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Analysis of White Point and Phosphor Set Differences of CRT Displays

There are a variety of CRT phosphor sets used to display color information. In addition, the white point, achieved when the red, green, and blue phosphors are excited by beam currents corresponding to the maximum digital count for each primary, is not standardized. Displaying a file containing RGB digital values on unlike monitors, with different phosphors andlor white points, would produce different colors. Computer stimulations were conducted to compute the colors for CRTs with di#erent phosphor sets and constant white points and for d@erent white points with constantphosphor sets. Test results demonstrated that CIELAB color differences were larger when the phosphor sets were different. Smaller color dt#erences resulted from dtfferences in white point, assuming a constant phosphor set. Overall average color differences were reasonably represented by a linear relationship to the average color difference between the phosphors. A linear relation was also found between the average color differences and the color differences between the white points. It was concluded that phosphor differences contribute more to color diflerences, and therefore standardization efforts should focus first on adopting a color phosphor set, and secondly on a white point.

Introduction

Color is becoming more available in the office environment, particularly in the area of computer generated information. As it proliferates, there is an increasing need to put it in hard copy form. In most cases it is desirable to have the hard copy version appear exactly like the color image on the CRT screen; so called WYSIWYG (what you see is what you get) color. To attain this result we require an unambiguous description of color on the CRT. The CIE system of calorimetry provides for this description in terms of CIE tristimulus values X, Y, Z.

For calorimetry to be useful, there are additional quantities that need to be specified. First we need to know the "white point"; that is the tristimulus values of the white on the screen when the luminance output of the three phosphors are at their maximum values. The other requirement is the tristimulus values of the primaries; the red, green, and blue phosphors. When the above quantities are known, the CIE tristimulus values X, Y, Z can readily be determined from the proportionate luminances or relative amounts of the CRT phosphor primaries. These relative amounts can also be thought of as the RGB digital values driving the CRT.

In practice, however, color images are stored in files according to their RGB triplets. The user generally does not know the phosphor set of the display used to generate the image files, or the white point of the display. Since there are no standards in the computer graphics environment regarding white point and phosphor set, the RGB triplets describing the color at each pixel location are an ambiguous description of the original color. If the states of two CRT displays are different, i.e., the "original" display had a different white point and/or phosphor set than the one presently being used, a displayed color will have a color error with respect to the "original." Therefore, the purpose of this investigation was to quantify this color error, or color difference, for a variety of phosphor sets and white point settings.

Theory

The CRT has a set of red, green, and blue phosphors which can be considered three primaries in a calorimetry sense.'

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Each of these phosphors has a given set of chromaticity coordinates, which can be directly measured with a spectroradiometer or may be provided by the CRT manufacturer.

$$\begin{aligned} &\text{Red Phosphor: } x_R, y_R, z_R \\ &\text{Green Phosphor: } x_G, y_G, z_G \\ &\text{Blue Phosphor: } x_B, y_B, z_B \end{aligned} \quad (1)$$

In turn, the RGB phosphors also have an associated set of tristimulus values:

Red Phosphor:

$$XR = CR*x_R \quad YR = CR*y_R \quad ZR = CR*z_R$$

Green Phosphor: (2)

$$XG = CG*x_G \quad YG = CG*y_G \quad ZG = CG*z_G$$

Blue Phosphor:

$$XB = CB*x_B \quad YB = CB*y_B \quad ZB = CB*z_B$$

where the C values are scaling factors equal to the sum of the tristimulus value of the phosphor (e.g., CG = XG + YG + ZG).

The tristimulus values of the display color can be written in terms of the phosphor chromaticity coordinates and the C factors as follows:

$$\begin{aligned} X &= CRx_R*R + CGx_G*G + CBx_B*B \\ Y &= CRy_R*R + CGy_G*G + CBy_B*B \\ Z &= CRz_R*R + CGz_G*G + CBz_B*B \end{aligned} \quad (3)$$

Where the RGBs are the amounts of the phosphor primaries, i.e., the digital triplets driving the CRT display. We have assumed linearity between the digital values and the displayed primary amount for this analysis, which is often not the case. Linearization techniques are discussed in references 2-4.

When white is displayed two conditions occur. The RGB values are usually unit, and the tristimulus values, on the left hand side of equation (3), correspond to some known value. For this situation we have three equations and three unknowns, and we can readily solve for the C's. As shown in eq. *(2),* the product of the C's and the chromaticity coordinates give the relative tristimulus values for the phosphors .

For two distinct phosphor sets, the tristimulus values of any selected color sample computed via eq. (3) will be different when the display is set up to the same white point and unity RGB digital values. Likewise, a phosphor set adjusted to separate white points will also have a difference in displayed tristimulus values. Therefore, if a file of RGB triplets is produced and drives two different CRTs, with either different white points and/or a different phosphor set, a difference would be expected in the tristimulus values of the displayed colors.

For our analysis we use the CIELAB color description. The values for L^*, a^*, b^* are calculated using the equations below[5]:

$$L^* = 116(Y/YI)^{1/3} - 16 \quad (4a)$$

$$a^* = 500[(X/XI)^{1/3} - (Y/YI)^{1/3}] \quad (4b)$$

$$b^* = 200[(Y/YI)^{1/3} - (Z/ZI)^{1/3}] \quad (4c)$$

where X, Y, and Z are the CIE tristimulus values for the color and XI, YI, and ZI are the tristimulus values for the white point.

To analyze the color differences, delta *E* values in CIELAB space are computed as the Euclidean distance between the two displayed colors according to the following relationship?

$$\Delta E^*_{ab} = [(L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2]^{1/2}. \quad (5)$$

We have chosen the $L^*u^*b^*$ color space for our evaluation because it more accurately represents the Munsell system and large color differences,[6,7] which are of interest in color reproduction.

Simulations

There are two cases of practical interest. The first case assumes that all CRTs are set up to the same white point, but there are different phosphor sets. The second case assumes that all the phosphor sets are the same, except the white points are different.

Several computer programs were written to calculate the average CIELAB color differences for the two cases described above. Four illuminants and five phosphor sets were used in the simulations. Figure 1 shows a 1931 CIE chromaticity plot of the five phosphor sets used, while Table I lists the tristimulus values of the white points.

The selection of potential phosphors was not exhaustive. Two of the sets are TV standards; the original NTSC set and the newer SMPTE set. The other three sets were chosen to encompass the chromaticity gamut of registered phosphor sets.[8]

Four white points were selected to include the range common to illuminants in industrial environments. The 9300K point is representative of TVs in Japan and some graphics display tubes. D65 and D50 are the CIE daylight series correlated color temperatures of 6500K and 5000K. D65 is traditionally popular with colorimetrists and it is also the SMPTE recommended white.' CIE daylight D50 has long been established as the standard viewing illuminant for photographic transparencies.[10] The last white point is CIE cool white fluorescent (F2), which is a common light source in the office environment.

The tristimulus values for each phosphor set were cal-

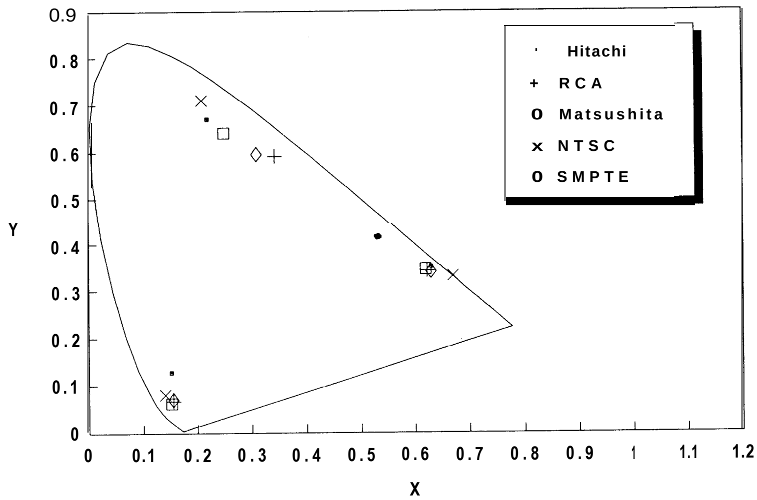

FIG. 1. CIE 1931 chromaticity diagram showing the phosphor sets used in the simulations.

TABLE 1. Illuminant tristimulus values.

	Tristimulus values		
White point	X	Y	Z
9300K	97.135	100.00	143.930
D65	95.047	100.00	108.883
D50	96.396	100.00	82.414
F2 (CWF)	99.187	100.00	67.395

culated using eq. (3), the selected white point, and the registered chromatic&y coordinates. This produced the tristimulus values of the displayed color in terms of the RGB digital values. The full range of digital values was assumed to range from 0 to 255 (8 bits), from which every fourth (6 bits precision) value was sampled. Thus, a sampling of 262,144 colors from the total 16,777,216 colors was implemented in the simulation.

Since two different phosphor sets referenced to the same white point, yielded two XYZ triplets, a color difference resulted between the displayed colors for the same RGB values. L^* ,a^* ,b^*, and delta E values were computed for each RGB value, according to eqs. (4a-c) and (5). Once the color sampling was complete, the average color difference, delta E^*ab of the 262,144 colors was calculated. Comparisons were performed for all pairwise combinations of phosphor sets and white points; yielding a total of 40 comparisons.

The simulations for the second case were identical to the first case, with the exception that two different white points were compared within a particular phosphor set. The selected white point tristimulus values were used in the calculation of the a^* and b^* values (equations 4b-c) only, because the Y tristimulus value of the white point is always 100, and therefore L^* is unaffected. The color difference

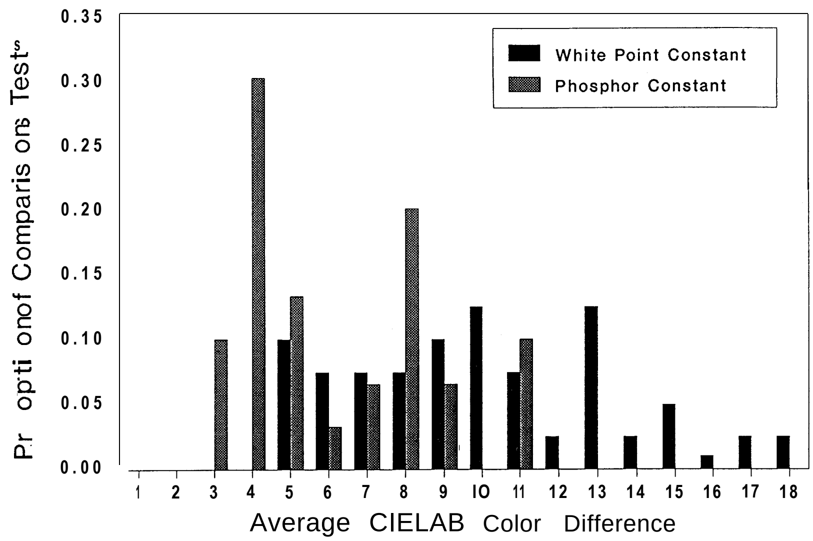

FIG. 2. Average CIELAB color difference histograms for the two different cases examined: (1) varying phosphor (white point constant legend) and (2) varying white point (phosphor constant legend). A total of 262,144 color samples were used in computing each of the average color differences.

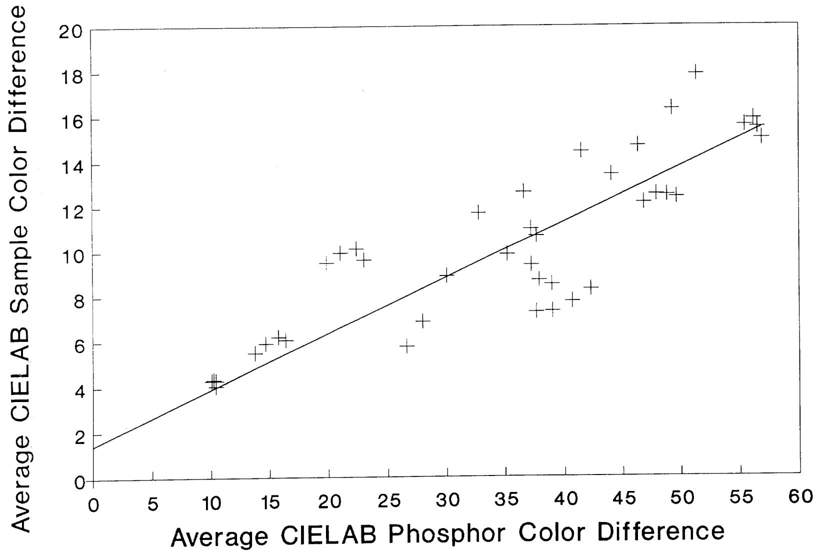

FIG. 3. Average CIELAB color difference for 262,144 color samples versus the average color difference between phosphors. The phosphor color difference was calculated as the average of the differences between the red, green and blue phosphors of each color set.

calculated in this manner forces the grays to have zero color difference. Implicit in this calculation is the assumption that the observer is adapted to the white point of the display, which seems reasonable. Again, all combinations of white points and phosphor sets were evaluated.

Results

The simulation results demonstrated a wide range of average color differences. Results from the simulations with different phosphor sets and constant white point, and different white point and constant phosphor set, are shown as a histogram in Fig. 2. For a constant phosphor set, the range in the coefficient of variation, for each of the color difference distributions, varied from 0.549 to 0.789. For constant white point the range of the coefficient of variation was 0.558 to 0.860.

Keeping the white point constant and varying the phosphor set yielded average CIELAB color differences as high as 18, and in no case analyzed was there a zero color difference. Such a high color difference, although not uncommon in color reproduction,[11] would probably be considered unacceptable for some applications. For a constant phosphor set, and varying white point, the overall average color difference was found to be lower.

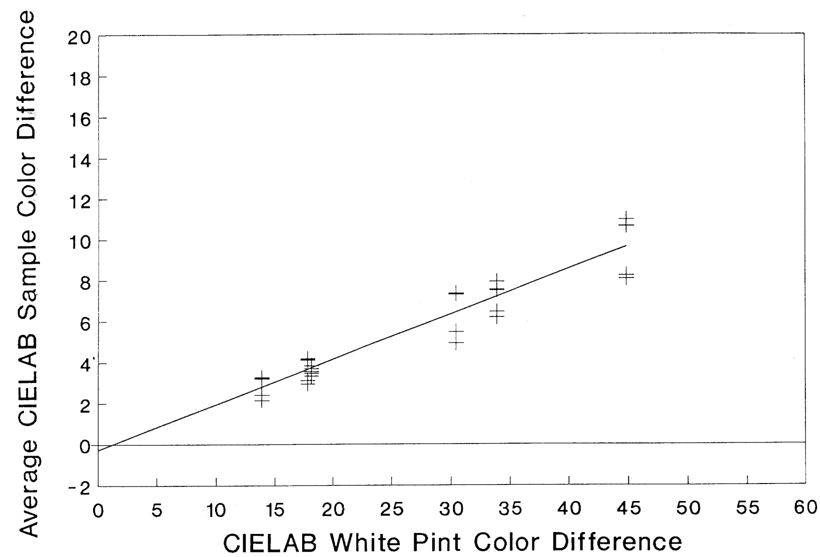

FIG. 4. Average CIELAB color difference for 262,144 color samples as a function of the difference between white points. White point differences were determined by using one as a reference and calculating the other white points with respect to this reference.

Discussion

It would be useful to find color difference relationships between different phosphors sets and/or white points. To accomplish this goal, additional color difference information from the phosphor set and white point data was needed. The new information entailed calculating CIELAB color difference values between the same color phosphors (e.g.) red, green and blue) in different phosphor sets and the color difference between white points. Color difference values between phosphors were computed for all white points using the tristimulus values of one white point in each comparison as a standard. For example, when 93OOK was used as the standard, e.g., *XI*, YI, and 21 in eq. (4a-c), the CIE $L^*a^*b^*$ coordinate for all other white points were computed with respect to 9300 K. This calculation was repeated for all combinations of white points.

With the stimulation data and the color difference data between phosphors and between white points, two analyses were undertaken. The first analysis is of the average color difference for the 262,144 samples assuming a constant white point as a function of the average color difference between phosphors. The results shown in Fig. 3 can be represented by a linear least-squares-fit, which is a straight line following the equation:

$$\text{Average } \Delta E^*_{ab} = 0.247(\Delta E^*_{ab} \text{ Phosphors}) + P.42. \quad (6)$$

The largest deviation from the regression line was t 3.72.

In the second analysis, the average color difference for the 262,144 samples assuming different white points and constant phosphor sets was compared with the color difference between the white points. The following equation summarizes the data shown in Fig. 4.

$$\text{Average } \Delta E^*_{ab} = 0.221(\Delta E^*_{ab} \text{ White Points}) - 0.264 \quad (7)$$

with the largest deviation of -1.56 and $+1.34$ from the regression line.

These results suggest that if color information created on one monitor with phosphor set A, at a particular white point, is to be viewed on another monitor, with phosphor set B and set to the same white point, then the average color difference between color samples will be directly proportional to the average color difference between the phosphors of each monitor (eq. (6)). Likewise, color information displayed on CRTs with the same phosphor set but different white points, will yield an average color difference directly proportional to the color difference between the white points (eq. (7)).

Conclusions

Analysis of CRT phosphor sets and white points demonstrated average CIELAB color differences as high as 18 ΔE^*_{ab} when a CRT is driven with a fixed set of RGB triplets. Where the white point set-up was different but the phosphor set was held constant, lower color differences resulted. These average color differences were typically less than 10 ΔE^*_{ab}. The opposite case, where the phosphor set varied with a constant white point, exhibited larger color differences.

The implications for computer graphics applications are clear; it is more important to standardize on the phosphor set than the white point, if color differences are to be minimized. Nonetheless, this does not imply that the white point standard be ignored.

It should also be mentioned that although the CIE tristimulus values of color samples can be matched across CRT displays, if phosphor sets and white points are the same, the color appearance is not guaranteed. other factors, including the absolute luminance level of the samples and the chromaticity and luminance of the visual surround, also determine color appearance.

1. G. Wyszecki and W. S. Stiles, Color *Science* (2nd Ed.), John Wiley & Sons, New York, 1982.
2. D. L. Post and C. S. Calhoun, An evaluation of methods for producing desired colors on CRT monitors, Color *Res Appl.,* 14, 172 (1989).
3. R. I. Motta and R. S. Berns, The calorimetric calibration of a CRT imaging system for color appearance research, Inter Society Color Council Meeting Digest, 1988, pp 28-30.
4. D. II. Brainard, Calibration of a computer controlled color monitor, Color *Res. Appl., 14, 23 (1989).*
5. *Calorimetry* (2nd Edition), CIE Publication 15.2 (1986).
6. T. Seim and A. Valberg, Towards a uniform color space: A better formula to describe the Munsell and OSA color scales, *Color Res Appl., PI,* 11 (1986).
7. R. D. Lozano, Evaluation of different color-difference formulae by means of an experiment on color scaling-preliminary report, *Color Res. Appl., 2, 13 (1977).*
8. "Optical Characteristics of Cathode Ray Tubes," TEPl16-B, Electronic Industries Association, November 1987.
9. "Color Temperature for Color Television Studio Monitors," SMPTE Recommended Practice, RP 37- 1969.
10. "Illumination of Conditions for Viewing Color Transparencies and Their Reproductions, International Standard IS0 3664, 1975.
11. Pearson, M., Image reproduction calorimetry, *Color Res. Appl.* **11,** 47 (1986).

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