Miscalibration of a Display - the Importance of Different Factors to Colour Reproduction

Heikkilä I., Sivonen J., Juhola H.*

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Abstract: The main sources of error in the colour reproduction of CRT displays are associated with offset, gain and gamma, phosphor and white point colours, as well as the ambient light. It is, however, true that all the parameters cannot always be measured with the highest accuracy. Especially, if the display calibration is based on visual tests, its accuracy is limited because the observer makes only a limited number of tests. Therefore, the measuring accuracy of the parameter should be linked to its importance in the colour calibration of the display.

This study tests the importance of the parameters to the display colour calibration. A display is measured to establish the parameters, and the outputs are calculated for 50 test colours. The results are used as a reference. In the tests, one parameter - for example the gamma value - is distorted at a time, and the outputs of the test colours, as well as colour differences between them and the reference colours are calculated. The importance of the different parameters is analysed by running the similar tests for every factor.

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* VTT Information Technology, Media, Finland

Introduction

The colour calibration of CRT displays is based on certain models and the colour reproduction of the display is assumed to follow these models. The device is characterized by measuring the values of the model parameters, and the display is colourcalibrated by applying the models with the measured parameter values. Display calibration and its inaccuracies have been discussed extensively in the literature, for example Barco et al (1995) and Deguchi et al (1999).

Recently also tolerances have been calculated in the display hardware, including offset, gamma and phosphor colour (Maroney, 1999). This study relate also to the tolerances, but from the point of view of unaccurate measurements of parameters. It is true that the display parameters cannot always be measured with the highest accuracy. Especially if the display calibration is based on visual tests, its accuracy is limited because the observer makes only a limited number of tests. When all parameters can not be measured with the highest accuracy, it is reasonable that the measuring accuracy of the parameter should depend on the importance of it.

This study tests the importance of the main parameters to the colour calibration of the display. Two models are used to characterize the colour reproduction of the CRT display. The first model uses three parameters – offset, gain and gamma – and it is used to characterize tone reproduction. The three parameters are measured for different phosphor colours, so that the offset describes an additive error in tone reproduction, the gain describes a multiplicative error and the gamma describes the nonlinearity of the tone reproduction. The display can therefore be linearized by using the first model.

The second model is used to characterize the colour reproduction of the linearized display. The model is based on the additivity of colours. When the tristimulus values of colours emitted from different phosphors are known, the resulting colour can be calculated by summing up the tristimulus values. According to the convention, the colours of white and phosphors are descriped using CIE1931 x, y chromaticity values. Namely, the chromaticity values are characterized for red, green and blue phosphors, as well as for a white.

Finally, to calibrate the colour reproduction of a display, also the ambient light reflected from the screen has to be included in the calculations. The additivity of colour applies also to the ambient light: the light emitted from the display is added by the ambient light reflected from the display screen. The ambient light is characterized in terms of CIE Y,x, y values.

Objectives

The objective of this study is to test the importance of different parameters in display calibration. The results will be used to propose guidelines for the visual calibration of displays when all parameters cannot be measured with the highest accuracy as the observer makes only a limited number of visual tests.

Methods

One display is used as a reference in the tests of this study. It is measured to establish offset, gain and gamma, phosphor and white point colours, and the ambient light reflected from the screen. Also the intensity of the ambient light is measured.

The output test colours are calculated by using the undistorted values of the measured parameters. In the calculations, every display channel is first linearized by:

$$output = offset + gain \cdot input^{gamma} \tag{1}$$

where the input and the output are the intensity values of R, G and B. The output R,G,B values are used with the transformation matrix to calculate the corresponding tristimulus values. The transformation matrix M is solved by using the phosphor colours as well as the white point colour:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [M] \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2}$$

The tristimulus values of the three channels are summed up to represent tristimulus values emitted from the display:

$$\begin{aligned} X_{displ} &= X_{red} + X_{green} + X_{blue} \\ Y_{displ} &= Y_{red} + Y_{green} + Y_{blue} \\ Z_{displ} &= Z_{red} + Z_{green} + Z_{blue} \end{aligned} \tag{3}$$

Thereafter, the tristimulus values of the ambient light reflected from the display are calculated and added to the tristimulus values of the light emitted from the display:

$$\begin{aligned} X_{tot} &= X_{disp} + X_{ambient} \\ Y_{tot} &= Y_{disp} + Y_{ambient} \\ Z_{tot} &= Z_{disp} + Z_{ambient} \end{aligned} \tag{4}$$

Finally, the CIELAB values of the test colours are calculated. These calculated colours are saved and used as a reference.

The importance of the different parameters is tested thereafter. The value of one parameter is distorted at a time, and the corresponding output colour is calculated by using the equations 1 – 4. For instance, to test the importance of the offset, its value is distorted and the output colours as well as the colour differences between them and the reference colours are calculated. By running the similar distortion for all parameters, their importance to the colour calibration of the display can be tested.

In this study, the tests are made on 50 test colours taken from the reproducible colour space of the reference display. The test colours are picked from the Y levels of 0.1, 0.3, 0.5, 0.7 and 0.9. The test colours are shown in Figure 1.

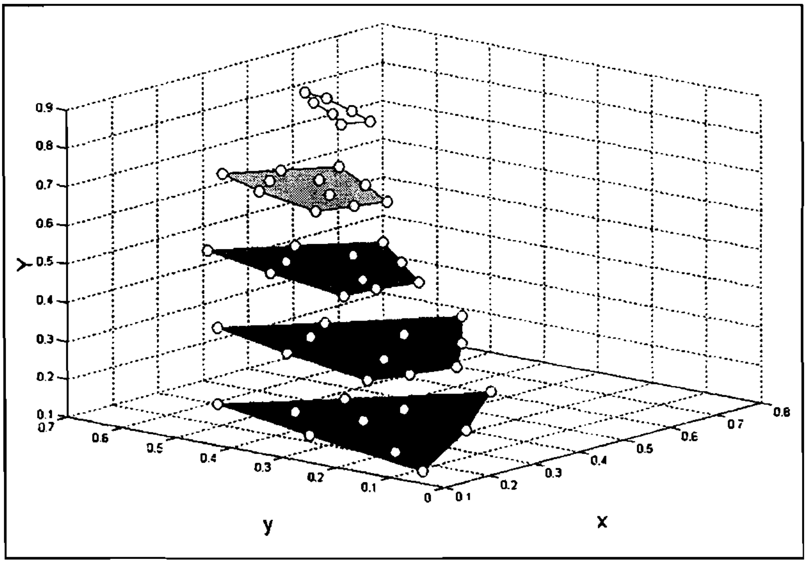

Figure 1. Test colours. The test colours (round points) were taken from the Y levels of 0.1, 0.3, 0.5 0.7 and 0.9.

Measurement of the parameters

The reference display used in this study is DELL D1025HE and its parameters were measured by the Minolta CS –1000 spectroradiometer. Before the measurements, the contrast and the brightness settings of the display were adjusted, so that the maximum dynamic range is used. The measurements were made in a dark room. The offset, gain and gamma values were measured for every channel. The gamma value was estimated in the least square sense by fitting the power function to the measured tone ramp.

The colours of phosphors and white were also measured in a dark room. Finally, the colour as well as the intensity of the ambient light reflected from the display were measured. Normal office lighting – a fluorescent lamp with a correlated colour temperature of 6500 K – was used. The values of the measured parameters are shown in Tables 1 and 2.

Table 1. The values of offset, gain and gamma measured on the DELL D1025HE.

Offset			Gain			Gamma		
Red	Green	Blue	Red	Green	Blue	Red	Green	Blue
0	0	0	1	1	1	1.9	2.2	2.2

Table 2. The phosphor and white point chromaticities, and the reflected ambient light on the DELL D1025HE. The tristimulus value of Y for the white point in a dark room is 1, and for the ambient light reflected from the screen 0.04.

Phosphor chromaticies				White point	Ambient light
	Red	Green	Blue	Y = 1	Y = 0.04
x	0.6200	0.2800	0.1500	0.3140	0.3200
y	0.3420	0.6050	0.0630	0.3380	0.3350

Distortion of the parameters

To distort the measured values of the parameters in the calculations, the essential question is how much the values of the parameters should be distorted. To decide the magnitude of the distortions, ten other displays were measured to find the typical range of variation for the values of the parameters. The magnitude of the distortion was chosen to correspond to the "typical" differences between the displays.

Results

As mentioned, this study tests the effects of inaccurate measurements of the different parameters on the colour calibration of CRT displays. In all tests, the measured values of the parameters (Tables 1 and 2) are used as undistorted reference values. In the tests, the value of one parameter is distorted at a time, and the resulting colour error is calculated for the 50 test colours shown in Figure 1.

The results are shown in Tables 3 – 8 and in Figures 2 – 6. In the Tables, the average colour errors are calculated for different luminance levels. Table 9 shows the average effects of the distortions of different parameters.

Table 3. The effects of offset distortions at different luminance levels. The undistorted offset values are R=0, G=0, B=0.

Distorted offset			Y=0.1			Y=0.3			Y=0.5			Y=0.7			Y=0.9		
R	G	B	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC
0.02	0.02	0.02	5.50	4.69	2.36	4.21	2.62	3.20	3.31	1.95	2.62	2.44	1.64	1.70	2.45	0.95	2.14
0.04	0.04	0.04	9.93	8.61	3.99	7.90	4.98	5.92	6.46	3.69	5.17	4.96	2.98	3.65	5.04	1.66	4.63
0.06	0.06	0.06	13.67	12.01	5.21	11.37	7.11	8.51	9.41	5.33	7.53	7.54	4.19	5.89	7.57	2.27	7.08
0.08	0.08	0.08	16.95	15.05	6.16	14.56	9.06	10.88	12.16	6.89	9.70	10.07	5.34	8.08	10.05	2.77	9.52
0.10	0.10	0.10	19.87	17.80	6.93	17.55	10.89	13.06	14.75	8.39	11.69	12.43	6.40	10.08	12.47	3.26	11.89
0.00	0.04	0.00	17.18	6.15	16.04	9.75	3.46	9.09	6.96	2.69	6.39	5.11	2.15	4.62	2.64	1.02	2.44
0.00	0.04	0.04	12.61	6.73	10.60	8.70	3.85	7.72	7.08	2.90	6.40	5.40	2.32	4.81	4.78	1.14	4.55
0.04	0.03	0.02	8.54	7.07	4.44	5.94	4.00	4.13	4.49	2.96	3.26	3.40	2.43	2.22	3.47	1.39	3.00
0.06	0.02	0.06	13.43	7.29	11.08	10.92	4.05	9.69	9.55	2.82	9.03	8.13	2.35	7.70	6.88	1.45	6.63
0.08	0.03	0.04	12.02	9.19	7.42	9.34	5.17	7.39	8.00	3.68	7.01	6.77	2.99	5.94	6.18	1.80	5.81

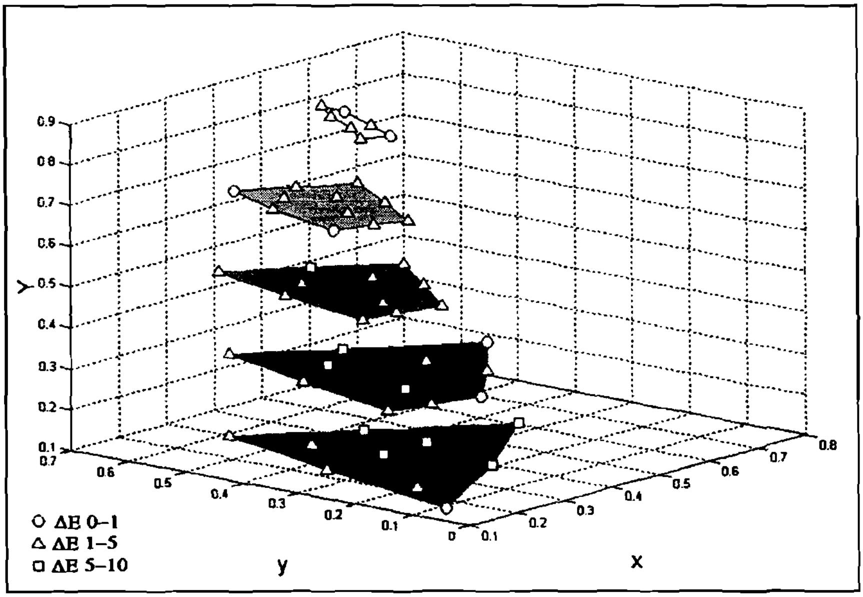

Figure 2. The effects of offset distortions on different test colours. The reference values are R=0, G=0, B=0. The distorted values are R=0, G=0.04, B=0.

Table 4. The effects of white point distortions at different luminance levels. The reference white point is x=0.3140, y=0.3380.

Distorted white point		Y=0.1			Y=0.3			Y=0.5			Y=0.7			Y=0.9		
x	y	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC
0.3457	0.3585	5.04	0.73	4.91	5.89	1.76	5.22	6.37	1.58	5.98	6.91	1.30	6.76	5.58	0.54	5.53
0.3324	0.3474	2.77	0.45	2.65	3.58	1.18	3.07	3.73	1.07	3.42	3.94	0.92	3.81	3.03	0.36	2.99
0.3127	0.3290	1.58	0.18	1.55	1.70	0.49	1.60	1.51	0.41	1.43	1.45	0.40	1.38	1.11	0.22	1.07
0.2990	0.3149	3.63	0.31	3.58	3.55	0.57	3.45	3.82	0.49	3.77	4.06	0.41	4.03	3.71	0.38	3.69

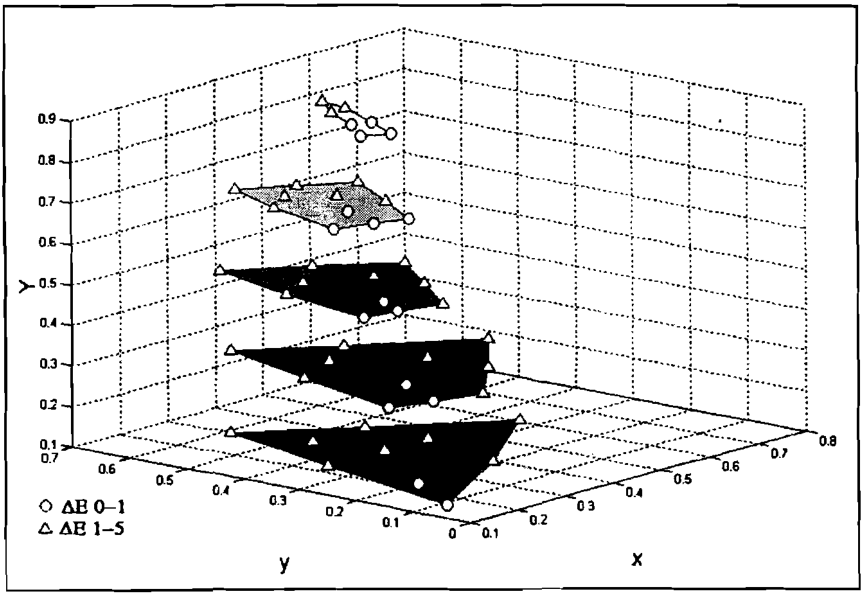

Figure 3. The effects of white point distortions on different test colours. The reference white point is x=0.3140, y=0.3380. The distorted white point is x=0.3127, y=0.3290.

Table 5. The phosphor combinations used in the tests.

	Rx	Ry	Gx	Gy	Bx	By
Combination 1	0.6250	0.3400	0.3100	0.5920	0.1500	0.0630
Combination 2	0.6250	0.3500	0.2800	0.6100	0.1550	0.0700
Combination 3	0.6350	0.3330	0.2800	0.5950	0.1520	0.0630
Combination 4	0.6100	0.3500	0.3070	0.6000	0.1500	0.0650
Combination 5	0.6550	0.3420	0.2980	0.5890	0.1510	0.0640
Combination 6	0.6140	0.3450	0.2960	0.5900	0.1400	0.0710
Combination 7	0.6300	0.3400	0.2900	0.6000	0.1500	0.0670
Combination 8	0.6180	0.3500	0.2800	0.6050	0.1520	0.0630
Combination 9	0.6040	0.3410	0.3090	0.5880	0.1510	0.0680

Table 6. The effecst of phosphor chromaticity distortions at different luminance levels.

	Y=0.1			Y=0.3			Y=0.5			Y=0.7			Y=0.9		
	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC
Combination 1	1.16	0.40	1.09	3.64	1.39	3.31	4.78	1.27	4.55	6.48	1.17	6.36	3.06	0.45	3.02
Combination 2	0.58	0.20	0.50	1.60	0.42	1.46	1.43	0.35	1.30	1.30	0.33	1.21	1.42	0.29	1.37
Combination 3	0.50	0.21	0.45	1.72	0.74	1.52	1.54	0.67	1.36	1.49	0.64	1.32	1.27	0.25	1.21
Combination 4	1.17	0.22	1.14	3.65	0.55	3.59	4.65	0.49	4.61	6.13	0.41	6.12	3.39	0.16	3.38
Combination 5	0.65	0.44	0.43	2.66	1.48	2.02	3.30	1.36	2.85	4.24	1.23	4.03	2.16	0.47	2.09
Combination 6	1.72	0.16	1.71	3.91	0.30	3.90	3.81	0.27	3.80	4.18	0.24	4.17	3.05	0.21	3.04
Combination 7	0.55	0.25	0.47	1.30	0.63	1.02	1.52	0.56	1.30	2.08	0.45	1.99	1.15	0.19	1.12
Combination 8	0.49	0.07	0.48	1.34	0.23	1.31	1.22	0.21	1.19	0.90	0.21	0.86	0.67	0.09	0.65
Combination 9	1.58	0.34	1.54	4.49	0.91	4.38	5.31	0.82	5.23	6.72	0.69	6.67	2.50	0.27	2.47

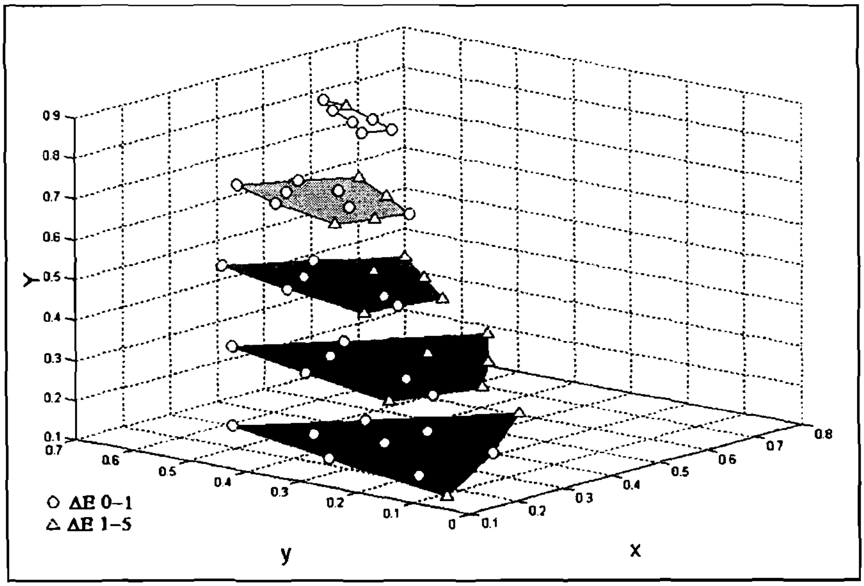

Figure 4. The effects of phosphor combinations on different test colours. The reference values are Rx=0.6200, Ry=0.3420, Gx=0.2800, Gy=0.6050, Bx=0.1500, By=0.063. The distorted values are Rx=0.6180, Ry=0.3500, Gx=0.2800, Gy=0.6050, Bx=0.1520, By=0.0360.

Table 7. The effects of gamma distortions at different luminance levels. The undistorted gamma values are R=1.9, G=2.2, B=2.2.

Distorted gamma values			Y=0.1			Y=0.3			Y=0.5			Y=0.7			Y=0.9		
R	G	B	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC
1.7	1.7	1.7	6.06	2.82	5.21	9.28	4.56	7.76	9.52	4.85	7.94	5.92	2.62	5.16	4.83	0.84	4.73
1.9	1.9	1.9	3.09	1.07	2.85	5.63	2.27	5.04	5.89	2.61	5.21	3.60	1.39	3.29	2.48	0.38	2.43
2.0	2.0	2.0	2.60	0.67	2.48	4.14	1.24	3.87	4.30	1.55	3.97	2.83	0.80	2.71	1.87	0.26	1.84
2.2	2.2	2.2	2.47	0.74	2.36	2.21	0.64	2.11	1.95	0.44	1.90	2.00	0.34	1.96	1.53	0.28	1.51
2.4	2.4	2.4	4.25	1.57	3.94	4.50	2.29	3.80	4.15	2.28	3.40	3.71	1.43	3.39	3.19	0.69	3.09
2.6	2.6	2.6	5.93	2.18	5.49	7.00	3.74	5.74	6.82	3.99	5.31	5.60	2.46	4.98	4.92	1.09	4.77
1.7	2.0	2.0	2.92	1.30	2.59	3.44	1.95	2.59	3.50	2.03	2.66	2.61	1.18	2.28	2.17	0.45	2.11
2.1	2.3	2.3	2.00	0.77	1.83	2.08	1.10	1.72	1.95	1.11	1.57	1.71	0.68	1.55	1.42	0.31	1.38
2.0	2.2	2.4	1.56	0.35	1.51	1.68	0.30	1.64	1.60	0.20	1.58	1.57	0.16	1.56	1.56	0.13	1.55
2.2	2.0	1.9	4.42	0.96	4.26	5.61	1.05	5.39	5.55	1.31	5.34	4.29	0.61	4.22	3.29	0.41	3.25

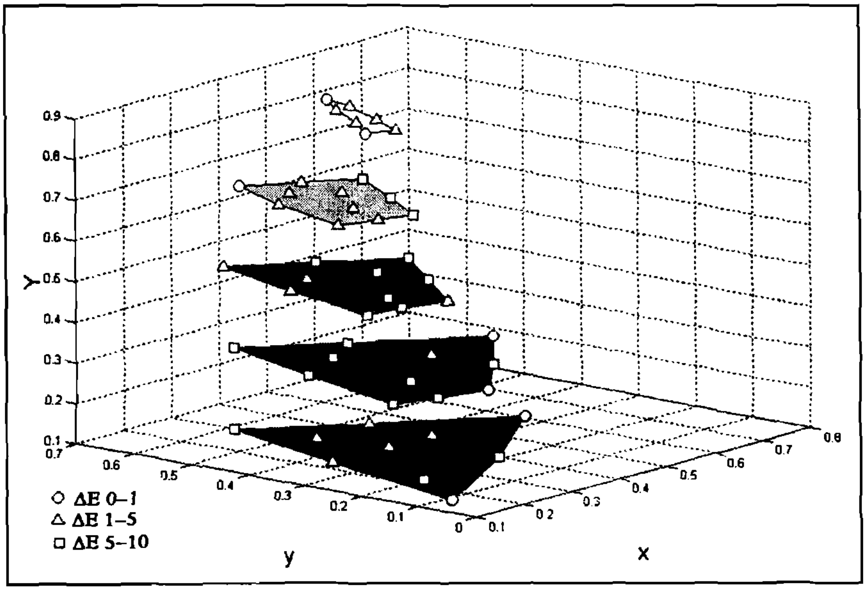

Figure 5. The effects of gamma distortions on different test colours. The reference values are R=1.9, G=2.2, B=2.2. The distorted values are R=1.9, G=1.9, B=1.9.

Table 8. The effects of the ambient light distortions at different luminance levels. The undistorted ambient light is Y=0.04, x=0.3200, y=0.3400.

Distorted ambient light			Y=0.1			Y=0.3			Y=0.5			Y=0.7			Y=0.9		
Y	x	y	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC
0.0000	0.3200	0.3350	21.76	14.88	14.77	13.34	4.75	12.35	8.79	2.38	8.34	6.26	1.00	6.14	3.96	0.28	3.94
0.0200	0.3200	0.3350	7.53	5.68	4.34	5.56	2.22	5.05	3.97	1.15	3.75	2.95	0.49	2.89	1.89	0.14	1.88
0.0600	0.3200	0.3350	5.37	4.30	2.65	4.44	1.99	3.92	3.40	1.07	3.18	2.65	0.46	2.59	1.74	0.13	1.73
0.0400	0.3127	0.3290	0.98	0.00	0.98	0.57	0.00	0.57	0.42	0.00	0.42	0.30	0.00	0.30	0.20	0.00	0.20
0.0400	0.3457	0.3585	3.62	0.00	3.62	2.06	0.00	2.06	1.48	0.00	1.48	1.06	0.00	1.06	0.71	0.00	0.71
0.0400	0.3324	0.3474	1.84	0.00	1.84	1.06	0.00	1.06	0.76	0.00	0.76	0.55	0.00	0.55	0.37	0.00	0.37
0.0400	0.2990	0.3149	3.06	0.00	3.06	1.81	0.00	1.81	1.33	0.00	1.33	0.97	0.00	0.97	0.66	0.00	0.66

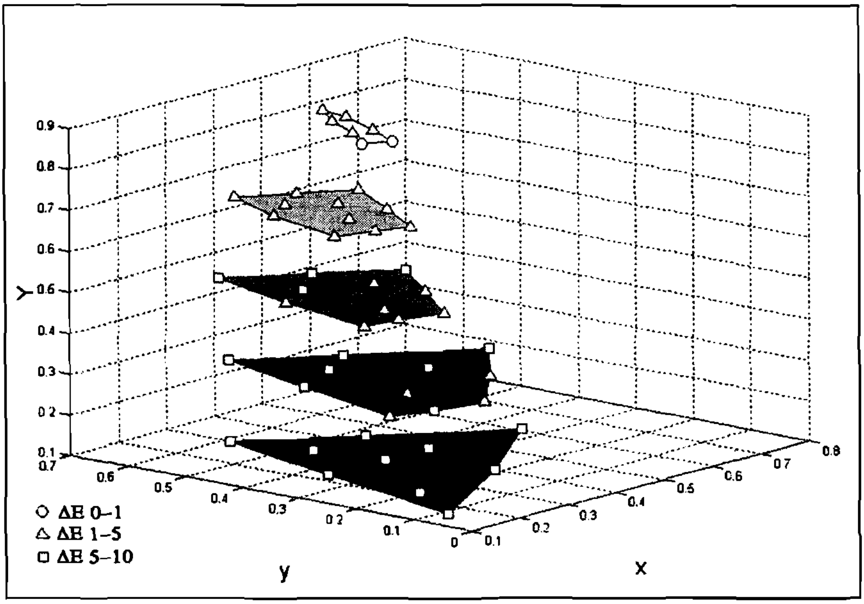

Figure 6. The effects of the ambient light distortions on different test colours. The reference values are Y=0.04, x=0.32, y=0.34. The distorted values are Y=0.02, x=0.32, y=0.34.

Table 9. The average effects of the distortions of different parameters.

	Y=0.1			Y=0.3			Y=0.5			Y=0.7			Y=0.9		
	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC	ΔE	ΔL	ΔC
offset	12.97	9.46	7.42	10.02	5.52	7.96	8.22	4.13	6.88	6.63	3.28	5.47	6.15	1.77	5.77
gamma	3.53	1.24	3.25	4.56	1.92	3.97	4.52	2.04	3.89	3.38	1.17	3.11	2.72	0.48	2.67
phosphor	0.94	0.25	0.87	2.70	0.74	2.50	3.06	0.67	2.91	3.73	0.60	3.64	2.07	0.26	2.04
White point	3.26	0.42	3.17	3.68	1.00	3.33	3.85	0.89	3.65	4.09	0.76	3.99	3.36	0.37	3.32
ambient light	6.31	3.55	4.47	4.12	1.28	3.83	2.88	0.66	2.75	2.11	0.28	2.07	1.36	0.08	1.36

According to the test results, the inaccurate measurement of any parameter may cause significant errors in the colour calibration of a display. It is, however, true that the type of the colour calibration error depends on the parameter. The results show that inaccurately measured gamma values cause colour calibration errors both in luminance and in chromaticity, and the errors are significant in the whole reproducible colour space (Table 7 and Figure 5). Also the miscalibration of the offset is an important source of colour calibration errors but the effect is dissimilar to the miscalibration of the gamma. The miscalibration of the offset causes the most significant colour calibration errors at a low level of luminance (Table 3 and Figure 2). The results also show that it is important to measure the offset separately for every channel. If the offset value of one channel is measured inaccurately, it will produce very large errors in colour calibration.

The miscalibration of the white point colour seems to be equally important in the whole luminance range, due to the principle followed in the calculation of the CIELAB values. The L*a*b* values were calculated in every simulation by using the real white point of the display, not the white point of the reference display. Therefore, if a distortion changes the white point of the display, the distorted white point is used in the calculations of the L*a*b* values. The colour calibration of a display seems to be sensitive to the inaccuracy of the white point measurement. This is illustrated by Figure 3, where the white point of D65 (x=0.313, y=0.329) is used as a distorted white point. As mentioned, the colour temperature of the reference display was adjusted before the measurements to 6500 K. Therefore the measured white point (x=0.314, y=0.338) deviates from D65 only slightly.

The chromaticities of the three phosphors were varied concurrently in the simulations. Every phosphor colour set is used on the displays. For the simulations some sets were measured from the displays and some were those given by the display manufacturers. Compared with the other parameters, the inaccuracy of the measurement of phosphor chromaticities produces, on the average, the smallest colour calibration error on the display (but see Engeldrum(1990): the resulting colour calibration error is largely dependent on the phosphor sets used in the calculations).

The ambient light reflected from the screen causes significant colour calibration errors, especially if the light intensity is measured inaccurately. The accurate measurement of the ambient light intensity seems to be more important than the accurate measurement of the ambient light chromaticity. The colour calibration error resulting from the inaccurate measurement of the light intensity is shown in Figure 6 where the ambient light intensity is distorted to Y=0.02. The reference intensity is 0.04. The ambient light chromaticity was not distorted. The miscalibration of the ambient light has the strongest effect at a low level of luminances.

Discussion

The results provide some guidelines for display calibration, if the values of the parameters cannot be measured with the highest accuracy. First, we propose that the display offset and gamma should be measured for every channel separately and with a higher accuracy. The accurate calibration of the display gamma is important because miscalibrations cause colour calibration errors in the whole reproducible colour space. On the other hand, inaccuracies in the measurements of the display offset may cause very large colour calibration errors, especially at a low level of luminances.

We also propose that the white point of the display should be measured with a higher accuracy. The miscalibration of the white point causes colour calibration errors in the whole reproducible colour space.

On the average, the smallest colour calibration errors come from the miscalibration of phosphor chromaticities. Therefore, if the values of all parameters cannot be measured with the highest accuracy, we propose a lower accuracy for the measurement of phosphor chromaticities. For instance, the sets of red, green and blue phosphors used in the displays could be grouped into a few groups, and lowaccuracy measurements could be used to find the group of the calibrated display.

Also the effects of the miscalibration of the ambient light reflected from the screen were simulated. According to the test results, an inaccurate measurement of the ambient light chromaticity causes smaller colour calibration errors than an inaccurate measurement of the light intensity. Therefore, the main emphasis in the ambient light measurements should be on the intensity of the light.

Conclusions

The objective of this study was to analyse the importance of the miscalibration of the different parameters in CRT displays. The question is significant if the display is calibrated by visual tests and the values of all parameters cannot be measured with the highest accuracy, due to the limited number of visual tests made by the user. Calculations were made to analyse the importance of the miscalibration of the offset, the gain, the gamma, the phosphor and white point colours and the ambient light.

One parameter was disrtorted at a time, and the resulting colour calibration error was calculated. The magnitude of the distortion was based on the measurements of ten displays – the range of variation in the parameters was used as the range where the parameters were distorted in the simulations. According to the test results, the smallest colour calibration errors are caused, on the average, by inaccurate measurements of the phosphor colours. On the other hand, especially the offset, the gamma and the white point of the display should be measured with a higher accuracy. An inaccurate measurement of the ambient light intensity reflected from the display causes larger colour calibration errors than the inaccurate measurements of the ambient light chromaticity.

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