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ACCURACY OF COLOUR PRODUCTION ON A CRT DISPLAY AS A FUNCTION OF THE MEASUREMENT INSTRUMENT USED FOR CALIBRATION

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Accuracy of colour production on a CRT display as a function of the measurement instrument used for calibration

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Abstract — This investigation determined the error associated with colour reproduction when different light meters were used to characterize a CRT. Luminance measurements were taken with three light-measuring instruments to produce gamma tables. The tables were used to calibrate 28 colours. Results showed that the most acceptable instrument was one that accurately measured light below 0.001 cd/m^2 and that used colour-matching tables to weight the radiant energy. Less-sensitive instruments that used fixed filters to model the colour-matching functions produced colours that were perceptibly different from the specified colours. The reproduction errors were evaluated against colour discrimination thresholds and ΔE^*. If accurate reproduction of luminance is not essential, a less-sensitive instrument with a cutoff of 0.01 cd/m^2 and three separate filters for modeling the colour-matching functions may be adequate. Complete gamma-correction tables (voltage input/luminance output) for each gun were not necessary. Accurate colour calibration can be based on a limited number of luminance measurements plus an interpolation procedure to determine the intervening values in the gamma tables. The reliability of the initial characterization was tested after an interval of 9 months. The maximum luminance of the monitor decreased considerably over this time period. A simple recalibration method, outlined by Lucassen and Walraven (Ref. 1) was effective in restoring luminance accuracy. This method allows for periodic adjustments to the luminance output on a CRT using a small number of measurements.

Keywords — *Colour accuracy, colour displays, CRT colour calibration, luminance meters.*

1 Introduction

Colour coding is used on electronic displays such as cathode-ray tubes (CRTs) for a wide range of applications. In order to reproduce specified chromaticities on electronic displays, some form of initial and ongoing calibration of the display system is usually required. The most accurate and commonly used calibration method for producing specified colours is complex and requires expensive equipment to characterize the CRT.[2,3] However, because many applications may not require a high level of colour accuracy, a relatively simple method of CRT characterization may be sufficient, employing easier-to-use portable less-expensive light-measuring instruments and fewer measurements. Unfortunately, little data are available on the relative size of the error associated with simpler and less-expensive measurement methods, making it difficult for display designers to specify a suitable calibration procedure for a given application. The purpose of this investigation was to evaluate the accuracy of CRT colour production with different initial and ongoing CRT characterization and calibration methods.

In order to specify colours on a CRT, it is necessary to determine the chromaticity coordinates of the phosphors and the luminance characteristics of the three guns as defined by a set of gamma functions or gamma-correction tables. Nominal chromaticity coordinates are usually available from the manufacturer or may be determined using a spectroradiometer. The gamma functions describe the voltage-input to luminance-output relationships of a particular monitor where the voltage inputs to the three CRT colour guns are expressed in digital-to-analog converter (DAC) values. A gamma-correction table is determined by measuring the luminance of each phosphor over a range of DAC values. These tables can be used directly or a function can be fit to the data.

The luminance values for the lookup tables can be measured with a spectroradiometer, colorimeter, or photometer. Spectroradiometers are usually expensive, difficult to operate, and relatively non-portable. However, if calibrated and operated accurately, they produce reliable results. Colorimeters and photometers range from very expensive and complicated laboratory instruments to relatively inexpensive easy-to-use field instruments. Our interest was in the suitability of a colorimeter and/or photometer that was simple to use, inexpensive, and portable. We wanted to determine if the errors in production of chromaticity coordinates and luminances resulting from the use of these types of instruments were within tolerable limits compared to the errors with an expensive high-quality light-measuring instrument such as our laboratory spectroradiometer.

In addition, we wanted to explore alternative ways of reducing the time and effort associated with characterization and calibration of CRTs. We examined two meth-

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ods that have been suggested by other researchers. One method involves measuring the luminance of a subset of DAC values and using an algorithm to predict the luminance of the intervening values. Several algorithms have been developed for generating gamma-correction tables from a relatively small number of measurements. One evaluation found that the most useful was the piecewise linear interpolation method with constant chromaticities (PLCC).[3] The second method is designed to reduce and simplify ongoing calibration. It is well known that the luminance of the guns on a CRT drifts over time.[1,4] Lucassen and Walraven[1] proposed a simple recalibration method to correct this drift that avoided the requirement for a complete recharacterization of the CRT. The accuracy of this method was compared with complete recalibration 9 months after the initial calibration.

To evaluate the accuracy of colour reproduction using the different measurement devices and algorithms discussed above, a set of 28 chromaticities evenly spaced on the 1976 UCS chromaticity diagram was used. The difference between the specified chromaticity coordinates and luminance of each test stimulus and the actual chromaticities and luminance produced on the display was calculated and evaluated in terms of chromatic and luminance discrimination thresholds.

2 Method

2.1 Apparatus

Three different light-measuring devices were used to characterize the CRT: a spectroradiometer consisting of an EG&G Gamma Scientific GS-4100 Intelligent Radiometer, NM-3H Monochromator, and a GS 2100 Telemicroscope (measured sensitivity was 0.001 cd/m^2), a Minolta CS-100 Colorimeter with a DP-101 Data Processor (specified minimum is 0.01 cd/m^2), and a Hagner Universal Photometer (specified minimum is 0.1, actual is 0.2 cd/m^2). In addition to sensitivity, the instruments differed in the process used to determine the luminance. With the spectroradiometer, the energy in each 5-nm band was weighted by the three colour-matching functions.[5] With the colorimeter, the energy passed through three separate filters that modeled the colour-matching functions, and with the photometer, the energy passed through a single fixed filter that modeled the photopic function. The evaluation was carried out on a Sun 3/110 workstation with a Hitachi HM-4119-S-AA-O Monitor. All three instruments were initially calibrated with an EG&G Gamma Scientific RS-10A Spectral Irradiance Head standard light source at a luminance of 622 cd/m^2.

2.2 Procedure

Luminance measurements of a 10-cm square displayed in the center of the screen were taken in a dark room with each system. The output of each gun was measured in turn while the remaining two were held at zero. Measurements wit the spectroradiometer and colorimeter were made simultaneously at every second DAC value between 0 and 255 (th maximum value). For these measures, the spectroradiometer and colorimeter were positioned at an angle of 20° t each side of the normal to the screen (so both could operat simultaneously). With the photometer, only every eighth DAC value was measured.

In addition, the chromaticity coordinates for each gun were determined with the spectroradiometer. Most calibration procedures assume constant chromaticities independent of voltage.[2] This assumption is true in the upper voltage range of the monitor but is violated in the lower range. For the current evaluation, the mean CIE (Commission Internationale de l'Eclairage) u', v' chromaticities of the red, green, and blue phosphors based on measurements from 100 to 255 DAC values were used.

From the three sets of measurements, four lookup tables pairing luminances with DAC values resulted. One table (called LONG) consisted of the values obtained from the spectroradiometer readings at every second DAC value. The other three lookup tables consisted of the measurements at every eighth DAC value based on the spectroradiometer (RAD), colorimeter (COL), and photometer (PHOT) measurements. For these three tables, the PLCC[3] was used to determine the intervening values.

The four sets of tables were used with the measured chromaticity coordinates of the guns to determine the DAC values for 28 chromaticities (Fig. 1) evenly spaced on the CIE 1976 UCS diagram. The chromaticities were produced at three luminance values, 3, 10, and 30 cd/m^2, to conform with levels used in previous applications.[3,4] Specific functions for converting a set of u', v' coordinates and a luminance value (L) into the luminance values for three known primaries can be found in Post and Calhoun,[3] Lucassen and

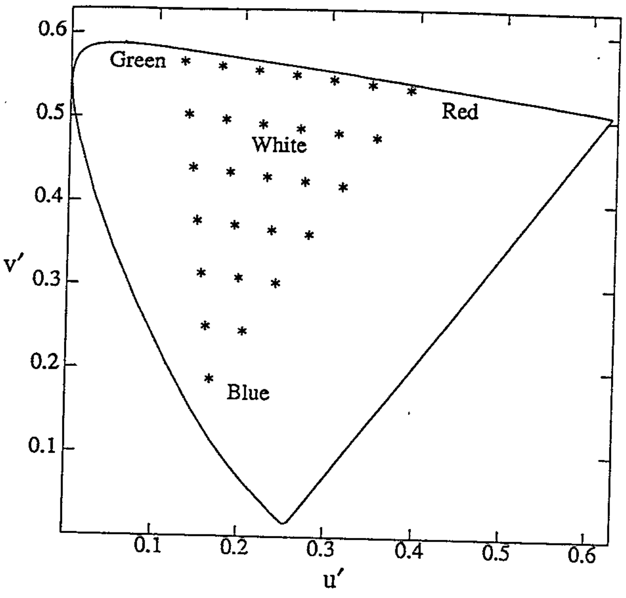

FIGURE 1 — The 1976 CIE colour diagram with the location of the 2 specified test stimuli.

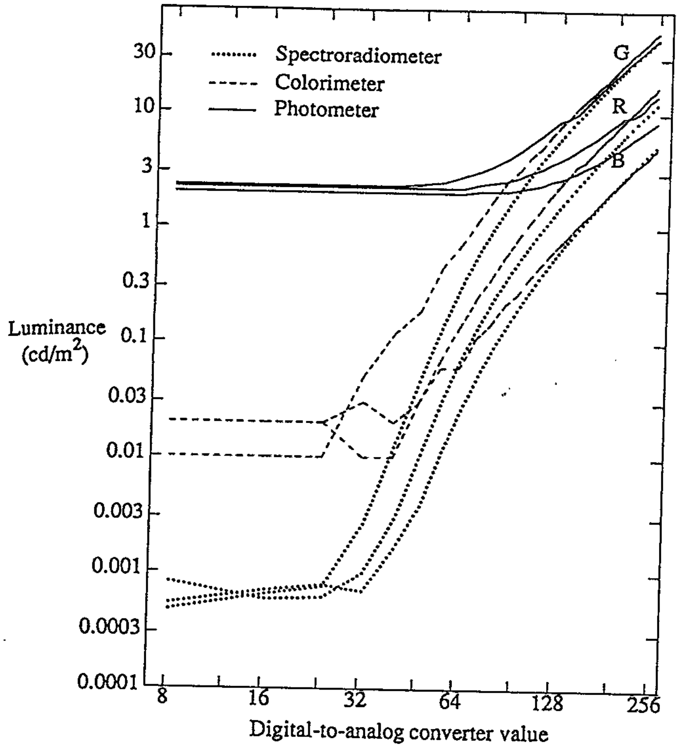

FIGURE 2 — Initial gamma data measured with a spectroradiometer, colorimeter, and photometer.

Walraven,[1] or more generally in Wyszecki and Stiles.[5] These functions were used to convert the u', v', and L values into the appropriate luminance values for the three phosphors. Next, the gamma tables were used to determine the DAC values that corresponded to each luminance value. The resulting DAC values were displayed as squares on the screen and measured using the spectroradiometer. Finally, the measured values were compared to the specified u', v', and L values.

Nine months later, the monitor was recalibrated using the spectroradiometer only. The calibration with the new gamma tables was compared with the original to determine the changes over time. In addition, the monitor was recalibrated using a modification of a procedure suggested by Lucassen and Walraven.[1] With their method, a white reference stimulus is measured during initial calibration. When recali-ration is required, the white reference stimulus is measured again. The ratios of the three R, G, and B values used o produce these references are used to correct the original gamma tables. In this evaluation, three initial references, 0% of the maximum luminance for each colour gun, were used. During the recalibration, these values were again measured and correction ratios for each gun (C_r, C_g, C_b) were calculated. These correction ratios were used to adjust he original gamma tables and to produce new DAC values or the original test set of chromaticities. The corrected values were displayed on the screen and their chromaticities measured.

TABLE 1 — Minimum and maximum luminance (cd/m²) measured with each instrument.

Condition	Red		Green		Blue	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
PHOT	2.2	14.7	2.3	46.5	2.0	8.6
COL	0.01	17.3	0.01	52.6	0.02	5.0
LONG	0.0004	13.1337	0.0004	48.2285	0.0005	5.5822
RAD	0.0009	13.1336	0.0005	48.2285	0.0005	5.5822

3 Results

3.1 Gamma data

Gamma data obtained from the initial set of measurements using the three instruments are shown in Fig. 2. (LONG was excluded from the figure because it is an expanded version of RAD.) Table 1 shows the minimum and maximum luminances measured by each instrument. It is clear that the photometer and the colorimeter were less sensitive and produced a different shaped curve than the spectroradiometer. The measurements of the photometer were most deviant from those of the spectroradiometer. Its estimates were consistently higher than those of the spectroradiometer and it could not differentiate luminances below 2 cd/m². The effect of the insensitivity of the photometer was that the bottom 30% of the range of DAC values were mapped onto the same luminance level. The colorimeter could discriminate luminances down to about 0.01 cd/m². In addition, the colorimeter estimates of the luminances of the red and green guns were consistently higher than those of the spectroradiometer.

3.2 Luminance and chromaticity errors

For each instrument, the measured u', v', L for each stimulus was compared with the specified value and a $\Delta u'$, $\Delta v'$, ΔC^*, ΔE^* were calculated. At 10 and 30 cd/m², there were large errors in luminance because of limitations in the CRT chromaticity and luminance gamut. The maximum output of the blue gun was 5.6 cd/m², while the maximum output of the red gun was 13.1 cd/m². These limitations made it impossible to produce chromaticities that required a large input from the blue gun and, to a lesser extent, the red gun. One method of reducing this error is to replace the initial set of test chromaticities with the u', v', L values calculated from the R, G, B DAC values derived from the initial test set of chromaticities, the gamma tables, and gun chromaticity coordinates. When the derived set of u', v', L values were compared with the measured chromaticity coordinates and luminances, the errors at 3, 10, and 30 cd/m² were similar to each other and larger than the error between the original test set and the measured values at 3 cd/m². For this reason, only the results at 3 cd/m² are reported (Table 2, Fig. 3).

The average colour and luminance errors are shown in Table 2, along with the standard deviations and the largest

TABLE 2 — The average measurement error of 28 colours when the gamma data were collected with a spectroradiometer, colorimeter, and photometer. LONG refers to the table of luminance values measured at every second DAC value using the spectroradiometer. RAD, COL, and PHOT refer to the tables of values where measurements were made at every eighth DAC value and the PLCC model was used to determine intervening values in the gamma correction tables. The actual minimum and maximum values rather than differences are shown for ΔC^* and ΔE^*.

Instrument	Unit	Mean	Std. dev.	Minimum	Maximum
LONG	$\Delta u'$	0.0013	0.0010	0.0000	0.0043
	$\Delta v'$	0.0023	0.0023	0.0000	0.0086
	$\Delta C*$	1.0890	0.5482	0.3534	2.3664
	ΔL	0.2325	0.0734	0.0445	0.3672
	$\Delta E*$	1.4423	0.4419	0.7545	2.5589
RAD	$\Delta u'$	0.0013	0.0007	0.0000	0.0025
	$\Delta v'$	0.0011	0.0010	0.0000	0.0035
	$\Delta C*$	0.8541	0.2769	0.4567	1.1759
	ΔL	0.1602	0.0371	0.0638	0.2272
	$\Delta E*$	1.0909	0.1784	0.7512	1.4633
COL	$\Delta u'$	0.0063	0.0053	0.0000	0.0173
	$\Delta v'$	0.0146	0.0144	0.0002	0.0378
	$\Delta C*$	4.7211	1.8856	1.6574	10.0901
	ΔL	0.7957	0.2168	0.2193	1.0241
	$\Delta E*$	6.0518	1.6924	2.659	10.749
PHOT	$\Delta u'$	0.0447	0.0391	0.0002	0.1416
	$\Delta v'$	0.0730	0.0594	0.0004	0.2207
	$\Delta C*$	31.4010	15.8450	1.3799	68.751
	ΔL	2.8395	0.2601	2.0496	2.9995
	$\Delta E*$	43.7336	12.5459	26.773	76.662

TABLE 3 — The average measurement error of 28 colours after 9 months (DRIFT). RAD shows the error when data were collected with a spectroradiometer using a full recalibration. RECAL shows the error when a simplified recalibration method was used.

Method	Unit	Mean	Std. dev.	Minimum	Maximum
RAD	$\Delta u'$	0.0036	0.0022	0.0002	0.0074
	$\Delta v'$	0.0036	0.0032	0.0001	0.0100
	$\Delta C*$	1.4555	0.7876	1.0214	2.0770
	ΔL	0.0640	0.0399	0.0006	0.1437
	$\Delta E*$	1.4743	0.7894	0.7206	6.5448
DRIFT	$\Delta u'$	0.0014	0.0012	0.0000	0.0041
	$\Delta v'$	0.0051	0.0037	0.0001	0.0118
	$\Delta C*$	2.7127	1.0750	1.5999	4.9710
	ΔL	0.3943	0.0351	0.3240	0.4711
	$\Delta E*$	3.2418	0.8671	1.8101	5.1504
RECAL	$\Delta u'$	0.0028	0.0019	0.0001	0.0079
	$\Delta v'$	0.0067	0.0050	0.0002	0.0145
	$\Delta C*$	2.6039	0.9348	0.9152	3.7708
	ΔL	0.0864	0.0633	0.0103	0.2628
	$\Delta E*$	2.6427	1.4053	0.6948	6.6040

and smallest values. When expressed as a percentage of deviation from the expected luminance of 3 cd/m^2, the luminance error for LONG (7.7%) and RAD (5.3%) were similar, whereas the error in luminance was larger when the colorimeter (26.5%) was used, and very large when the photometer (94.6%) was used. As can be seen from Table 2, the error in luminance estimation was a factor of about 5 for the colorimeter and as much as 15 times greater than the spectroradiometer for the photometer. The errors in u', v' were about a factor of 10 greater for the colorimeter and a factor of 50 greater for the photometer as compared to the errors with the spectroradiometer. The composite measures of ΔE^* and ΔC^* show that both chromaticity and luminance errors result when the photometer is used to collect gamma data.

Figure 3 shows the actual shifts in the chromaticity coordinates for the 28 stimuli at 3 cd/m^2. As can be seen, the specified chromaticities tended to map onto the red, green, or blue vertices or towards the achromatic point (indicated by the cluster around the center of the diagram) when the gamma tables produced with the photometer were used. The direction of the shifts in the chromaticity coordinates determined with the colorimeter-based gamma tables were much smaller and random. The shifts with the spectroradiometer were too small to be produced on the figure.

3.3 Perceptual differences

The importance of these errors was evaluated in two ways. First, they were compared with the limits of the visual system for colour discrimination as defined by the MacAdam ellipses.[6] Using an average of the major axes of MacAdam ellipses of chromaticities within the range of a colour monitor, Lucassen and Walraven[1] calculated an average of 0.005 in the x, y chromaticity space for a just-perceptible chromaticity difference. Based on these calculations, the error for colours calibrated with the spectroradiometer are smaller than perceptible differences (the average for LONG was $x = 0.0026$, $y = 0.0027$, and the average for RAD was $x = 0.0018$, $y = 0.0012$). The errors for the colorimeter are slightly over the limit of perceptibility ($x = 0.0120$, $y = 0.0152$) and those for the photometer are well above perceptible levels ($x = 0.0900$, $y = 0.0980$).

Another measure of colour discrimination or differences in chroma is ΔC^*. However, a better measure of discrimination, which takes into account differences in luminance as well as differences in hue and purity, is ΔE^*. Both measures predict the discrimination of two colours as a function of their location in the CIE 1976 Uniform Colour Space, taking into account the chromaticity coordinates and luminance of the brightest surface in the scene in which the two colours occur. For a CRT, the brightest point on the screen is assumed to be standard illuminant D65 ($u' = 0.1978$, $v' = 0.4684$) at a luminance of 100 cd/m^2. For a more complete description of ΔC^* and ΔE^*, and formulae for calculating them, the reader is referred to Ref. 5. A ΔE^* difference on the order of 2–3 has been estimated to approximate a just-noticeable difference.[1] ΔE^* was calculated for each stimulus and an average ΔE^* determined for each measurement device using D_{65} and $Y_n = 100$ as the reference point. As shown in Table 2, only the spectroradiometer provided an average ΔE^* close to perceptible differences at 3 cd/m^2. All of the chromaticities shifted more than three ΔE^* using PHOT and COL gamma data. LONG produced 10 and RAD produced 4 chromaticities outside this criterion.

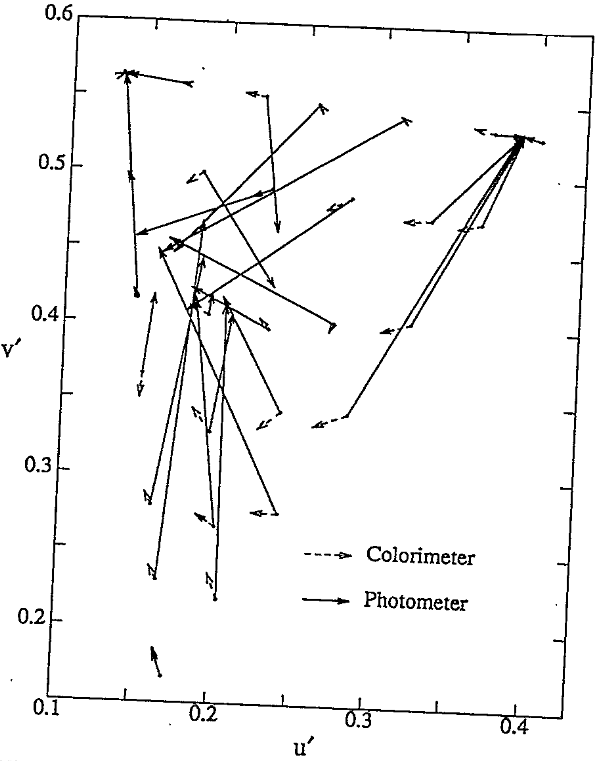

FIGURE 3 — Errors in reproduction with the colorimeter and photometer when the specified luminance of the stimuli was 3 cd/m^2. Error resulting from measurements made with the spectroradiometer are not shown because they are too small to be seen clearly.

3.4 PLCC model

The difference between LONG and RAD was the use of the Piecewise Linear Interpolation model assuming constant chromaticity coordinates (PLCC model) to interpolate between measures. The similarity of the results confirms the findings of Post and Calhoun[3] that this interpolation method provides a means of reducing the number of luminance measurements required during characterization without compromising accuracy. Indeed, the PLCC interpolation resulted in a smaller luminance error than measures taken at every second DAC value and spectroradiometer measurements using the PLCC model showed the smallest ΔE^* value at 3 cd/m^2.

3.5 Recalibration

The primary purpose for recalibration was to investigate the deviation from specified chromaticities over a 9-month period and to investigate the effectiveness of the simple recali-

TABLE 4 — The average measurement error of 28 colours when the gamma data were collected with a colorimeter (COL) and when a model was used to extrapolate beyond the sensitivity of the instrument (MATH).

Method	Unit	Mean	Std. dev.	Minimum	Maximum
MATH	$\Delta u'$	0.0104	0.0075	0.0001	0.0267
	$\Delta v'$	0.0186	0.0132	0.0038	0.0475
	$\Delta C*$	9.0092	3.8657	3.2535	16.3631
	ΔL	0.7831	0.2866	0.1155	1.2244
	$\Delta E*$	10.4102	3.6138	7.5903	31.036
COL	$\Delta u'$	0.0103	0.0084	0.0000	0.0273
	$\Delta v'$	0.0143	0.0118	0.0011	0.0439
	$\Delta C*$	9.1320	3.5071	2.9039	13.0776
	ΔL	0.8167	0.3093	0.0132	1.2711
	$\Delta E*$	10.0245	3.3093	7.1726	32.983

bration method suggested by Lucassen and Walraven[1] for correcting errors. The specified chromaticities were the original specified coordinates shown in Fig. 1.

Luminance output for each gun decreased over 9 months, causing slight shifts in the chromaticity coordinates of the 28 stimuli measured using the RAD lookup tables. The shifts in chromaticity coordinates from the specified coordinates using the original gamma tables and the corrected gamma tables are shown in Fig. 4 (nominal luminance 3 cd/m^2). When the simple recalibration method was applied to the original gamma curves, most of the chromaticity shifts observed were about equal in magnitude but differed in direction. However, as Table 3 shows, the average error afte 9 months (DRIFT) consisted mostly of a luminance chang (13.1%), resulting in an average ΔE^* value above 3. Afte the simple recalibration (RECAL), the errors were approximately the same as the errors observed with the new gamm tables collected after 9 months (RAD). The luminance erro expressed as a percentage was 2.1% for the full recalibratio (RAD) and 2.9% with the simple recalibration (RECAL). Th similarities in the $\Delta u'$, $\Delta v'$, and ΔC^* values for the DRIFT an RAD conditions also show that the change over time was primarily in luminance. The chromaticity coordinates, eve without recalibration, were close to the limits of perceptibility in the x, y space (for DRIFT $x = 0.0042$, $y = 0.0065$; fo RECAL $x = 0.0049$, $y = 0.009$; and for RAD $x = 0.0068$, $y =$ 0.0040). The recalibration procedure effectively reduce the luminance error resulting in an average ΔE^* of less tha 3. Thirteen colours shifted more than a ΔE^* of 3 units afte 9 months. Following recalibration, nine colours exceede this criterion. When the ΔE^* criterion was relaxed to fou the six colours that exceeded this criterion were reduced t zero following recalibration.

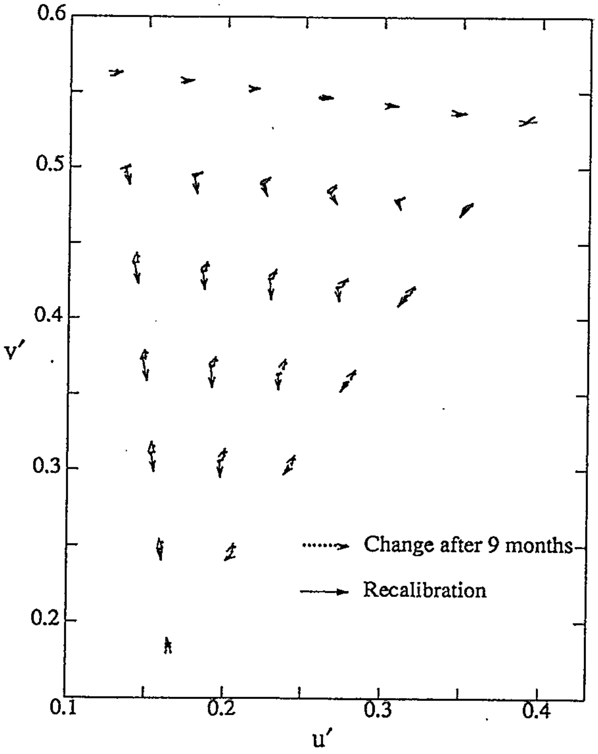

FIGURE 4 — Errors in reproduction 9 months after initial calibration using the initial spectroradiometer measurements without and with correction. Nominal luminance of the stimuli was 3 cd/m^2.

3.6 Extrapolation of the colorimeter gamma tables

Although the average u', v' error arising from the characterization with the colorimeter was close to the limit of perceptibility, the luminances were consistently low. Based or these results, an instrument of similar quality to the colorimeter used in this study could be used for calibration if thc gamma data could be adjusted to compensate for some o the luminance error. An initial examination of the gamm: data suggested that the inaccuracy of the colorimeter anc the photometer might be due to their insensitivity at lov luminance levels. Another possible explanation is that thc limitations were due to the use of fixed filters in these instruments which may not accurately model the CIE colour-matching functions.

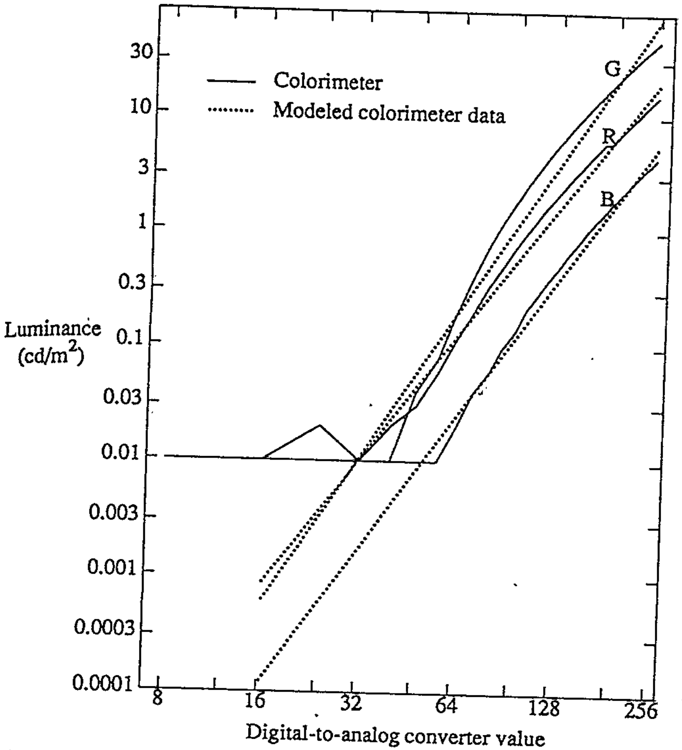

FIGURE 5 — Second set of gamma data collected with a colorimeter and the linear functions fit to the data.

If the problem was insensitivity to light at low luminances, one might compensate by extrapolating the gamma tables used for calibration below the colorimeter's sensitivity threshold. In effect, the PLCC model uses an extrapolation method with the assumption that 0 DAC produces 0 luminance.[3] To assess the possibility of improving the calibration data using a similar extrapolation method, a new set of gamma data were collected with the colorimeter following the procedure outlined in the main evaluation. A simple linear equation of the form $y = mx + b$ was fit to a logarithmic transform of the above threshold data for each of the three guns. This function produced the best fit to the gamma data above threshold for each gun compared to logarithmic, third- and fourth-order polynomial, and exponential equations. The variances accounted for (R^2) by the linear equations were $R^2 = 0.990$ for red, $R^2 = 0.971$ for green, and $R^2 = 0.989$ for blue. The function was used to determine DAC values for luminances below the threshold sensitivity of the colorimeter. For luminances above threshold, the actual gamma data and the PLCC were used. The three modified gamma tables were then used to predict the DAC values for the same 28 chromaticities and the spectroradiometer was used to measure the actual chromaticity coordinates and luminance of the DAC values. Finally, the error in u', v', L values for the modified gamma tables were compared with the errors using the colorimeter gamma data and the PLCC.

Figure 5 shows the new gamma data for the colorimeter, along with the function to fit to each curve. Figure 6 shows the chromaticity difference between the specified u', v' values and the measured u', v' values for each of the 28 test stimuli at 3 cd/m^2 using the colorimeter data and the extrapolated data. The difference between specified chromaticities and measured values using the modeled data are shown in Table 4. Data extrapolation did not reduce the error associated with using the colorimeter to measure luminance. In neither case were the stimuli produced within three ΔE^* units of the specified u', v', L values.

There were discrepancies between the maximum luminances obtained by the colorimeter and spectroradiometer when measuring the gamma data (Table 1) despite calibration of both instruments to a standard light source before beginning the study. One possible way of adjusting for this difference is to calculate a multiplicative correction factor for red, green, and blue channels of the colorimeter relative to the spectroradiometer. The correction factors derived from the maximum luminances for each channel (R = 0.7591, G = 0.9169, and B = 1.1164) were applied to the colorimeter calibration data and new u', v', and L values were calculated using the resulting DAC values. The average difference between the CIE coordinates obtained with the spectroradiometer and the colorimeter ($u' = 0.0070$, $v' = 0.0108$, $L = 29\%$) were compared to the difference between the spectroradiometer and the colorimeter with corrected gamma functions ($u' = 0.0074$, $v' = 0.0136$, $L = 20\%$). The results of this correction show a slight improvement in luminance. The lack of much improvement in luminance using this method may be attributed to the inconsistent differences between the maximum luminances measured with the colorimeter and spectroradiometer. The other drawback to this correction is the requirement to calibrate the colorimeter using a more accurate instrument, thus defeating the purpose of using a colorimeter.

4 Discussion

Not unexpectedly, the accuracy of colour reproduction depended on the sensitivity and quality of the light-measuring instrument used to characterize the CRT. In general, the less sensitive and precise the light-measuring device, the larger the error in colour reproduction. Our results found that using an instrument that had a threshold of 0.01 cd/m^2 or higher and that used filters to model the colour-matching functions resulted in colours that could differ perceptually from the required chromaticities.

However, the use of a less accurate and sensitive measuring instrument (minimum accurate readings at 0.01 cd/m^2), such as the colorimeter used in this study, may be a reasonable alternative for some applications. The chromaticity coordinates produced on the screen were on average only slightly above the perceptual limits defined by Lucassen and Walraven. The main problem was with the reproduction of the luminance values despite original calibration to a standard lamp before beginning the study. The colorimeter tended to underestimate the luminance values. However, if relative rather than absolute identification of

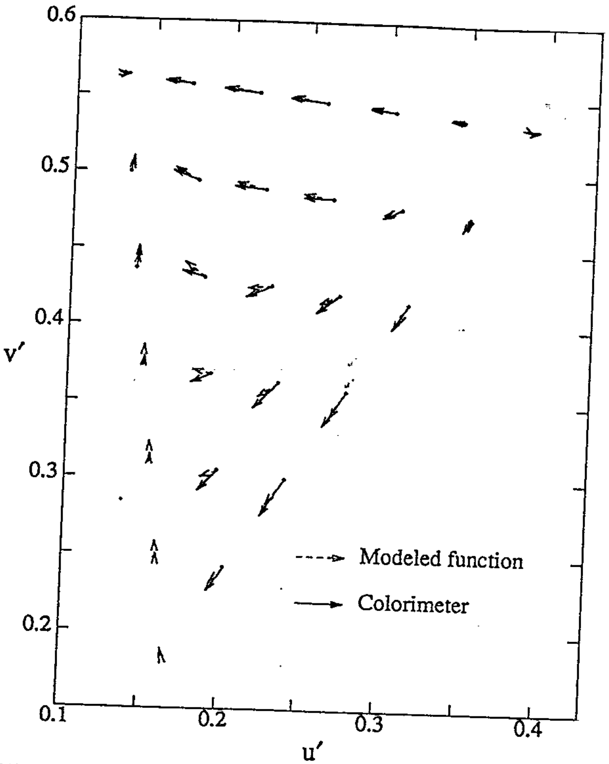

FIGURE 6 — Errors in reproduction with the colorimeter-based gamma tables and the same tables extrapolated using a linear fit to the data. The specified luminance of the stimuli was 3 cd/m^2.

colours is sufficient for the task being carried out, colour calibration based on measurements with a hand-held instrument with 2% accuracy and a minimum reading of 0.01 would be acceptable. Such applications usually require a small number of chromaticities and little or no luminance coding. Inexpensive hand-held instruments with a stated accuracy of 0.1 (actually 0.2) and a single filter that models the photopic function are unacceptable for characterizing a CRT.

The comparison of the LONG and RAD results confirm the findings of Post and Calhoun[3] and suggest that with any of the instruments, it is not necessary to measure the luminance of the guns at every DAC value. The number of measurements required for calibration can be reduced by using the PLCC interpolation between measured points. In this study, this method was found to be effective when 33 measurements were taken. It is possible that even fewer measurements could be taken without a loss in accuracy.[1] In fact, in our evaluation, the linear interpolation between points provided a better estimate of luminance than using a table with measured values at every second DAC value. It is not clear why this should be the case. It may be that there is an error associated with individual measurements due to moment-to-moment fluctuations in the luminance of the screen.

When producing colours from specified CIE coordinates, care should be taken to ensure that the chromaticities are not outside the CRT limitations. This is especially true when colours are requested at a high luminance level, for example, at 10 or 30 cd/m^2. Although these levels are easil produced for white, they may not be producible for the blue and, to a lesser extent, the red phosphor. If there is a requirement for saturated reds and blues at relatively high luminance, there should be a check for out-of-range values in the computed DACs. Even when careful and accurate measurements are made and all chromaticities are reproducible, some error can be expected in the conversion from CIE coordinates to specific R, G, B values, or the reverse, as a result of not fully meeting some of the assumptions of the calibration model used to convert CIE coordinates to specific DAC values.[7]

While the data suggest that the CRT characterization required for initial colour calibration cannot be simplified substantially for many applications, it appears that recalibration can, by using the procedure outlined by Lucassen and Walraven to correct for errors in luminance. Our results show that chromatic drift over 9 months was relatively small and that the errors in reproduction using the corrected gamma tables were on the order of those found when the gamma tables were completely redone. However, simple recalibration may not be sufficient to account for the changes in the monitor due to circumstances other than normal use, such as violent jostling, defective components, and varying environmental conditions. If the monitor has been subjected to any of these unusual disturbances, a full characterization may be necessary.

5 Conclusions

The purpose of the study was to investigate the effectiveness of colour characterization using different types of light-measuring instruments to collect the gamma data. When the gamma data were collected with a spectroradiometer capable of measuring luminances of less than 0.001 cd/m^2 and the luminances were computed using the colour-matching functions directly, all the test chromaticities were close enough to the specified values that the differences should not be perceptible. However, these types of instruments can be expensive, difficult to use, and relatively non-portable.

Equipment exists, such as the colorimeter and photometer in this evaluation, that are inexpensive, easy to use, and portable. However, as we have shown, the result is the production of colours that differ perceptually from specified colours. In the case of the photometer, the results were totally unacceptable. The colorimeter, however, could be used in applications where luminance specification is not critical and only a limited number of hues are being used.

In those applications where precisely calibrated colours are essential, the task of characterizing the CRT can be reduced by using the PLCC method of interpolation. In our evaluation, the errors in colour production using PLCC were equal to or smaller than errors using tables based on luminance measurements at every second DAC value.

Recalibration of the monitor after a 9-month interval indicated that the luminance of the guns could drift substantially over time and that periodic recalibration is necessary.

A simple recalibration procedure was found to be as effective as a full characterization in adjusting for the drift in luminance of the three phosphors. Errors in producing specified chromaticities following recalibration were similar to the error associated with a full characterization.

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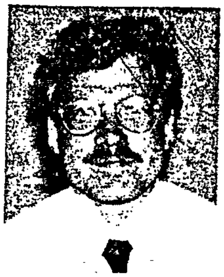

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