated in the Appendix of Refs. [1][2]. No fit parameters are needed. Implications for display gamuts are discussed as well.

Values for the required parameters may be measured with a spectroradiometer, as we did for the iPad Air 2. But they can also be taken from published technical specifications, as we did here for the Samsung Galaxy S4. The required data can for example be found in Refs. [5][6] for the following OLED-based mobile displays: Samsung Galaxy S8, S7 and S6, Samsung Galaxy Tab S2 9.7, Huawei Mate S and HP Spectre X360. For LCD-based displays, the required specifications can be found in the same places for the Apple iPhone 7, the Apple iPad Pro 9.7, the Apple iPad mini 4, the LG G5 and the Microsoft Surface 3.

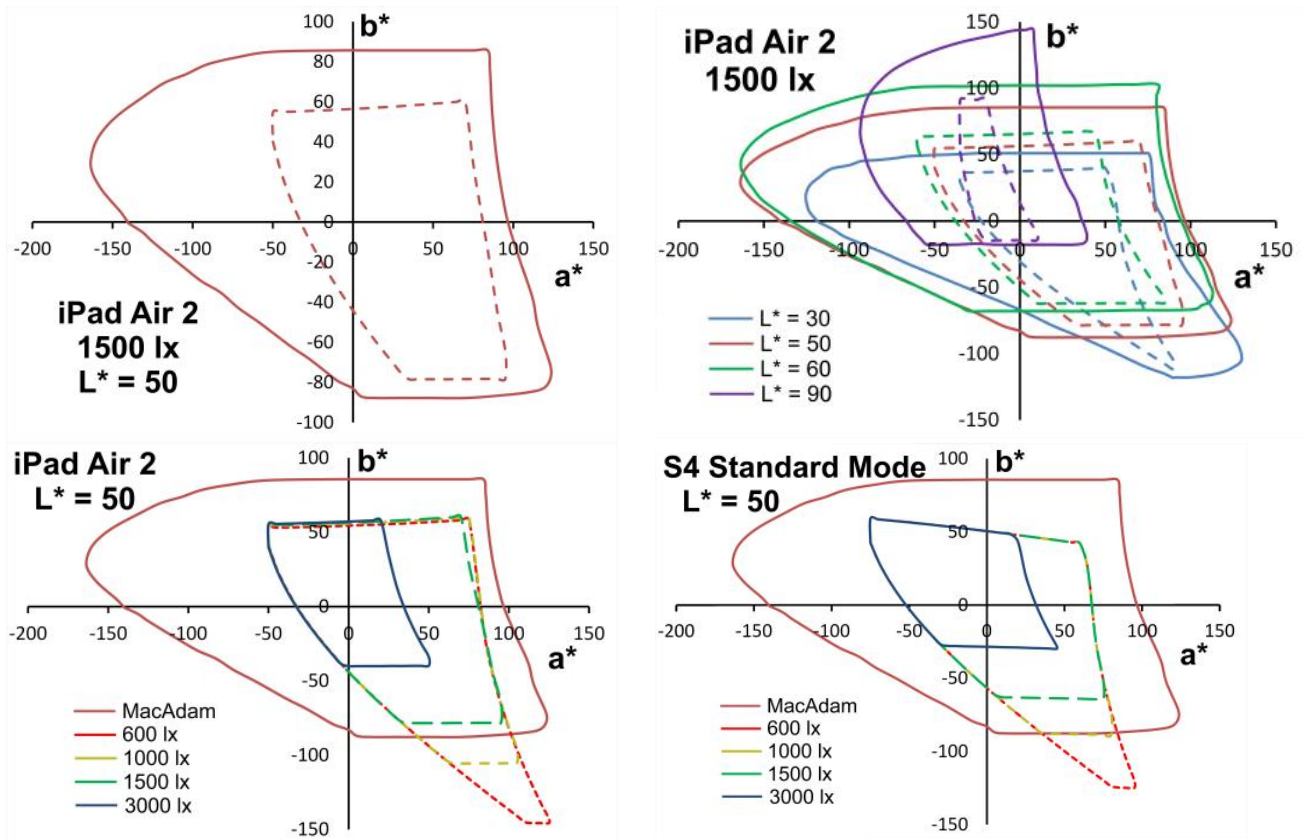


Figure 1: Dashed lines show calculated color gamuts for iPad Air 2 (a) at 1500 lx ambient illuminance, representing object colors with $L^*=50$ and (b) same for $L^* = 30, 50, 60$ and 90 , (c) for object colors with $L^*=50$ viewed under ambient illuminance of 600, 1000, 1500 and 3000 lx, (d) same for Samsung Galaxy S4 display under Standard Mode. In all cases, also the MacAdam-Rösch color solid (under D65) is shown with solid lines.

REFERENCES

- [1] Kirchner, E., van der Lans, I., Martínez-Verdú, F.M. and E. Perales. 2017. *Improving color reproduction accuracy of a mobile liquid crystal display*, Journal Optical Society America A; 34:101-110.
- [2] Kirchner, E., van der Lans, I., Martínez-Verdú, F.M. and E. Perales. 2017. *Improving color reproduction accuracy of an OLED-based mobile display*, Color Research Application (in press).
- [3] Berns, R.S., Motta, R.J. and M.E. Gorzynski. 1993. *CRT colorimetry, Part I: Theory and practice*. Color Research Application;18:299–314.
- [4] International Electrotechnical Commission, Technical Committee 100. 1998. *Audio, video and multimedia systems and equipment, Project team 61966: Color Measurement and Management in Multimedia Systems and Equipment, Part 2.1: Default RGB colour space – sRGB*.
- [5] Website from Displaymate, www.displaymate.com
- [6] Website from Notebookcheck, www.notebookcheck.com
- [7] Martínez-Verdú, F.M., Perales, E., Chorro, E., De Fez, D., Viqueira, V., and E. Gilabert. 2007. Computation and visualization of the MacAdam limits for any lightness, hue angle, and light source, Journal Optical Society America A; 24:1501-1515.
- [8] Perales, E., Chorro, E., Cramer, WR, and F.M. Martínez Verdú. 2011. Analysis of the colorimetric properties of goniochromatic colors using the MacAdam limits under different light sources. Applied Optics, 50: 5271-5278.