An Investigation into the Perception of Colors under Dynamic Modulation of Color Rendering in Real Life Settings

Maria R. Thompson1 and Una-May O’Reilly2
1. School of Architecture and Planning 2. Computer Science and Artificial Intelligence Lab
Massachusetts Institute of Technology - Cambridge, MA, USA

ABSTRACT

An affirmative finding as whether color rendering can be strategically modulated would present additional significant benefits to the use of light emitting diodes, LEDs, in general illumination. The intent of this research is to appraise the perception of changes in color rendering (CR) when these happen in people’s surroundings, and verify our hypothesis that a range of such generated color distortions will be negligible under realistic viewing conditions. We report the results of a series of psychophysical experiments based on subjective ratings of color changes under continuously modulated color rendering. Visual tests were performed in a full scale real life scenario where subjects looked from three different angles at two identical dinning scenarios positioned side-by-side under incandescent (fixed) and LED illumination (changing CR). Our results confirmed our fundamental hypothesis, showing that the majority of subjects did not detect the color changes in their peripheral angles while the same color changes were noticeable with direct observation. This implies that, to some extent, it is possible to perform modulation of color rendering invisibly in the areas surrounding someone’s central view.

INTRODUCTION

Implementation of LED systems, is expected to establish a new paradigm in architectural lighting [1-2]. Digitally controlled LED systems have been exploited for manipulation of the light spectrum. However, general lighting applications demand light that is perceived as white. When the prevailing lighting in a room transitions through different qualities of white, it can impact not only the spatial aesthetics, but also how effective and efficiently people’s eyes can process the visual information therein [3]. In today's context of exploring the unlimited controllability of LEDs, the main properties of white light – color temperature and color rendering – ought to be carefully studied to ensure safe and appropriate visual conditions.

We are interested in how the visual system perceives changes in the spectral components of white illuminants. In this work we assess human perceptual tolerance to color rendering manipulation. By strategically adjusting color rendering one may be able to enhance visual performance (CR tuned to boost the prominent colors within a room), or further expand the energy efficiency of a lighting system (reducing CR increases efficacy of radiation). The notable point is that while modulating color rendering, the light level and color temperature can stay constant and hence the appearance of the light source stays the same. But, how colors are rendered under such a changing white light is a key, ensuing question. Psychophysical evidence strongly indicates that color vision decreases with eccentricity [4-7], and that people cannot detect even sizeable visual changes when these are slow progressive changes [8-9]. We conducted two previous laboratory experiments using one specific CR modulation and verified a reduction in sensitivity when the color changes were not seen side-by-side, and that our CR modulation was mainly noticeable when looking at saturated reds samples [10]. Our ultimate intent was to substantiate whether this CR modulation would be perceived in the presence of context. With the noteworthy exception of [11], seldom are color perception experimental analyses conducted in the context of natural settings. In this paper we report the results and analysis of a series of experiments whereby: (a) Subjects are positioned at 0°, 10° and 20° from stimuli; (b) Stimuli consist of the combination of colors within a full scale, real life spatial context, with prominent saturated red components; (c) We perform continuous CR modulations of LED white spectra of fixed illuminance and chromaticity. Our results show that sensitivity to our CR modulation was strongly connected with direction of gaze (0°, 10° and 20° from stimuli), and confirmed our fundamental hypothesis, showing that the majority of subjects did not detect the color changes at 10° and 20° angles while the same distortions were noticeable during foveal vision tests.
EXPERIMENTAL SET-UP

The experiment was carried out within a darkened room (approximately 30 Lux) with an area of approximately 950 square ft and 11 ft ceiling height, containing three open experimental chambers of 50 square ft. each, positioned on a slight angle from each other. All three chambers were decorated with same layout and were painted with light grey matte paint to maintain neutral and smooth background illumination. The layout and materials were selected so the setting would have a prominent saturated red component, and would work as a representative day-to-today scenario. Chambers #1 and #3 were illuminated with incandescent light and chamber #2 with three LED fixtures (figure1).

Figure 1 – Experimental set-up. Chambers #1, #2 & #3.

Each incandescent set-up was mounted at 12 feet height from floor and comprised: (1) 17 bulbs (100W soft white A19); (2) Diffuser layer (acrylic K12 prismatic lens), and color temperature correction filter (Rosco #3208: Quarter Blue), mounted together at 3 feet inches below the bulbs. Each LED fixture was mounted at 9 feet from the floor and consisted of: (1) An enclosure equipped for suitable heat dissipation; (2) 3 LED systems (each composed of an LED panel, a custom made digital controller and power supplies), and (3) Diffuser layer (ROSCO #111). Each LED panel contained 58 LED modules (6 Red, 24 Yellow, 16 Green and 12 Blue). The digital controller, mounted to the panel, is a custom made PCB with programmable microprocessor, operating java based software to perform PWM modulations of the four individual channels from a PC computer. Besides enabling full control of each color channel, the software enables us to create any set of RYGB spectra and choose a combination individually or to sequence through multiple combinations within any time interval.

The four color channels of the LED panels – controlling one single set of dominant wavelengths 633 nm (Red), 587 nm (Yellow), 525 nm (Green) and 470 nm (Blue) -- were individually tuned to produce eleven composite white spectra with different color rendering (Ra varying from 34 to 92) but matching chromaticity and light level with the incandescent chamber (Graph 1). Table 1 summarizes the results from the measurements of the eleven LED spectra and the incandescent, showing the general CRI–Ra, special CRI-R9, CCT (K) and LER (lm/W). The individual values per light source are displayed in table 1, but we measured approximately 260 lux horizontally which represents approximately 30 cd/m² of vertical luminance. Therefore all the study was performed in high high-mesopic to low-photopic light levels which allows for good color vision. Museum lighting normally defines their light levels this way which allow for accurate color vision but reduced light on paintings.
Graph 1 and Table 1 - Spectral power distribution, SPD, for reference and test illuminants. 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. 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 yellow emission and consequently spectrum #1 presents very poor rendering, but high efficacy.

EXPERIMENTAL PROCEDURES

Thirty subjects (eleven male and nineteen female) with normal color vision participated in the experiment. The main goal of the experiments was to determine if and when they would detect incremental changes in the color rendering of eleven LED white spectra when chromaticity and illuminance stayed the same as the incandescent reference. The experiment was divided in three sections, each dedicated to threshold detection in peripheral (20°), off-center (10°), or foveal vision. For all three sections the main procedure stayed the same: subjects were sitting in a central position facing the chambers, while in chamber #2, the LED sequenced the eleven LED spectra continuously, and one of the incandescent chambers had fixed incandescent illumination. We only compared two chambers at a time having LED chamber #2 with either incandescent chamber #1 or #3. The subjects (two at a time) were instructed to keep their gaze at the flower arrangement in the incandescent chamber, while the LED chamber was prompted to sequence the 11 spectra each for 30 seconds. During this time four beeps indicated the start, middle and end of the interval. At the end beep subjects answered the questionnaire and marked if they noticed a change in the appearance of either chamber and if they first noticed the change in the beginning, middle or end of the interval. The beep cycle assisted the subjects with the timing of each interval and allowed them to locate when they first notice a change (if they did). We classified the 11 spectra in 3 color rendering regions: High CRI (spectra #11, 10, 9 & 8), Medium CRI (spectra # 7, 6, 5 & 4) or Low CRI (spectra # 3, 2 &1). We could then interpret the questionnaire responses (beginning, middle or end) and determine if they noticed the change at a high, medium or low CR range. Three sequence modes were defined: (a) Decreasing CRI (sequencing LED spectra #10 to #0), Increasing CRI (sequencing LED spectra #0 to #10) and the control test (no change in lighting).

The 20° experimental section was divided in 6 intervals: 2 intervals for decreasing CRI sequence; 2 intervals for increasing CRI sequence; and 2 intervals for control test (no change in lighting). Subjects sit 30 feet away from the chambers. The 20° angle was measured between the subjects’
focal point (flowers) in chamber #1 under fixed incandescent lighting; and the reference point (flowers in chamber #2), under sequencing LED lighting.

The 10° section was very similar to section 1 with the same positioning and instructions for subjects. For this section only chambers #1 and #2 were used and the layout was modified to allow a 10° angle of vision between subjects’ focal point (flowers in chamber #1), and the reference point (flowers in chamber #2). The foveal vision section was divided into 4 intervals: 2 intervals for decreasing CRI sequence; 1 interval for increasing CRI sequence; and 1 interval for the control test. Subjects were seated 10 feet away from chamber #2, and were asked to look freely within chamber #2, while the LED lighting was sequencing.

RESULTS

Graph 2 shows the combined results for the three tests (Peripheral at 20°, Off-Center at 10° and Foveal at 0°), revealing that the majority of the population did not appreciably notice the changes in color caused by the modulations in color rendering. We see however from graph 3 that this result was not consistent throughout all tests, as subjects’ responses were notably different for the 0°, 10° and 20° assessments. While in the peripheral vision tests less than 10% of the population noticed anything at all, during the foveal vision tests the majority of the population reported to have noticed something changing in the scene. In every experimental section, a control test was introduced to test the validity of the judgments made by the observers. Graph 3 shows that some changes were reported when none had, in fact, occurred, but these were sufficiently seldom (p<0.1) to validate the conclusions drawn from the tests.

The results on graph 3 demonstrate that sensitivity to color rendering modulation was strongly connected with direction of gaze (20°, 10° and 0°), with significant (p<0.1) reduction in sensitivity as we moved the test field away from the foveal field of view. They confirmed our fundamental hypothesis, showing that most subjects did not detect color changes in their periphery (20°), while they did perceive these changes with direct observation (0°). Moreover, the results provide us with noteworthy information concerning visual perception at 10°. As the proportion of people noticing change at 20° did not reach significance (p<0.05), it is clear that subjects had no discernment concerning the color changes at this angle, and therefore we will focus the following analysis on a comparison between the results from the 0° and 10° vision tests.

The 10° tests represented perhaps the most provocative stage in our investigation, as we did not have sound expectations for their outcome, and as the 10° angle has been vastly studied in terms of color perception [12-15]. The 10° angle represented in our study the exact middle position between our peripheral viewpoint and center of gaze, and the results also reveal that this angle represents a differentiated interval for color perception. Graph 3 illustrates a sequential ascendance in sensitivity from peripheral to foveal verifying that 10° represented a middle point in terms of sensitivity to our CR changes. But even though there was a significant increase in sensitivity at this point in comparison with the 20° position, still less than about 50% of the population noticed any CR change. This shows that at this angle subjects had limited sensitivity to the changes in color, and substantiates that CR modulation can be made unnoticeable even closely to foveal region. On the other hand, the number of people noticing the changes indicates that further research should be encouraged to examine in more detail the various aspects of visual performance correlates for this particular field of view (such as rates of changes for LED spectra, light levels, color temperature, distance, colors within the room other than red, etc.) in order to achieve an effective (truly invisible) control strategy.
Not only did the results inform us about how much visual sensitivity decreased when the test field was moved outward from the fovea, but they also provided insights in how people perceived the color changes at these two fields of view. Graph 4 shows that in both foveal and 10° tests there was no significant perceptual difference between the two LED sequencing modes (spectra sequencing to gradually decrease or increased CRI), although we see a slight tendency of the observers to notice a change for the increasing CRI mode. We were persuaded to join these results with a collection of unsolicited comments from subjects both during the real tests and during the pilot tests, which revealed a unanimous differentiated reaction from subjects to the increasing CRI sequencing mode. This is a suggestion that, at 10° view angle, the change in CRI (by adding or subtracting red energy from the LED mixing) made lightness changes more perceptible to subjects than the actual changes in the chromatic aspects of colors (hue and saturation). Further research should be encouraged that would evaluate perception of changes in lightness and chromaticity in isolation, as well as more detailed analysis of sequencing rate and direction of change.

Another qualitative aspect observed from the 10° tests results is illustrated in Graph 5, with subjects’ responses to the different color changes evoked by spectra of High, Middle and Low CRI. We see reversed and unexpected trends comparing results from foveal and 10° tests. In foveal tests, most subjects only noticed the changes when the sequence employed spectra with reduced CRI (Ra 68 to 34) which is when greater color distortions happen, and was foreseeable. But in the 10° tests most subjects noticed changes when looking at the mid to high CRI range (Ra as high as 94), which was unpredicted. We expected that at 10° subjects would notice the most
prominent color distortions (caused by spectra of low range CRI) and that the color changes promoted by spectra of higher range CRI would only be noticed with foveal observation. Our results show that the opposite happened. It can be inferred that during foveal tests, when people were looking directly into the scene, they were attentive to all details within the chamber, and only detected the more outstanding color distortions. But when looking at the same scene from 10° angle, they saw the collective average of what was happening, and then captured the smaller color changes caused by spectra of higher CRI. Further research could evaluate perception of CR changes resulting from sequencing spectra in high, middle and low CRI ranges in isolation.

![Graph 4](image1.png)

**Graph 4** – Results for 20°, 10° and 0° tests for different sequence types.

![Graph 5](image2.png)

**Graph 5** – Results for 20°, 10° and 0° tests for different Color Rendering Index.

**CONCLUSION**

We had an initial strong hypothesis that people would not notice a certain class of color distortions when these happened (a) immersed within a ‘real life’ spatial context, (b) in people’s periphery at 20°; and (c) under continuous modulation of color rendering. Ultimately we predicted that we would be able to perform modulation of color rendering invisibly at people’s surrounding areas. To support our hypothesis we had psychophysical evidence strongly indicating that color vision decreases with eccentricity [4-7], and that people cannot detect even sizeable visual changes when these are slow progressive changes [8-9]; in combination with the results from our own baseline experiments showing a reduction in sensitivity when color changes were not seen side-by-side [10]. Also from our baseline study we had confirmation that saturated red
components represented the worse case scenario for perceiving our CR modulation in a discrete sequence. These propositions were the foundation of the design of these series of experiments, which mainly constituted the following set-up: (a) Subjects positioned at 0°, 10° and 20° from stimuli; (b) Stimuli consisting of the combination of colors within a ‘real life’ spatial context, with prominent saturated red components; (c) Continuous color rendering modulation of RYGB LED white spectra of fixed illuminance and chromaticity.

We have encouraging affirmative findings as our results provide strong indication that continuous modulation of CR within a ‘real life’ spatial context can be made invisible at people’s surroundings. The results first confirmed our fundamental hypothesis, showing that the vast majority of subjects had no discernment of any color changes at 20° angle tests, while during foveal tests the same color changes were noticeable for most subjects (p<0.1). Secondly, the results for 10° angle (off-center position) reiterate that sensitivity to our CR modulation was strongly connected with direction of gaze, when they demonstrate a sequential ascendance in sensitivity from 20°, through 10° to 0° fields of view. However, it is important to point out that even though there was a significant increase in sensitivity to color changes from 20° to 10° fields (p <0.1), still less than about 50% of the population noticed any change during the 10° tests. This shows that at this angle subjects still had limited sensitivity to the changes in color, and substantiates that CR modulation can potentially be made unnoticeable even closely to foveal region.

Our results also provided qualitative information about perception of color changes at the three tested fields. Slight but intriguing perceptual difference were noticed to (a) the two LED sequencing modes (spectra sequencing to gradually decrease or increased CRI); (b) different color changes evoked by spectra of High, Middle and Low CRI; as we found reversed and unexpected trends comparing results from foveal and 10° tests.

As much as these qualitative findings (highlighted by the results from the 10° tests) were truly provoking, we are wary of over interpreting their significance in the light of potential limitations of our procedures for inspecting such specific aspects. In order to have confirmatory results concerning, for instance, differentiated visual sensitivity to changes in lightness and chromaticity within a room, it is necessary to investigate these two aspects in isolation. But psychophysical investigations of color perception in the presence of context should be encouraged when progressing into such a specialized research path. We believe that even the most rich color perception psychophysical evidence listed above has to be put to test. The world around us is way messier than the laboratory conditions, and it is important for practitioners to receive convincing demonstration that these types of results can be extrapolated to real life.

ACKNOWLEDGEMENTS

This work would not have been possible without the dedicated support from Robert Levin, Joseph Laski, Robert Cilic & Makarand Chipalkatti, from Osram Sylvania; Iuliu Vasilescu & Ron Wiken, from CSAIL, MIT; Ruth Rosenhotz & Paymon Hosseini, from Dept. of Brain and Cognitive Sciences, MIT. Special thanks should also be given to Dr. Janos Schanda for the continuous support, precious information and encouragement.

REFERENCES


