Colorimetric Characterization of a Liquid Crystal Display

Rik Marco Spieringhs, Industrial Engineering and Innovation Sciences, TU/e, Signify Research Laboratory, HTC 7, Eindhoven, May 2019, The Netherlands.

Introduction

In the late 1920's researchers like William David Wright and John Guild became interested in the possibilities to define quantitative links between the physical electromagnetic spectrum and colors perceived by human observers [1][2]. These independently performed studies, by William David Wright and John Guild, resulted in the CIE 1931 RGB color space determined by the International Commission on Illumination (CIE) in 1931. The color space maps the scope of all possible physical light spectra to an objective description of these colors, based on color matching experiments by metamerism [3]. Figure 1 shows an example of a television display that was color matched to a Tungsten light bulb, both having different spectral power distributions. Color matching functions were fundamental for the reproduction of images by just red, green and blue lights.

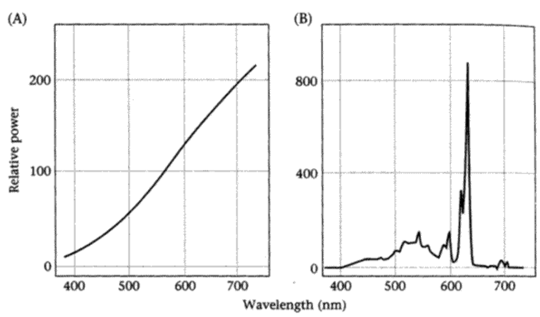

Figure 1. the relative power distribution of a Tungsten light bulb on the left and a color matched TV display on the right (picture retrieved from the book 'foundations of vision' by Wandell [4]).

Upon knowing that images could be reproduced by just red, green and blue lights, engineers started to create the first most famously adopted electronic cathode-ray-tube (CRT) display. CRT displays used three electron emitters (for red, green and blue) to focus electronic beams into specific focusing and deflection coils [5]. At the time of this study, however, these CRT displays were mostly replaced by its successor, namely the liquid crystal displays (LCD). LCDs were superior to the predecessor in their qualification of spatial uniformity, sharpness, contrast ratio and luminance [6]. LCD based monitors were largely used in the industry as well as in visual experiments. Some visual experiments included colors to determine certain relationships between and within participants. A high colorimetric accuracy was, therefore, of utmost importance for conducting these visual experiments. To optimize the colorimetric accuracy several characterization techniques were used. The traditional characterization techniques were well summarized by Berns, in his paper about the methods for characterizing CRT displays [7]. The traditional techniques tried to characterize the electro-optical transfer functions of the display with the least colorimetric differences between measured and predicted color coordinates. A common technique used to determine these color differences was the color difference formula CIEDE2000 [8].

The study by Fairchild and Wyble [6], on the colorimetric characterization of an LCD, investigated the GOG model and the look-up table (LUT) model. The results of this study indicate that the GOG model was limited in its performance compared against the one-dimensional LUTs to characterize the electro-optical functions. The researcher, however, did note that the LUT model was still not perfect and further improvements should be applied. The study of Day, Taplin and Berns [9], on the colorimetric characterization of an LCD, revised this LUT technique and improved it with a nonlinear optimization to optimize the LUTs with minimal CIEDE2000 color differences.

Research aim

This study was aimed at exploring the LUT technique and the colorimetric characterization and evaluation of an Philips Brilliance 220B^{LP} LCD.

Method

The experiment consisted of measuring different colors projected on the LCD, creating a model with the measured 1931 CIE XYZ values, and evaluating the model with a verification procedure.

Design

In the experiment, a spectroradiometer was aimed orthogonal to an LCD. A laptop was connected to the LCD and projected full colored figures by their digital counts. The spectroradiometer was connected to the same laptop and provided the CIE 1931 XYZ coordinates for each colored figure. The CIE 1931 XYZ coordinates for each predetermined digital count combination was stored inside a matrix in Matlab.

Experimental Setup

The Photo Research JETI Specbos 1211 spectroradiometer had a relative luminance accuracy of +- 2% (against the NIST luminance standard) and a relative color accuracy of +- 0.002 in CIE 1931 x,y, according to their online brochure retrieved at May 2019.

The laptop was an MSI GE70, MS1757, with the color setting set at the system standard sRGB IEC61966-2.1. The laptop was connected to the display by an VGA to VGA cable.

The Philips Brilliance 220B^{LP} LCD had the dimensions of 22 inches diagonal and 19.8x9x17.6in (WxDxH). The display type was an LCD monitor/TFT active matrix. The aspect ratio was 16:10, the native resolution 1680x1050 at 60Hz, the contrast ratio 1000:1, the horizontal angle 160°, the horizontal refresh rate 83 kHz, the vertical refresh rate 75 Hz, 300cd/m^2 peak luminance and has an anti-glare, anti-static screen coating. The laptop, spectroradiometer, and LCD can all be seen in figure 2.

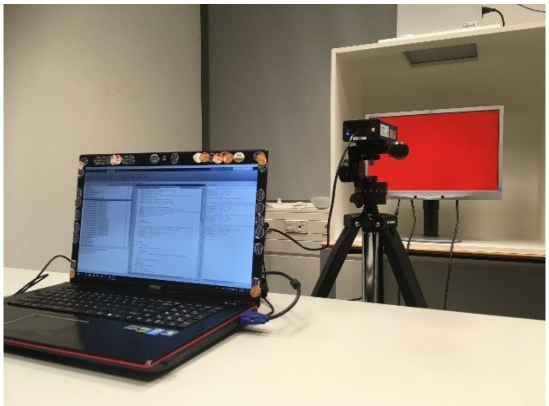

Figure 2. Picture of the experimental setup, showing the Liquid Crystal Display, the JETI spectroradiometer and laptop used to project stimuli.

Software

The Matlab software was used for the colorimetric characterization. Matlab was used to control the stimuli shown on the display and to control the JETI Specbos 1211 spectroradiometer. Matlab was also used to create the LUT model and evaluate the model. Only the Matlab software was used to minimize any interferences of color rendering differences between software packages.

Stimuli

The stimuli consisted of a 1680 x 1050 pixel square figure filling the whole LCD screen. The RGB digital counts of the figure projected on the LCD screen were changed by a Matlab script. The stimuli consisted of three ramps with their digital counts from 5 to 255 in increments of 5 for each primary, red (5:5:255, 0, 0), green (0, 5:5:255, 0) and blue (0, 0, 5:5:255) individually. Furthermore, the stimuli consisted of a gray ramp, where the digital count for each channel was the same, also from 5 to 255 in increments of 5 (5:5:255, 5:5:255, 5:5:255). The black with a digital count of only zeros (0,0,0) and the white with digital counts of 255 for each primary (255, 255, 255), the max red (255, 0, 0), max green (0, 255, 0) and max blue (0, 0, 255) were measured. A verification grid, with equal distances of 31 digital counts in a three-dimensional grid was measured for the evaluation of the model, that started at the coordinate (31,31,31) and ended at the coordinate (255,255,255).

Procedure

Before the measurement started the JETI Specbos 1211 was connected to the laptop by an initializing script. The screen saver was disabled on the laptop and the color settings for the Philips Brilliance 220B^{LP} LCD and Laptop were set at the sRGB mode, such that both systems worked on the same color rendering. Furthermore, the laptop was made sure to be connected to the display and JETI Specbos 1211. The figure projected on the LCD was set to fill to the whole screen. After the display had warmed up for one hour the measurement started.

During the measurement, all lights inside the room were turned off. First, the red ramp was measured with additionally the maximum red and black. Second, the green ramp was measured with additionally the maximum green and black. Third, the blue ramp was measured with additionally the maximum blue, black and white. Fourth, the gray ramp was measured and finally, the verification grid was measured.

Results

In the study by Fairchild and Wyble, 1998, and Day, Taplin and Berns, 2004, notable were that a shift in primaries could occur due to a display flare not being accounted for. The red, green and blue ramps, therefore, were first analyzed for the differences in chromaticity coordinates in the CIE 1976 UCS diagram. The chromaticity constancy of the primaries without flare compensation see figure 3, did show this shift in primaries. Before any other analyses were done the mean of the four black measurement CIE 1931 XYZ data points were subtracted from all measurement data. After the flare compensation there still seemed to be some small shifts for some digital counts of the primaries. These shifts seemed to appear in the first few measurements at the lower digital counts (<40). The measurements 1, 2, 3 and 5 of the red ramp, the measurements 1, 3 and 4 of the green ramp and the measurements 1, 3 and 4 of the blue ramp, see figure 4, were problematic, however, explainable by the inaccuracies of the spectroradiometer at lower light levels.

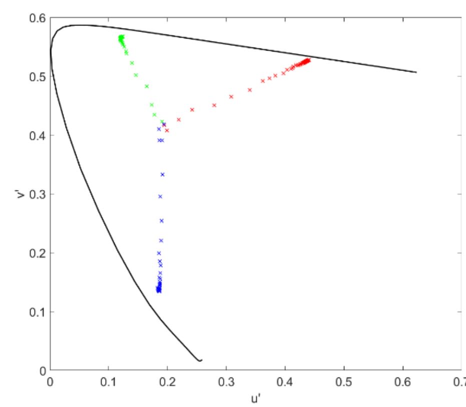

Figure 3. The measured chromaticities of each red, green and blue ramp.

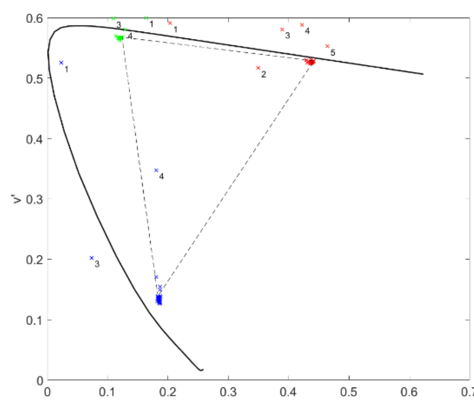

Figure 4. The measured chromaticities of each red, green and blue ramp after black correction. Dashed lines indicated the gamut between all primaries at their maximum digital count (255).

Luminance and Contrast

The luminance and contrast of the LCD were examined by the black, white, red, green and blue maximum. The red maximum luminance, 43.37 cd/m^2, and blue maximum luminance, 13.46 cd/m^2, were relatively lower than the green maximum luminance, 151.78 cd/m^2. When summed (R+G+B), the luminance would supposedly be 207.86 cd/m^2. The luminance of the white point was 208.61 cd/m^2 and the luminance of the black point was 0.183 cd/m^2. The approximate contrast ratio of the LCD was 1134:1, higher than what the manufacturer claimed it to be.

Additivity

The additivity of the LCD, after black correction, was very good, hardly any difference in CIE 1931 XYZ coordinates between the summation of primaries and the white point measured was noticeable. Table 1 illustrated the small differences for each XYZ value.

Table 1, CIE 1931 XYZ differences between the sum of RGB primaries and the white point.

VALUE	WHITE	SUM(R+G+B)	DIFFERENCE
X	194.86	195.10	0.001%
Y	207.86	208.06	0.009%
Z	228.07	227.72	0.008%

Primary Transform Matrix & Inverse

The primary transform matrix was determined by using the CIE 1931 XYZ values of the maximum red, maximum green and maximum blue combined inside a matrix after black correction see equation 1. In this equation also the display flare was added after multiplying the linear RGB with the primary transform matrix. The inverse model was provided by equation 2.

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} 81.42 & 43.37 & 2.46 \\ 74.62 & 151.78 & 18.62 \\ 39.65 & 13.46 & 207.78 \end{vmatrix} \begin{vmatrix} R \\ G \\ B \end{vmatrix} + \begin{vmatrix} 0.198 \\ 0.183 \\ 0.379 \end{vmatrix} \quad (1)$$

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \begin{vmatrix} 0.0165 & -0.0047 & 0.0002 \\ -0.0078 & 0.0089 & -0.0007 \\ -0.0026 & 0.0003 & 0.0048 \end{vmatrix} \left(\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} - \begin{vmatrix} 0.198 \\ 0.183 \\ 0.379 \end{vmatrix} \right) \quad (2)$$

LUT Model

The electro-optical transfer function was determined by using three one dimensional look-up tables (LUTs). The electro-optical transfer function determined the relationship between the perceived lightness and the voltage ladder. Each of the look-up tables corresponded to a digital count of 256. The gray ramp was used to determine each LUT and was scaled between zero and one by using equation 2. The radiometric scalars were plotted in figure 5 and a piecewise cubic hermite polynomial interpolation was fitted for each of the RGB values of the gray ramp. By the interpolation, all remaining values for the digital counts between zero and 255 of the LUT were determined. The relationship between the RGBlinear could be described by equation 3, where the DC stands for the digital count for red, green and blue.

$$\begin{gathered} Rlin = LUT(RedDC) \\ Glin = LUT(GreenDC) \\ Blin = LUT(BlueDC) \\ 0 \leq RedDC, GreenDC, BlueDC \leq 255 \end{gathered} \quad (3)$$

The forward model consisted of the combination of equation 1 and 3, where the RGB in equation 1 was determined by the three one dimensional LUTs. The backward model consisted of the combination of equation 2 and the inverse of equation 3, that resulted in three new one-dimensional LUTs to get the RGB digital counts.

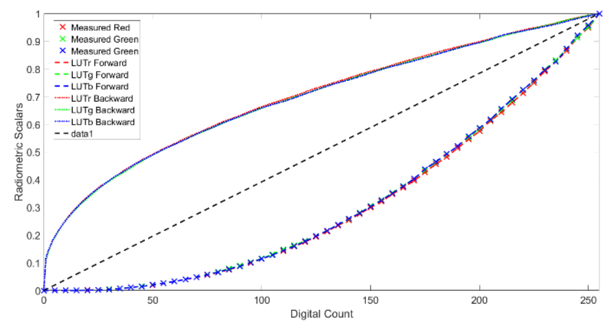

Figure 5. The projected radiometric scalars of the measured, R, G and B data points, by their digital count. Interpolated values were retrieved using the PCHIP method projected for the LUTs in the forward and backward model.

Model Performance

The performance of the model was examined for the measured and predicted CIE 1931 XYZ values of the verification grid. The CIE 1931 XYZ were first converted to CIE 1976 L*a*b* coordinates and then examined by the Euclidian distance by the CIEDE2000 formula. The CIEDE2000 color differences between the measured and predicted were reported. The average CIEDE2000 color difference was 0.5347 ΔE_{00}, the standard deviation was 1.750 ΔE_{00}. The CIEDE2000 color differences were plotted for their respective digital count for the red, green, blue and gray ramp in figure 6. The color differences showed a gradual incline at the lower digital counts and then decreased again at the higher digital counts. The color difference for the gray ramp was almost zero. The red, green and blue ramp interestingly showed a large increase in color difference around the digital count of 180.

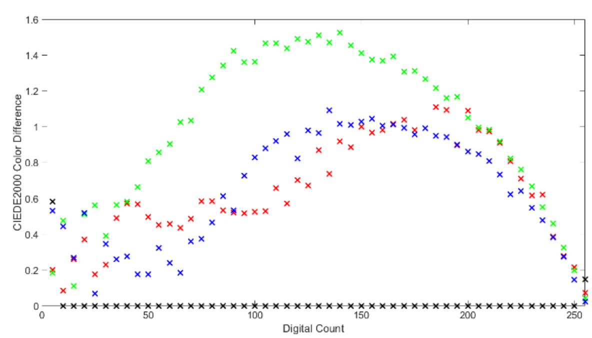

Figure 6. The CIEDE200 mean color differences for the red, green, blue and gray ramp, plotted against their relative digital count.

The average, standard deviation and the maximum CIEDE2000 color difference were reported in table 2. The average, as also observed in figure 6, was lowest at the gray ramp and the highest for the red ramp.

Table 2, CIEDE2000 mean color differences between measured and predicted red, green, blue and gray ramps.

COLOR	AVERAGE	STANDARD DEVIATION	MAXIMUM
RED RAMP	0.6435	0.2893	1.1091
GREEN RAMP	0.9939	0.4358	1.5261
BLUE RAMP	0.6383	0.3219	1.0921
GRAY RAMP	0.0143	0.5824	0.5824

To further examine this relationship of CIEDE2000 color differences for the different digital counts, the black, gray, white, dark red, red, dark green, green, dark blue and blue colors were examined, see table 3. The higher and lower digital counts indeed showed to have lower color differences, whereas the digital counts in between were relatively much higher.

Table 3, CIEDE2000 color differences between measured and predicted colors.

COLOR	DIGITAL COUNTS			CIEDE2000
	Red	Green	Blue	
BLACK	0	0	0	0.2229
GRAY	125	125	125	0.0000
WHITE	255	255	255	0.1470
DARK RED	125	0	0	0.6710
RED	255	0	0	0.0728
DARK GREEN	0	125	0	1.4745
GREEN	0	255	0	0.0417
DARK BLUE	0	0	125	0.9798
BLUE	0	0	255	0.0236

Based on the knowledge that LCDs The angular displacement of the Philips Brilliance 220B[LP] LCD was examined for four different locations for the color white. The measured versus the predicted white for the outer left of the screen had a CIEDE2000 color difference of 2.926 ΔE_{00}, the outer right of the screen had a color difference of 4.718 ΔE_{00}, the top of the screen had a color difference of 6.487 ΔE_{00}, and the bottom of the screen had a color difference of 1.613 ΔE_{00}.

Discussion

The Philips Brilliance 220B[LP] LCD used in the experiment was manufactured in July 2014 and therefore to the date of the experiment was almost five years old. Furthermore, different settings on the display could have resulted in different results. The color settings of the LCD were set at the sRGB setting, which was a very common color setting for LCDs. This color setting might have also had an influence on the results found in this study.

To further investigate this sRGB setting of the LCD, the color difference was calculated between the actual measured CIE 1931 XYZ of the verification patches and the predicted XYZ of the '*rgb2xyz*' function in Matlab. The *'rgb2xyz'* Matlab function used the standard sRGB relationship and all XYZ values were first converted to CIE 1976 L*a*b* coordinates. The CIEDE2000 average color difference was surprisingly high 4.7521 ΔE_{00}, indicating that the accuracy of the LCD setting was bad.

Conclusion

The additivity of the Philips Brilliance 220B[LP] LCD was outstanding, however, was underestimated in its promised contrast ratio. The model created by the measured data had small CIEDE2000 mean color difference at most digital counts. The CIEDE2000 color differences were even better at the lower and higher digital counts. The verification of the model showed overall decent CIEDE2000 color differences between the measured and predicted data with an average of 0.5347 ΔE_{00} and a standard deviation of 1.750 ΔE_{00}. The current model was lacking in its accuracy at different angular displacements, which could be explained by the old LCD that was used. The model could have been improved by using the nonlinear optimization for the matrix to minimize the CIEDE2000 mean color differences. The nonlinear optimization was not considered for the model created in this study. While this nonlinear optimization could have minimized the overall color difference, the nonlinear optimization would have, undesirably, increased the color difference at some digital combinations. Furthermore, the chromaticity of the primaries was inconsistent with outliers at lower light levels. The chromaticity of the primaries, even after black correction, did show a small drift for the blue primaries. These inconsistencies could also have contributed to some of the CIEDE2000 color differences found in the study. For further research, other models should be considered to best characterize the Philips Brilliance 220B[LP] LCD.

References

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