AN IMPROVED METHOD OF VISUAL GAMMA CORRECTION FOR LCD DISPLAYS

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ABSTRACT

In this study an improved method for visual gamma correction is developed. Eight half tone patterns were designed to generate relative luminances from 1/9 to 8/9 for each colour channel. A psychophysical experiment was conducted to find the digital count corresponding to each relative luminance by visually matching the half tone background to the uniform colour patch. Both inter- and intra-observer variability for the eight luminance matches in each channel were assessed and the luminance matches proved to be consistent across observers ($\Delta E_{00}<3.5$) and repeatable ($\Delta E_{00}<2.2$). Based on the individual observer judgements, the display opto-electronic transfer functions (OETF) were estimated by using 3rd order polynomial regression. The performance of the proposed method is evaluated by predicting the CIE tristimulus values of a set of coloured patches using these observer-based OETFs and comparing them to the OETF obtained from actual luminance measurements. The resulting colour differences range from 2 to 4.6 ΔE_{00}. We conclude that this observer-based method of visual gamma correction is useful to estimate the OETFs for LCD displays. Its major advantage is that no particular functional relationship between digital inputs and luminance outputs has to be assumed.

Keywords: display calibration, psychophysical, gamma correction, luminance matching, observer-based calibration.

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INTRODUCTION

Display gamma correction is an essential step for colour management, since the display optoelectronic transfer function[1], OETF, varies in different displays and significantly affects colour appearance. The OETF is used to describe the relationship between the digital signal used to drive a given display channel and the luminance produced by that channel. This is usually a nonlinear relationship for computer-controlled devices. For CRT displays, this function has a physical basis, sometimes referred to as "gamma" and it is the aspect of the display characterisation described by the gain-offset-gamma (GOG) portion of the traditional CRT-characterisation model[2].

However, for LCD displays, the OETF depends on the specific cell construction, the operating mode, and usual remapping via a voltage ladder or look-up table to compensate for a suboptimal relationship between voltage and perceived lightness or to mimic CRTs[3]. As described by Glasser [4], the OETF of an LCD display can be very different from that of a CRT as shown in Figure 1. Rather than a gamma curve, Kwak et.al[5] also described the OETF for LCD display is a S-curve and build a model to predict it. Nowadays, although display manufacturers have attempted to reduce the difference of the OETF between CRTs and LCDs, there is still no guarantee that the GOG model works for all LCD displays. Many researchers [3,6] have suggested to solve this problem for LCD display characterisation by building one-dimensional look-up tables (LUTs), generally formed by interpolation, such as the PLCC model[7].

Observer-based gamma correction methods [8,9] have been developed to avoid the necessity of colour measurement instruments and have been successfully used in commercial software for CRT display characterisation in many instances, such as Adobe Gamma and EasyRGB. This technique requires an observer to match the typical black-white half tone pattern (relative luminance of 0.5), to a uniform luminance patch. Based on observer judgments, the gamma value can be estimated by assuming a particular OETF (power function for CRTs) and gamma correction can then be performed. However, luminance matches based on a single pattern are not sufficient to estimate the unknown OETF of an arbitrary LCD display, since more than one point of the OETF needs to be estimated if the functional form of the OETF is unknown (cf fig. 1). The purpose of the present study is to use a set of spatial half tone patterns that allow us to estimate several points on the OETF based on visual luminance matches and to evaluate whether the OETF derived from observer judgments is sufficiently accurate to characterise displays.

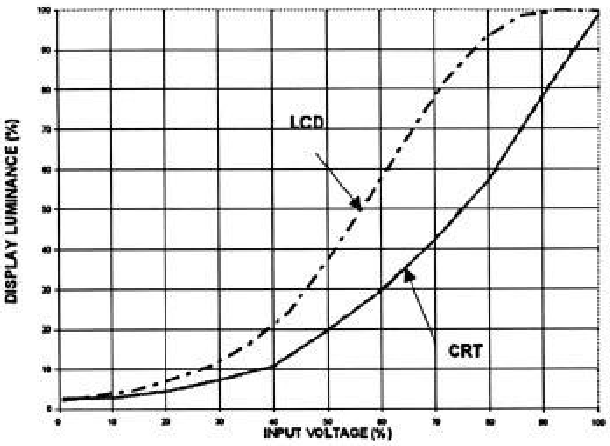


Fig 1. Typical OETF for a CRT and LCD (from Glasser[3]).

To estimate the OETF, we use 8 different half tone images in order to generate 8 data points for the OETF of each colour channel. Psychophysical experiments are then conducted with 30 naïve observers to evaluate the performance of the proposed observer-based gamma correction.

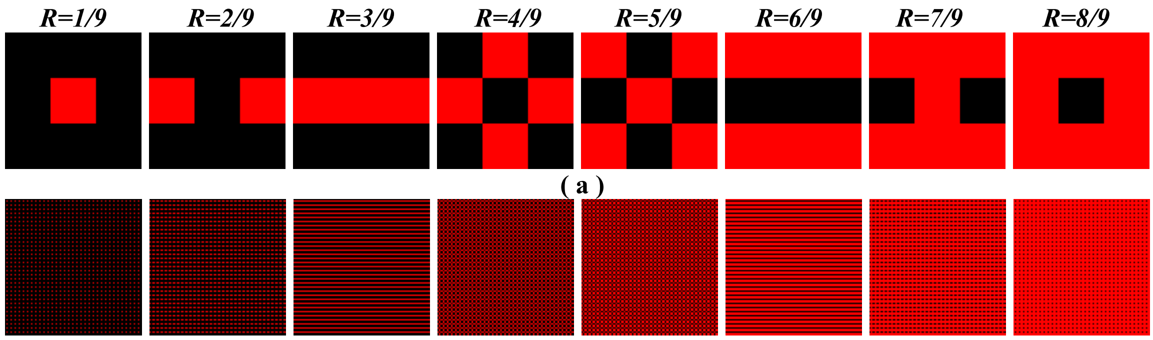
METHOD

To estimate the OETF for the three channels of an LCD display, the following three steps are performed: Firstly, half tone patterns are designed in order to generate different relative luminances for each of the three colour channels. Secondly, the digital RGB values corresponding to the relative luminances for each channel are identified by perceptual observer judgments. Finally, based on the 8 measurements obtained for each colour channel, the relationship between input digital RGB signals and the output luminances is characterised by fitting a 3rd order polynomial function.

Pattern Design

Relative luminances are derived by asking observers to visually match the luminance of a uniform disk with the overall luminance of the background, a half tone pattern. 8 different half tone patterns were used generating backgrounds with relative luminances varying from 1/9 to 8/9 for each colour channel (Figure 2). Each half tone pattern consists of 9 3x3 pixel blocks; the pixels in each block can either be assigned the peak output (highest digital value) or black (digital value of 0) as illustrated in Figure 2a. Different average luminances are achieved correspondingly by using different distributions of blocks with peak output and black as demonstrated in Figure 2b.

To evaluate the performance based on visual luminance matches, ground truth data are obtained by displaying these patterns on three different LCD panels and measuring the output luminance associated with each pattern using a spectroradiometer (PhotoReserach PR650). The relative luminance of each pattern is then calculated based on the luminance of each individual block, as listed in Table 1. This calculated luminance is referred to as ‘Reference’ in Table 1. The rows below contain the measured relative luminances of the 8 different spatial patterns when displayed on three different LCD displays. There is in general a good agreement between the measurements and the reference luminance; only for 4 out of 32 data points, we find deviations larger than 5 %. This could be due to the cross-talk of LCD panel elements that is supposed to be solved for modern active-matrix displays. Based on these preliminary ground truth measurements, we adopted Display 1 for the current study.



(b)

Fig 2. Pattern Design. (a) Distribution of peak colour (red) and black for a 3x3 pixels block
(b) Corresponding Pattern as it appears on the screen

Table 1: Measured relative luminances for the eight half tone patterns

Reference	*0.11*	*0.22*	*0.33*	*0.44*	*0.56*	*0.67*	*0.78*	*0.89*
Display 1	0.12	0.22	0.34	0.44	0.58	0.67	0.78	0.90
Display 2	0.10	0.21	0.34	0.39	0.50	0.67	0.76	0.87
Display 3	0.12	0.22	0.29	0.43	0.53	0.64	0.76	0.85

Psychophysical Experiment

Stimuli were displayed on a 21 inch Dell LCD panel, rendered by a Dell T3400 PC with a Nvidia FX5700 graphic card. The display has a D93 white point with a maximum luminance of 114 cd/m^2. A graphical interface was designed to provide standard viewing conditions and to collect the observer responses. As shown in Figure 3, a uniform disk with a 2^o diameter is displayed on a half tone background pattern (6^o x 6^o of visual angle). The test pattern is surrounded by a uniform mid-grey.

During the experiment, the observer is seated in front of the display at a distance of 100 cm. Due to the viewing angle dependency of LCD panel, the height of the chair is also adjusted by each observer until the centre of the uniform patch is at the same level to the observer’s eyes. The experimental room is lit with a cool white fluorescent light to simulate standard office lighting. The task of the observer is to adjust the luminance of the central uniform patch by using the slider located at the bottom of the interface until it matches the luminance of the half tone background. There is no time limit for this matching task, but usually matches are achieved within 10 seconds. The digital RGB value of the central uniform colour patch is saved after each luminance match. To obtain a measure of observer intra-variability, the same task was repeated during a separate session within a 5 minute interval.

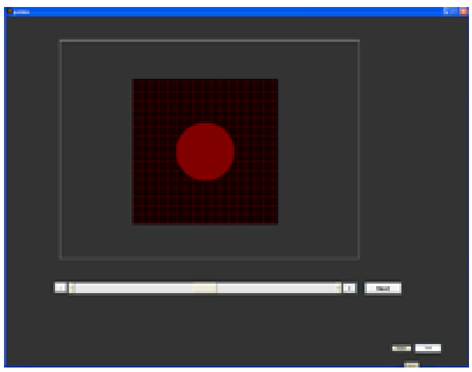


Fig 3. Experimental interface

The entire experiment lasted approximately 15-20 minutes for each observer. 30 observers participated in the experiment (age range: 21-57 years; 17 females). All of them were naïve as to the purpose of the experiment, with the exception of 2 of the authors. All participants were colour-normal as assessed with the Cambridge Colour Test[10]. The total number of observer assessments is 1440 (30 observers x 8 background patterns x 3 channels x 2 sessions).

Estimating the OETF

Based on the experimental data for each observer, the OETF representing the relationship between digital input signals and the relative luminance for each channel can be derived. Conventionally, when the relative luminances are measured with a spectroradiometer, a linear or non-linear interpolation is used since each individual data point is fairly reliable. In our study the relative luminances are obtained by luminance matches performed by naive observers; as a consequence each luminance estimate contains an inherent error. To make the derivation of the OETF more robust and less susceptible to noise, we use a 3rd order polynomial regression to characterise the OETF for each channel, which is fixed to pass point (0,0) and (1,1).

RESULTS AND DISCUSSION

From the perceptual luminance matches we obtain an estimate of the digital RGB value associated with a particular relative luminance of the background pattern. For example, a red-black background pattern (Fig.2) defined by R = 2/9 (i.e. a relative luminance of 0.22) is matched to a uniform disk with a digital R value of about 0.55 (fig. 4).

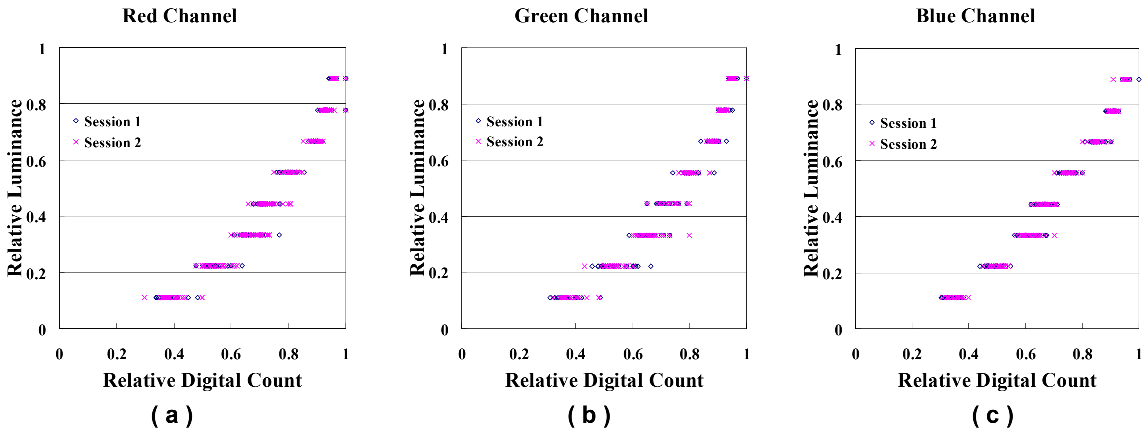


Fig 4. Experimental results (a) Red Channel, (b) Green Channel, (c) Blue Channel

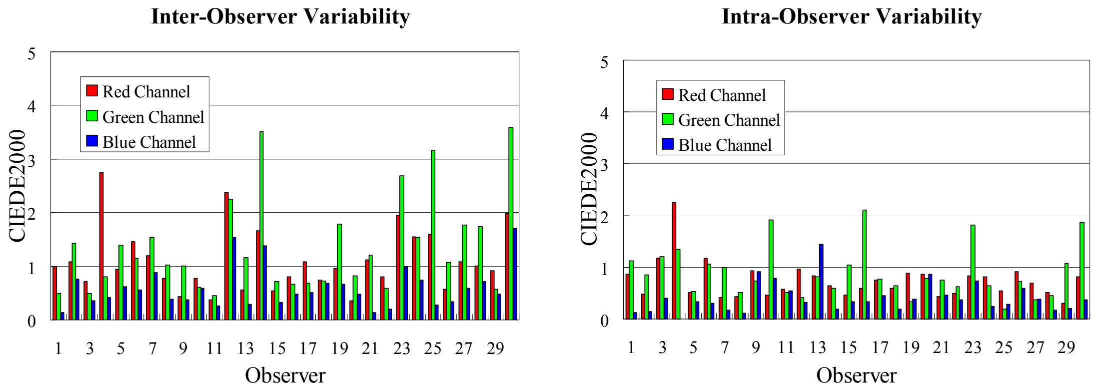
These luminance matches are therefore informative about the nonlinear mapping from the digital input values to the light output. In Figures 4a-c the relative luminance of the background pattern is plotted as a function of the digital input value of the matching uniform disk, for all 30 observers and for all 3 channels (Red, Green, Blue). The blue open diamonds and red crosses indicate the matches obtained in experimental session 1 and 2 respectively. The figures clearly illustrate the non-linear relationship between digital counts and relative luminance confirming that this nonlinearity can be determined using visual judgements. Due to this nonlinearity, the lowest relative luminance (1/9) corresponds to a relative high digital input (approximately 0.4).

Observer Variability

Gamma correction based on visual judgments is only useful if there is consistency between observers and repeatability for each individual observer. Inter-observer variability indicates the extent to which individual observers agree with the average observer whereas intra-observer variability indicates how consistent the individual observer is across different sessions. To calculate both variability measures, each digital RGB value is transformed into device-independent CIE XYZ tristimulus values by using the ground truth measurements obtained with the spectroradiometer. Then the CIEDE2000 colour difference formula [11] was used to calculate MCDM [12], the mean color difference to the mean value, for each colour channel for inter-observer variability. For intra-observer variability, the CIEDE2000 colour difference between the observer's judgment in session 1 and in session 2 was calculated and averaged for each colour channel. Individual observer performance for both inter- and intra- observer variability are shown in Figure 5, while the average and standard deviation for all 30 observers' performance for each colour channel are listed in Table 2.

Table 2. Inter-observer and intra-observer variability for 30 observers

Inter-Observer Variability				*Intra-Observer Variability*			
Channel	*Mean Difference*	*Max Difference*	*STDEV*	*Channel*	*Mean Difference*	*Max Difference*	*STDEV*
Red	1.1	2.7	0.7	Red	0.7	2.2	0.4
Green	1.4	3.5	0.8	Green	0.9	2.1	0.5
Blue	0.6	1.5	0.4	Blue	0.4	1.4	0.3



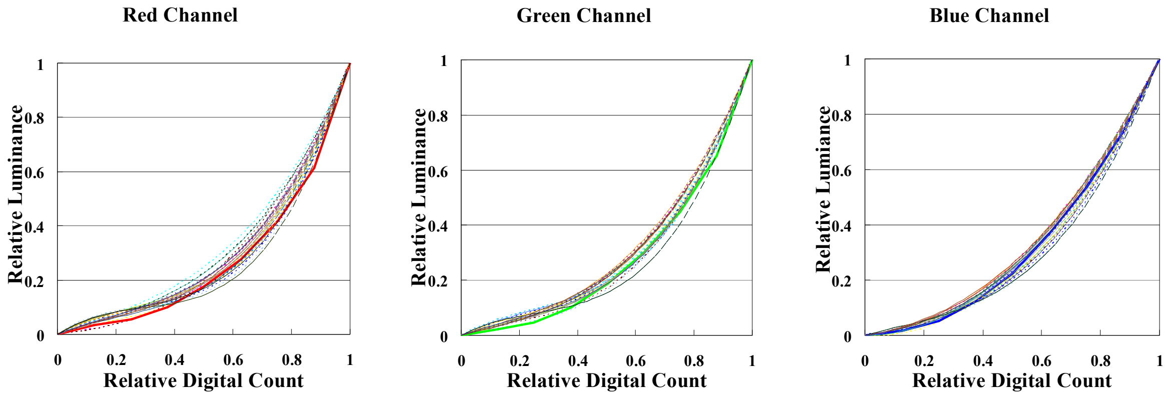
(a) **(b)**

Fig 5. **Observer Variability** (a) inter–observer variability, (b) intra-observer variability

The inter-observer variability, as shown in Figure 5a and Table 2, is always within 4 ΔE_{00} of the grand average. The smallest variability is found for the blue channel (mean=0.6) and the largest for the green channel (mean=1.4). The small variability for the blue channel is probably due to the low absolute luminance output of the blue channel and the low spatial resolution of the yellow-blue channel in the human visual system[13,14]. The low spatial resolution facilitates matches between the patterned background and the homogeneous disk, since the patterned background appears almost homogenous for the blue channel. The intra-observer variability is roughly 2/3 higher of the inter-observer variability (cf Table 2). The green channel has also much larger intra-observer variability (ΔE_{00} = 0.9) compared to that of the blue channel (ΔE_{00} = 0.4). In general, the observer variability is fairly small indicating that this luminance matching task can be performed reliably and consistently by naive observers. From observer variability results for 30 observers, there is no clear gender-dependence. The variability between observers found in this study is probably not due to the particular task involved, that is, luminance matching between a homogenous disk and a patterned background, but is likely to be a consequence of the variation in V_λ observed in the population. Having established the observer consistency in this luminance matching task we can now use this information to derive the OETFs.

Estimating the OETF

Based on the measurements of each individual observer (Figures 4a-c), the OETFs are derived by fitting a 3rd order polynomial as indicated in Figure 6 by the dashed lines. The solid line depicts the fitted curve based on the spectroradiometric measurements assuming the average luminous efficiency function for photopic viewing conditions (V_λ)[12]. For all three channels, the OETF derived from the measured luminances is roughly in the middle of the visual luminance relationships derived from our set of observers result (Figure 5a-c), hence confirming that there is no bias introduced by using perceptual luminance matches. It can also be seen that visual luminance matches yield good estimates of the OETF for higher luminances (relative digital input above 0.4).

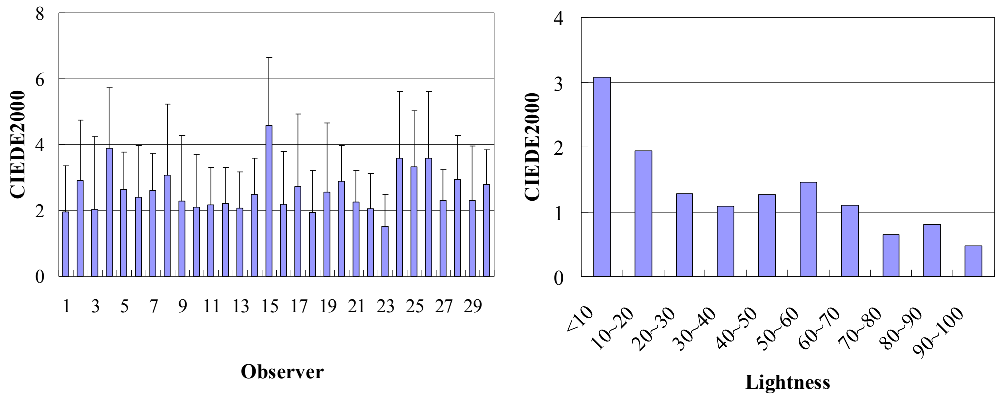


(a) (b) (c)

Fig 6. **OETF based on observer luminance matches** (a) Red Channel, (b) Green Channel, (c) Blue Channel. The solid line depicts the curve obtained from actual luminance measurements (ground truth data).

Performance Evaluation

To evaluate the performance of the visual gamma correction technique, we predict the CIE tristimulus values of a set of coloured patches using the fitted OETF based on the luminance measurements and compare these ground truth data with the tristimulus values predicted from the luminance matches of the individual observers (cf fig 6). The 8-bit RGB values for each channel were sampled at 15 intervals from 0 to 255. Hence, 18x18x18 RGB digital signals were generated for testing purposes. Then the colour difference (ΔE_{00}) between the coloured patch based on the observer's OETF and the coloured patch derived from the measured OETF (based on CIE V_{λ}) was calculated for each of the 18^3 colours and mean and standard deviations were obtained. Figure 7a illustrates the average colour deviation (across all 18^3 colour patches) between the individual observers and the ground truth data, whereas Figure 7b shows the colour deviation between the average observers and the ground truth data.



(a) (b)

Fig 7**. Performance for OETF estimation** (a) Colour deviation for each individual observer. (b) Colour deviation as a function of lightness derived from the average of our sample.

Table 3: Performance of OETF estimation based on observer data

30 Observers	Mean	Min	Max	STDEV
ΔE_{00}	2.6	1.0	4.6	0.7

The colour errors resulting from the OETFs fitting based on individual observer data are listed in Table 3: the average colour difference is approximately 2.6 with a maximum value of 4.6 ΔE_{00}, which is well within tolerable colour differences. To further illuminate the source of the observed colour errors, we calculated the colour differences based on the average luminance match (in our sample) for each luminance level separately. Figure 7b shows that the performance is worse for dark colours (lightness <20), which is due to the fact that our estimation is biased towards high luminances. The mean colour difference derived from our average observer is very small, approximately 1.7 ΔE_{00}. The novelty of our approach is the use of particular spatial patterns to derive the OETF. Our method will work as long as there is no clear flicker which is the case for LCD displays. Although LCDs suffer from a cross-talk problem, which could result in a slight error in the estimated relative luminance, this problem becomes less severe in modern LCD panels. Because of the non-linear relationship, although the relative luminance steps are equal, the estimation is biased towards high digital values and there is less dark digital input adopted. It could be better to consider more dark samples in the pattern design.

We used a 2^o uniform colour patch surrounded by a 6^o background in this study, viewed from 100 cm. A different viewing distance could also affect the observer performance, since the spatio-chromatic sensitivity of human observers does not fall off uniformly with viewing distance[12]. Viewing distance will also affect the perceived task difficulty: for larger viewing distances the half tone background pattern is easier to match to the uniform disk since the individual patterns that constitute the background can no longer be resolved resulting in a perceptually uniform background.

CONCLUSIONS

The purpose of our study was to improve and extend gamma correction techniques based on perceptual judgements to LCD panels, since current visual gamma correction methods are most suitable for CRTs but can completely fail for LCDs. Since it is well-known that the display OETF has significant effects on the colour appearance of images, it is vital to obtain a reliable estimate of the relationship between digital input values and the actual light output. We have tested our method using a sample of 30 naïve observers and the resulting colour differences (deviation from ground truth data) are well within the acceptable colour limits. We conclude that our novel gamma correction techniques can play a significant role in improving current colour management systems.

ACKNOWLEDGEMENTS

The equipment was funded by the Wellcome Trust (GR/080205). This work has been supported by TruColour Ltd and the Spanish research project TIN2008-04998; KX and CF were supported by TruColour Ltd.

REFERENCES

1. CCIR Recommendation 709, "Basic parameter values for the HDTV standard for the studio and for international programme exchange,"now ITU-R BT. 709.
2. R.S. Bern, R.J. Motta and M.E. Gorzynski, "CRT Colorimetry. Part I: theory and practice", *Color Research and Application*, **18** pp. 299–314, 1993.
3. E.A. Day, L. Taplin and R.S. Berns,"Colorimetric characterization of a computer-controlled liquid crystal display", *Color Research and Application,* **29**, pp. 365–373, 2004.
4. J. Glasser, "Principles of display measurement and calibration", Chapter 14 in *Display Systems: Design and Applications,* L.W. MacDonald and A.C. Lowe, Eds., John Wiley & Sons: Chichester, UK, 1997.
5. Y. Kwak and L. MacDonald , "Characterisation of a desktop LCD projector ", *Displays,* 21, **5**, pp. 179–194, 2000.
6. M.D.Fairchild and D.R.Wyble, "Colorimetric characterization of the Apple studio display (Flat panel LCD)", *Munsell Color Science Laboratory Technical Report*, 1998.
7. D.L. Post and C.S. Calhoun, "An evaluation of methods for producing desired colours on CRT monitors", *Color Research and Application*, **14**, pp. 172–186,1989.
8. L. MacDonald, "Colour in visual Display"., Chapter 7 in *Colour Physical for Industry* , Second Edition, pp. 373–426 , 1997.
9. A.Neumann, A.Artusi, L.Neumann, G.Zotti and W.Purgathofer, "Accurate display gamma functions based on human observation", *Color Research and Application*, **32**, pp. 311–319 2007.
10. J.P. Reffin, S. Astell S. and J.D. Mollon, "Trials of computer-controlled colour vision test that preserves the advantages of pseudoisochromatic plates". *Colour Vision Deficiencies X,* pp. 69–76, 1991.
11. M.R. Luo, G.Cui, and B.Rigg, "The development of the CIE 2000 Colour Difference Formula," *Color Research and Application*, **26**, pp. 340350, 2001.
12. F.W. Billmeyer, Jr. and P.J. Alessi, "Assessment of color-measuring instruments", *Color Research and Application*, **6**, pp. 195–202 1981.
13. G.Wyszscki and W.S. Stiles, *Color Science: Concept and Methods, Quantitative Data and Formulae*, Second Edition, John Wiley & Sons, 1982.
14. S.M. Wuerger, A.B. Watson, and A. Ahumada, "Towards a spatio-chromatic standard observer for detection". In *Human Vision and Electronic Imaging VII*, B.E. Rogowitz and T.N. Pappas, Eds, Proceedings of SPIE, San Jose, CA, Vol. **4662**, pp. 159–172, 2002.