Perceptually-matched Transparent Display Gamma under Various Background-Surround Conditions

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ABSTRACT

Models for predicting perceptually-matched gamma curves for TOLED and TLCD are proposed based on psychophysical experiment results of HDR LCD simulation. Through-screen luminance plays a major role, and background luminance (15 to 30 degrees of visual angle) is more important than surround luminance (over 30 degrees) in the prediction.

1 INTRODUCTION

Transparent displays have been used in various applications such as smart showcases, smart windows, smart glasses, etc. With the rapid development of OLED technologies, high-performance transparent OLED has launched to the market in recent years. There were two major types of transparent displays: transparent OLED (TOLED) and transparent LCD (TLCD). The former performed color addition, which showed a clear image when the through-screen luminance was low; the latter performed color subtraction that needed a strong through-screen luminance to enhance its image contrast.

Transparent displays could be applied under different kinds of lighting environments. The ambient lighting condition would seriously affect its contrast of the on-screen image. Therefore, many previous studies have been contributed to finding the best tone curves for transparent displays with different viewing conditions. Some of them adopted real displays for experiments with limited parameters [1][2], and the others carried out by the use of display simulation without testing different surround conditions in practical [3][4]. Gray scale perception of a transparent OLED display under different color temperature in different surround luminance also were studied recently [5].

In the present study, a graphical user interface (GUI) was developed using Matlab to simulate the viewing conditions of both TOLEDs and TLCDs on a high dynamic range (HDR) LCD display. A psychophysical experiment was conducted to exam which tone-adjusted parameters could provide the best perceptual match from a standard sRGB display in dim condition to the transparent displays in various viewing conditions. 12 young observers participated in the experiment. The observers' response was analyzed and further used to model the optimal parameters of tone curves for TOLED and TLCD with different combinations of through-screen, background, and surround luminance.

2 EXPERIMENT

The following sections describe tone adjustment, appearance simulation, experimental setup, viewing environment, and the psychophysical experiment's procedure.

2.1 Tone Adjustment

Fig.1 illustrates the tone adjustment method [1]. The modified tone reproduction curves can be obtained by Equations 1-3, where $gamma$ is the exponential relation between normalized RGB signals and normalized display luminances. The default value of the sRGB standard under the dim surround condition is about 2.2. For adjusting the grayscale's gamma, the sRGB signals are converted to sYCC space first, and then apply Equation 1 with the adjusted gamma to Y signal (Luma), where the values have been normalized to the range between 0 and 1. The contrast of the Y_{bright} signals can be enhanced by an S-curve shown as Equation 2 and normalized by Equation 3. Besides, the display contrast is controlled by factor S. The higher value of S results in higher contrast, and 0 represents the image without contrast enhancement (i.e., $Y_{contrast}$ = Y_{bright}).

$$Y_{bright} = Y^{gamma/2.2} \quad (1)$$

$$Y_s = -1/\left[1+\exp\left(10 \cdot s \cdot \left(2 \cdot Y_{bright} - 1\right)\right)\right] \quad (2)$$

$$Y_{contrast} = \left(Y_s - \min(Y_s)\right)/\left(\max(Y_s) - \min(Y_s)\right) \quad (3)$$

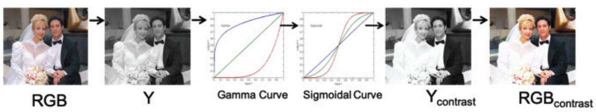

Fig. 1 Workflow of the tone adjustment

In order to find the best perceptual-match of the tone curve for each condition, a paired comparison method was used in this study, which is considered easier than categorical judgment for an observer to make an evaluation. However, the paired comparison will lead to excessive image pairs for visual comparison if a large number of tone curves are adopted. Hence, only four gamma levels were tested. The gamma values were set as 1.70, 1.95, 2.20, and 2.45, respectively, to adjust the brightness of the image. The *s* values in Equation 2 which can adjust the contrast of the image were 0.2, 0.1, 0.0 and 0.0 accordingly. After the tone adjustment, the test images were converted back to sRGB space for appearance simulation.

2.2 Appearance Simulation on a HDR Display

In this study, a HDR display with sRGB gamut and D65 white point was utilized to simulate the visual appearance of transparent displays with different background and surround luminances. Due to the color imaging principles of TOLED and TLCD are very different, two different approaches were applied to simulate the transparent images. For the image simulation of TOLED, the self-luminous white point luminance was assumed as 100 and 200 cd/m^2 in the experiment. The tone-adjusted sRGB images were converted into XYZ space and normalized the Y to 100 for 100 cd/m^2 condition (or 200 for 200 cd/m^2 condition), and then added the through-screen XYZ values with four levels of through-screen luminance (*Yt*) listed in **Table 1**. Finally, the XYZ image converted to HDR sRGB space for simulation. In terms of TLCD image simulation, the tone-adjusted sRGB images were converted to XYZ space, and then multiplied the white point luminances (*Yw*) in Table 1 by the relative XYZ values.

2.3 Experimental Setup

The experiment was conducted in a completely dark environment in which the illuminance is about 0 lux, and stimuli were shown on a HDR display. The display's specifications are an AH-IPS LCD in 27" diagonal size, 4K HDR resolution, and its peak luminance was close to 390 cd/m^2. The reason of using a LCD instead of an OLED display is to ensure the phenomenon of complex luminance reduction of an OLED display will not influence the simulation.

The screenshot of the experimental interface (GUI) and the experimental condition are shown in **Figs. 2** and **3**, respectively. In addition, the luminance of the surround and background areas illustrated in **Fig. 2** are varied according to the levels listed in **Table 1**. Observer viewed the GUI with a chin holder in 50 cm distance (**Fig. 3**). The viewing field of the test image was in 20 degrees roughly. The background area was from 15 to 30 degrees. Surround area was within 25 to 50 visual degrees roughly.

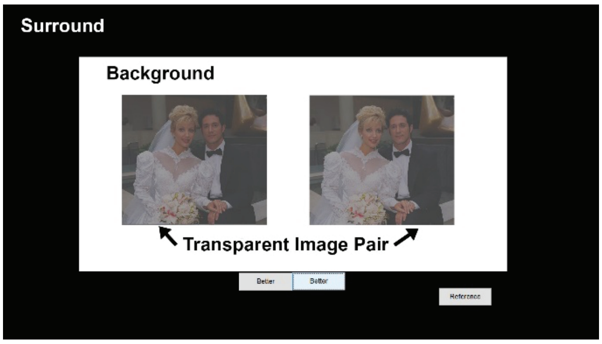

Fig. 2 GUI of the visual experiment

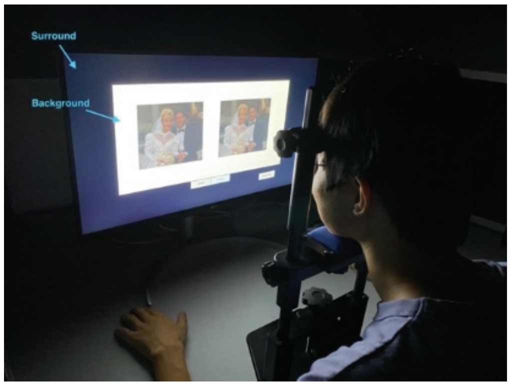

Fig. 3 Viewing environment

Table 1 Parameters of the visual experiment

Display	Factors	Levels (cd/m^2)
TOLED	White Point Luminance (*Yw*)	100, 200
	Through Screen Luminance (*Yt*)	0, 4, 20, 100 for 100 Yw
		0, 20, 100 for 200 Yw
	Background Luminance (*Yb*)	0, 20, 100, 350
	Surround Luminance (*Ys*)	0, 350
TLCD	White Point Luminance (*Yw*)	20, 100, 350
	Background Luminance (*Yb*)	0, 20, 100, 350
	Surround Luminance (*Ys*)	0, 350

2.4 Visual Experiment

Totally 960 combinations, containing 2 images x 6 pairs x 10 displays (7 TOLEDs and 3 TLCDs) x 4 backgrounds x 2 surrounds, were assessed for an observer. Twelve young observers with normal color vision, including six males and six females aged 21 to 23, participated in this experiment. Before starting the experiment, each observer had to adapt to the dark environment for 2 minutes and then continued to view an sRGB reference image with the sRGB standard viewing condition. After a two-second adaptation of background and surround luminances, a pair of test images (a transparent image pair) was randomly displayed on the GUI. During the experiment, the observer was asked to choose one of the displayed images that was relatively similar to the reference image on the aspect of visual appearance. A “Reference” button was placed in the GUI bottom-right corner for the observer to show the sRGB reference image again if forgetting its appearance. The luminance adaptation is essential before each evaluation. Referring to Fig. 4, two ISO12640-3 CIELAB/SCID standard images [6] proposed for the testing of consistent color appearance were tested in the experiment.

Fig. 4 Test images

3 RESULTS

The paired comparison data was analyzed by Thurstone's Law of Comparative Judgment with Case V assumption [7]. The perceptually-matched gamma was determined by interpolating corresponding gamma values of the height of z-scores.

3.1 TOLED

TOLED’s perceptually-matched (PM) gamma against through-screen luminance (*Yt*), background luminance (*Yb*) and surround luminance (*Ys*) are shown in **Fig. 5**. As can be seen, the perceptually-matched gamma has some negative correlation with *Yt* and Ys, but no relation to *Ys*.

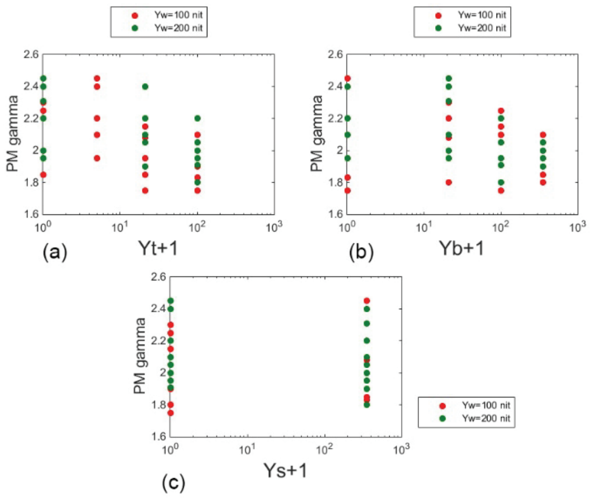

Fig. 5 TOLED’s perceptually-matched (PM) gamma with (a) through-screen luminance (*Yt*), (b) background luminance (*Yb*) and (c) surround luminance (*Ys*)

3.2 TLCD

Fig. 6 shows TLCD’s perceptually-matched gamma with through-screen luminance (*Yt*), background luminance (*Yb*) and surround luminance (*Ys*). As can be seen, the perceptually-matched gamma has positive correlation to *Yw*, little correction on Ys, but no relation to *Ys*.

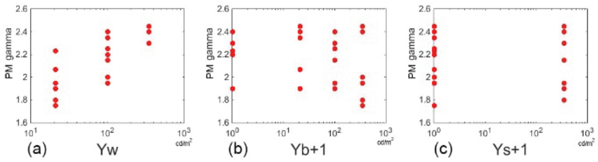

Fig. 6 TLCD perceptually-matched (PM) gamma with (a) white point luminance (*Yw*), (b) background luminance (*Yb*) and (c) surround luminance (*Ys*)

4 MODELING

To predict the perceptually-matched gamma, we found that contrast ratio of the display (X_1), and contrast ratio between the display and the background-surround (X_2) in logarithmic scales are important factors. The coefficient c_1 to c_4 are solved by a last squared regression.

4.1 TOLED

For TOLED, Equation 4 to 7 are used. The symbol *Yt*, *Yw*, *Yb* and *Ys* are referred to **Table 1**. **Table 2** lists the optimal coefficients and the correlation coefficient (*r*) of 4 different cases. Case 4 which uses three polynomial terms in the linear regression performed the best. **Figure 7(a)** shows the correlation coefficients with different background-surround value *p*. The *r* reach highest value when *p* is equal to 0.9. It means the background luminance is far more important than the surround luminance in predicting the perceptually-matched (PM) gamma values. **Figure 7(b)** shows prediction accuracy of **Case 4** (*p*=0.9) where the correlation coefficient is 0.805.

$$X_1 = \ln(Yt+2)/\ln(Yw+2) \quad (4)$$

$$X_2 = \ln[p \cdot Yb + (1-p) \cdot Ys + 2]/\ln(Yt+Yw+2) \quad (5)$$

$$X_3 = \sqrt{X_1 \cdot X_2} \quad (6)$$

$$\text{PM Gamma} = c_1 X_1 + c_2 X_2 + c_3 X_3 + c_0 \quad (7)$$

Table 2 Optimal coefficients and the correlation coefficient (*r*) of perceptually-matched TOLED gamma fitting (*p*=0.9)

Case	c_1	c_2	c_3	c_0	*r*
1	-0.3530	x	x	2.2586	**0.5449**
2	x	-0.1977	x	2.2197	**0.3144**
3	-0.3755	-0.2320	x	2.4495	**0.6572**
4	-1.3150	-0.9122	1.4832	2.6069	**0.8050**

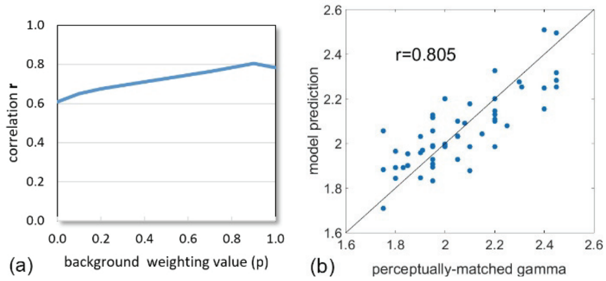

Fig. 7 (a) Correlation *r* of perceptually-matched TOLED gamma fitting in different background-surround luminance weighting. (b) Optimal model prediction

4.2 TLCD

The perceptually-matched TLCD gamma fitting of is similar to the way for TOLED do except that the X_1 and X_2 terms are replaced by Equation 8 and 9. **Table 3** lists the optimal coefficients and the correlation coefficient (*r*) of 4 different cases. **Figure 8(a)** shows the correlation coefficients with different background-surround value p. The *r* reach highest value when *p* is equal to 0.9. It again indicates the background luminance is far more important than the surround luminance in predicting the perceptually-matched gamma values. **Figure 8(b)** shows prediction accuracy of **Case 3** (p=0.9) where the correlation coefficient is 0.927.

$$X_1 = \ln(Yw + 1)/\ln(100 + 1) \quad (8)$$

$$X_2 = \ln[p \cdot Yb + (1 - p) \cdot Ys + 1]/\ln(Yw + 1) \quad (9)$$

Table 3 Optimal coefficients and the correlation coefficient (*r*) of perceptually-matched TLCD gamma fitting (*p*=0.9)

Case	c_1	c_2	c_3	c_0	*r*
1	0.7404	x	x	1.4561	**0.8208**
2	x	-0.3238	x	2.4831	**0.7299**
3	0.5475	-0.1875	x	1.8206	**0.8981**
4	0.2433	-0.4829	0.4089	2.0440	**0.9271**

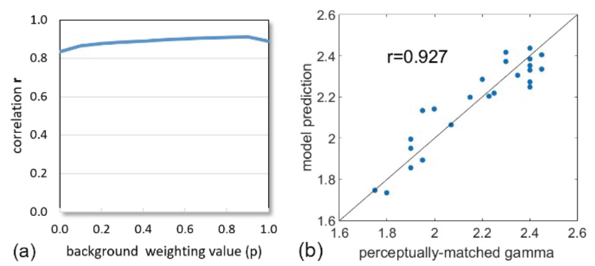

Fig. 8 (a) Correlation *r* of perceptually-matched TLCD gamma fitting in different background-surround luminance weighting. (b) Optimal model prediction

5 CONCLUSIONS

A psychophysical experiment has been done to estimate perceptually-matched tone curves of transparent display under various background-surround conditions. The results show that contrast ratio of the display, and contrast ratio between the display and the background-surround in logarithmic scales are important factors. The perceptually-matched gamma values can be predicted roughly using a n-term polynomial function of the contrast ratios, where TOLED needs 4 terms and TLCD needs only 3 terms to make the correlation coefficients above 0.8. Background luminance is far more important than the surround luminance in predicting the perceptually-matched gamma values. As the background in the experiment was in 15° to 30° viewing angles, it indicates that the surround luminance outsize the 30° visual field is not an essential parameter in estimating the perceptually-matched gamma of a transparent display.

As the models were derived from virtual transparent displays, experiments on real transparent displays are needed to verify the performance of the models in our future work.

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