An Investigation into the Perception of Color under LED White Composite Spectra with Modulated Color Rendering

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ABSTRACT

Whether Color Rendering can be strategically modulated is an open question in the field of solid state lighting. An affirmative finding would bestow additional significant benefits to the use of solid state sources for general lighting applications. We report results of a pilot study that evaluates the perceptual impact of modulation of color rendering using multi-chip light emitting diodes, LEDs. We examined seven LED white composite spectra with different color rendering, but equal chromaticity and light levels, in terms of how they rendered a set of color samples to the human eye, in comparison with an incandescent bulb. Our procedure was to conduct a psychophysical experiment with direct observation where subjects' comparisons of color palettes were solicited. The LED color mixing was primarily based on the modulation of the ratio of red to yellow emissions to create a sequence of LED spectra of higher efficacy. Our analysis shows that green and blue samples were much less affected by the color rendering modulation than the red or yellow samples, but still the color differences on green samples were much more discernible than the blue samples. Red and yellow samples offered material for more detailed analysis and investigation. For saturated red and yellow samples, human observation was strongly associated with the rebalance of red to yellow emissions. Visual perception of lower saturation red and yellow samples were not as predictable, and our results offered material for future investigation, as color differences were found more tolerable under spectra of reduced color rendering. For example, subjects reported to be fairly comfortable with color differences observed for low saturation red samples (including our red toned skin color sample) under spectra of considerably low color rendering. These results provided us with a baseline against which we plan to further investigate other viewing conditions. Our ultimate plan is to assess the noticeability of dynamic modulation of color rendering in architectural settings where we speculate the perceived color distortions will range from negligible to nil.

INTRODUCTION

LEDs have changed the concept of lighting not only in an expectation of the optimal efficiency but also in tremendous opportunities for "smart" lighting applications. For general lighting, digitally controlled multi-chip LED systems offer many advantages such as chromaticity control, better light quality, and higher efficiency [5]. One of the main potential benefits of smart lighting for general lighting applications is the manipulation of the properties of colored light and white light. Besides luminous efficiency, color rendering is an essential property and figure of merit for a white light source used in illumination applications. We investigate the hypothesis that different color rendering qualities may be desirable within one single environment and that a modulation of color rendering would be acceptable for users. Strategic modulation of color rendering could potentially be used for various different purposes, such as perceptual manipulation of colors (i.e. to enhance appearance of merchandise, emphasize space or architectural features, etc), or energy savings (i.e. to employ higher efficacy low color rendering lighting on unoccupied areas). For example, modulated color rendering can potentially enable a system that dynamically shifts from 'energy saving mode' (low color rendering)' to 'quality mode' (high color rendering) according to occupancy.

Other studies have investigated color-mixing LED white spectra in order to manipulate chromaticity [6], and digitally controlled colored light is becoming ever more popular and successful for architectural lighting [10]. Our goal is to manipulate the spectral composition of light sources without altering the visual apperance of the lit environment. In other words, we propose to change the lighting of a room 'invisibly' (unoticeably to user's), as we believe that color rendering rebalancing can be finely controlled to match environmental features (such as surface colors) and users' needs.

A human factors laboratory experiment was conducted whereby ten subjects evaluated twenty four color samples under test and reference sources with direct observation on a double booth set up. The LED color mixing routine was primarily based on the modulation of the ratio of red to yellow emissions to create a sequence of LED spectra of higher efficacy. It is well known that the red-green contrast is very important in color rendering and that the red component tends to be a key factor in color appearance. The lack of red component shrinks the reproducible color gamut, which in turn tends to make the illuminated scene appear undistinguishable or dull [3]. One specific purpose of this investigation was to understand how the manipulation of red and yellow LED emissions would affect perception of colors, especially of red and yellow color samples. Our ultimate goal is to determine the boundaries of color rendering manipulation after which the system becomes unsuitable for general illumination.

EXPERIMENT - SET UP

Booths

The experiment was carried out in a dark room containing two identical booths of dimensions 22 × 15 × 28 inches. Booth #1 was equipped with an incandescent bulb and booth #2 was equipped with a LED panel containing Red, Yellow, Green and Blue LEDs. The color samples were placed on the floor of each booth (figure 3). The inside of the booth was painted with light grey matte paint to maintain smooth background illumination.

Color Samples

The color order system used in this study was the Color-Aid system. Similar to the popular Munsell system, this system scales colors in hue, saturation and lightness and organizes color in all regions of this three dimensional color space [7]. Twenty four Color-Aid samples were used in the experiment -- namely, GW-T2 , YGc-T2, YG-T2, BW-T3, B-T3, C-T3, RO-T2, RW-T3, O-T2, YO-T2, YO-T3, YW-T3, RW-HUE, RO-HUE, YO-HUE, YW-HUE, Y-HUE, RO-P2-1, RO-P2-2, RO-P2-3, O-P2-1, O-P2-2, O-P2-3 -- and these samples were organized in four color charts (figure 1). Each subject looked at the group of three colors to place their judgments, and gave individual ratings for each color.

The spectral reflectance of the color samples were measured using a Photo Research, Inc. PR-705 Spectra Scan tele-spectroradiometer. The reflectance spectra were obtained by comparing the measured spectral radiance to that obtained from a barium sulfate plaque placed at the location of the color samples.

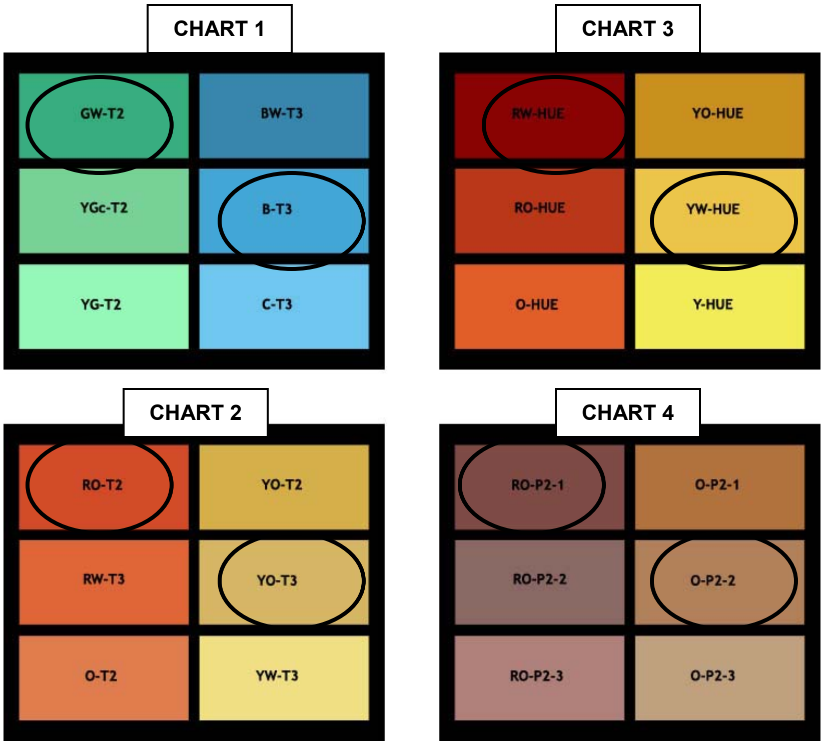


Figure 1 – Four color charts used during the experiments. Circled eight color samples analyzed.

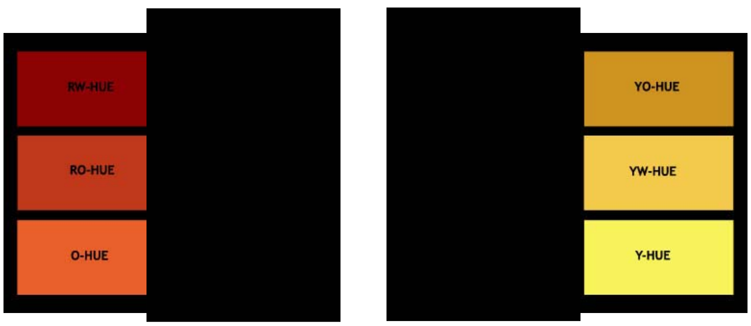


Figure 2 – Example of color chart (chart 3) as it was presented to subjects during experiment.

Figure 3 – Subject facing illuminated booth openings and color charts.

Light Sources

The four color channels Red Yellow Green Blue RYGB of the LED panel were individually tuned to produce twelve composite white spectra with different color rendering but same chromaticity and light level of the reference source, an incandescent bulb (figure 4).

Correlated color temperature and lumen levels were held constant at approximately 3000 K and 300 lux respectively, while each of the LED white spectra had a different general Color Rendering Index (CRI - Ra) varying from 89 to 28. The incandescent bulb operated in 110 V and was filtered with a ROSCO filter #3206 to slightly raise the original incandescent color temperature.

Using one set of dominant wavelengths -- 633 nm (**R**ed), 587 nm (**Y**ellow), 525 nm (**G**reen) and 470 nm (**B**lue) commercially available from Osram Sylvania (LINEARlight OS-LM01A series) – we performed a succession of color-mixing calculations to craft a list of white composite spectra that would mimic the chromaticity and lumen level of the incandescent bulb. In order to maintain the chromaticity and lumen level and to vary the color rendering, the general color mixing approach used was to change the ratio of red to yellow, keep the blue component fixed and make minor adjustments to green. We first created a spectrum with high color rendering (and high red emission), namely spectrum #12, and then sequentially created the other spectra of reduced color rendering by gradually reducing the red component while increasing the yellow component. The lowest color rendering spectrum, spectrum #1, has no red and very high yellow emission. The main objective of this particular approach was to compensate for the reduced red emission with yellow emission to attain higher efficacy sources. All the balance against the blue and green spectral components is obtained with the yellow emission, and consequently spectrum #1 presents very poor rendering, but high efficacy. For all spectra the blue component was held fixed while minor adjustments were made to the green mainly to keep a constant chromaticity and illuminance level. Of the twelve spectra created, seven were selected for the psychophysical experiment. Table 1 summarizes the results from the measurements of these seven LED spectra and the incandescent, showing general CRI–Ra, special CRI, CCT (K), LER (lm/W), and other key parameters.

A detailed analysis of the general and 14 special CRIs calculated for five of the tested spectra using the CIE 1995 procedure demonstrates the results of the above described color-mixing routines (figure 5). As expected, the greatest impact resulting from the reduced color rendering values of spectra #3 and #4 occurred on samples with higher proportions of the red component, which is evident in the R9 and R8 values for these spectra. In contrast, spectra #11 featured even distributions of the general and special CRIs, with most values being in excess of 80 points. We can see that most spectra obtained high CRI values for samples with high proportions of the yellow component – such as R2 and R10 – and similarly spectra of reduced Ra had the special CRI values for blue(ish) and green(ish) samples less affected.

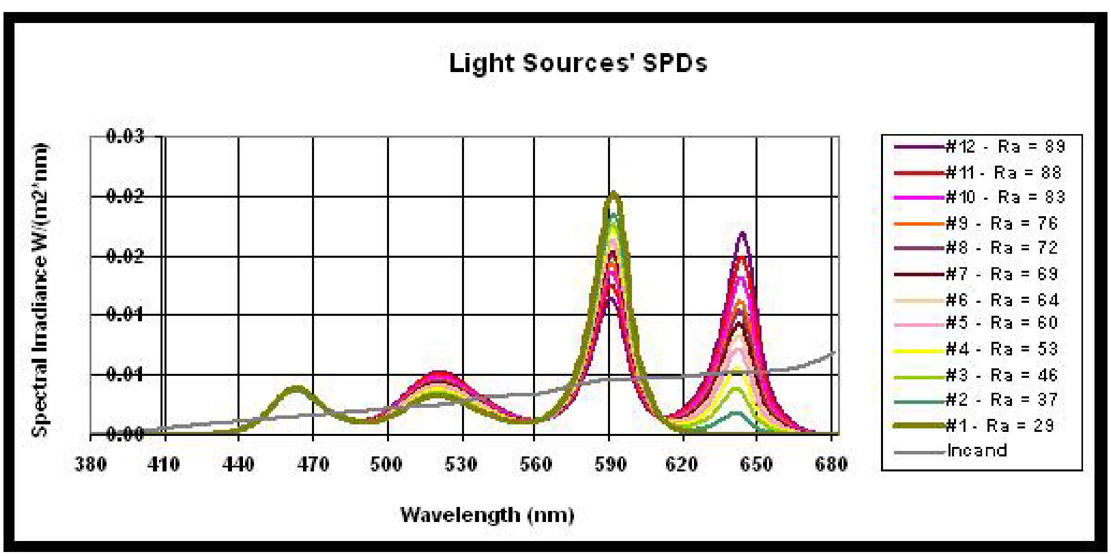


Figure 4 – Spectral power distribution, SPD of twelve LED composite white spectra.

	#2	#3	#4	#5	#6	#9	#11	Incand.
lux	279	280	284	284	287	286	289	275
LER (lm/W)	415	398	385	373	366	345	322	
CCT	3001	2992	2984	3007	2996	3022	3043	2968
CRI	**37**	**46**	**53**	**60**	**64**	**76**	**88**	**98**
x	0.4354	0.4358	0.4364	0.4351	0.4358	0.4341	0.4330	0.4375
y	0.4011	0.4007	0.4010	0.4011	0.4014	0.4009	0.4012	0.4014
u-v	0.0010	0.0012	0.0011	0.0009	0.0009	0.0009	0.0006	0.0012
Ra	37	46	53	60	64	76	88	98
R1	32	42	49	57	62	76	93	98
R2	84	87	90	93	94	98	95	100
R3	45	50	54	59	61	69	78	97
R4	30	41	49	59	64	80	95	97
R5	45	54	61	69	73	86	96	98
R6	89	91	92	92	92	88	83	99
R7	26	34	42	49	54	67	82	97
R8	-55	-33	-16	3	13	44	80	95
R9	**-269**	**-206**	**-158**	**-112**	**-85**	**-12**	**68**	**90**
R10	83	89	94	99	98	89	78	100
R11	44	56	66	77	83	96	78	96
R12	68	72	75	77	78	78	75	98
R13	51	58	64	71	74	86	98	98
R14	65	69	71	74	76	81	87	98

Table 1 – Summarized results for seven composite white spectra and incandescent used in visual tests.

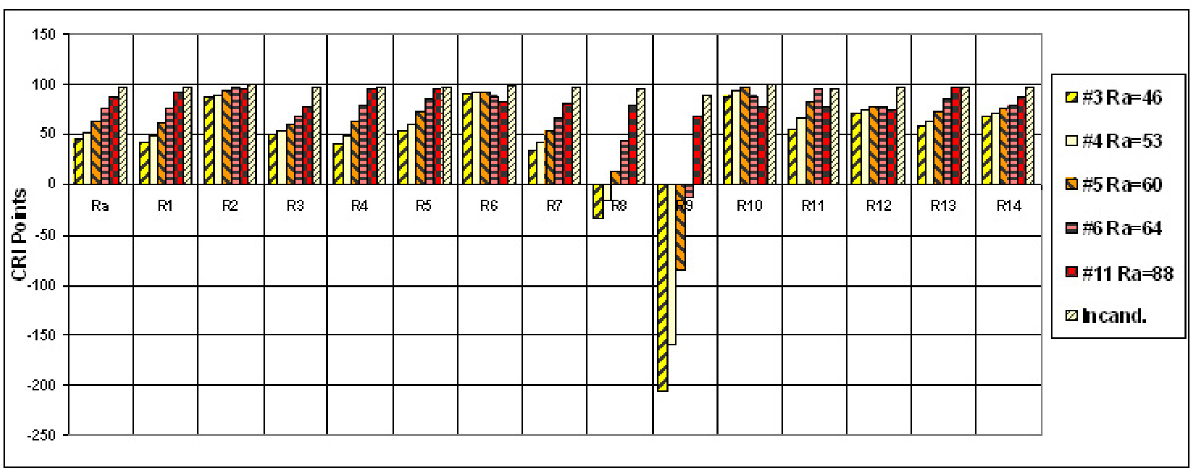


Figure 5 – General and Special CRIs of five selected LED spectra and incandescent source..

Product Spectra and Colorimetric Color Differences ΔE*

The graphs in figures 7, 8 and 9 show plots with the spectral reflectance of eight selected color samples (figure 1), and the “product spectra”, generated by multiplying each of the spectral reflectance by the seven SPDs of the light sources used in the experiment (figure 6). The product spectra represent the color balance reflected from the color samples to the subjects’ eyes under each light source from within the booths during the experiment. In order to make the analysis of the graphs more tangible we included tables containing the calculated colorimetric color difference, ∆E*, for the color samples under each LED spectra. The colorimetric color difference, ∆E*, is a number denoting the difference between the reflectivity of the color sample under the reference source (filtered incandescent bulb) and under each tested LED source. The calculations for ∆E*, followed CIE document CIE 15:2004 [9], which uses the CIELAB object color space. We will in the next section compare these physical measurements with the psychophysical results to verify whether visual observation agreed with the measurements.

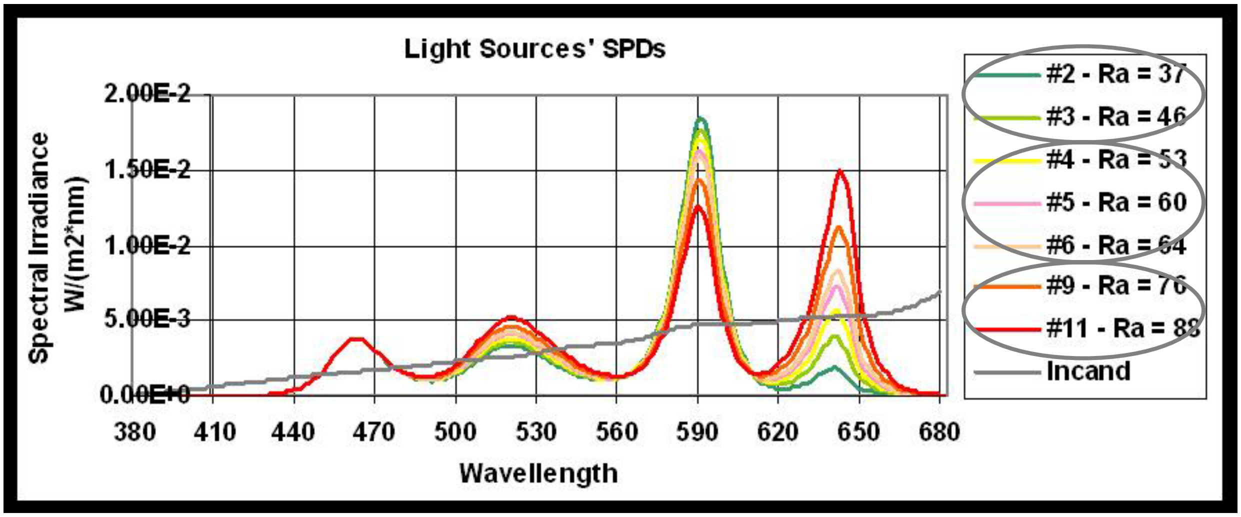


Figure 6 – Spectra power distribution, SPD, of seven selected LED spectra and incandescent bulb.

The title of each plot displays the ColorAid name of the correspondent color sample. In the plots, the blue dashed line represents the spectral reflectance of the sample, plotted against the product spectra of this sample and the light sources (a grey solid line representing the product spectra with the incandescent bulb and colored solid lines representing the LED spectra). The plots show how the individual colored emission from the LED spectra interacts with the reflectivity of the color samples and we can compare the change of the red to yellow ratio from sample to sample. For example, LED spectra #11, represented by a red solid line (with the highest amount of red emission and highest CRI), has always the highest energy in the red region and the lowest energy in the yellow region. Although all the seven selected spectra are relevant for our investigation, we will focus the attention of our analysis on spectra #4, #5, and #6 which represent the middle range CRIs among the seven spectra. This is because we are fairly certain that the high CRI spectra such as #9 and #11 will generally provide acceptable rendering for the observers, and that the very low CRI spectra such as #2, and #3 will generally provide poor rendering, but we are particularly inquisitive about the results for spectra such as #4, #5, and #6 to see how the reduced CRI influenced

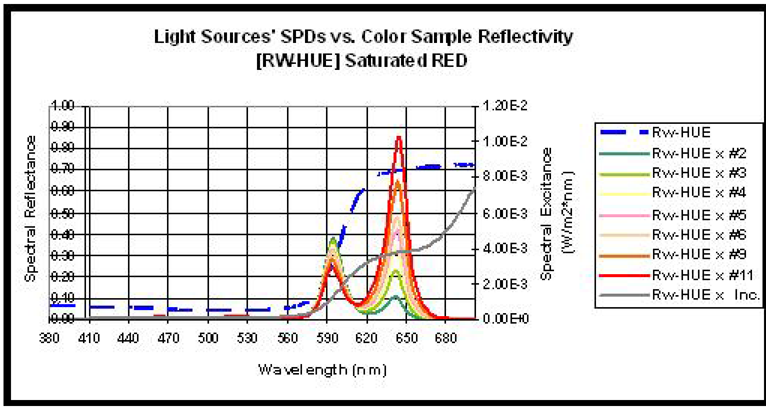
Some trends were observed when comparing the reflectivity and SPDs from the plots with the ∆E* values from the tables. In this study, lower ∆E* values will correspond to 'most incandescent like', and therefore most of these trends will be related to the fact that the spectrum of the incandescent bulb is continuous in nature, and so has energy at all wavelengths to offer to the reflectivity of any color sample, but the LED system consists of narrow band emissions that can be very specific in rendering certain color samples. Therefore a critical part of our analysis is to carefully examine the relationship between the spectral characteristics of the illuminants and the reflectivity of the sample, shown in these plots.

Looking at the plots and tables in figure 7, we see that the red samples RW-HUE and ROT2, have the highest values of ∆E* compared to the other samples, and the values were even higher for RW-HUE, the more saturated red. One possible explanation for this is the fact that red color samples (particularly saturated ones) reflect mainly red light, and in order to render them properly, the illuminant depends on the amount of red emission of its spectral composition. We see in this plot that the incandescent spectrum (the product spectrum of this sample with the incandescent bulb) has more energy on the red than on the yellow region. When the LED spectra (product spectra with LED) present a similar proportion of red and yellow emissions, such as spectra #11, it will tend to generate lower ∆E* values compared to when the red to yellow ratio is inverted, such as in spectra #2. For that reason, it makes sense to see that the ∆E* values increased substantially as we gradually subtracted red light emission from our LED lamp. Also to be noted is the sharp cut-off of the reflectivity of the saturated red sample RW-HUE on the yellow region, which shows that this sample reflects little of the yellow emission from the LED illuminants. As a result, the LED spectra with high yellow and low red emission (such as #2, #3, #4, #5 and #6) have very high ∆E*, and spectra #11, with high energy in red, has very low ∆E*.

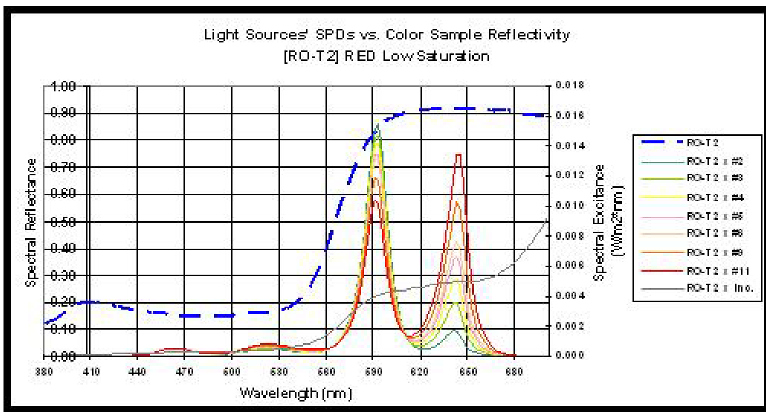
The red samples lower saturation, namely RO-T2 and RO-P2-1 show similar profiles, but lower ∆E* because they are less saturated and therefore reflect also yellow wavelengths. For the blue sample, B-T3 we see in figure 9 that the ∆E* values were much lower. This can be explained because the blue color sample, like the saturated red, is very selective in reflecting wavelengths. It reflects mostly blue light and therefore the changes in the yellow and red emissions did not generate big color differences for this sample. Looking at the reflectance curve of this sample we see that it is low in the red and yellow regions (little red or yellow light reflected) and it is flat (similar amounts of either emissions reflected), which deemphasizes the effect of changing red and yellow emissions of the LED spectra. We can also see that the blue emission from the LED lamp was held fixed for all spectra, which may be another reason for the lower ∆E* values if compared to the red or green sample. The green sample GW-T2, also portrayed in figure 9, shows much higher ∆E* values than the blue one, and a possible explanation for this can be found when looking at the green emission from the LED spectra in relation to the reflectivity curve of this sample. We see that the green emission varies considerably among the spectra, following the change of the red to yellow ratio. Another reason may also be that the reflectivity of the green sample is higher in the yellow than in the red region, which makes the rendering ability of the spectra more dependent on the red to yellow ratio.

When we look at figure 8 at the plots and ∆E* tables for yellow samples YW-HUE, YO-T3 and O-P2-2, we see that for these samples the ∆E* values are much lower compared to all other samples. This can be explained by the fact that in almost all our LED spectra, except for spectra #9 and #11, we have vast quantities of yellow emission; and this yellow emission was well balanced with the yellow wavelengths from the incandescent bulb. Another trend observed was that, for the saturated yellow sample, YW-HUE, the ∆E* was higher than for the others. This is shown in the plots and can be explained because the more saturated the color, the less will it reflect other wavelengths. The saturated yellow sample reflected modest amounts of green and almost no blue light from the LED spectra, which emphasized the importance of the red and yellow emissions, and the contrast with the incandescent spectrum. That is probably why we see that this sample obtained higher ∆E*.

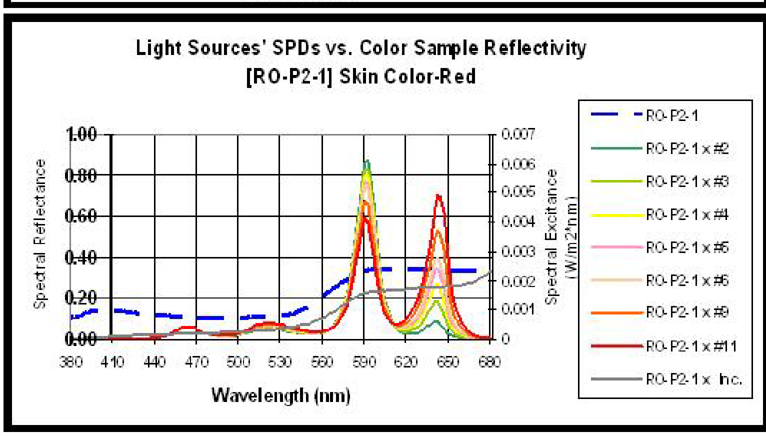
Another important trend was noticed for the yellow samples. We saw that for the red, green and blue color samples, the higher the yellow emission in our LED spectra, the lower was the CRI and the higher the ∆E* values. Therefore an increase in yellow emission corresponded to a decrease in rendering quality of the LED spectra, and this was confirmed by the ∆E* calculations and by the visual experiments. But for the yellow samples, the higher the yellow emission from the LED spectra, the better was the color rendering, in spite of the reduced CRI and increased ∆E* values. For example, in the yellow samples we saw that there was a decrease of the ∆E* values from spectrum #11 to spectrum #2, hence, ∆E* values decreased as CRI increased. This can once again be explained because a sample of high yellow reflectivity will need considerable amount of yellow emission from the illuminant, and as mentioned before, the yellow emission was progressively increased from spectra #11 to #2. The best' LED spectra for the yellow samples (or lowest ∆E*) are not the ones with high Ra, but rather the ones with a good proportion of yellow emission that will be compatible with the yellow energy from the incandescent. We see that spectra #11, with very little yellow emission, had much higher ∆E* values.



Color Sample	∆E*
RW-HUE - inc.	x #2 = 24.00
RW-HUE - inc.	x #3 = 20.82
RW-HUE - inc.	x #4 = 18.14
RW-HUE - inc.	x #5 = 15.12
RW-HUE - inc.	x #6 = 13.55
RW-HUE - inc.	x #9 = 8.42
RW-HUE - inc.	x #11 = 2.99

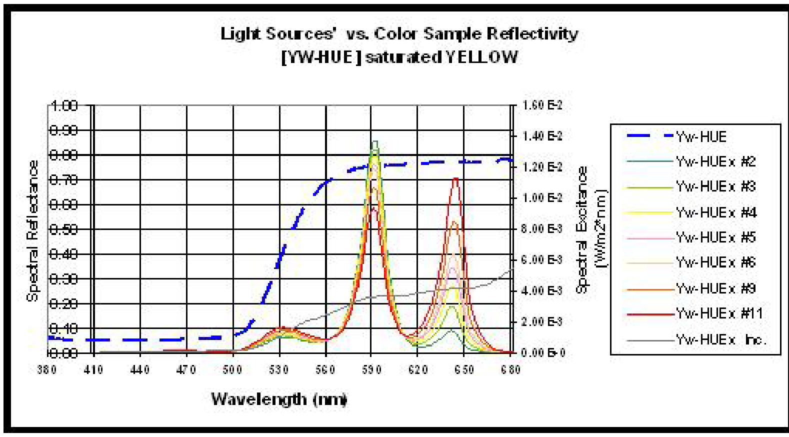


Color Sample	∆E*
RO-T2 - inc.	x #2 = 13.60
RO-T2 - inc.	x #3 = 11.27
RO-T2 - inc.	x #4 = 9.34
RO-T2 - inc.	x #5 = 7.12
RO-T2 - inc.	x #6 = 6.18
RO-T2 - inc.	x #9 = 4.17
RO-T2 - inc.	x #11 = 6.59

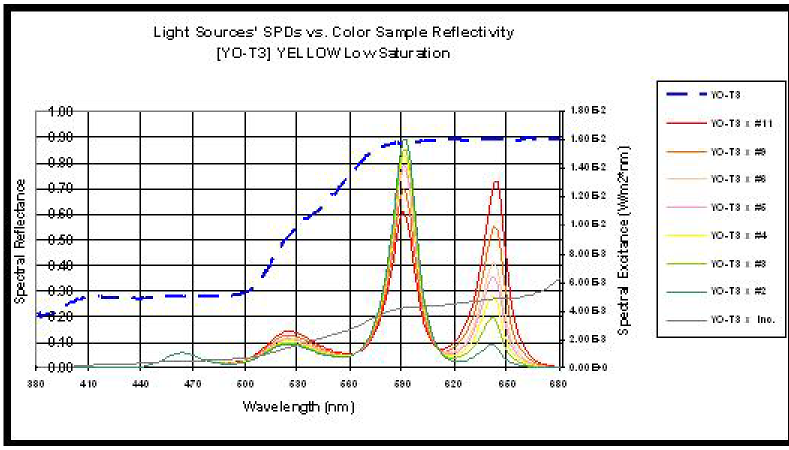


Color Sample	∆E*
RO-P2-1 - inc.	x #2 = 7.03
RO-P2-1 - inc.	x #3 = 5.85
RO-P2-1 - inc.	x #4 = 4.91
RO-P2-1 - inc.	x #5 = 3.90
RO-P2-1 - inc.	x #6 = 3.52
RO-P2-1 - inc.	x #9 = 3.02
RO-P2-1 - inc.	x #11 = 4.42

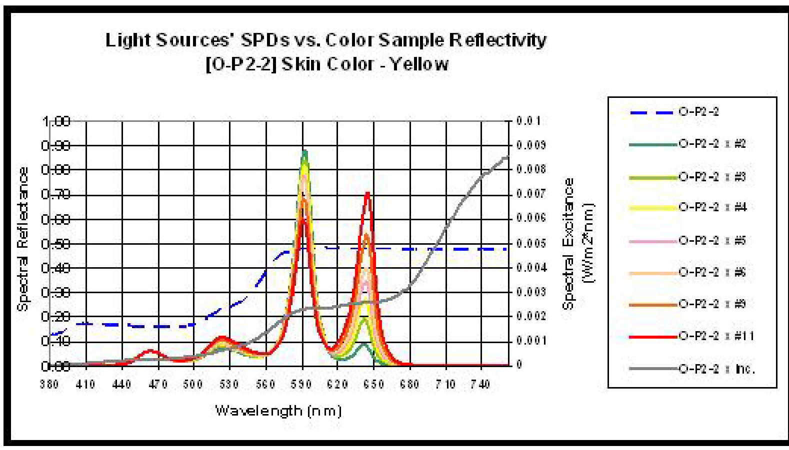
Figure 7 – Spectral reflectance of RED color samples against SPD of product spectra and ∆E* *table.*



Color Sample	ΔE*
YW-HUE - inc.	x #2 = 1.79
YW-HUE - inc.	x #3 = .89
YW-HUE - inc.	x #4 = 1.38
YW-HUE - inc.	x #5 = 2.63
YW-HUE - inc.	x #6 = 3.31
YW-HUE - inc.	x #9 = 5.62
YW-HUE - inc.	x #11 = 8.44

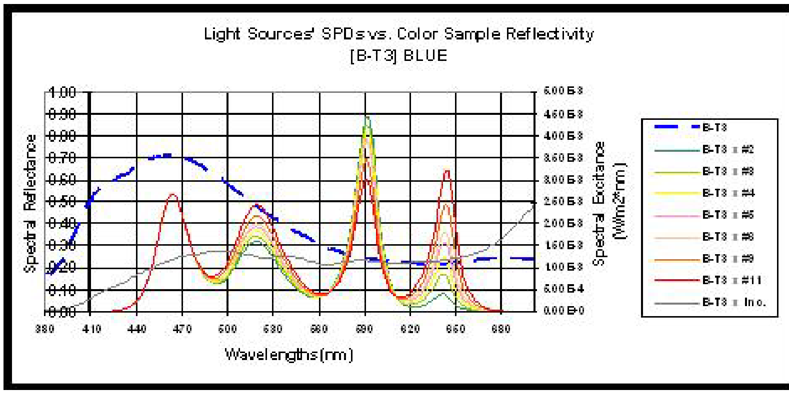


Color Sample	ΔE*
YO-T3 - inc.	x #2 = 2.60
YO-T3 - inc.	x #3 = 1.69
YO-T3 - inc.	x #4 = 1.14
YO-T3 - inc.	x #5 = 1.24
YO-T3 - inc.	x #6 = 1.60
YO-T3 - inc.	x #9 = 3.15
YO-T3 - inc.	x #11 = 5.21

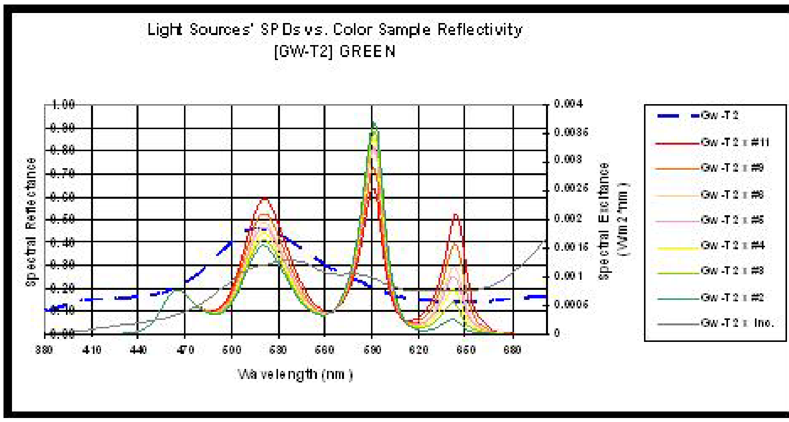


Color Sample	ΔE*
O-P2-2 - inc.	x #2 = 3.37
O-P2-2 - inc.	x #3 = 2.44
O-P2-2 - inc.	x #4 = 1.8
O-P2-2 - inc.	x #5 = 1.49
O-P2-2 - inc.	x #6 = 1.63
O-P2-2 - inc.	x #9 = 2.91
O-P2-2 - inc.	x #11 = 4.94

Figure 8 – Spectral reflectance of YELLOW color samples against SPD of product spectra and ΔE table.*



Color Sample	ΔE*
B-T3 - inc.	x #2 = 3.95
B-T3 - inc.	x #3 = 3.10
B-T3 - inc.	x #4 = 2.53
B-T3 - inc.	x #5 = 2.15
B-T3 - inc.	x #6 = 2.18
B-T3 - inc.	x #9 = 2.90
B-T3 - inc.	x #11 = 4.52



Color Sample	ΔE*
GW-T2 - inc.	x #2 = 9.09
GW-T2 - inc.	x #3 = 7.64
GW-T2 - inc.	x #4 = 6.49
GW-T2 - inc.	x #5 = 5.24
GW-T2 - inc.	x #6 = 4.74
GW-T2 - inc.	x #9 = 3.62
GW-T2 - inc.	x #11 = 4.40

Figure 9 –Spectral reflectance of BLUE and GREEN color samples against SPD of product spectra and ΔE* *table.*

PSYCHOPHYSICAL EXPERIMENT

Procedure

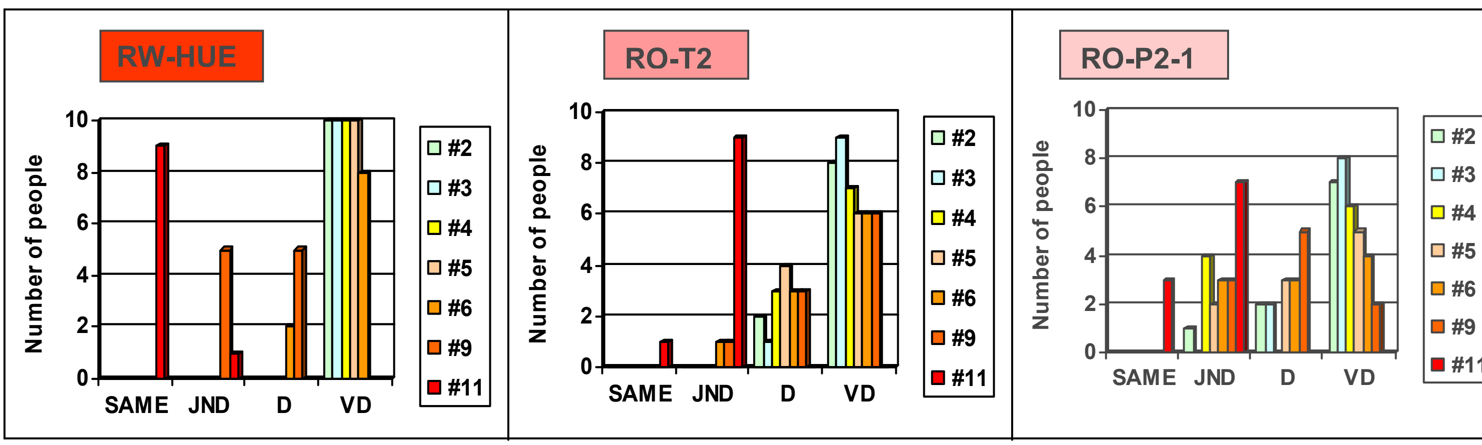
Ten subjects (six male and four female) with normal color vision participated in the experiment. During the experiment, one subject was seated 24 inches away looking at the booths and positioned in the center line between booths. Each subject looked at the illuminated color samples on each booth (test and reference) and then placed their judgment on the comparison. The tested sources were rated with respect to the reference source by the difference in appearance. Subjects were asked to respond if the color samples looked “same”, “just noticeably different”, “different” or “very different” to the successive presentations. The seven different test spectra were presented in random order. In between samples the subjects remained in the room and were asked to turn around and look at the dark surface of the opposite wall for approximately 1minute.

Results and Analysis from Psychophysical Experiments

We will continue to use ΔE* values as a reference and will continue to focus on the mid-range CRI spectra, #4, #5, and #6 for the analysis of the psychophysical experiment results.
The bar charts on figures 10, 11 and 12 show the number of responses (minimum of 0 and maximum of 10 subjects) on the abscissa and the types of responses (‘SAME’, ‘JND’ – Just noticeable difference, ‘D’-Different, ‘VD’-Very different) on the ordinate, and the legend containing the seven selected spectra.

The analysis of the data from the psychophysical experiment helped us understand what magnitude of ΔE* constitutes a significant color difference for each color sample. We see that for the red colors, the ΔE* values ranging from 3 to 4 were said to be ‘just noticeably different’; ΔE* from 4 to 9 were considered ‘different’ or ‘very different’; and ΔE* above 9 were unanimous judged as ‘very different’. As expected, for the yellow sample ΔE* values had the opposite logic, ΔE* between 2 and 3 were judged to “look the same” and lower values had responses varying from ”just noticeably different” to “very different”. For the blue samples, ΔE* values above 4 were said to be “different”, ΔE* values between 2 and 4 varied from “look the same” to “just noticeably different”. For the green sample, ΔE* above 7 were judged as “different”, whereas ΔE* ranging from 3 to 6 were said to “look the same” or “just noticeably different”.

For the red samples, the results plotted on the charts were consistent with the ΔE* calculated for these colors: the bigger the ΔE* value, the more noticeable was the color difference to the observers. We also see that for these samples the color differences were more strongly perceived by the observers for reds of higher saturation, which was also confirmed by the ΔE* values. We see that the saturated red sample RW-HUE, got much higher delta values and was judged to be “very different”, and that the less saturated samples, RO-T2 and RO-P2-1, got lower ΔE* values and were considered “different” or even “just noticeably different”. These results confirmed what could have been expected from our intuition, as it is well known that the more saturated the color the more selective will it be in reflecting wavelengths. Our saturated red sample reflects mainly red light and so it makes sense that as we subtracted red light components from our LED spectra, the observers would readily discern this. On the other hand, the less saturated red samples reflected more yellow light, and then the yellow emission compensated for some lack of red. This was clearly confirmed by the visual appraisal when these spectra were considered ‘different’ or even ‘Just Noticeably Different’, as opposed to “very different” for the saturated red.



Color Sample	ΔE*ab
RW-HUE - inc.	x #2 = 24.00
RW-HUE - inc.	x #3 = 20.82
RW-HUE - inc.	x #4 = 18.14
RW-HUE - inc.	x #5 = 15.12
RW-HUE - inc.	x #6 = 13.55
RW-HUE - inc.	x #9 = 8.42
RW-HUE - inc.	x #11 = 2.99

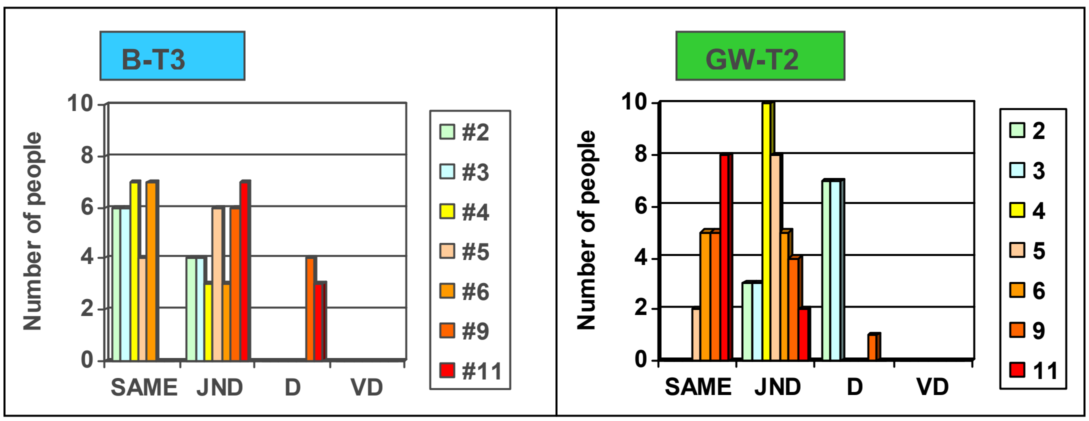
Color Sample	ΔE*ab
RO-T2 - inc.	x #2 = 13.60
RO-T2 - inc.	x #3 = 11.27
RO-T2 - inc.	x #4 = 9.34
RO-T2 - inc.	x #5 = 7.12
RO-T2 - inc.	x #6 = 6.18
RO-T2 - inc.	x #9 = 4.17
RO-T2 - inc.	x #11 = 6.59

Color Sample	ΔE*ab
RO-P2-1 - inc.	x #2 = 7.03
RO-P2-1 - inc.	x #3 = 5.85
RO-P2-1 - inc.	x #4 = 4.91
RO-P2-1 - inc.	x #5 = 3.90
RO-P2-1 - inc.	x #6 = 3.52
RO-P2-1 - inc.	x #9 = 3.02
RO-P2-1 - inc.	x #11 = 4.42

Figure 10 – Subject ratings for red color samples under light sources.

Looking at figure 11 containing the bar charts for the blue B-T3 and green GW-T2 color samples, we see clearly that the blue sample received higher ratings (color differences less noticeable) from the subjects than the green sample. We see that most observers thought that the color differences for the blue sample were nearly unnoticeable (most rated 'look the same', some 'just noticeably different') for all spectra except #9 and #11. Something worthy of note happened here, as the spectra with higher CRI (#11 and #9) were the ones with worse visual performance. One possible explanation for this could be that, as mentioned in the previous section, a blue sample reflects mostly blue light and consequently changes in the yellow and red emissions would not be expected to be registered by the observers. Also, if we look at the reflectivity of the blue sample on figure 9 we see that it is lower on the red region, which may help to explain why the blue sample benefited less from spectra with high emission in red (and high CRI).

Still on figure 11 when we look at the bar charts for the green sample, GW-T2 we see that the color differences for this sample were more perceptible than for the blue sample (most rated on 'just noticeably different' and 'different'). This can be explained because a green sample reflects other colors (including considerable amounts of yellow and red wavelengths), and consequently the appearance of this color was affected by the variations of the red to yellow ratio. We can also see from the charts that the spectra of higher CRI performed better visually, and that the results from the visual experiments were consistent with the ΔE* table. This can be explained when we look at the plot on figure 9 and see that the spectra with high CRI were also the ones with higher green emission (green and red emission were consistent). We can only expect that higher green emission will benefit a green color sample.

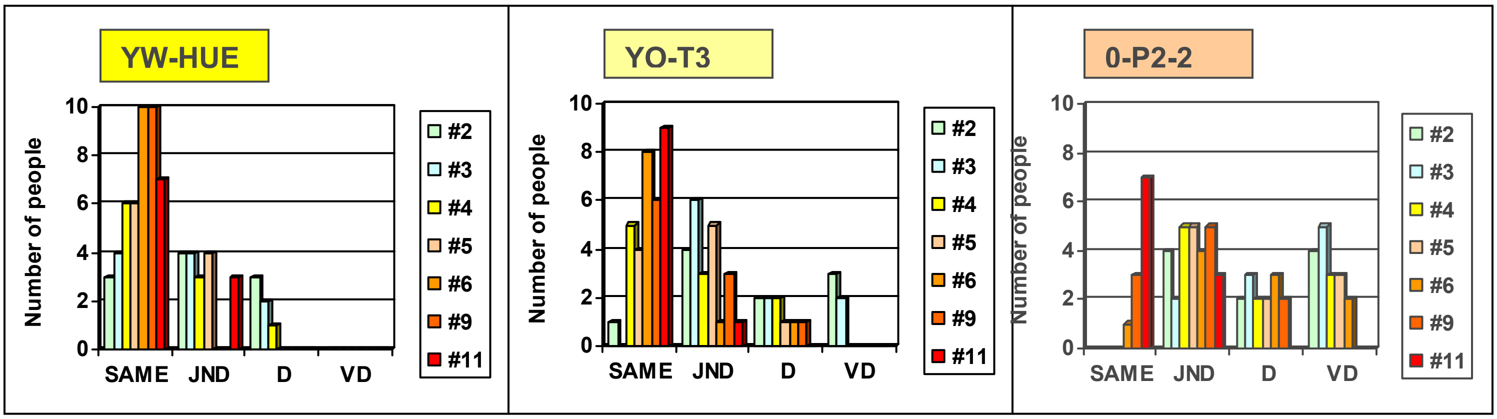


Color Sample	ΔE*ab
B-T3 - inc.	x #2 = 3.95
B-T3 - inc.	x #3 = 3.10
B-T3 - inc.	x #4 = 2.53
B-T3 - inc.	x #5 = 2.15
B-T3 - inc.	x #6 = 2.18
B-T3 - inc.	x #9 = 2.90
B-T3 - inc.	x #11 = 4.52

Color Sample	ΔE*ab
GW-T2 - inc.	x #2 = 9.09
GW-T2 - inc.	x #3 = 7.64
GW-T2 - inc.	x #4 = 6.49
GW-T2 - inc.	x #5 = 5.24
GW-T2 - inc.	x #6 = 4.74
GW-T2 - inc.	x #9 = 3.62
GW-T2 - inc.	x #11 = 4.40

Figure 11 – Subject ratings for blue and green color samples under light sources.

The charts with the yellow samples (figure 12), show that these results seemed less intuitive. Here, the higher the ΔE*, the less noticeable was the color difference to the observers. One possible explanation for this comes from the fact that, for yellow samples, wealth of yellow emission should be expected to be a good thing for visual observation, and we know that a higher a yellow emission in our LED spectra, elevated the ΔE* values. The charts also show that the more saturated the yellow sample, the weaker was the correlation between the user experience and the measured ΔE*. This can be explained because the saturated yellow will tend to benefit even more from the increase in yellow energy since it reflects less of other wavelengths. For example, the charts show that for the saturated sample YW-HUE, subjects practically did not notice any difference between the incandescent and the LED spectra, even though this was the yellow sample with highest ΔE*. On the other hand, the samples of lower saturation were judged to be ‘different’ and even ‘very different’, which can be explained because these samples reflect good amounts of red, yellow, some blue and sometimes appreciable green light, and therefore the yellow emission from the LED spectra was less predominant. Another way to see the influence of the saturation on the visual appraisal is when we compare the performance of spectra #2 and #3 (highest in yellow emission) amongst the three different yellow samples. The charts show that for the saturated sample, most subjects answered “look the same” or “just noticeably different” for these spectra. For less saturated yellow samples, the charts show that spectra #2 and #3 performed considerably worse, with the many subjects answering “very different” and “different”.



Color Sample	ΔE*ab
YW-HUE - inc.	x #2 = 1.79
YW-HUE - inc.	x #3 = .89
YW-HUE - inc.	x #4 = 1.38
YW-HUE - inc.	x #5 = 2.63
YW-HUE - inc.	x #6 = 3.31
YW-HUE - inc.	x #9 = 5.62
YW-HUE - inc.	x #11 = 8.44

Color Sample	ΔE*ab
YO-T3 - inc.	
YO-T3 - inc.	x #3 = 1.69
YO-T3 - inc.	x #4 = 1.14
YO-T3 - inc.	x #5 = 1.24
YO-T3 - inc.	x #6 = 1.60
YO-T3 - inc.	x #9 = 3.15
YO-T3 - inc.	x #11 = 5.21

Color Sample	ΔE*ab
O-P2-2 - inc.	x #2 = 3.37
O-P2-2 - inc.	x #3 = 2.44
O-P2-2 - inc.	x #4 = 1.8
O-P2-2 - inc.	x #5 = 1.49
O-P2-2 - inc.	x #6 = 1.63
O-P2-2 - inc.	x #9 = 2.91
O-P2-2 - inc.	x #11 = 4.94

Figure 12 – Subject ratings for yellow color samples under light sources.

Conclusions

In this study we examined human’s sensitivity to color rendering modulation when color temperature and light levels stayed the same. We studied seven LED white composite spectra of different color rendering, but equal chromaticity and light levels, in terms of how they rendered a set of color samples to the human eye, in comparison with an incandescent bulb. Our procedure was to conduct a psychophysical experiment with direct observation on a parallel double booth set up where subjects’ comparisons of color palettes were solicited.

The color rendering modulation performed amongst the LED spectra was primarily based on a modulation of the ratio of red to yellow emissions: we increased yellow to compensate as we progressively subtracted red in an effort to produce a sequence of white LED spectra of higher efficacy. Blue was held fixed and minor adjustments were made for green emission. Seven white spectra were generated and organized from highest to lowest color rendering index, CRI. We focused our analysis on three mid-range CRI spectra, as the results for spectra of very high and very low CRI were foreseeable.

We found that for saturated red and yellow samples, human observation was strongly associated with the rebalance of red to yellow ratio. In some cases these results were opposite to the measured values of CRI or ΔE^*. For example, color differences were much more discernible for saturated red samples under spectra of reduced red emission (and reduced CRI), which was expected and was confirmed unanimously by our subjects. On the other hand, color differences for saturated yellow samples were practically unnoticed under spectra of reduced CRI, as these spectra had higher yellow emission. This result could also have been anticipated and was confirmed by our visual experiment. Visual perception of lower saturation red and yellow samples were not as predictable, and our results offered noteworthy material for future investigation, as color differences were found more tolerable under mid-range CRI spectra. For example, subjects reported to be fairly comfortable with color differences observed for low saturation red samples (including our red toned skin color sample) under spectra of considerably low CRI (and high ΔE^*values). Green and blue samples were considerably less affected by the color rendering modulation than the red or yellows, but it was clear that the color differences on green samples were much more discernible than the blue samples.

Our results provided us with an encouraging baseline against which we plan to further investigate other viewing conditions, and a broader range of color samples. For example, we plan to expose subjects to non-direct observation of color samples to verify whether our current results would persist; as well as looking into a representative group of non saturated red samples. Future work should also attempt to further analyze the nature of the ΔE^* data, including any correlations of directions of color shift with observer responses. We intend to identify which reduced color renderings could potentially be acceptable to users in real life environments. Understanding that the true color of an object requires a certain reference illuminant in mind, our current experimental results should be able to facilitate the classification of colors that are most affected by a range of reduced CRIs (and potentially affected by other reduced CRIs). Our ultimate goal is to be able to assess noticeability of dynamic modulation of color rendering in architectural settings where we speculate the perceived color distortions will range from negligible to nil. We believe that a study with a ‘real life’ experimental set-up would be greatly beneficial to further substantiate our current results and also to help appreciate the relationship between color distortion and color preference. It is important to bear in mind that ratings of composite white light from multi-chip LED systems rely heavily on the set of test samples used on the experiment [8]. The manner under which these color pallets are presented should certainly have consequences in the perception and acceptance of color distortions, and consequently of color rendering modulation.

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