Color Reproduction of Outdoor LED Displays with Compensation for Ambient Lighting Conditions

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Abstract

Outdoor LED Displays is the most used display technology in outdoors due to it high luminance output capabilities. In such case the observers eyes try to adapt to the ambient lighting surrounding the display which is continuously changing through the day. This result in the actual perceived adapted colors from the display suffer major discrepancies when compared to the target color in the displayed media. In this paper, we propose a model for the outdoor LED display that suffers from flares reflections. Then we modify the model based on the mixed chromatic adaptation model developed by the CIE TC8-4 committee. Next a reverse model is developed to predict new color values in order to appear matching to the original target colors. Finally, we evaluate the model performance and investigate the effect of varying model parameters trough psychophysical experiments.

Keywords: *LED display, color appearance, chromatic adaptation, incomplete adaptation, mixed adaptation.*

1. INTRODUCTION

Light Emitting Diode Video display is a complex device that utilize at least one LED in each prime colors namely Red, Green and Blue to generate the target color of each of the displayed image pixels. These pixels are arranged in arrays to generate the full image size. This arrangement means for example that a display of common resolution of 800x600 will contains at least 1.44 million LEDs. The very high luminance level of the outdoor ambient conditions in daytime makes the LED display technology, the dominant solution that utilizes solid-state technology to realize an outdoor visible display currently. Having the display installed in outdoors makes the observers' Human Vision System, HVS suffer from a continuously changing ambient lighting condition.

The perception of the display colors is a very complex process handled between the eyes and several levels of the nervous system. This is handled in the HVS by a chromatic adaptation process, which is a continuous dynamic mechanism of the HVS to enhancing the visual appearance to a particular viewing condition by discounting the color of the illumination and to preserve the appearance of a seen object. It can be explained by the independent sensitivity adjusting or gain control of the three cone responses.

Several color appearance models was developed to predict color appearance and color matching in different viewing conditions. Many of these models such as Hunt, RLAB, CIECAM97s and CIECAM02 [1] can achieve a relatively accurate color predicting results but assume certain complex observing conditions that can only be maintained in labs or indoors. However, direct application of these models to self-luminous displays results in non-accurate results due to three main reasons [2] [3]:

- The HVS will not be completely adapted to the display even in a complete dark room. This is due to the fact that the display as a light source deviates dynamically from standard illuminant E [2].
- The presence of two or more conflicting illuminants (the ambient light sources and the display itself) results in mixed adaptation state to each illuminant [2] [3].
- The HVS will not have enough time to reach a complete adaptation process according to the time course of chromatic adaptation in figure 1 [2] [4].

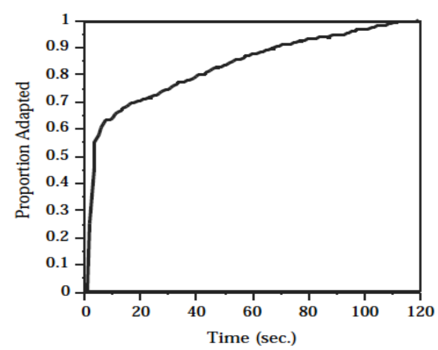

Fig. 1: Time course of chromatic adaptation [4]

In order to develop appropriate model to this mixed adaptation problem, the Commission Internationale de l'Eclairage (CIE) lunched a special committee to investigate the state of adaptation of the visual system when comparing softcopy images on self-luminous displays and hard copy images viewed under various ambient lighting conditions. This committee called TC8-4 was lunched in 1998 and issued its final report in 2010 [5]. Concurrently many researches were made to investigate the problem of

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color appearance of softcopy images on a self-luminous electronic display [6][7][8][9][10][11][12]. However, most of that work was specifically modeling CRT, LCD or PDP displays and none of these researches has modeled LED displays. In contrast with these technologies, the LED display model varies as the presence of the display in outdoors. The model features the high effect of flares due to sun light and other sources and the short time that the observer has to adapt to the display.

This paper is organized as follows. In section two we propose a model for outdoor LED displays, then we construct a forward color appearance model based on the results of CIE TC8-4. In section three we show how to we inverse the model to predict adaptively, based on the readings from true color and photometer sensors, the correct color values that should be used to obtain better matching image. Section four presents the visual experiments conducted to validate the proposed model. Finally, the conclusion of the research work is given in section 5.

Outdoor LED display modeling.

The outdoor LED display is made of LED elements arranged in array housed in a black matt plastic housing. The image on the display is composed of pixels each having three LED in prime colors. The display surface is designed in a manner containing textures to disperse reflections from the observer's eyes and louvers to enhance contrast by protecting the LED elements from direct sun light. Figure 2 shows a typical LED display module.

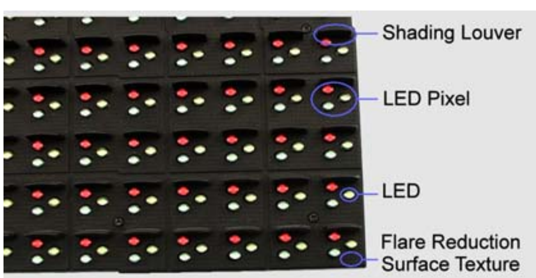

Fig. 2: LED Display Module.

2.1 LED display model.

The ambient light in the surroundings of the LED display affects the HVS of the observer, especially when the display is installed outdoors and susceptible to direct sunlight in daytime and other light sources at night. Hence, we can consider the color projected on the retina as a combination or summation of three light sources as in Figure 3 namely:

- Illuminations emerging from the LED display itself denoted by its tri-stimulus values of X_{LED}, Y_{LED} and Z_{LED}.
- Direct ambient light entering the eyes denoted as X_{AMB}, Y_{AMB} and Z_{AMB}.
- Reflected ambient light from the LED display surface denoted as X_{REF}, Y_{REF} and Z_{REF}.

Hence, we can define the actual illumination from the LED display surface with the addition of this reflection of the ambient light on the LED screen as an offset to the colors originally produced by the red, green and blue LEDs in each pixel. This can be formed as:

$$\begin{aligned} X'_{LED} &= X_{LED} + X_{REF} \\ Y'_{LED} &= Y_{LED} + Y_{REF} \\ Z'_{LED} &= Z_{LED} + Z_{REF} \end{aligned} \qquad (1)$$

Where the terms X'_{LED}, Y'_{LED} and Z'_{LED} are the tri-stimulus values of the actual light beams projected on the retina from the LED display.

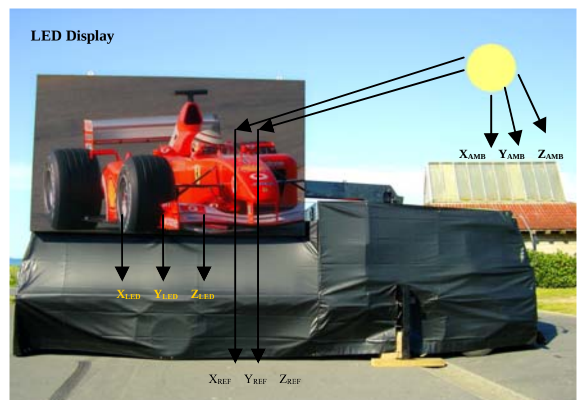

Fig. 3: Outdoor LED Display

And the terms X_{REF}, Y_{REF} and Z_{REF} are directly related to the LED display surface texture and are measured and calculated in the display factory from:

$$\begin{aligned} X_{REF} &= K_x \cdot X_{AMB} \\ Y_{REF} &= K_y \cdot Y_{AMB} \\ Z_{REF} &= K_z \cdot Z_{AMB} \end{aligned} \qquad (2)$$

Where K_x, K_y, and K_z, are the reflectance factors of the LED display surface.

In order to proceed with chromatic adaptation processing, these tri-stimulus components values must be normalized [1]. To achieve this the three components will be divided by the absolute (nominal) luminance of the LED display white point or $Y'_n(LED)$ as follows:

The LED Display tristimulus values:

$$\begin{aligned} \overline{X}'_{(LED)} &= (1/Y'_{n(LED)}) \cdot X'_{(LED)} \\ \overline{Y}'_{(LED)} &= (1/Y'_{n(LED)}) \cdot Y'_{(LED)} \\ \overline{Z}'_{(LED)} &= (1/Y'_{n(LED)}) \cdot Z'_{(LED)} \end{aligned} \qquad (3)$$

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Then, the LED Display white point can be calculated as:

$$\begin{aligned}\overline{X}'_{n(LED)} &= (1/Y'_{n(LED)})\cdot X'_{n(LED)}\\ \overline{Y}'_{n(LED)} &= (1/Y'_{n(LED)})\cdot Y'_{n(LED)}\\ \overline{Z}'_{n(LED)} &= (1/Y'_{n(LED)})\cdot Z'_{n(LED)}\end{aligned} \quad (4)$$

Where

$$\begin{aligned}X'_{n(LED)} &= X_{n(LED)} + X_{REF}\\ Y'_{n(LED)} &= Y_{n(LED)} + Y_{REF}\\ Z'_{n(LED)} &= Z_{n(LED)} + Z_{REF}\end{aligned} \quad (5)$$

Then the ambient white point can be formulated as

$$\begin{aligned}\overline{X}_{AMB} &= (1/Y_{AMB})\cdot X_{AMB}\\ \overline{Y}_{AMB} &= (1/Y_{AMB})\cdot Y_{AMB}\\ \overline{Z}_{AMB} &= (1/Y_{AMB})\cdot Z_{AMB}\end{aligned} \quad (6)$$

Where the "¯" means a normalized value.

2.2 Chromatic adaptation.

In order to apply chromatic adaptation the above values must be transferred first from the tri-stimulus values to cone excitations signals. This transformation can be reasonably approximated by a linear transformation (3x3 matrix). In our approach we will use MCAT02 normalized transformation matrix as proved by Katoh and CIE TC8-4 to achieve best result for mixed adaptation cases with self luminance displays as ours [2] [5]. Hence,

- The LED display cone signals:

$$\begin{bmatrix} L_{(LED)} \\ M_{(LED)} \\ S_{(LED)} \end{bmatrix} = M_{CAT02} \begin{bmatrix} \overline{X}'_{(LED)} \\ \overline{Y}'_{(LED)} \\ \overline{Z}'_{(LED)} \end{bmatrix} \quad (7)$$

- The LED display white point:

$$\begin{bmatrix} L_{n(LED)} \\ M_{n(LED)} \\ S_{n(LED)} \end{bmatrix} = M_{CAT02} \begin{bmatrix} \overline{X}'_{n(LED)} \\ \overline{Y}'_{n(LED)} \\ \overline{Z}'_{n(LED)} \end{bmatrix} \quad (8)$$

- The Ambient white point:

$$\begin{bmatrix} L_{AMB} \\ M_{AMB} \\ S_{AMB} \end{bmatrix} = M_{CAT02} \begin{bmatrix} \overline{X}_{AMB} \\ \overline{Y}_{AMB} \\ \overline{Z}_{AMB} \end{bmatrix} \quad (9)$$

2.3 Calculation for Adapted White Point

Many past experiments and research showed that the human visual system will be adapted to some point between the display white point and the ambient white point except for color temperature in the range of 5500 to 6500K [3] [8]. In case of a display installed in outdoors, the ambient Correlated Color Temperature (CCT) is not only continuously changed during the day time but also will be in a transient state in night time between street light CCT (usually 2000K when using sodium based street lamps) and bright light of different CCTs emitted from passing by cars. To calculate the adapted white point we will follow two steps a) incomplete adaptation, and b) mixed adaptation.

a) Incomplete adaptation to the LED display (ICA)

Previous work made by M.D. Fairchild in 1992 showed that the human visual system will never be completely adapted to the white point of self luminance display even if the display is installed in a totally dark room especially when the display's white point is different from the E illuminant (equal-energy illuminant) [5] [2]. Based on the CIECAM02 color appearance model we calculate the incomplete adapted white point from the equations:

$$\begin{aligned}L'_{n(LED)} &= L_{n(LED)}/d_L\\ M'_{n(LED)} &= M_{n(LED)}/d_M\\ S'_{n(LED)} &= S_{n(LED)}/d_S\end{aligned} \quad (10)$$

Where d_L, d_M and d_S can be calculated from the equations:

$$\begin{aligned}d_L &= D + L_{n(LED)}(1-D)\\ d_M &= D + M_{n(LED)}(1-D)\\ d_S &= D + S_{n(LED)}(1-D)\end{aligned} \quad (11)$$

Where D is the D factor from CIECAM02 and can be calculated as introduced by Luo et al. in the LLAB model and later modified in the CIECAM02 Color Appearance Model [2] [5] [13]:

$$D = F\cdot[1-(1/3.6)e^{\left(\frac{-L_A-42}{92}\right)}] \quad (12)$$

where F is the lightness contrast factor of degree of adaptation. F is suggested by CIECAM02 to be equal to 1.0, 0.9 and 0.8 in average, dim and dark surrounds respectively. L_A represent here the LED display adapting field luminance in Cd/m^2 (the luminance of the visual field just outside of the background) and can be measured with a photometer.

b) Mixed chromatic adaptation to the display and ambient (MCA).

Now when the display white point is different from that of the ambient (only equal at noontime) the HVS will be partially adapted to the white point of LED display and the ambient white point [5]. A case is true under condition the display is bright enough to be visible clearly. Defining R_{adp} as the adaptation factor to the white point of the LED display, the resulting adapted white point that is a mid-point between the two points can be expressed based on the CIECAM02 model as:

$$L''_{n(LED)} = R_{adp}\cdot\left(\frac{Y'_{n(LED)}}{Y_{adp}}\right)^{1/3}\cdot L'_{n(LED)} + (1-R_{adp})\cdot\left(\frac{Y_{AMB}}{Y_{adp}}\right)^{1/3}\cdot L_{AMB} \quad (13)$$

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$$M''_{n(LED)} = R_{adp} \cdot \left(\frac{Y'_{n(LED)}}{Y_{adp}}\right)^{1/3} \cdot M'_{n(LED)} + (1-R_{adp}) \cdot \left(\frac{Y_{AMB}}{Y_{adp}}\right)^{1/3} \cdot M_{AMB} \quad (14)$$

$$S''_{n(LED)} = R_{adp} \cdot \left(\frac{Y'_{n(LED)}}{Y_{adp}}\right)^{1/3} \cdot S'_{n(LED)} + (1-R_{adp}) \cdot \left(\frac{Y_{AMB}}{Y_{adp}}\right)^{1/3} \cdot S_{AMB} \quad (15)$$

Where

$$Y_{adp} = \left\{R_{adp} \cdot Y_{n(LED)}{}^{1/3} + (1-R_{adp}) \cdot Y_{AMB}{}^{1/3}\right\}^3 \quad (16)$$

Using the adapted white point, the resultant adapted color received by the HVS can be calculated using Von Kries adaptation model as follows:

$$L_s = \frac{L_{LED}}{L''_{n(LED)}} \quad (17)$$

$$M_s = \frac{M_{LED}}{M''_{n(LED)}} \quad (18)$$

$$S_s = \frac{S_{LED}}{S''_{n(LED)}} \quad (19)$$

Having the values L_s, M_s and S_s the actual perceived stimulus can be calculated by inverse transfer matrix M^{-1}_{CAT02} [13] as:

$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} = M^{-1}_{CAT02} \begin{bmatrix} \mathrm{L_s} \\ \mathrm{M_s} \\ \mathrm{S_s} \end{bmatrix} \quad (20)$$

Where X_s, Y_s and Z_s are the tri-stimulus values of the actual color perceived.

3. Reverse modeling.

In order to correct the display data eliminating the error in the perceived color, we will reverse the above model starting with the target color R_T,G_T and B_T (the desired Target color intended to be realized from the LED display) as input to the model.

First, we calculate the tristimulus values X_T, Y_T and Z_T

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \beta_{LED} \begin{bmatrix} R_T \\ G_T \\ B_T \end{bmatrix} \quad (21)$$

Where β_{LED} is the transfer matrix from the R,G,B to X,Y,Z space for that LED display (β_{LED} is device dependant calculated through the LED display characterization process). Now, calculating the target cone signals L_T, M_T and S_T as:

$$\begin{bmatrix} L_T \\ M_T \\ S_T \end{bmatrix} = M_{CAT02} \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} \quad (22)$$

Then using (17), (18) and (19) we can calculate L_{LED}, M_{LED} and S_{LED} by reverse Von Kries which can be written in matrix form as:

$$\begin{bmatrix} \mathrm{L_{LED}} \\ \mathrm{M_{LED}} \\ \mathrm{S_{LED}} \end{bmatrix} = \begin{bmatrix} L''_{n(LED)} & 0 & 0 \\ 0 & M''_{n(LED)} & 0 \\ 0 & 0 & S''_{n(LED)} \end{bmatrix} \cdot \begin{bmatrix} L_T \\ M_T \\ S_T \end{bmatrix} \quad (23)$$

Then converting back to X,Y,Z space

$$\begin{bmatrix} X_{LED} \\ Y_{LED} \\ Z_{LED} \end{bmatrix} = M^{-1}_{CAT02} \begin{bmatrix} \mathrm{L_{LED}} \\ \mathrm{M_{LED}} \\ \mathrm{S_{LED}} \end{bmatrix} \quad (24)$$

Finally, we calculate the actual RGB values will be sent to the LED display:

$$\begin{bmatrix} R_{LED} \\ G_{LED} \\ B_{LED} \end{bmatrix} = \beta^{-1}_{LED} \begin{bmatrix} X_{LED} \\ Y_{LED} \\ Z_{LED} \end{bmatrix} \quad (25)$$

The above can be summarized as:

$$\begin{bmatrix} R_{LED} \\ G_{LED} \\ B_{LED} \end{bmatrix} = \eta \cdot \begin{bmatrix} R_T \\ G_T \\ B_T \end{bmatrix} \quad (26)$$

Where η is the correction matrix calculated from:

$$\eta = \beta^{-1}_{LED} \cdot M^{-1}_{CAT02} \cdot \begin{bmatrix} L''_{n(LED)} & 0 & 0 \\ 0 & M''_{n(LED)} & 0 \\ 0 & 0 & S''_{n(LED)} \end{bmatrix} \cdot M_{CAT02} \cdot \beta_{LED} \quad (27)$$

Eq. (27) shows that η depends only on the adapted white point. The value of the correction matrix η is calculated based on the β_{LED} parameters obtained through the LED display characterization and the readings from true color and photometer sensors.

4. Experiments and results.

In order to investigate the performance of (26) and (27) we conducted a series of visual experiments. The experiments aimed to compare the CIE ΔE^*_{94} between original non modified image displayed on a LED display and a corrected image using (26) while changing the ambient lighting condition and the value of R_{adp} used in η calculations.

4.1 Experiment setup

To insure reliable results, the design of the experiments were prepared according to the CIE guidelines [14] and the ASTM standard guide for designing and conducting visual experiments. The experiments strictly followed the guidelines provided in the past by the CIE/TC8-04 to insure experiment comparability [5]. The simultaneous binocular (SMB) matching technique was used in the following setup:

- A Long dark room with eliminated ambient light entrance.
- A 512 x 512 resolutions with 3.2mm pixel size LED display was used. The display was calibrated and characterized at a white point of 6500K CCT. The

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display was made using high contrast LED elements. This LED display as most outdoor display has a very wide dynamic luminance range from 0.01 Cd/m2 to a maximum of 4800 Cd/m2 at 6500K. The LED display brightness was automatically adjusted to suit the surrounding luminance level. We adjusted the experiment images to be surrounded by 100% white proximal field of two pixels then five pixel wide (20%) uniform gray background. The Display was characterized with a Minolta CS-1000 spectroradiometer normal to the screen at 0° viewing angle. The resulting matrix has average error of characterization for the Macbeth colorchecker of 0.62 ± 0.53 ΔE^*_{ab}, with maximum error of 1.84 ΔE^*_{ab}. The display luminance was set to equal L_A using the reading from the photometer sensor.

- Observer seat located 12 meters away form the LED display to suit the display pixel density. In order to avoid viewing angle dependency which is evident on the display at off-axis viewing angles, the experimental arrangement were prepared to forces observers to view a limited region of the front area at angles very near to 10° (θ =10°) by the use of binocular limiter.
- Two digital sensors were used to measure ambient color conditions and photometer to measure the adapting field luminance. The two sensors were carefully positioned by setting the photometer just above the display and the color meter is placed behind the observer to measure ambient light.
- For the matching target, we used a color sheet image as a hardcopy with area 73x73cm (similar to displayed area). The hardcopy was printed using characterized and calibrated HP L65500 printer. The hardcopy were placed attached beside the LED display but can be moved around the display as asked by the observer.
- For the ambient lighting, we used a high power controlled lighting utilizing ten units of 290W LED lamp arrays. Each of these lamps has three controllable CCT modes namely 2300°K, 5000°K and 6500°K used to simulate different ambient lighting conditions. As originally designed to be used in street lighting, the setup configuration of lamp arrays inside the room was powerful enough to achieve a maximum illuminance level of 18600 Lux when measured behind the observer seat at one meter from ground level. In addition, it can be dimmed down to 0.5 Lux. This was crucial to simulate outdoor environment inside the experiment area. The lamps were installed in a manner that inhibits them from being visible by the observer and eliminates casting shadows or glare from the display or hardcopy surface.
- A Remote consol notebook was used to manage the experiment operation with a three keys mouse device used by the observer for scrolling the test images and confirm selections.
- Fourteen normal color vision observers, 12 males and 2 females, ages ranging from 24 to 29 years were participated.

Figure 4 shows the experiment setup used. Before conducting the experiments, a set of trials were made to judge the best distance L (to match CIE 10° observer) and observing time needed.

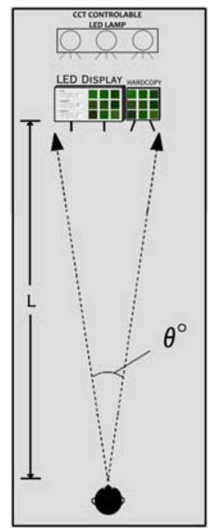

Fig. 4: Experimental Setup

4.2 Experiment Procedure

The aim of the experiment was to measure the average ΔE^*_{ab} for a nine sets of color patches each of which is a 3x3 array of colors on the LED display against a hardcopy with the same color patch. The experiment was repeated under three different ambient conditions listed in table 1, to simulate outdoor environment. The psychophysical procedure employed by instructing the observers to adjust three sliders on the display, chroma, hue and lightness, until they had made an optimum softcopy match to the hardcopy original. The observer had to move his eyes at some distances for the image comparisons with no time restrictions. The Previous experiments done by Katoh and others for CRT and LCD displays, shows a better color matching results when the value of R_{adp} ranges from 0.4 to 0.6 (the HVS is 40 to 60% adapted to the display) [3] [5] [10] so we restricted the trails to the values of 0.4, 0.5 and 0.6 to minimize the experiment running cycles.

Observers were given approximately two minutes to adapt to the environment of the testing room while the display is off. The whole process was repeated three times for the original non-modified image, our algorithm reproduced image with three values for R_{adp} and reproduced

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image using the original CIE TC8-4, which do not consider the flare effect into calculations. The TC8-4 were used in all conditions with R_{adp} set to 0.6.

The whole experiment complexity was 135 patches for each observer. After each matching, the spectral radiance of the softcopy and the hardcopy were measured using a calibrated Minolta CS-1000 spectroradiometer and recorded.

Table 1: Experimental Conditions

Conditions	Ambient Luminance ± 5%	Ambient White CCT
A	200 Lux	2300°K
B	1500 Lux	5000°K
C	18000 Lux	6500°K

We estimated L_A as 20% of the absolute luminance of the adapting field measured by the photometer. In addition, the value of F was substituted from Eq. (28) as:

$$F = \begin{Bmatrix} 1.0 @ L_A/L > 20\% \\ 0.9 @ 2\% < L_A/L < 20\% \\ 0.8 @ L_A/L < 2\% \end{Bmatrix} \quad (28)$$

4.1 Results and Discussions

The average values of ΔE^*_{ab} were calculated from the results obtained from the fourteen observers. Figure 5 shows the average ΔE^*_{ab} for the all experiment conditions. The results show a clear reduction in color error when applying either of the adaptation transforms. However, our proposed adaptive algorithm showed significant improvement over TC8-4's in ΔE^*_{ab} when the value of R_{adp} is set to 0.6.

The condition A ambient parameters were set to simulate Sodium vapor lighting at night. This severe amber lighting condition causes the perceived colors to looks more yellowish. The reproduced colors with either adaption transforms applied were greatly enhanced. The best result obtained is average ΔE^*_{ab} of 3.85 with our adaptive algorithm when R_{adp} is set to 0.6. However, we believe we can gain even better results if the variable in the model were carefully tuned.

Condition B settings simulates a typical overcast day. Again, the best result obtained when R_{adp} is set to 0.6. Moreover, the average ΔE^*_{ab} was improved by 38% when compared to the original CIE TC8-4 algorithm. This improvement was expected as the flare component value is directly related to the luminance level and started to count a significant effect.

Condition C was supposed to simulate normal sunny day at noontime. It was difficult to adjust the experiment setup to minimize any reflections from room surface to observers. At such high luminance level, the white point on the LED display appears similar to the hardcopy white point. This can be justified by the matching of the display white point with the ambient. However, the original non-modified images on the display colors appears faded due to the reflections from the display surface. The best result obtained for ΔE^*_{ab} was 2.15 at R_{adp} =0.5. This result is justified by the increased flare effect in condition C, the fact that the HVS will be less adapted to the display at higher luminance levels and the presence of Hunt effect at this high luminance level.

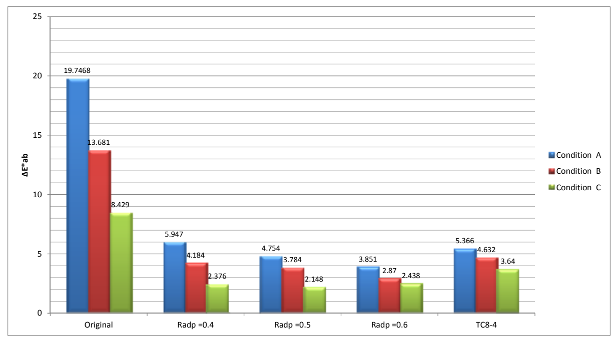

Fig. 5: Average ΔE^*_{ab} for all experimental conditions

The results also showed the need of carefully tuning the model parameters to enhance the reproduced colors even more. We also noticed that the physical position of the photometer sensor greatly affects the algorithm behavior by affecting the D value. A phenomenon that require more extensive study as the definition of the adapting field still require more auditing when the display size is large.

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In this paper, we developed an adaptive algorithm to correct the colors generated in outdoor LED displays. The proposed algorithm adaptively correct the display colors based on the reading from two sensors for ambient color and the display adaptive field. We conducted a psychophysical experiment to examine a corrected color patches images using the proposed algorithm compared to non-modified images and a corrected images using the adaptation model introduced by Katoh and CIE TC8-4. The results showed significant improvements in the displayed colors compared to the original ones. The experiment results also showed that further work could be carried out for carefully tuning the algorithm parameters in order to achieve optimum performance over different states of ambient lighting.

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