Appearance-based Primary Design for Displays

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Abstract

Emerging wide-gamut displays, enabled mainly by LED-based LCDs, are capable of displaying a wider range of chromaticities than more typical gamuts, such as sRGB. Two types of LED-based LCD display products have been produced and marketed. RGB-LED-based LCD displays can potentially deliver more saturated primaries with use of the relatively narrow spectral width LEDs, while white-LED-based LCD displays might provide high brightness and contrast but less saturated images by using high efficiency LEDs in combination with the LCD-panel RGB filters. This results in a potential tradeoff between saturation and brightness. This paper uses color appearance concepts to examine two possible display-primary designs to address the question whether the decrease in saturation of the display can be offset by the increased luminance resulting in similar, or even improved colorfulness. The two display primary designs were mathematically simulated for visual assessment on an RGB-LED-based LCD display: one by adding a white backlight and one by adding a white channel on the LCD. The experimental results indicate that perceived colorfulness can be maintained, or slightly improved, through small additions of less saturated, but higher luminance primaries to a wide gamut display. However, more significant reductions in primary saturation cannot be overcome by increased luminance.

Introduction

Current LCD display technologies often consider the trade-off between color gamut and brightness. Higher luminance displays are more colorful, and lower luminance wide gamut displays are more saturated. Figure 1 illustrates one possible example of the gamut tradeoff between white-LED-based LCD displays with a higher luminance level and RGB-LED-based LCD displays with greater saturation.[1] The color gamut of the LCD display is determined by the emission spectrum of the backlight and the transmission spectra of the LCD panel color filters (Fig. 2). While a white-LED system can have a higher light efficiency than those of other colored LEDs, the emission spectrum is not always ideal since white LEDs are often composed of a blue LED with an added yellow phosphor to create a white impression. These typical emission spectra have two peaks, one of blue wavelengths and the other in the yellow wavelength range, which results in extended yellow and blue regions in the CIELAB gamut shown in Fig. 1. This type of backlight display limits the chromaticity gamut to slightly wider than sRGB if power consumption is limited and high luminance is desired. RGB LED backlight technology allows for a wider chromaticity gamut to reproduce previously impossible colors, potentially covering most standards like Adobe RGB, NTSC, and DCI. The more saturated primaries are defined by the narrow spectral bands of the LEDs in addition to the RGB filters in the LCD display panel.

In the current display market, typical consumer RGB-LED-based LCD displays reach about 250cd/m^2, and professional RGB-LED-based LCD displays can achieve up to 600cd/m^2[2] due to emission efficiency and thermal issues. These RGB backlit displays could achieve higher luminances with the addition of white LEDs or with a full white channel[3-5] on the LCD. However, adding such elements would cause a change in saturation and colorfulness.

Assume a color image is viewed under various levels of illumination. It is recognized that the colorfulness of the various image elements is quite low under a low level of illumination, while the colorfulness of the image elements is significantly higher at higher luminance levels.[6] Hunt[7] found this effect in his study of the perception of color across changes in light and dark adaptation: a color stimulus with low saturation at 10000cd/m^2 is required to match another color stimulus with high saturation at 1 cd/m^2. In other words, the perceived colorfulness of a given color stimulus increases with luminance level. If this is considered in terms of a chromaticity diagram, the perceived chromaticity shifts toward the spectrum locus as the luminance levels increase, or shifts toward the adapted white as luminance levels decrease. Similar to the increase in chromatic contrast (colorfulness) with luminance referred to as the Hunt effect, Stevens[8] found that brightness (or lightness) contrast increases with increasing luminance. Therefore, is it possible that more colorfulness and contrast can be achieved by increasing the luminance, even at the expense of saturation?

This paper examines the tradeoff between luminance and saturation through the psychophysical scaling of perceived colorfulness for various sets of simulated display primaries. Ten pictorial images were test stimuli evaluated across a variety of simulated displays that either included fractional additional white backlight or fractional additional white primary. Subsequently, two paired comparison psychophysical experiments and computational colorimetric analysis were performed to investigate the possibility of an optimal level of added white and the relationship between perceived colorfulness and the prediction.

LCD Colorimetric Characterization

LCD colorimetric characterization based on the Day et. al model[9] was performed to provide accurate mapping between LCD digital counts and absolute tristimulus values. A 23'' HP DreamColor LP2480zx Professional Monitor with a resolution of 1920x1200 addressable pixels and driven by a 13'' 2.53 GHz Intel Core 2 Duo MacBook Pro was characterized in a dark room and used in the experiments to simulate displays of various chromaticity gamuts and luminance levels.

Before characterizing the display, all color management software was disabled and the display was set to its native white point and native gamma. The luminance of the display was set to

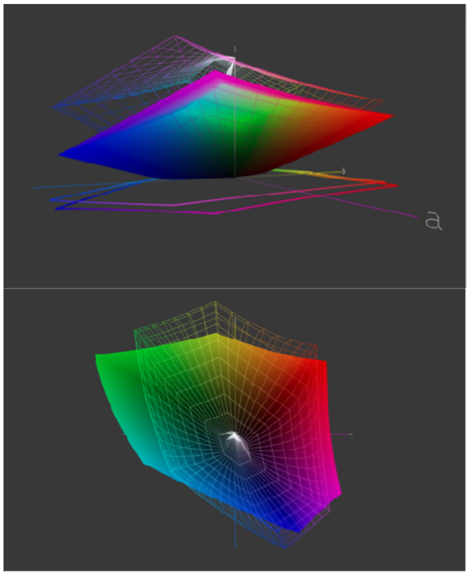

Figure 1*. RGB (RGB (solid) vs. White (wireframe) LED-based LCD display with the same power consumption (Top: Side view; Bottom: Top view. The computed ratio of the maximum luminance output between White and RGB-LED-based LCD display was around 2.5. The gamuts were rendered in CIELAB color space using the measured values in Table 2)*

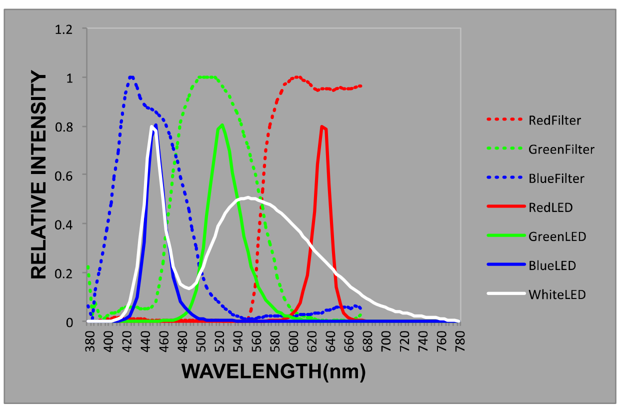

Figure 2. *Spectral distributions of RGBW LED and RGB LCD filters (Measurements from a typical white-LED-based and a typical RGB-LED-based LCD display)*

the maximum output of 250cd/m^2. The display setting for color space was User FULL. The display was warmed up for at least 30 minutes for the best color performance, which is recommended by HP. Three sets of input digital counts were generated for the characterization. The first one was composed of R, G, B and neutral color ramps organized from 0 to 255 with an increment of 25 in digital counts. Another two sets of ramps were 5x5x5 factorial combinations (0-255 and 0-20). Based on the input of digital counts of RGB channels, an automated Matlab routine was developed to display the test patches and complete the measurements. A total of 295 ramps were displayed in random order. A LMT Colorimeter C1210 was used to measure the irradiance of the color patch on the display.

After obtaining the optimized model, another three groups of ramps were measured under the same conditions as above to verify the optimized model. The first group was composed of luminance series ramps, all of which were equally spaced in luminance between white point and black level of the display. Another two groups were R/G and Y/B isoluminant ramps. The measured tristimulus values of the three sets of ramps were then compared to those of the target to evaluate the optimized model.

Table 1. Summary of colorimetric characterization results for the display

	Mean ΔE00	Max ΔE00	90th percentile ΔE00
Luminance series	0.82	1.67	1.59
R/G series	1.09	5.37	0.84
Y/B series	0.39	0.58	0.54

The average CIEDE2000 color difference were 0.82, 1.09, and 0.39 for the luminance series, R/G series, and Y/B series respectively as shown in Table 1. Note that in the R/G series the maximum CIEDE2000 color difference was 5.37, but the 90th percentile color difference was 0.84, which indicated that one target tristimulus value might have been out of the display gamut. The relatively small average color difference for the three target datasets provides evidence of an acceptable display characterization model.

Simulation Algorithm

Test image

A pubic-domain image database from The HDR Photographic Survey[10] was used as a source of experimental images. Ten locally-rendered versions of the scene data were selected to cover a variety of dynamic range and color gamuts, as well to provide different scene content (Night, Day, People, Nature).

Figure 3. *Ten test images from The HDR Photographic Survey*

Image Simulation 1

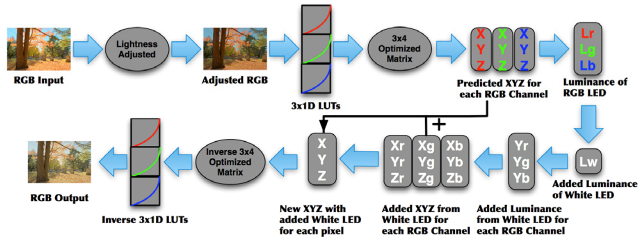

Figure 4*. A flowchart of image preparation by adding desaturated primaries (or white light to the RGB backlight)*

The ten original images were coded as 8-bit RGB JPEG. To investigate the experimental question, two different image processing algorithms were used for the display simulation: adding percent of white point and adding desaturated primaries to simulate white light added to the backlight. Fig. 4-5 illustrate the two different flowcharts for the image preparation.

In order to simulate the colorfulness effect in a more practical way, a pilot measurement was done using a typical bare display panel and RGB as well as a white (W) LEDs. The luminance and chromaticities of the RGB and W LEDs through RGB LCD filters were measured three times and the averaged results are listed in Table 2.

Table 2. Luminous transmittance and chromaticities of LED through LCD filters

RGBW LED through RGB LCD Filter	Chromaticity Coordinates		Luminous Transmittance
	x	y	
RedLED through Red Filter	0.6968	0.3031	0.0280
GreenLED through Green Filter	0.1765	0.7366	0.0242
BlueLED through Blue Filter	0.1497	0.0278	0.0143
WhiteLED through Red Filter	0.6369	0.3493	0.0056
WhiteLED through Green Filter	0.3203	0.5984	0.0166
WhiteLED through Blue Filter	0.1540	0.0924	0.0015

During the measurements, each of the RGB LCD channels was turned full on (fully transmitting) while the other two were off (display minimum). For example, the luminance transmittance of red LED through the red filter on LCD was computed as a ratio of the luminance of red LED to red filter with a digital count of 255 and the luminance of the red LED. The following calculation for the image simulation was based on these measured practical data.

The lightness of each RGB test image was adjusted by -25 in Adobe Photoshop CS3 to ensure that all the data were well within the display gamut and to allow headroom for increasing luminance in the following simulations. The adjusted RGB images were then converted into the absolute tristimulus values for each red, green, blue channel of LCD using a 3x1 LUT and a 3x4 optimized matrix as described in display characterization section. The luminance of each RGB LED backlight was calculated using the transmitted luminance and the filter transmittance for each RGB channel on the simulated display. For instance, the Eq. (1) shows the calculation of luminance of red LED backlight.

$$\begin{cases} Y_{R,R=255} = L_R \times T_{R,R=255} \\ Y_{R,R=DC} = L_R \times T_{R,R=DC} \end{cases} \Rightarrow \frac{Y_{R,R=255}}{Y_{R,R=DC}} = \frac{T_{R,R=255}}{T_{R,R=DC}} \tag{1}$$

where $Y_{R,R=DC}$ represents the luminance of red LED backlight through LCD red filter at a certain digital count DC, L_R is the luminance of red backlight, and $T_{R,R=DC}$ is the transmittance of red LED backlight through the red filter at a certain digital count DC.

$T_{R,R=DC}$ can be derived from Eq. (1).

$$T_{R,R=DC} = \frac{Y_{R,R=DC}}{Y_{R,R=255}} T_{R,R=255} \tag{2}$$

Therefore, the luminance of red LED backlight was calculated by combing Eq. (1) with Eq. (2), as shown below.

$$L_R = \frac{Y_{R,R=DC}}{T_{R,R=DC}} \tag{3}$$

$$L_R = \frac{Y_{R,R=255}}{T_{R,R=255}} \tag{4}$$

Similarly, L_G and $L_B$were calculated by following the above calculations.

In order to quantify the added white backlight, the percent white was defined as a luminance ratio between the luminance produced by the simulated white LED and the total luminance of the RGBW combination. The percentage of white LED was computed using the Eq. (5).

$$\text{Percent}_W = \frac{L_W}{L_W + L_R + L_G + L_B} \tag{5}$$

The luminance of the added white LED was calculated as:

$$L_W = \frac{(L_R + L_G + L_B) \times \text{Percent}_W}{(1 - \text{Percent}_W)} \tag{6}$$

Similar to Eq. (2), the transmittance of white LED through the LCD red filter at a certain digital count DC was computed as shown in Eq. (7).

$$T_{W,R=DC} = \frac{Y_{R,R=DC}}{Y_{R,R=255}} T_{W,R=255} \tag{7}$$

The luminance of white LED through LCD red filter was represented as:

$$Y_{W,R=DC} = L_W \times T_{W,R=DC} \tag{8}$$

Therefore, $Y_{W,R=DC}$ was calculated using Eq. (7-8). $Y_{W,G=DC}$ and $Y_{W,B=DC}$ were also computed by following the similar calculation as shown in Eq. (9).

$$\begin{cases} Y_{W,R=DC} = L_W T_{W,R=255} \dfrac{Y_{R,R=DC}}{Y_{R,R=255}} \\ Y_{W,G=DC} = L_W T_{W,G=255} \dfrac{Y_{G,G=DC}}{Y_{G,G=255}} \\ Y_{W,B=DC} = L_W T_{W,B=255} \dfrac{Y_{B,B=DC}}{Y_{B,B=255}} \end{cases} \tag{9}$$

Equation (10) shows the calculation of the absolute tristimulus value of the white LED through red LCD filter using the chromaticities in Table 2. Similarly, one can calculate the absolute tristimulus value of the white LED through green and blue LCD filters.

$$\begin{cases} \dfrac{Y_{W,R=DC}}{y_{W,R=255}} = \dfrac{X_{W,R=DC}}{x_{W,R=255}} \\ \dfrac{Y_{W,R=DC}}{y_{W,R=255}} = \dfrac{Z_{W,R=DC}}{1 - x_{W,R=255} - y_{W,R=255}} \end{cases} \tag{10}$$

Thus, the absolute tristimulus value of each pixel after adding white LED backlight was computed in Eq. (11). The assumption here is that cross-terms are negligible (i.e. green LEDs through blue LCD filter, and blue LEDs through green filter, etc.).

$$\begin{bmatrix} X_{RGBW,RGB=DC} \\ Y_{RGBW,RGB=DC} \\ Z_{RGBW,RGB=DC} \end{bmatrix} = \begin{bmatrix} X_{W,R=DC} \\ Y_{W,R=DC} \\ Z_{W,R=DC} \end{bmatrix} + \begin{bmatrix} X_{W,G=DC} \\ Y_{W,G=DC} \\ Z_{W,G=DC} \end{bmatrix} + \begin{bmatrix} X_{W,B=DC} \\ Y_{W,B=DC} \\ Z_{W,B=DC} \end{bmatrix} + \begin{bmatrix} X_{R,R=DC} \\ Y_{R,R=DC} \\ Z_{R,R=DC} \end{bmatrix} + \begin{bmatrix} X_{G,G=DC} \\ Y_{G,G=DC} \\ Z_{G,G=DC} \end{bmatrix} + \begin{bmatrix} X_{B,B=DC} \\ Y_{B,B=DC} \\ Z_{B,B=DC} \end{bmatrix} \tag{11}$$

Finally, the absolute tristimulus values of the image on a given simulated display were transformed to the RGB output image using the inverse model of the HP DreamColor display used for visual assessments.

Image Simulation 2

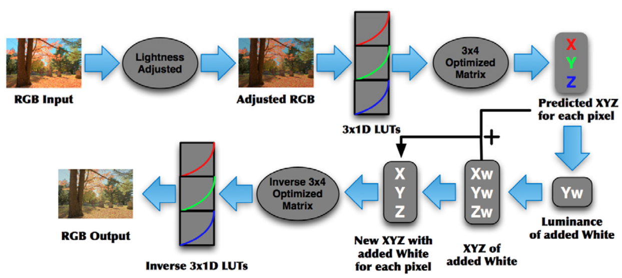

Figure 5. *A flowchart of image preparation by adding white subpixels*

The second simulation was to add different amounts of the tristimulus values of the display white point into each pixel depending on the digital count. This would be similar to adding a desaturating white channel to an RGB LCD display to increase its luminance as opposed to adding a white backlight. The predicted absolute tristimulus value of each pixel was obtained using the same process as the first simulation. Eq. (12) shows how to calculate the luminance value of the added white Y_W from the defined percent white Percent_W and the luminance value Y_{RGB} of the original image at each pixel.

$$\text{Percent}_W = \frac{Y_W}{Y_W + Y_{RGB}} \tag{12}$$

The absolute tristimulus values of the added white $X_W Y_W Z_W$ were computed using Y_W and the chromaticities of the display white point, shown in Eq. (13).

$$\begin{cases} \dfrac{Y_W}{y_{W,R=255}} = \dfrac{X_W}{x_{W,R=255}} \\ \dfrac{Y_W}{y_{W,R=255}} = \dfrac{Z_W}{1 - x_{W,R=255} - y_{W,R=255}} \end{cases} \tag{13}$$

The new tristimulus values XYZ_{RGBW} are a sum of the tristimulus values of original image and the tristimulus values of added white.

$$\begin{bmatrix} X_{RGBW} \\ Y_{RGBW} \\ Z_{RGBW} \end{bmatrix} = \begin{bmatrix} X_{RGB} \\ Y_{RGB} \\ Z_{RGB} \end{bmatrix} + \begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix} \tag{14}$$

Fig. 6 illustrates this effect by comparing the generated images from the two image simulations. The defined percentages of white in the comparison were 0 to 90% with an interval of 10%.

Figure 6. *Comparison between the two simulations (The defined percent white here is from 0 to 90% with an interval of 10%; the test image is Cemetery Tree.)*

Clearly, the simulation adding the white subpixel desaturated the images significantly. One hundred percent added white would result in a pure white image. The calculation of the percent white done at the LCD backlight level is likely a more practical simulation given a goal of increased colorfulness. It should be noted that the images with percentage 60%~90% appear to be washed out in Fig. 6(a). That is due the limited dynamic range of the LCD display, which could not represent the images with higher tristimulus values (unless the original image was produced with a very low luminance level). The analysis of image histogram indicated that the images with less than 50% added white were within the display gamut, and the image with 50% added white was slightly bit clipped during gamut mapping, which also indicated that a high dynamic range display[11] would allow for a more far reaching simulation. However, it is unlikely that such high levels of added white would be desired in a display, so limiting the simulated range to 50% is appropriate.

The next step is to consider how much white should be added into the primaries of the display for a given application. Beyond the physical limitations of the LCD dynamic range, a pilot psychophysical experiment was also conducted to select a meaningful range of percentages of the added white for the final experiments. In the end, six different percentages of white (0, 10%, 20%, 30%, 40%, 50%) were selected for the simulations.

Psychophysics

A paired comparison paradigm was used to quantify the colorfulness of the images on the LCD display. The technique was first quantitatively described by Thurstone[12] in 1927 to find out the best option among a range of the options. In other words, each option is compared with every other option to determine the preferred option in each case. The frequency results are tallied and converted to z-scores to find the overall preference with the highest interval scale value. The scaled percepts (in this case colorfulness) of the stimuli are normally distributed (by definition) on the resulting interval scales and thus, with the assumption of the perceptual magnitudes normally distributed on the true perceptual scale, the analysis produces the desired perceptual scale. Since the normal distribution is utilized, the evaluation of statistical significance of differences between stimuli is facilitated.

Two psychophysical experiments were conducted based on the two simulation algorithms. The observers were seated 100cm from the front of the display in a dark room. A pair of images was displayed on the HP DreamColor display with a gray background (20% of white point) as shown in Fig. 7. Each pair was presented normal to the observer's resting line of sight. For each of the ten scenes, six images were generated by adding different percent white, from 0% to 50% with an increment of 10%. A total number of 15 pairs, (6x5)/2=15, were generated for each scene. All of the images and pairs were shown to the observer in a random order and the observer was asked to choose which one appears more colorful in each pair. Thirty color-normal observers, 19 males and 11 females, with an age range of 23-66 years, participated in the study. Of all the participants, 15 observers are experienced in color science related research area and the others had minimal experience in making color appearance judgments.

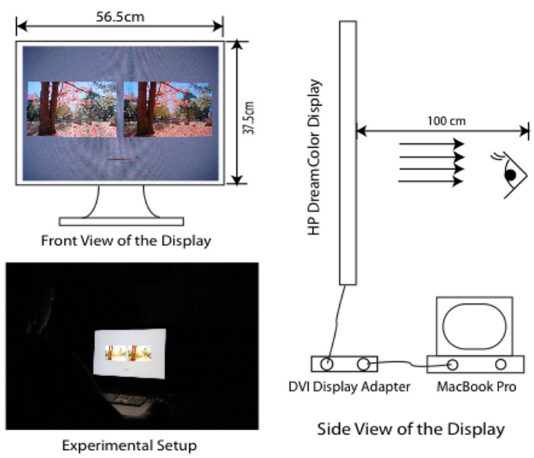

Figure 7. Image simulation experimental setup. Top left: Image layout on the LCD. Bottom: Paired comparison experiment being doing by an observer. Right: Arrangement of LCD display and observer.

Results and Discussions

Thurston's Law of Comparative Judgments, Case V,[12] was used to compute the interval scales of perceived image colorfulness from the observers' judgments.

Experiment based on adding the white backlight

The results from the images with 50% white were not analyzed, because part of the image information was clipped. The mean perceived colorfulness corresponding to different percent white averages across images is summarized in Fig. 8. A 95% confidence limit was also computed for each percent white.[13] The images with 40% percent white were most colorful, but a further investigation on the percent white was desired to confirm this result.

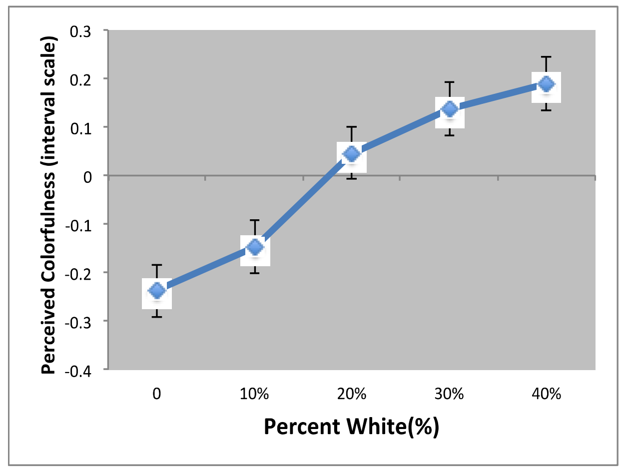

Figure 8. Perceived colorfulness (interval scale) and the corresponding added percent white for overall images

In order to analyze the colorfulness effect for the different image content, the scaled colorfulness for each percent white for each image is illustrated in Fig. 9. The results from Image 7 (M3 Middle Pond) and Image 8 (Paul Bunyan) were most significantly consistent with that in Fig. 8. Overall, the images with 30% or 40% percent white were deemed most colorful for each scene content. Due to the significant individual variation in perceived colorfulness, the differences between different percent white were not always statistically significant.

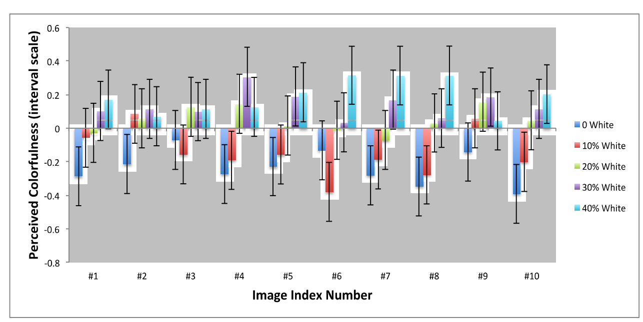

Figure 9. Perceived colorfulness (interval scale) and the corresponding added percent white for each image

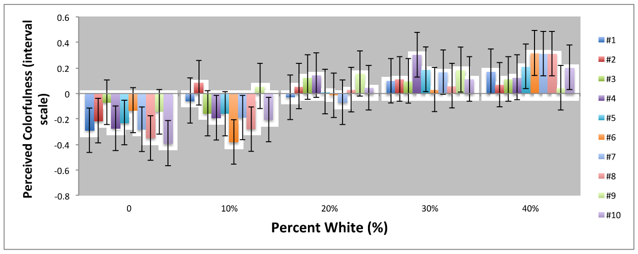

Figure 10*. Perceived colorfulness (interval scale) and the corresponding image for each percent white*

To understand the variation of perceived colorfulness with the same percent white for each image, the preference for the different images at the same percent white is illustrated in Fig. 10. The results in Fig. 9-10 show that the perceived colorfulness is independent of image content suggesting that the colorfulness effect applies across the gamut.

In order to further examine, and potentially predict, the results from the psychophysical experiment, several color attributes were predicted using CIELAB and CIECAM02.[14] Fig. 11 summarizes the calculated the luminance level, CIELAB chroma, saturation, CIECAM02 colorfulness across percent white levels. All color attributes were computed pixel by pixel for each image, and the averaged value were selected over the pixels and the images. In the top left plot of Fig. 11, it can be seen that the maximum luminance level DreamColor can achieve is around 235 cd/m2. CIELAB chroma decreased with added percent white except at 40% perhaps due to gamut clipping at that level. The prediction of CIELAB saturation (modeled as the ratio of C* to L*) decreased with the added percent white nearly linearly. CIECAM02 colorfulness basically increased with the added percent white, but the increase in predicted colorfulness is not large, as was also seen in the visual results.

To investigate the correlation between the perception and the prediction, Fig. 12 visualizes the perceived colorfulness from psychophysics and the predicted chroma and colorfulness. It appears that there is an approximate linear relation between the perceived colorfulness and the predicted chroma. The statistical analysis shows a good linear relation with an r square of 0.91 by excluding 40% percent white data. However CIELAB chroma is

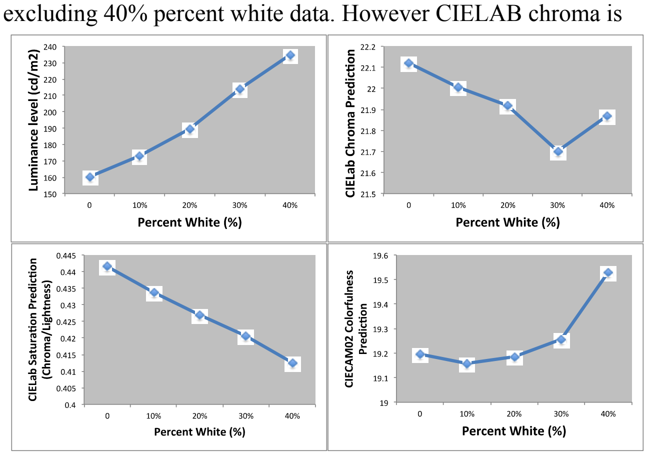

Figure 11*. Luminance/Chroma/Saturation/Colorfulness vs. Percent white for overall images*

inversely proportional with perceived colorfulness since it does not account of the increased luminance of the images. On the other hand, there is no statistically significant relation between the perceived colorfulness and CIECAM02 colorfulness although the CIECAM02 predictions do increase with increased perceived colorfulness over the range of images investigated.

Overall, the small range of variation in the CIELAB and CIECAM02 values should be noted. This indicates that a display can indeed be increased in perceived colorfulness by making it brighter, as long as the corresponding desaturation is quite small. The second experiment examines what happens with larger desaturation levels.

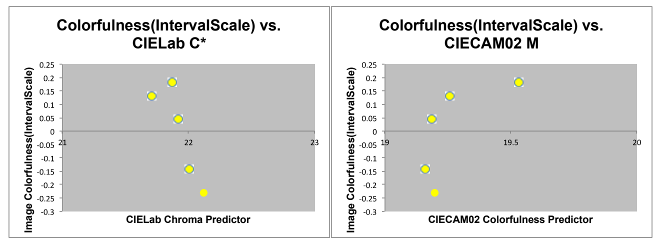

Figure 12. *Perceived Colorfulness vs. CIECAM02 Colorfulness M/CIELAB Chroma C**

Experiment based on adding the white channel

In order to compare with the first simulation, another psychophysical experiment was performed to examine greater levels of desaturation by adding a simulated white channel instead of a simulated white backlight. Fig. 13 illustrates the mean perceived colorfulness corresponding to different percent white averaged across all images. For this simulation, the perceived colorfulness decreased with added percent white and the range of the changes were significantly larger (therefore the 95% confidence intervals are also relatively smaller). The differences between different percent white were statistically significant, and the preferred choice was more consistent in this experiment. Accordingly, the primary design with adding white channel is not appropriate to increase luminance for wide gamut displays while the one with added white backlight might provide a small practical benefit, and perhaps the benefit would be greater with a higher

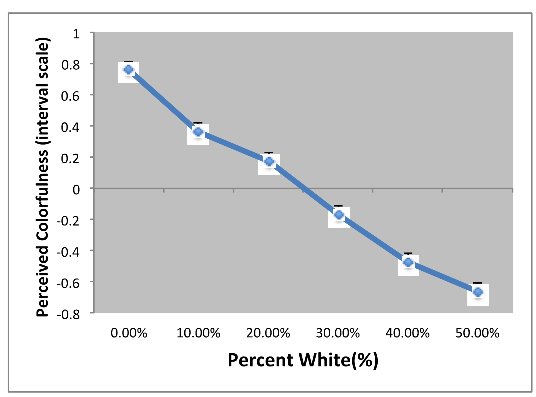

Figure 13. *Perceived colorfulness (interval scale) and the corresponding added percent white for overall images*

luminance display. Furthermore, Fig. 14 correlates the perceived colorfulness from psychophysics to the predicted chroma and colorfulness. Both of CIELAB chroma and CIECAM02 colorfulness were good predicators in modeling the decrease in perceived colorfulness with added percent white. Note that the range of changes in these predictors is significantly larger than in the first experiments.

As a potential future study, it would be useful and necessary to verify the above results on a high dynamic range display to allow for a wider range of simulated luminance levels and changes.

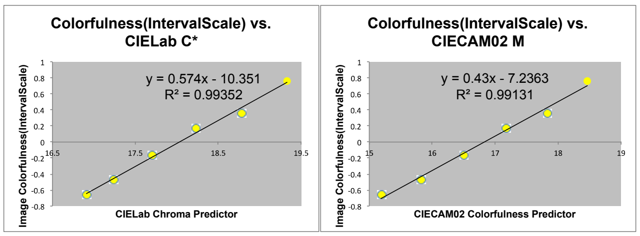

Figure 14. *Perceived Colorfulness vs. CIECAM02 Colorfulness M/CIELAB Chroma C**

Conclusions

Two simulations of adding white to display primaries were explored to investigate color appearance changes with corresponding changes in luminance and chromaticity gamut. This is of interest since there is a perceptual interaction between luminance, chromaticity, and colorfulness that allows for the possibility that displays with smaller chromaticity gamuts, but higher luminance levels, might have larger perceived colorfulness gamuts. These tradeoffs were described and explored psychophysically through two paired comparison experiments. The results indicated that a design of RGBW-LED-based LCD display might be an appropriate approach in preserving or improving perceived colorfulness with the increased luminance and that the CIECAM02 colorfulness predictor is capable of predicting the observed trends for both small and large changes in the saturation of display primaries. Ultimately, the goal is to be able to use color appearance predictors to evaluate potential display primary configurations and the tradeoffs between chromaticity gamuts and appearance gamuts. Future work should include this investigation on a high dynamic range display to determine the value of adding white to the backlight in real imagery.

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