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Visual gamma correction for LCD displays

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ABSTRACT

An improved method for visual gamma correction is developed for LCD displays to increase the accuracy of digital colour reproduction. Rather than utilising a photometric measurement device, we use observers' visual luminance judgements for gamma correction. 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 on an LCD display to find the digital signals corresponding to each relative luminance by visually matching the half-tone background to a 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 function (OETF) was estimated by using either a 3rd order polynomial regression or linear interpolation for each colour channel. The performance of the proposed method is evaluated by predicting the CIE tristimulus values of a set of coloured patches (using the observer-based OETFs) and comparing them to the expected CIE tristimulus values (using the OETF obtained from spectro-radiometric 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 OETF for LCD displays. Its major advantage is that no particular functional relationship between digital inputs and luminance outputs has to be assumed.

1. Introduction

Display characterisation is an essential step for colour management. The traditional CRT techniques have been summarised by Berns [1] and can be described as two stages: the gain-offset-gamma (GOG) model [1] to characterise the display opto-electronic transfer function (OETF) [2] relating the rgb digital signal used to drive a display channel to the relative luminance produced by that channel; the second step involves a 3×3 linear transform to convert the relative RGB luminances to device-independent CIE XYZ tristimulus values. The first stage is usually referred to as display gamma correction and is critical for display characterisation, since the OETF varies between displays and significantly affects colour appearance. The OETF is usually a non-linear function for computer-controlled devices. For CRT displays, this function, sometimes referred to as "gamma", has a physical basis; the non-linear part of the GOG model can be described by a power function with exponent 'gamma' [2].

In contrast, 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 Fig. 1. Rather than using a power function, Kwak and MacDonald [5] modeled the OETF for LCD displays as an S-shaped curve.

Although display manufacturers have attempted to standardise the behaviour of CRT and LCD displays, there is currently no guarantee that the GOG model works for all LCD displays. Many researchers [3,6] have suggested to solve the problem of LCD display characterisation by building one-dimensional look-up tables (LUTs), generally formed by interpolation, such as the Piecewise Linear interpolation assuming Chromaticity Constancy model (PLCC) [7].

Observer-based gamma correction methods [8–10] have been developed to avoid the necessity of colour measurement instruments and have been successfully used in commercial software for CRT display characterisation, such as Adobe Gamma (Adobe, US) and EasyRGB (Logical, Italy). This technique requires an observer to match the typical black-peak-output half tone pattern (relative luminance of 0.5), to a uniform luminance patch. Based on observer judgments, the parametersc can be estimated by assuming a particular OETF (power function for CRTs) and gamma correction can then be performed. However, this technique is not immediately applicable to LCD displays for two reasons: First, 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

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form of the OETF is unknown (cf Fig. 1). Second, little is known about the observer variability of such luminance matches on LCD displays.

The purpose of the present study is to use a modified set of spatial half tone patterns [9] 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.

To estimate the OETF, we use eight different half tone images in order to generate eight 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.

2. Methods

To estimate the OETF for the three channels of a LCD display, the following three steps are performed: First, half tone patterns are designed in order to generate different relative luminances for each of the three colour channels. Second, the digital rgb values corresponding to the relative luminances for each channel are obtained by perceptual observer judgments. Finally, based on the eight measurements obtained for each colour channel, the relationship between input digital rgb signals and the output luminances is estimated.

2.1. Pattern design

Relative luminances are obtained by asking observers to visually match the luminance of a uniform disk with the overall luminance of surrounding area which is rendered using a half tone pattern. Note that for a CRT display, there is a common problem with rendering vertical stripe or checkerboard patterns as the light beam scanning the screen line by line has to switch between full strength and zero very rapidly and it is not physically able to do so. This particular problem does not exist for LCD displays. Thus, eight different half tone patterns were used to generate backgrounds with relative luminances varying from 1/9 to 8/9 of the peak-output luminance for each colour channel (Fig. 2). Each half tone pattern consists of a 3 × 3 pixel block; the pixels in each block can either be assigned the peak-output (highest digital value) or black (digital value of 0) as illustrated in Fig. 2a. Different average luminances are achieved correspondingly by using different distributions of blocks with peak-output and black as demonstrated in Fig. 2b.

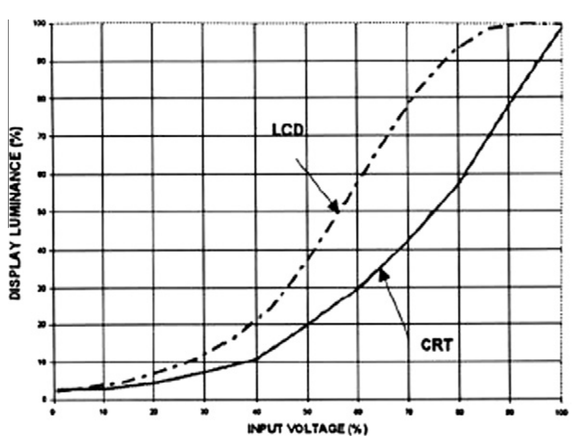

Fig. 1. Typical OETF for a CRT and LCD (from Glasser [4]).

To evaluate the performance based on visual luminance matches, these patterns are displayed these patterns on three different LCD panels and measuring the output luminance associated with each pattern using a spectroradiometer (PhotoResearch 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 eight 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 measurements, we adopted Display 1 for the current study.

2.2. Psychophysical experiment

Stimuli were displayed on a 21" Dell LCD panel, rendered by a Dell T3400 PC with a Nvidia FX5700 graphics 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 Fig. 3, a uniform disk with a 2° diameter is displayed on a half-tone background pattern (6° × 6° 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 panels, the height of the chair is also adjusted by each observer so that the centre of the uniform patch is at the observer's eye level. The room is lit with a cool white fluorescent light to simulate typical 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 visually matches the luminance of the half-tone background (Fig. 3). There is no time limit for this matching task, but usually matches are achieved within 10 s. 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 in a separate session within a 5 min interval.

The entire experiment lasted approximately 15–20 min for each observer. Thirty observers participated in the experiment (age

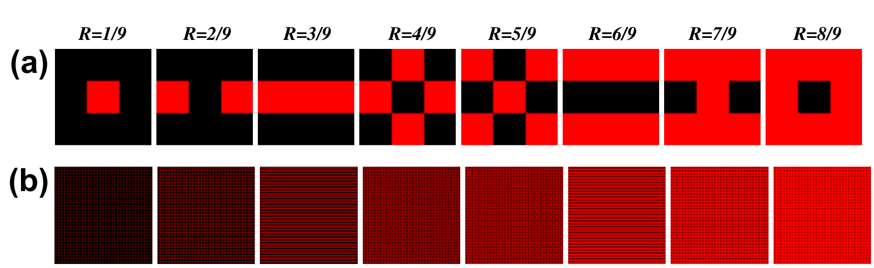

Fig. 2. Pattern design: (a) distribution of peak colour (red) and black for a 3 × 3 pixels block (b) corresponding pattern as it appears on the screen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

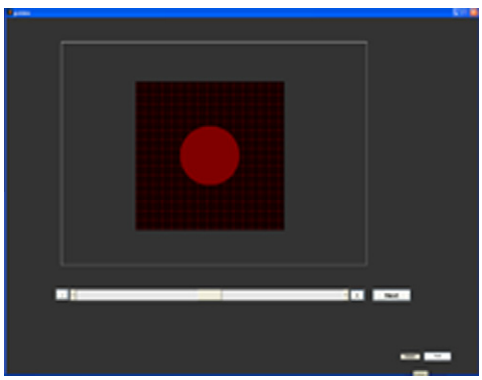

Fig. 3. Experimental interface.

range: 21–57 years; 17 females, 13 males). 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 [11]. The total number of observer assessments is 1440 (30 observers × 8 background patterns × 3 channels × 2 sessions).

2.3. Estimating the OETF

Based on the experimental data for each observer, the OETF representing the relationship between input digital rgb 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, in addition to linear interpolation, we also use a 3rd order polynomial regression to get a robust estimate of the relative luminances to characterise the OETF for each channel, which is fixed to pass point (0, 0) and (1, 1).

3. 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. These luminance matches are informative about the non-linear mapping from the digital input values to the light output. In Fig. 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 three channels (red, green, blue). The horizontal axis represents the relative digital input given by each subject, while the vertical axis represents the relative luminance corresponding to the background pattern. The blue open diamonds and red crosses indicate the matches obtained in experimental sessions 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).

3.1. 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 individual observers are 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 [12] was used to calculate the mean colour difference to the mean value (MCDM) [13], for each colour channel for inter-observer variability. For intra-observer variability, the CIEDE2000 colour difference between each observer's judgments 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 Fig. 5, while the average and standard deviation for all 30 observers' performance for each colour channel are listed in Table 2.

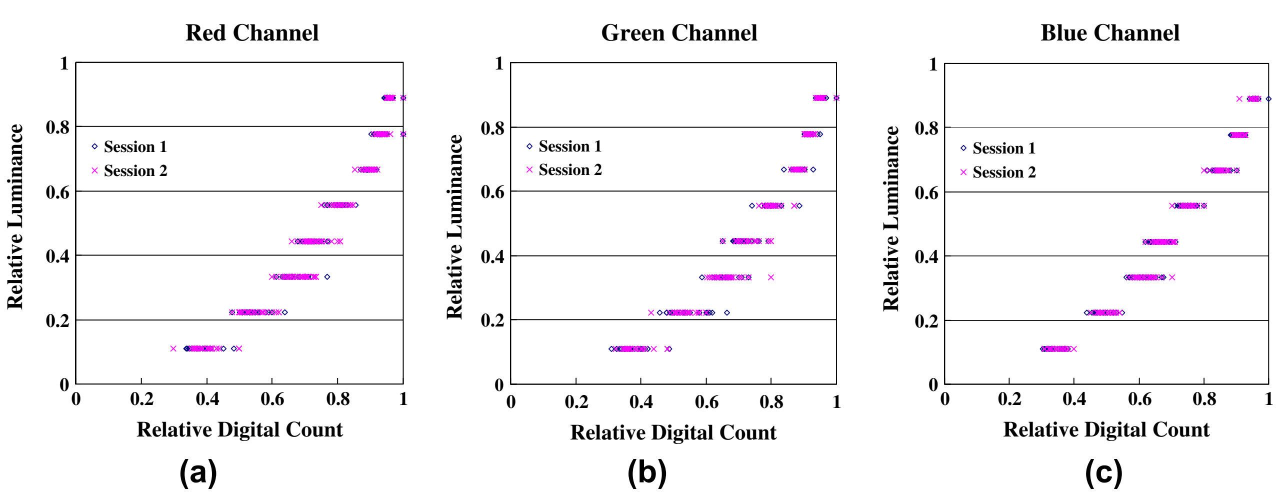

Fig. 4. Experimental results (a) red channel, (b) green channel, and (c) blue channel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

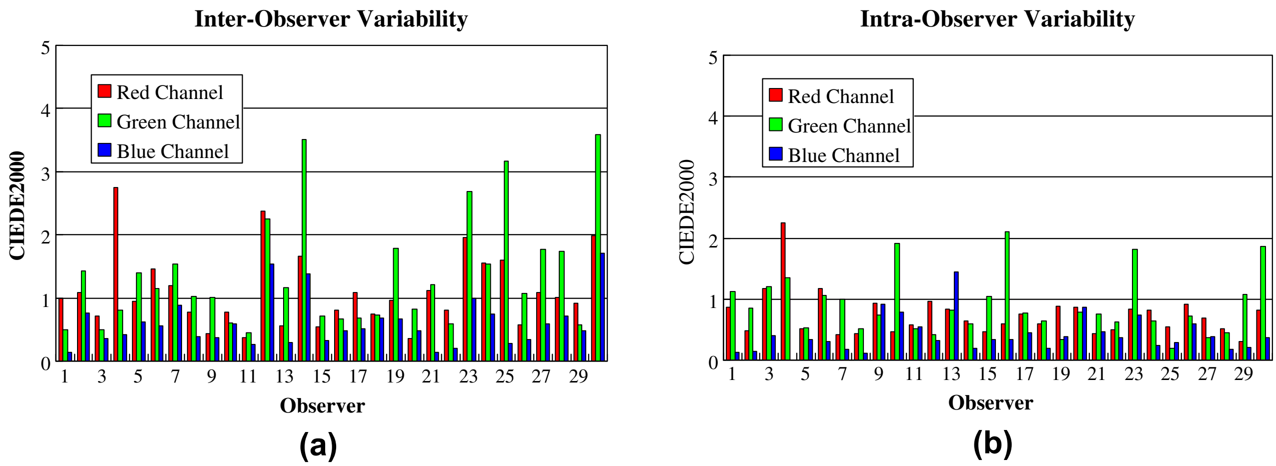

Fig. 5. Observer variability (a) inter-observer variability, and (b) intra-observer variability.

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

The inter-observer variability, as shown in Fig. 5a and Table 2, is always within 4 ΔE_{00} of the overall 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 poor spatial resolution of the yellow–blue channel in the human visual system [14,15]. The poor 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 of the inter-observer variability (cf Table 2). The green channel has also much larger intra-observer variability ($\Delta E_{00} = 0.9$) compared to that of the blue channel ($\Delta E_{00} = 0.4$). In general, the observer variability is fairly small indicating that this luminance matching task can be performed reliably and consistently by naïve observers. In our sample of 30 observers we do not find an effect of gender. 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 [14]. Having established the observer consistency in this luminance matching task we can now use this information to derive the OETFs.

3.2. Estimating the OETF

For LCD display characterisation, conventional methods such as the PLCC model is widely applied to derive the unknown OETF based on data obtained through direct luminance measurement. In this study, the data used for estimating the OETF are obtained through observer judgements, which are less accurate than using a spectroradiometer, still reliable enough to derive a good estimation as shown before. Based on those observer data, both PLCC and 3rd order polynomial fitting are used to derive the OETF. For the PLCC model, the OETFs are derived by simple linear connections between the observed data points as plotted in Fig. 6a–c. These figures can also be used to represent observer variation for each colour channel. As an alternative, a 3rd order polynomial was also fitted to the data points. Both methods were applied to data from 30 observers. Polynomial fits for each individual observer are also plotted in Fig. 6e–f (dashed lines). OETF curves generated by PLCC model are less smooth than that generated by polynomial fitting, which indicates observer judgement is less consistent. The solid line depicts the fitted curve based on the spectroradiometric measurements assuming the average luminous efficiency function for photopic viewing conditions (V_λ). For all three channels, the OETF derived from the measured luminances by two different methods are roughly in the middle of the visual luminance relationships derived from our perceptual data obtained from the 30 observers (Fig. 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).

3.3. 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, $18 \times 18 \times 18$ rgb digital signals were generated for testing purposes covering the whole rgb gamut. 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.

It is important to evaluate the performance based on each individual observer rather than the mean over the set of observers since in real-world applications the gamma correction is likely to

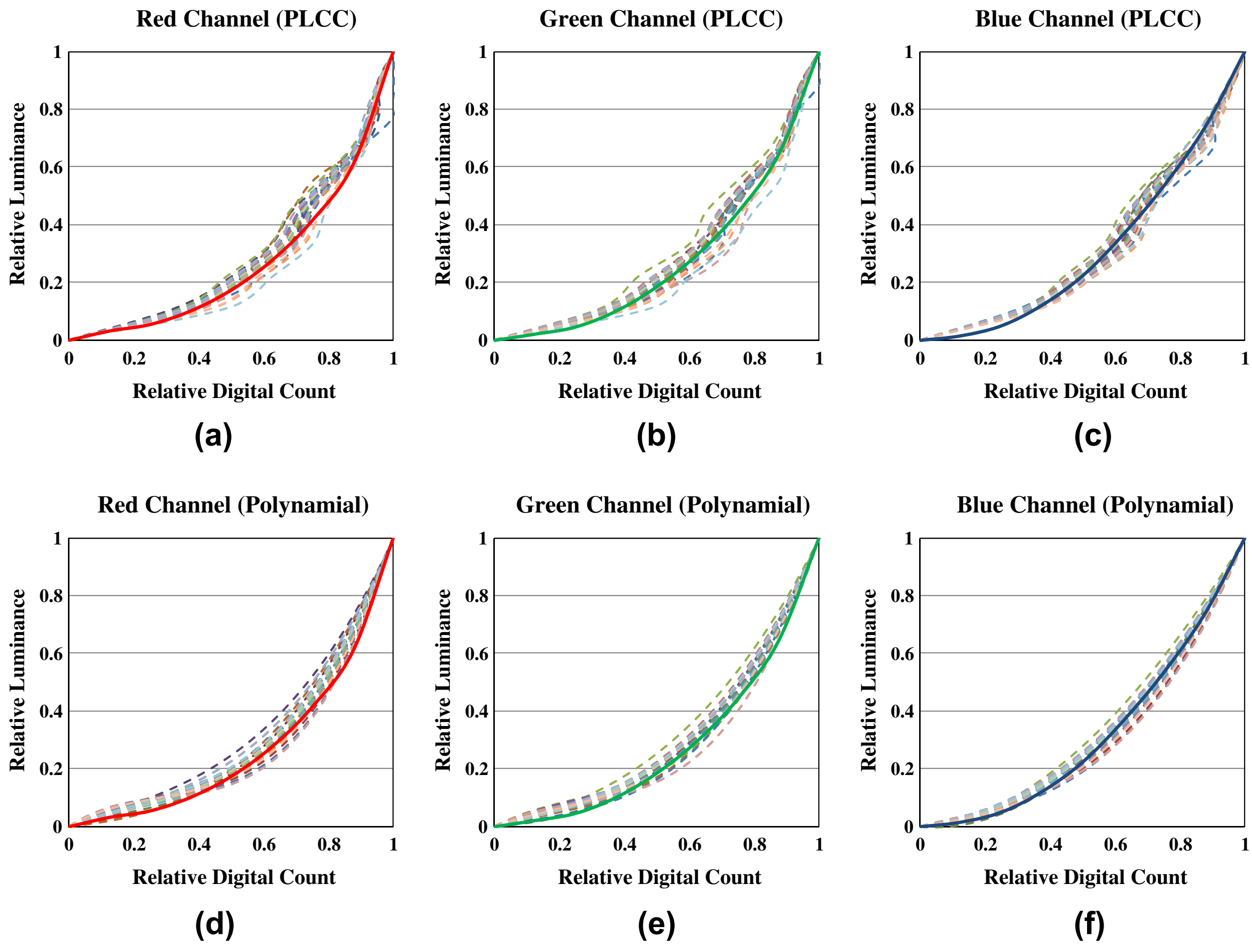

Fig. 6. Predicted OETF based on observer luminance matches (a) PLCC for red channel, (b) PLCC for green channel, (c) PLCC for blue channel (d) polynomial for red channel, (b) polynomial for green channel, and (c) polynomial for blue channel. The solid line depicts the curve obtained from actual luminance measurements (ground truth data). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

be performed based on an individual observer's data. Both the PLCC and the polynomial model based on each individual observer's data are evaluated in terms of the resulting error (CIEDE2000) as demonstrated in Fig. 7. Error bars indicate one standard deviation. The mean error, minimum, maximum and standard deviation of the resulting error of 30 observers are listed in Table 3.

From Fig. 7 and Table 3, it can be seen that the average model performance for the polynomial and the PLCC model is similar, 2.7 and 2.8 ΔE_{00} respectively. The variance in the observers' performance is smaller for PLCC (sd = 0.6) than for the polynomial model

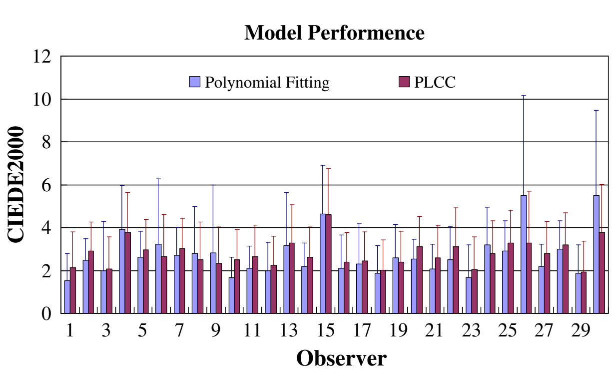

Fig. 7. Performance for OETF estimation based on individual observer visual data.

(sd = 1.0) implying that the PLCC model is slightly more stable when using individual observer data.

To investigate the performance of our gamma correction technique for different lightness levels, the errors (CIEDE2000) are replotted as a function of the lightness (L^*) of the test samples (Fig. 8a: Polynomial Fit; 8b: PLCC). This figure demonstrates that the prediction error for both models decreases sharply with increasing lightness. This poor performance for low lightness levels is caused by the lack of sampling at the lower end; e.g. the relative luminance of 0.1 corresponds to a digital rgb value of roughly 0.4 (cf Fig. 4). This dependence on lightness is more significant for the polynomial model, for which the prediction error is consistently below 4 ΔE_{00} when the lightness level is above 40.

Since any perceptual data contain variation, the accuracy in deriving the OETF may be improved by averaging results across observers or across repetitions from the same observer. Table 4 shows the performance when the average of the two visual assessments for the same observer is used, for both the polynomial and the PLCC model. Comparing Table 4 with Table 3 shows that there is only a slight improvement for the polynomial model and no

Table 3
Performance of OETF estimation based on individual observer data.

ΔE_{00} (30 observers)	Mean	Min	Max	STDEV
Polynomial	2.7	1.5	5.5	1.0
PLCC	2.8	1.9	4.6	0.6

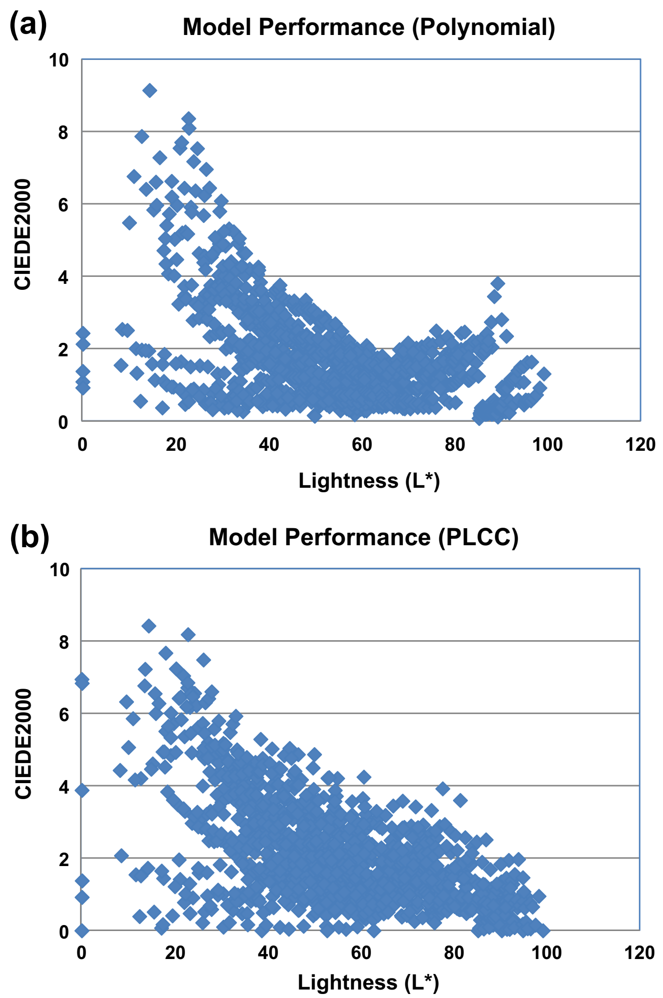

Fig. 8. Relationship of lightness and prediction error of by two models.

Table 4
Performance of OETF estimation based on the mean of two visual judgements.

ΔE_{00} (30 observers)	Mean	Min	Max	STDEV
Polynomial	2.6	1.4	6.2	1.0
PLCC	2.8	2.0	4.5	0.6

improvement for the PLCC model. The reason for little improvement for both models could be that the intra-observer variability is fairly low, i.e. a high repeatability.

When the average data over all 30 observers is used, the mean predictive error becomes 1.7 and 2.0 for the polynomial and the PLCC model, respectively.

To investigate the model performance for a small number of observers, a subset of up to 10 observers' data was randomly selected from 30 observers and input into the model. For each subset of observers, 200 random selections are made and the model performance is evaluated based on each of selection. The average value obtained through the 200 permutations represents the model performance for each number of observers. Fig. 9 illustrates the relationship between model performance and numbers of observers used. Error bars indicate one standard deviation. The model performance (ΔE_{00}) as a function of number of observers is also shown in Table 5.

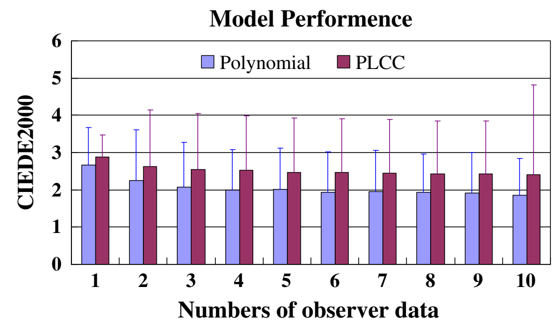

Fig. 9. Performance of OETF estimation in relationship to the number of observers' data used.

Table 5
Performance of OETF estimation based on different numbers of observers.

Observer number	1	2	3	4	5	6	7	8	9	10
Polynomial	2.7	2.3	2.1	2.0	2.0	1.9	2.0	1.9	1.9	1.8
PLCC	2.9	2.6	2.5	2.5	2.5	2.5	2.4	2.4	2.4	2.4

The polynomial model seems to benefit more from an increasing number of observers (error decreases from 2.7 to 1.8), in comparison to the PLCC model (2.9 reduced to 2.4). For the polynomial model, the performance is improved by about 15% when data from two observers are used. When four observers are used, the model performance is enhanced by approximately 26% comparing with the performance for individual observer. However, the tendency becomes less significant when the number of observers exceeds 4.

3.4. Discussion

We have further developed and tested an improved method for visual gamma estimation, using complex spatial patterns to derive the OETF [9,10]. The novelty of our approach is that we evaluated the performance of this modified visual gamma estimation method in relation to observer variability. Our method will work as long as there is no clear flicker which is satisfied 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 input–output relationship, in conjunction with equally spaced luminance steps, the estimation is biased towards high digital values. Our method could potentially be improved by considering more dark samples in the pattern design.

We used a 2° uniform colour patch surrounded by a 6° 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 [15]. The 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.

A polynomial model provides a better fit of the OETF than a PLCC model. The model performance increases significantly when data from up to four observers are averaged; beyond that point, no significant improvements in model performance are seen. In this study we did not consider the Piecewise Linear assuming Variation in Chromaticity (PLVC) model which is known to improve accuracy in particular for Liquid Crystal Displays [16]. Investigating the effect of observer variability on the device calibration using the PLVC model would be an interesting follow-on experiment.

4. Conclusions

The purpose of our study was to improve and extend visual gamma correction techniques to LCD panels, since current methods are most suitable for CRTs but generally fail when used with 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 modified gamma correction technique may play a significant role in improving current colour management systems.

Acknowledgements

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Appendix A

Table A1. Observer inter-variability for each colour.

Colour	Mean	Max	Colour	Mean	Max	Colour	Mean	Max
$R = 1/9$	1.56	5.14	$G = 1/9$	1.50	5.18	$B = 1/9$	0.70	1.94
$R = 2/9$	1.34	3.34	$G = 2/9$	2.03	7.64	$B = 2/9$	0.63	2.43
$R = 3/9$	1.32	3.56	$G = 3/9$	2.49	10.09	$B = 3/9$	0.87	2.93
$R = 4/9$	1.14	3.71	$G = 4/9$	1.47	5.46	$B = 4/9$	0.67	1.99
$R = 5/9$	0.94	3.35	$G = 5/9$	1.01	3.77	$B = 5/9$	0.62	1.86
$R = 6/9$	1.06	2.86	$G = 6/9$	1.03	2.52	$B = 6/9$	0.55	2.00
$R = 7/9$	1.00	5.31	$G = 7/9$	0.65	1.64	$B = 7/9$	0.41	1.25
$R = 8/9$	0.49	3.30	$G = 8/9$	0.67	3.54	$B = 8/9$	0.33	2.12

Table A2. Observer intra-variability for each colour.

Colour	Mean	Max	Colour	Mean	Max	Colour	Mean	Max
$R = 1/9$	0.89	3.46	$G = 1/9$	1.44	5.52	$B = 1/9$	0.44	3.72
$R = 2/9$	1.03	3.09	$G = 2/9$	1.39	7.89	$B = 2/9$	0.50	1.10
$R = 3/9$	0.87	6.80	$G = 3/9$	1.31	5.64	$B = 3/9$	0.56	3.72
$R = 4/9$	0.67	4.96	$G = 4/9$	0.64	1.43	$B = 4/9$	0.42	1.86
$R = 5/9$	0.69	2.43	$G = 5/9$	0.65	2.37	$B = 5/9$	0.37	1.44
$R = 6/9$	0.65	3.04	$G = 6/9$	0.74	3.71	$B = 6/9$	0.40	1.58
$R = 7/9$	0.54	2.49	$G = 7/9$	0.53	3.53	$B = 7/9$	0.20	0.98
$R = 8/9$	0.59	1.70	$G = 8/9$	0.46	1.54	$B = 8/9$	0.37	4.14

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