Optimal and Acceptable Color Ranges for Display Primaries

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Abstract

For many new display types the chromaticity coordinates of the primaries differ from those recommended by the EBU (European Broadcast Union). In order to identify optimal and acceptable ranges in which these primary colors may vary two studies were conducted: one related to the hue of the primaries (described in a previous paper[1]) and one related to their saturation (this paper) and the results were combined. In the first experiment of this paper, observers set the saturation of either one primary (R, G, or B) or of all three primaries at the same time, to an optimum, for 7 different (natural) images. In the second experiment, the same observers decreased the saturation until they perceived the image as "just acceptable" (defined as "having natural colors given its content"). Both experiments were conducted on an LCD monitor and repeated later with a different set of subjects on a CRT monitor. The results of the experiments show that for optimal image quality the saturation of the red and green primaries of a display must be at least 90% (with respect to the EBU standard). For the blue primary it can be somewhat lower (at least about 70%). In the acceptance task observers were the least tolerant in accepting a saturation reduction of the red primary (to 70%) and the green primary (to 60%), but they were almost twice as tolerant for the blue primary (to 35%). Ellipses were fitted to the results of the hue and saturation studies in 1976 CIE (u'v') color space such that display manufactures can easily test whether the color reproduction of their displays is optimal, acceptable, or unacceptable with respect to reproducing natural colors.

Introduction

There is a new trend to introduce color in hand-held displays. Video games, for example, already use displays with a limited number (8) of standard colors. For WAP applications and for displaying pictures, on the other hand, a much broader color palette should be available. Therefore, the question of having an acceptable color rendition or not is important.

Today's hand-held displays, however, do not meet color reproduction standards, as set by the EBU (European Broadcasting Union) or the SMTPE (Society of Motion Picture and Television Engineers), for example. This is illustrated in Figure 1, which shows the chromaticity coordinates of a PolyLED hand-held display, a reflective-LCD viewed in daylight, and the coordinates as set by the EBU. The figure shows that the chromaticity coordinates of the primary colors (Red, Green, and Blue) of both hand-held displays differ in saturation (distance from the white point) and in hue (rotation about the white point) with respect to the EBU primaries.

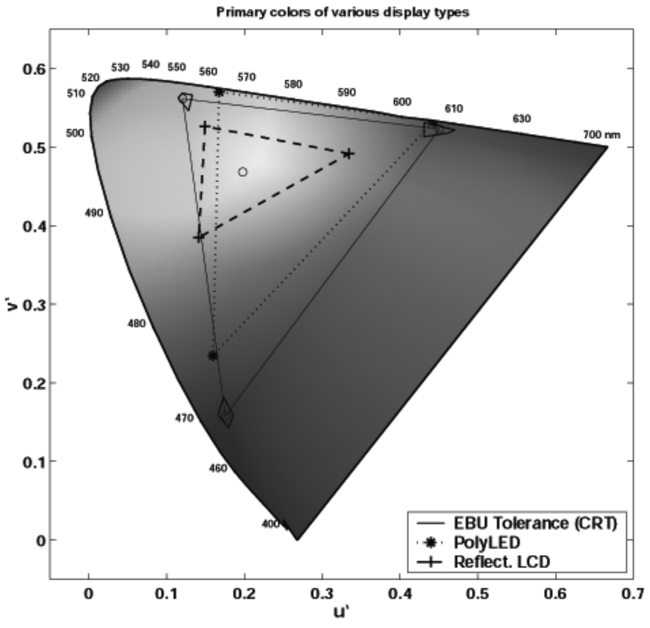

Figure 1. Chromaticity coordinates of the Red, Green, and Blue primaries as set by the EBU (European Broadcasting Union), and as measured on a typical PolyLED display and on a typical reflective LCD in daylight (D65). The circle (o) in the center of the plot is the white point (D65).

In order to provide display manufacturers with a guideline for the creation of an acceptable color reproduction of their displays, the effect of changing the primaries on the perceived color is investigated. In a previous study,[1] the optimal and acceptable hue ranges of each primary were determined. The present experiments complement this study with an investigation of the optimal and acceptable saturation ranges of each primary. The study is conducted for seven different still images of natural scenes (photographs), including images with mainly one primary color, and with a number of different colors. The study was planned initially to be conducted (only) on an LCD, because the LCD is a matrix display that is comparable to displays in mobile applications. However, its performance is already out of spec regarding the EBU standard. Therefore, the same study was repeated on a CRT, which has color rendering in close approximation to that of the EBU standard.

Method

Observers

Two groups with different observers participated in the present study. Both groups consisted of 15 observers (3 females and 12 males) in the age of 20 to 40 years. They were selected from people working at Philips Research Eindhoven. One group did the experiments on an LCD display, the other group on a CRT display. About half of the participants worked in a display-related field. Only a few of them worked on judging image quality on a regular/professional basis. All subjects had good (color) vision as was tested with an Ishihara's test for color deficiency and on the Landolt C-scale, respectively.

Images and Displays

Seven different images were used in the experiments. Three of these images mainly contain one single color, i.e. red in Portrait, green in Forest and blue in Glacier. The next three images contain mainly two colors, i.e. red and green in Veggies, blue and green in Peacock, red and blue in Tomatoes. The last image (Parrots) contains mainly four colors: red, green, blue and yellow. The images were stored on a hard disc of a PC as ppm-files (portable pixel map, i.e. uncompressed) in true color (24-bit color) and with a resolution of 375x300. The images could be displayed on demand in the center of the screen with a black background.

Two types of displays were used in the present study. In the first part of the study, an 18-inch Philips Brilliance 180P LCD monitor was used. Its brightness and contrast were set to 100% and the color point was set to 6500K. An NVIDIA graphics board with a RIVA TNT2 Model 64 graphics chip was used to drive the monitor in true color (24-bit) with a resolution of 1280x1024 (preferred resolution for this display) at 75 Hz. In the second part of the study, a 17-inch Philips Brilliance 107P CRT monitor was used. Brightness and contrast were set to 60% and 100%, respectively, and the color point was set to 6500K. The same graphics board was used as for the LCD monitor, but with a lower resolution (1024x768) in order to display the images on either display at about the same size; i.e. about 13.5 cm (5 inch) in diagonal. The choice for such small images was due to the fact that the experiment was designed for small hand-held displays.

The experiment took place in an office room with the display placed on a table 1 m from the wall. The observer sat 0.5 m in front of the screen. No light could enter from outside the room. The amount of artificial light that fell on the monitor, the wall behind the monitor and on the table was about 100, 150, and 200 Lux, respectively.

Simulation of Saturation Change

In displays, the chromaticities of the primaries cannot be fully controlled. Therefore, a chromaticity change of a primary was simulated. This was accomplished by following the next procedure:

1. Apply a gamma correction of 2.2 (the assumption is that the image was color corrected for viewing on a CRT with a gamma of 2.2).
2. Transform RGB to XYZ using the chromaticity coordinates of an ideal monitor (EBU standard), but with the chromaticity of the concerning primary reduced in saturation (i.e. translated towards the white point).
3. Transform back to RGB using the chromaticity coordinates of the actual monitor used in the experiment.
4. Clip RGB values larger than one and smaller than zero.
5. Apply an inverse gamma correction of 1/2.2 (to correct for the gamma of the actual monitor).

Panels 2-5 in Figure 2 show an example of a saturation reduction of 50% applied to the image Parrots, for each of the Red, Green, and Blue primaries and for all three primaries at the same time, respectively. The first panel shows the original image (100% saturation, EBU standard).

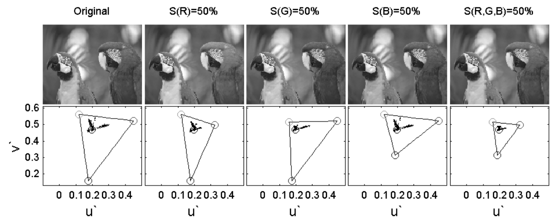

Figure 2. Example of the effect of a saturation change of a single primary (middle three columns of panels) and all three primaries (most right column of panels) on the image Parrots. The upper panels illustrate the actual color change in the image. The lower panels show the corresponding chromaticity coordinates of all pixels in the 1976 CIE (u', v') color space. The red, green, and blue circles in the lower panels represent the coordinates of the Red, Green, and Blue primaries, respectively.

Protocol

The experiments measured the optimal saturation (Task 1), and the just acceptable saturation (Task 2), for each of the three primaries (Red, Green, and Blue) separately, for all primaries at the same time. Seven different images were used. For each task, all conditions (Primary (n=4) x Image (n=7)) were presented in balanced order across subjects. Observers could adjust the saturation in steps of 5% in the range from 0% to 150%. In the case of saturations larger than 100% clipping was sometimes necessary. In general, only a limited number of pixels had to be clipped (for 150% saturation it was up to 10% of the pixels), because natural images usually have most pixels well within the borders of the display gamut.

Prior to the experiments, participants were given additional instructions to define the terms “optimal” and “just acceptable” more precisely. The optimum was said to be the image with color rendering that they preferred the most. While for “just acceptable” the images should be perceived as still natural (e.g. green grass, blue sky) given the image content (see Refs. 1 and 2 for a discussion about this aspect). To make their judgments, subjects were told that they could change the color of the image by pressing one of two buttons on the screen. They were unaware of the fact that pressing the left/right button corresponded to decreasing/increasing the saturation of one of the primaries with 5%. In some cases subjects judged a range of images as optimal. In that case they were asked to adjust to the image with lowest optimal saturation.

At the beginning of an experiment, subjects were made familiar with the task. They did three repetitions of all conditions for each task. The experiments for Task 1 and Task 2 were a least two hours apart and the experiment time for each task was about 30-40 minutes.

Results

Figure 3 shows the average saturation (Suv) in both Tasks (optimal and “just acceptable”) for the two types of displays (LCD and CRT) in the case of adjusting the Red, Green, or Blue primary or all three primaries at the same time. The error bars represent the standard error of the mean, where the mean is calculated by averaging the results across images and subjects. We collapsed the results across images, because for different images the data were about equal (not shown). When the 95% confidence intervals of two means do not overlap the difference between the two means is said to be statistically significant.

The figure shows that task 1 (i.e. the left two bars for each primary in Figure 3) yields results that are statistically significantly different from those of task 2 (i.e. the right two bars), this implies that the acceptable saturation is about 50% lower than the optimal saturation. Figure 3 also illustrates that not all primaries have the same results; the optimal and acceptable saturations for the Blue primary are statistically significantly lower than for the others.

As expected the results for changing all primaries at the same time is equal or higher than when changing only one of the primaries. It is surprising that for the blue primary the optimal and acceptable saturations are much lower than for the other primaries, because saturation changes are equally well visible for all primaries. Apparently, observers are more tolerant to accept a decreased saturation for the blue primary than for the other two primaries.

With respect to the interpretation of the results of Task 1 (optimum) it should be noted that observers were asked to adjust the saturation of the image to the *lowest* optimal saturation. This means that optimal saturation in this experiment is the lower limit for the optimum (e.g. higher saturations can still be optimal, but lower saturations are, for sure, not optimal anymore).

The results also indicate a significant interaction between Task and Type of monitor (LCD or CRT). For Task 2 (acceptance task) the results for different types of monitors are equal, but in Task 1 (optimum task) observers prefer a higher saturation on the CRT than on the LCD. This can probably be explained by the fact that the CRT has a somewhat larger color gamut than the LCD, i.e. less clipping occurred. In the case of Task 2 the displays can show the same colors. Apparently, other differences between the two displays were not relevant for determining the acceptable saturation ranges.

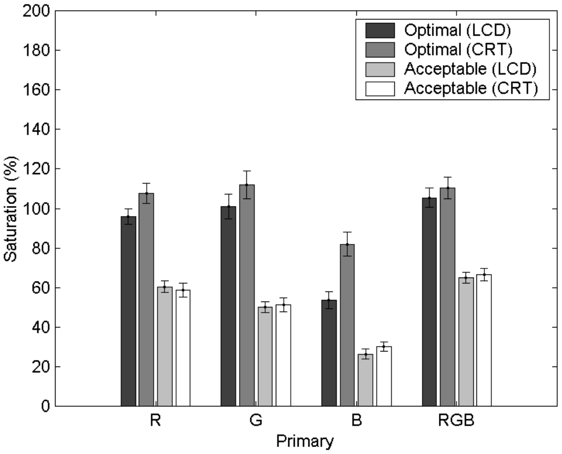

Figure 3. Plot of the optimal (Task 1) and “just acceptable” (Task 2) saturation (Suv) averaged across images for the R(ed), G(reen), B(lue) primaries separately and four all three primaries (RGB) simultaneously, and for two types of display (LCD and CRT). The error bars represent the 95% confidence intervals of the mean.

Discussion and Conclusions

The results of the saturation experiments suggest that for optimal image quality the saturation of the red and green primaries of a display must be at least 90%. For the blue primary it can be somewhat lower (at least about 70%). In the acceptance task (Task 2), observers were the least tolerant in accepting a saturation reduction of the red primary (to 70%) and the green primary (to 60%), but they were almost twice as tolerant for the blue primary (to 35%). The results of the acceptance task were about equal for the LCD and the CRT monitor, because the simulated colors were the same and apparently differences between the two monitors were not relevant in this experiment. In the optimum task (Task 1), however, the results for the LCD were somewhat lower than for the CRT. This is probably due to a ceiling effect: the saturation of the LCD primaries is lower than that of the CRT.

Ellipses were fitted to the results of the hue[1] and the saturation studies (this paper) such that display manufactures can easily test whether the color reproduction of their displays is optimal, acceptable, or unacceptable with respect to reproducing natural colors. Figure 4 shows these ellipses in the 1976 CIE (u'v') color space for colors that are optimal for 50% of the population (thin lines), acceptable to 75% of the population (dashed lines), or acceptable to 50% of the population (dotted lines), respectively.

As an example, the color points of a typical desktop LCD monitor and a hand-held reflective display, denoted with an asterisk (*) and a plus (+), respectively, are plotted on top of Figure 4. The results predict that for the LCD monitor the green primary is nearly optimal, the red primary gives color artifacts that are acceptable to more than 75% of the population, but the blue primary introduces color artifacts that are acceptable to only about 60% of the population. For the reflective display the results are much worse. The green primary is acceptable to 75% of the population, but the red and blue primaries give rise to color artifacts that are acceptable to less than 50% of the population.

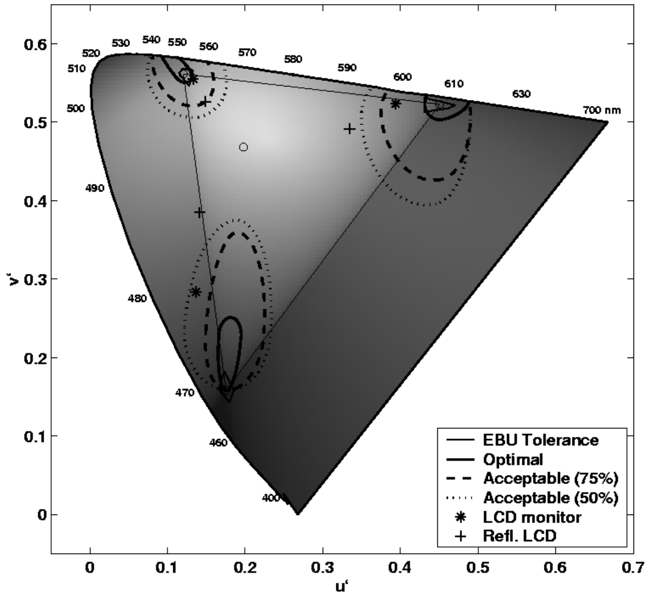

Figure 4. Optimal and acceptable chromaticity ranges of display primaries and the tolerance as defined by the EBU. If a primary is on the thick dotted ellipse, 75% of the subjects will say it is acceptable, on the thin dotted ellipse, only 50% of the subjects will say it is acceptable.

Since many of today's hand-held displays have a color gamut similar to that of the typical reflective display shown in Figure 4 it can be concluded that there is quite some room for improvement regarding the color rendering of reflective displays.

As a final remark, it should be noted that the present study was carried out on an (18-inch) transmissive LCD and on a (17-inch) CRT displaying small (5-inch diagonal) images. The results, though, can most probably be expanded to reflective or tansflective LCDs and other technologies that are under evaluation for small hand-held applications, such as polyLED, organic LED, etc. In all these cases the results from the present study give display manufactures a guideline to test whether the color reproduction of their display is optimal, acceptable or unacceptable.

Acknowledgements

We would like to acknowledge Mark Mertens, Elena Vicario, Ingrid Vogels and Geert Depovere for their constructive comments on a preliminary version of this paper and Jan Engel for the statistical discussions.

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Biography

Erno Langendijk received his M.S. degree in Physics from Nijmegen University (the Netherlands) in 1994 and a Ph.D. in Physics from Delft University (the Netherlands) in 2002. During his Ph.D. he worked at TNO Human Factors (Soesterberg, the Netherlands) and at the University of Wisconsin (US). Since 2000 he has worked at Philips Research Eindhoven (Nat.Lab.) in the Netherlands. His work has primarily focused on the visual perception of display systems.

Ingrid Heynderickx received from the University of Antwerp (Belgium) her M.S. degree in Physics in 1983 and her Ph.D. degree in Physics in 1986. In 1987, she joined Philips as a research scientist, and meanwhile worked in different areas of research. Since 1999, she is a principal scientist, heading the project on Visual Perception of Display Systems.