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Does External Illumination Affect Color Acceptability Threshold for a Mixed Display Technology Cockpit?

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Abstract

Color Acceptability is a complex phenomenon. Contrary to perceptibility, color acceptability is defined as the level of color difference that is considered under the limit of preferred color reproduction on two media. A system comprising two automotive OLED and LCD displays was used in this experiment. A previous study (presented at [1]*) by the authors had identified this limit for a daylight scenario where an external illumination of 3000 Lux at 5300K was illuminating the surface of the displays. In this study a night-time driving scenario was simulated with a projector light source illuminating the displays at 50 lux and 1318K. Statistical analysis is used to quantify statistically significant differences between various conditions.*

Introduction

An automotive cockpit goes through a variety of changes during driving. These changes can be due to the variations in external illumination conditions. Indeed, the illuminance levels falling on automotive displays while driving during the day may range from approximately 35k lux in bright sunlight to 10k lux in indirect sunlight, while driving during the night they may range from a few tens of lux to a few lux [2]. Human eye has different sensitivity and response to day and night situations [3] and due to this varied range of illuminance and spectra, its color perception might get affected.

Automotive cockpits are becoming more diverse. With the increase in the number of displays inside the cockpit, discussions are in place that the technologies between them can be mixed, giving rise to the so-called Mixed Display Technology Cockpit (for example in the new Mercedes Benz S-Class) [4]. In a previous study done by the authors (preliminary results presented at [1]), an experiment was done with 44 observers to study the color acceptability threshold (from here on referred to as CAThresh) to establish the level of color difference acceptability for a mixed display cockpit during the day situation for 3000 lux of illuminance and 450 cd/m^2 of luminance. A similar experiment is done in this study to establish the same threshold in the night situation (50 lux illuminance and 50 cd/m^2 display luminance) with the motive to understand and document their differences. The experiment took place in two sites (Renault Technocenter, Guyancourt and ENTPE, Lyon) with a total of 47 observers (24 males and 23 females) split as 23 and 24 observers at the two sites. The median age for all the observers was 46 years. 18 observers out of the 47 classified themselves as "Experienced". This meant that they had prior experience in conducting color matching or difference evaluation tasks. 33 observers used correction glasses and were allowed to wear it while doing the experiment. Each observer had to undergo an Ishihara test successfully before commencing the experiment. Color deficient observers were not allowed to participate in the experiment.

A color-difference formula is a mathematical equation providing a non-negative value (DE) from color coordinates (e.g. tristimulus values) of two color samples. The CIE has come a long way in proposing a formula for color difference evaluation. In 1976, the CIE recommended the usage of CIELAB for color difference evaluations using the CIELAB coordinates of the two samples and calculating the Euclidean distance between them in the CIELAB space. In 2000, the CIEDE2000 formula [5] was recommended, which also used the CIELAB space for color difference calculation but with weighting functions for lightness, chroma, and hue differences, the hue/chroma interaction term, and a correction of the a* axis in the neutral region. Some recently proposed color difference formulae for example, CIECAM02-UCS, CAM16-UCS etc also take into account parameters related to viewing condition, illumination level, background etc, the latter recently declared as the new CIE color appearance model (CIE document 248-2022) thereby replacing the CIECAM02 model[6].

Color Acceptability Threshold research deals with understanding the limits of color difference perceptibility and acceptability for a group of observers. [7] evaluated the color difference acceptability threshold for Micro-Tile displays and found it to be 3.3 CIEDE76 for complex natural scenes. [8] studied image color difference on an EIZO LCD monitor and found the color acceptability threshold to be 3.6 CIEDE76. [9] mentioned the T50 tolerance threshold between 1 and 5 CIEDE2000 for five CIE color centers displayed on an EIZO LCD. [10] found out the color difference perceptibility tolerance in the range of 1.11 - 4.06 CIEDE76 and a value of 6.6 CIEDE76 for a rough estimate of acceptable threshold for scenes displayed on a CRT monitor. Various studies in the past have found out that the *Just Noticeable Difference* and color acceptability threshold might not be exactly the same [11]. [12] studied this in the automotive context through a psychophysical experiment. The experiment involved the construction of a subjective visual scale ranging from "Very Satisfied" to "Satisfied" in 6 steps, though many studies [11][13][14][15][16][17] have considered the observers response to be in a way that they either pass or fail the color pair's difference. For the current study, two aspects were considered important. The first was to relate the physical continuum of color difference to the subjective continuum in terms of perceptibility of color difference (results to be published later, not included in this paper), and the second was to judge if a perceived difference is acceptable or not, and by how much. Thus, a hybrid scale inspired by [18] and [19] was used for this study.

Displays and Apparatus

Two automotive cockpit displays were used in this study, an OLED, and an LCD. Nighttime driving condition having an illuminance of 50 lux was simulated in this experiment. A projector light source (ETC Connect Source 4 LED [20]) was used to reproduce an illuminance of approximately 50 lux at the center of both displays. The CIEXYZ tristimulus values of the projected light was: [92, 57, 0] , CCT 1318K (closest Daylight temperature of 2500K, CIEDE2000 of 34) in an attempt to make it colorimetrically similar to High Pressure Sodium light sources used for public lighting and the displays were always kept at 50 cd/m^2. It is important to note that the luminance of the displays is always calculated considering the external illumination source used. This is done by using a spectroradiometer for measuring the luminance of the displays.

To characterize the displays, a spectroradiometer (Jeti Specbos 1211UV) was used. ICC profiles were created and their A2B *Colorimetric* tag was used to build a model with which tristimulus values for any RGB combination can be calculated. D65 and 10-degree colorimetry was used for all calculations. ArgyllCMS [21] and DisplayCal [22] were used as an open source alternative to create the ICC profiles, especially because of their support for a spectroradiometer for the profile generation process.

Experimental Setup

The night experiment was conducted alongside the day situation. A setup/workflow was created that allowed us to quickly switch between day and night conditions. This included using two separate light sources to replicate day or night situation respectively and using two modulated power sources for the displays, so that the luminance could be quickly switched to the night mode of 50 cd/m^2 when required. It is important to note that while conducting the experiment for one situation, the other light source was completely turned off. The observers were seated at a distance of 60-80 cm in front of the displays but were allowed to move their eyes or head.

Figure 1: *An observer performing the experiment with 50 lux illuminance and 50 cd/m^2 display luminances.*

The background of the scene consisted of gray curtains and all other surfaces were either painted black or dark gray to maintain color neutrality during observations.

The OLED display had a diagonal size of 7 inches and the LCD had a diagonal size of 12 inches. Both displays had a neutral background of L* = 50 (calculated using the MATLAB script) with respect to the display white point, considering the display white as the whitest point in the scene having L* = 100. The OLED display had an anti-reflective layer, as is expected in an entertainment display panel while the LCD display had a glossier appearance.

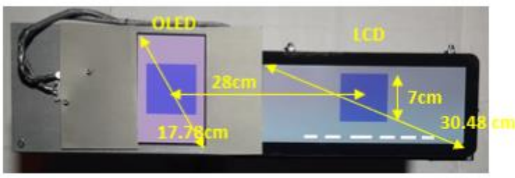

Figure 2: *Geometrical specifications of the two displays.*

135 colors uniformly distributed in the CIELAB color space were considered in this study. These colors were situated around 5 CIE color centers [23] (see Table 1).

Around each of these 5 color centers, color difference values of 0 to 12 in steps of 1.5 were searched in either of the three directions of lightness, hue or chroma. Therefore, 9 colors per direction were searched for the 5 color centers making it a total of 135 colors. The same CIEXYZ values were also used to calculate other color difference values for example, CIEDE2000, CIEDE76, CIECAM02-UCS, DI99d, OSA-GP and CAM16-UCS. The RGB triplets that would reproduce these colors were calculated using the B2A tag of the ICC profile taking chromatic adaptation into consideration (as ICC colorimetry is D50 and we have considered D65/10 degrees for our study). In all cases, before starting the experiment, the colors were again measured with the spectroradiometer to consider the noise of the system and modelling errors. All the evaluation of the results were done using these measurements so that it was representative of what the observers finally saw. The ICC based calculations were done using MATLAB due to its support for the ICC workflow and profile parsing capabilities.

Table 1: CIELAB color coordinates of the CIE color centers

CIE Color Centers	L*	a*	b*
CIE Gray	62	0	0
CIE Red	44	37	23
CIE Yellow	87	-7	47
CIE Green	56	-32	0
CIE Blue	36	5	-31

A GUI designed completely in Python (Tkinter library) was used to conduct the psychophysical experiment. For each of the color pair, an observer was given six options on the visual scale.

The subjective visual scale used for the experiment had the following levels:

0: Not Perceptible
1: Barely Perceptible
2: Perceptible but Acceptable
3: Barely Acceptable
4: Just Unacceptable
5: Unacceptable

The observers were clearly explained the meaning of each of the 6 options that were available to them at the bottom of the right display. Once a colored pair was shown there was no time limit for the observers to choose the option.

Each observer was shown 135 color pairs in a random order according to the Latin square formation so that order bias can be avoided. For each color pair, one of the 5 color centres was shown as the reference color on the OLED display while 135 threshold colors were shown on the LCD display. The task of the observer was to choose one of the 6 options that represented his choice regarding the level of perceptibility or acceptability that he or she perceived between the color pair shown on the two displays. Once he/she clicked on the option the next color pair would automatically appear. The observers were told that there was no correct or wrong answer. On average, an observer took 15 minutes to complete the experiment.

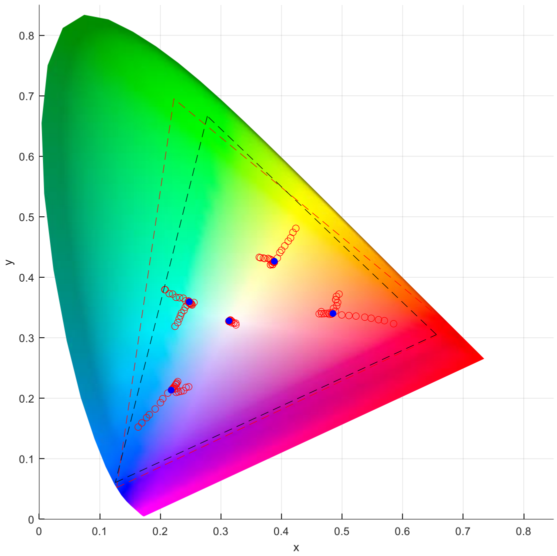

Figure 3: *Color centers considered in this study with the display gamuts (CIExy color space). Blue dots: CIE color centers. Red circles: Thresholded colors.*

An observer could select one of the 6 options that were available to him at the bottom of the right display. For the 47 observers there were 47 * 135 data points for the experiment. The data was processed in a way that any value equal to 4 or less was marked as 1 whereas values more than 4 were marked as 0. This signified that any choice equal or less than the "Barely Acceptable" choice means that the color pair was acceptable for the observer because he did not perceive a color difference between them, whereas a value more than 4 (Just Unacceptable and Unacceptable) signified that the color pair was unacceptable for the observer because a color difference was perceived between them. Once the data was processed this way, it was easier to use it to fit a curve that represented the trend of the observations.

As explained, for the data analysis part, the division between choice 3 (Barely Acceptable) and choice 4 (Just Unacceptable) was chosen as the point of Acceptability and Unacceptability. Thus, any choice less than or equal to 4 was coded as 1 and any choice more than 4 was coded as 0 (1 means accepted and 0 means rejected). TSK Fuzzy algorithm [11][15][24][25] was used to fit the processed data. It can be easily seen from the distribution of the data points shown in Figure 4 that it follows an S-shape pattern and thus a fitting approach to respect the spread of this data was required. The anfis [26] function from MATLAB® was used to apply the TSK-Fuzzy Logic algorithm in which a combination of least-squares and back-propagation gradient descent methods are used to fit the training data set. By default, the function uses a grid partitioning of the input variable range with two membership functions.

Using the TSK fuzzy regression fit, the 75/25% Acceptability/Unacceptability point was recognized. It was defined as the point where 75 percent of the observations were accepted, and 25 percent of the observations were rejected. This threshold was chosen instead of the 50/50% A/U point to have a stricter range of color difference acceptability criteria. As other color difference formulae were also used to calculate color differences in their respective color space/formula (in case there is no related color space for ex, CIEDE2000), 75/25% A/U were also calculated for all color differences considered.

The TSK Fuzzy regression fitted curves were used to calculate their 95% confidence intervals. This was done by considering each predicted point on the y-axis (for each x-axis value) to be a part of a normal distribution of all possible means of the y-outcome (see equation 1 below). Acceptance% values are the processed Acceptability/Unacceptability percentage values for the 135 colors for any group of observers (with sample size *n = number of color pairs =135*). *RMSE* is defined as the Root Mean Square Error for the fit of the data (considering the degrees of freedom, *n-2*). Using the equations 1 and 2 below the confidence interval (*C.I.*) can be calculated for each fitted outcome on the y-axis. $S_{\hat{y}^*}$ is the standard deviation of the y-distribution for the predicted value of $\hat{y}^*$ and $t_{\alpha|2^*}$ is the t-distribution value for an α value of 0.05 (confidence level 0.95).

$$C.I. = \widehat{Acceptance\%} \pm t_{\alpha|2^*} S_{\hat{y}^*} \quad (1)$$

$$S_{\hat{y}^*} = RMSE * \sqrt{\frac{1}{n} + \frac{(dE^* - \overline{dE})^2}{\sum (dE - \overline{dE})^2}} \quad (2)$$

Once calculated for all the y-axis points, the individual upper and lower confidence interval points were joined and plotted together to give an impression of the overall confidence interval for the fit (figure 4, blue dashed lines). This confidence interval was calculated for a 95% confidence level, thus signifying that there is a 95% confidence that the best fit for all possible samples drawn (for any A/U % samples from a population) would have the true best fit inside this region. Thus for any other samples drawn from the same population would have the fit inside this confidence region with a 95% probability.

The 75/25% value of acceptability/unacceptability is determined with the help of a horizontal line intersecting the fitted curve. The 95% confidence interval for the Acceptance% is determined using the method described above. Correspondingly, the confidence interval for the 75/25% A/U color difference values is thus defined by the x-axis points corresponding to the intersection of the horizontal line with the confidence interval curves for the Acceptability%. This gave us the confidence interval for the color difference values for the 75/25% A/U for a group of observers and 135 colors. It is imperative to note that the 75/25% A/U color difference value does not lie at the midpoint of the upper and lower bound of the color difference confidence interval.

Confidence intervals can be used to signify statistical significance of observed differences between groups, assuming that the samples are normally distributed. In our case, it was assumed that the 75/25% A/U values would be part of a normal distribution for any sample of color pairs. For this experiment, confidence intervals and sample size (number of color pairs) were used to calculate the standard deviation and mean of the normally distributed sample group. Using the individual standard deviation (s_1 *and* s_2 *for sample size* n_1 *and* n_2) and means for the two groups (m_1 *and* m_2), a pooled estimate of the common standard deviation (S_p) [27] [28] can be calculated as:

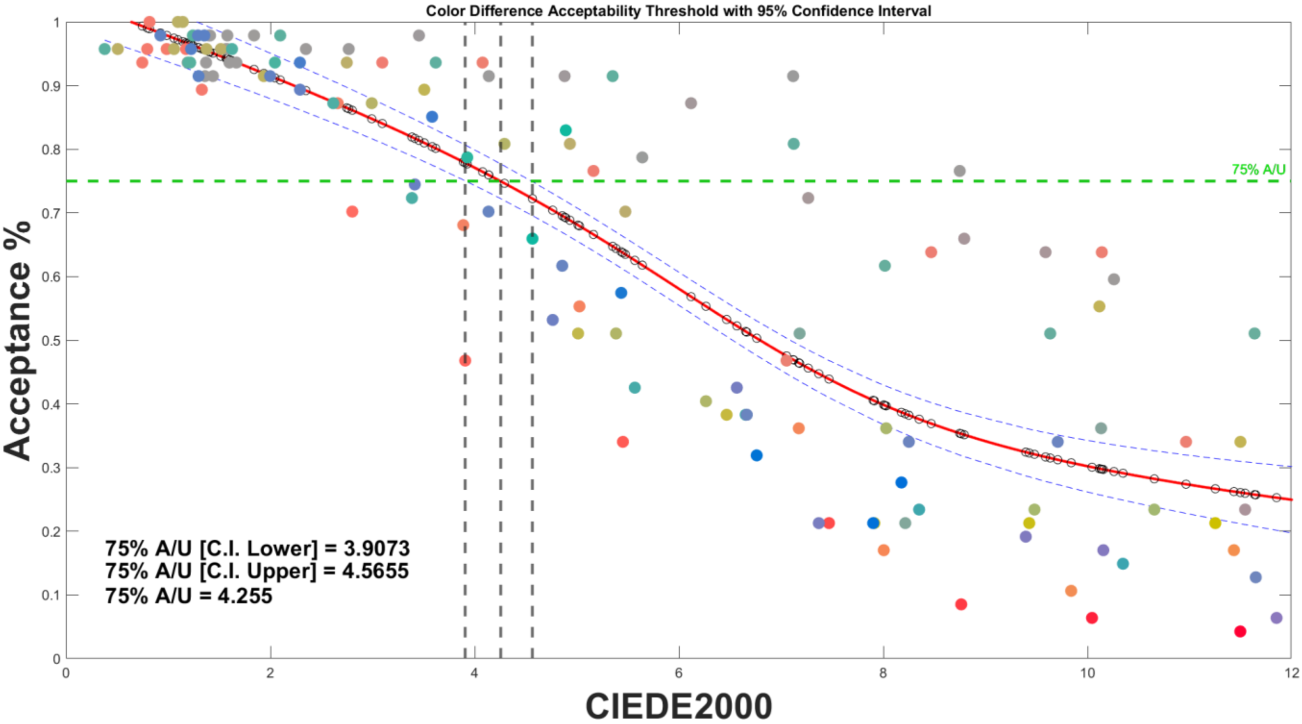

***Figure 4:** 75/25% A/U Color Acceptability Threshold for a group of 47 observers with their 95% confidence interval. Color pairs shown in pseudo color. Red line represents the TSK Fuzzy algorithm fitted curve, and blue dashed line are the 95% confidence intervals.*

$$S_p = \sqrt{\frac{(n_1-1)*s_1{}^2+(n_2-1)*s_2{}^2}{n_1+n_2-2}} \quad (3)$$

Using the pooled estimate of the standard deviation, the pooled confidence interval (*P.C.I.*) can be calculated as:

$$P.C.I = (m_1 - m_2) \pm tS_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}} \quad (4)$$

, where $\boldsymbol{m_1}$ ***and*** $\boldsymbol{m_2}$ are calculated by averaging the upper and lower bounds of the confidence interval for color differences and t is the value from the standard t-distribution table for 95% confidence and degrees of freedom as $\boldsymbol{n_1 + n_2 - 2}$**.**

Confidence intervals from two groups can be used to test a null hypothesis that group means are statistically not different ($m_1 - m_2 = 0$). For this the pooled confidence interval can be used. If the pooled confidence interval does not contain 0, this signifies that the null hypothesis can be rejected, and that there is a statistically significant difference between the individual group means at the 95% confidence interval (because the pooled C.I. was calculated with a 95% confidence). This approach was used to document the statistical significance of differences between experienced observers and all observers, males and females, younger v/s older and between sites.

Results

The fitted curve gives the best approximation of the relationship between color difference values and the level of acceptability and unacceptability in percentages. The minimal training RMSE after 10 epochs was 0.15. The 75/25% A/U for all the 47 observers was identified as **4.25** with a 95% confidence interval between 3.9 and 4.56 CIEDE2000 (Table 2). The values in bold indicate a statistically significant difference with respect to the threshold for all the observers. Each observers' group is abbreviated with a letter in Table 2. The subscripts besides confidence interval of each group specify the groups with which it has significant differences. For the discussion below, # represents "number of observers".

Table 2: 75/25% A/U Color Acceptability Threshold for all observer groups with their 95% Confidence Intervals

75% A/U Thresholds with Confidence Intervals for All Groups (CIEDE2000)

Categories	75% A/U with C.I.
All Observers (#47)	4.25 (3.9 - 4.5)
Experienced (E) (#18)	**3.71 (3.3 - 4)** ^{Y,O,M,U,L}
Unexperienced (U) (#29)	4.66 (4.3 - 5) ^{E,G}
Male (M) (#24)	4.38 (4 - 4.7) ^{E,G}
Female (F) (#23)	4.1 (3.6 - 4.5) ^{L}
Younger (<=45) (Y) (#23)	4.26 (3.9 - 4.5) ^{E,L}
Older (>45) (O) (#24)	4.24 (3.8 - 4.5) ^{E,L}
Site 1: Renault (G) (#23)	3.81 (3.5 - 4.1) ^{M,U,L}
Site 2: ENTPE (L) (#24)	**4.84 (4.5 - 5.1)** ^{Y,O,E,F,G}

75/25% A/U for experienced observers (#18) was 3.71 (95% C.I.: [3.38 ,4.07]) and was statistically significantly different from unexperienced observers (#29) who had a 75/25% A/U of 4.66 C.I.: [3.3, 5.01]. Male (#24) and females (#23) had similar

75/25% A/U with no statistical differences. Observers at the Renault site (#23) had a 75/25% A/U of 3.81 (95% C.I.: [3.5 ,4.13]) and had a statistically significant difference with the group of observers from ENTPE, Lyon (#24) who had had a 75/25% A/U of 4.84 (95% C.I: [4.56 , 5.16]). One reason for this could have been that more observers in Renault considered themselves as experienced (13 out of 23) and had prior experience or were involved with color difference evaluation tasks frequently. On the other hand, 5 out of 24 observers in ENTPE had identified themselves as experienced. Younger people (#23) having age less than or equal to 45 had a 75/25% A/U of 4.26 (95% C.I.: [3.9 , 4.56]) which was not statistically significantly different from the older population (#24) of age more than 45 who had a 75/25% A/U of 4.24 (95% C.I. : [3.88 , 4.56]).

Individual color center trends were also evaluated (see Table 3). The data was split into subsets corresponding to the colors located around the 5 color centers. This resulted into 5 subsets having 27 colors each for the Gray, Red, Yellow, Green, and Blue threshold colors around the 5 color centers. It was found that the Greys had the highest 75:25% A/U value of 8 CIEDE2000 and the Reds and Blues had the lowest value at 3.5 CIEDE2000 (see Table 3). Thus, human observers reacted differently to the colors around the color centers, especially for grays, where even a high level of color difference in any direction of the color space was found to be acceptable by the observers.

Table 3: Color centers specific 75/25% A/U Color Acceptability Threshold

	Color Acceptability Threshold [CIEDE2000]					
	ALL	**Gray**	**Red**	**Yellow**	**Green**	**Blue**
75:25% A/U	4.25	**8**	**3.5**	4.1	4.7	**3.5**

Generally, it is difficult for observers to judge the dimension in which the color difference differs (for example in Lightness, Chroma or Hue) [29]. Therefore, it was important to split the data into subsets which had only L*, C* or h* differences. As explained before, the 135 colors had 45 colors differing only in lightness, 45 only in Chroma and 45 only in Hue. 75:25% A/U for pure h* and pure L*was 3.38 and 3.53 CIEDE200 respectively compared to 4.04 CIEDE2000 for pure C* differences. Thus, observers are more susceptible to perceive differences in lightness or hue as compared to Chroma.

Table 4: 75/25% Color Acceptability Threshold for various Color Difference Formulae and Metrics

Color Acceptability Threshold	
	75% A/U
CIEDE2000	4.25
CIEDE76	5.63
CIECAM02 - UCS	4.58
CAM16 - UCS	4.48
DIN99d	4.63
OSA-GP	3.42

With the motive of publishing color acceptability threshold values for other color difference formulae referred to in literature, the original CIEXYZ and CIELAB values were used to transform the colorimetric values into color difference values in CIEDE76, CIECAM02-UCS, CAM16-UCS, DIN99d and OSA-GP. The acceptability threshold values for all the formulae can be found in Table 4.

Conclusion and Discussion

A psychophysical experiment to study observer response towards perceived color difference between an OLED and LCD display was conducted. 135 colors with measured color differences of 0-12 CIEDE2000 units were considered for the study among 47 observers. Overall, 75/25% A/U was found to be 4.25 with different groups of observers having different levels of acceptability thresholds. Males and females had significantly similar thresholds, while experience and unexperienced observers had statistically significant differences in acceptability thresholds. Observers at Renault had significantly lower acceptability thresholds as compared to ENTPE. This might be due to the reason that there were a greater number of experienced observers in Renault as compared to ENTPE. Reds and Blues had the lowest thresholds as compared to Grays, for which a very high level of acceptability threshold was observed. Younger and older people also had similar acceptability thresholds.

Acceptability thresholds for state of the art as well as older color difference formulae were also studied and published. This was done with the intention of making this data available to companies who are still using conventional color difference formulae (for ex CIEDE76) or have moved to more advanced ones (like CAM16-UCS).

Color acceptability threshold for the experiment done at day scenario [1] was **4.53** as compared to **4.25** for the night situation in the current experiment. Numerically, these thresholds are similar, but a statistical test to compare the two scenarios is pending. This cannot be tested with conventional two sample t-tests because different samples had been considered for conducting the two experiments (CIEDE2000 0 to 11 for the day situation v/s CIEDE2000 0 to 12 for the night situation), which finally resulted in different RGB combinations and CIEXYZ values for the experimental color samples tested. Therefore, additional investigation is needed to comment on the statistically significant similarity or difference between the two situations.

This was the second experiment in the series of experiments planned on this topic. The future studies will involve different various other aspects that might affect color acceptability thresholds.

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Author Biographies

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