Color Rendering Properties of LED Light Sources

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ABSTRACT

A laboratory human factors experiment was conducted to understand the color rendering properties of various LED-based reading lights. Human subjects rated their preference for a given scene illuminated by a test light source compared to an identical scene illuminated by a reference light source. In another experiment the same subjects viewed and rated the scenes individually when illuminated by a test light source. LED-based light sources were preferred more than halogen and incandescent light sources for overall color appearance. However, phosphor-based white LED light sources were rated poor for the appearance of human skin tones. This study shows that RGB mix white LED light sources have the best overall characteristics to be used as reading or task lights. This study has shown that CRI has no correlation to peoples' color preference. Therefore, the authors of this manuscript do not believe that CRI should be used as a target metric for color rendering properties in the development of solid-state light sources because it could negatively impact overall performance. A better metric is long overdue to quantify light source color rendering and preference properties.

Key Words: LED, White light LED, Architectural lighting, Color Rendering Index, CRI

INTRODUCTION

Architectural lighting is one of the potential applications for the rapidly developing high-brightness light emitting diodes (LEDs). Lumens per watt (lm/W) and color rendering index (CRI) are two commonly used metrics for evaluating light sources. The LED industry is working hard toward creating light sources with high luminous efficacy (lm/W) and high CRI values so the technology will be widely accepted for general illumination applications. There are two distinct approaches for creating white light with LEDs. The first is combining blue LEDs with a down conversion phosphor. The second is mixing monochromatic LEDs in appropriate proportions. In a previous publication the authors of this paper analyzed the advantages and disadvantages of these two methods [1]. That same publication demonstrated that a slight shift in peak wavelength of the red LED in a sample RGB color mixing approach caused the CRI value to change significantly [1]. The CRI value attained with 465, 525, and 640 nm RGB LED combination was 23. However, the CRI value improved significantly, to 70, when a 615 nm red LED was selected instead of a 640 nm LED [1]. It was hypothesized that, although the CRI value changes dramatically for the two mixed color white LED light sources, human subject response for color preference of objects illuminated by these light sources will be almost the same. Therefore a psychophysical experiment was conducted to understand the color rendering and color preference properties of various LED-based reading lights and to verify the above-mentioned hypothesis. The details of the experiment and the results are presented in this manuscript.

EXPERIMENT

The goal of this experiment was to understand the color rendering and color preference properties of various LED-based reading lights and compared them to conventional halogen and incandescent light sources. The study was conducted in the context of an aircraft reading light. Human subjects viewed two identical scenes placed side-by-side and rated their preference for a given scene illuminated by a test source compared to an identical scene illuminated by a reference light source. In a second experiment the subjects viewed and rated the scenes individually when illuminated by a test light source.

Figure 1 illustrates the experimental setup. The two cabinets were identical. A forehead holder was fixed in the middle frame of the apparatus to make sure that the subjects viewed the scenes from a constant distance, 50 cm, from the scene.

The opening of each cabinet measured 38 cm by 38 cm. The light sources were mounted above the display area pointing upwards to the domed section of the setup. The light reached the displayed objects after bouncing off the domed ceiling area and the walls of the cabinets that were painted with matte finish white paint. This ensured good mixing of light and uniform illuminance on the surface of the objects and the interior space. As shown in Figure 1, a color magazine, two soda cans, and a text card with various font sizes were placed inside the viewing area of the two cabinets. The objects on display were multicolored and were typical of what one would see under a reading light in an aircraft.

Figure 1: Front view of experimental setup

One of the cabinets was equipped with six test light sources, and the other was housed with two reference light sources. The light sources used in this study are listed in Table 1. A halogen and a RGB low CRI LED unit were used as reference light sources. Both cabinets contained identical RGB low CRI LED units so the null condition can be verified. This means the subject rating should be equal for both cabinets when illuminated by these sources if the two scenes are identical.

LED Reading Lights	RBG-Mix Low CRI
	RBG-Mix High CRI
	Phosphor/Amber
	5-mm Phosphor White
	High-power, Two-phosphor White
Conventional Reading Lights	Halogen / Incandescent

Table 1: Light sources used in the experiment.

A switch box containing eight switches controlled each of the reading lights in the two cabinets. All of the light units provided the same light level, 200 lux, on the surfaces of the displayed objects.

Two experiments were conducted to determine whether the color scheme on the magazine and the size of the fonts selected had any impact on subject rating. In experiment 1, the magazine cover contained pictures that were dominantly red in color, and the font sizes of the letters on the reading card were quite small, 4 – 10 points. In experiment 2, the magazine pictures were dominantly yellow in color and the reading card font sizes were relatively larger, 10 to 18 points. Altogether, 30 subjects, 15 male, 15 female, participated in the two experiments: twenty in the first and ten in the second. Their ages ranged from 20 to 49. The subjects were from various ethnic and cultural backgrounds. In both experiments, the subjects rated their preference for a given lighted scene while viewing the scenes side-by-side as well as individually, one at a time.

The experimental setup was located in a room with no ambient light. Subjects were screened for color deficiencies prior to starting the experiment. The subjects sat in a chair in front of the display cabinets with their forehead in the forehead holder. The experimenter switched the lights on and off, changing the lighting in the two cabinets randomly. The subjects were asked to complete a questionnaire about their perception of the scenes under each of the lighting conditions.

The questionnaire was organized into two parts. The first part was a side-by-side evaluation. The subjects stated their preferences for the lighting in the left or right cabinet. If they found both lighting conditions identical they assigned an equal preference rating. The second part of the experiment was the individual evaluation. The experimenter illuminated only one cabinet and the subjects expressed their preferences for the lighting on a -3 to +3 scale. A rating of zero indicated a neutral response, meaning the lighting was just acceptable for the aircraft reading light application; -3 indicated that the subject strongly disliked the lighting; and +3 indicated that the subject strongly liked the lighting. The questionnaire queried the subjects for their preferences for the color appearance of the overall scene, individual objects, such as the magazine and soda cans, and for readability of the fonts when illuminated by the different light sources. Finally, the subjects placed one of their hands inside the illuminated area and rated their preference for skin tone color appearance.

RESULTS

Figure 2 illustrates the spectral power distributions (SPDs) of the different light sources used in this study. Table 2 summarizes the light source characteristics measured inside the experimental setup. Throughout the experiment the illuminance level on the objects was maintained at approximately 200 lux. The chromaticity

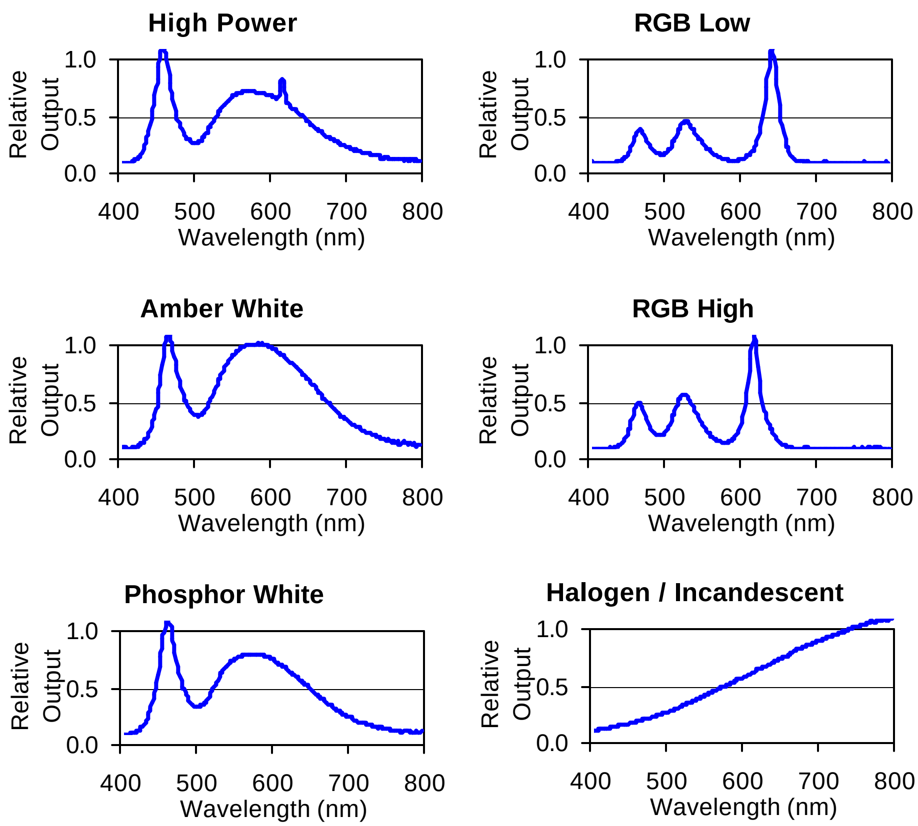

Figure 2: SPDs of the different light sources

values of the different light sources are shown in Figure 3. Both RGB mix LEDs mapped very closely to each other on the chromaticity diagram.

	CCT	CRI	CIE x	CIE y	Illuminance (lux)
High Power	4907	83	0.345	0.329	196
Amber white	4117	81	0.376	0.377	194
RGB Low	4279	25	0.368	0.367	190
Incandescent	2652	98	0.467	0.417	201
RGB High	4139	63	0.373	0.367	193
Phosphor white	5031	82	0.344	0.347	200
RGB Low	4269	23	0.368	0.366	194
Halogen	2835	98	0.453	0.415	202

Table 2: Light source characteristics, measured inside the experimental setup.

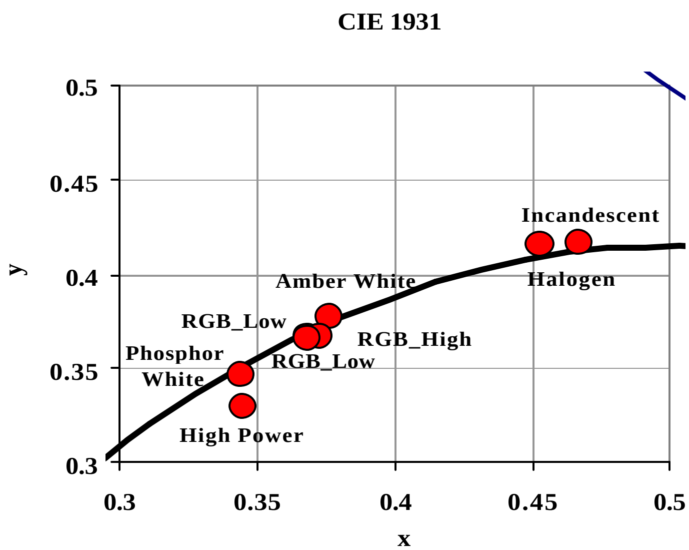

Figure 3: Chromaticity values of the different light sources

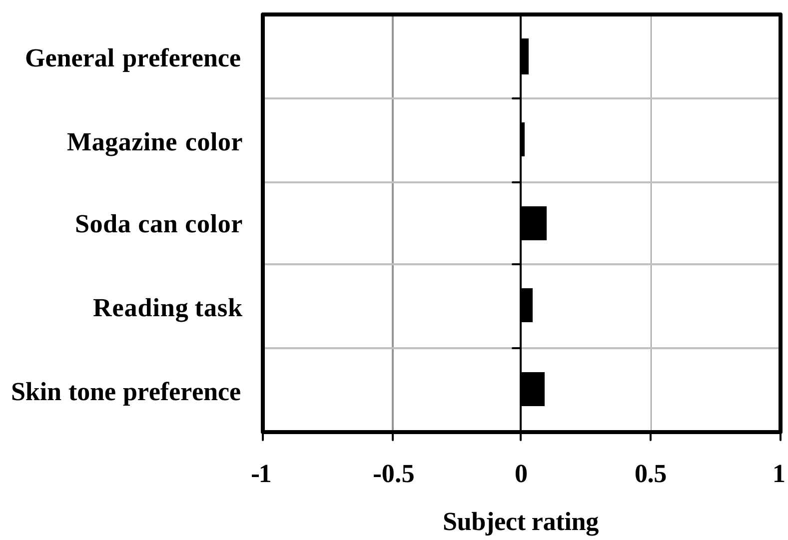

Figure 4: Null test results, subject ratings for both cabinets when illuminated by the low CRI RGB light sources.

Figure 4 illustrates the results of the null test. In this test both cabinets were illuminated by RGB low CRI LED light sources. Subject ratings for each cabinet were totaled and the difference between the two values was converted to a percentage value. A rating of –100% or +100% indicates a very high preference for the scene on the left or the scene on the right respectively. A zero indicates equal preference for the two scenes. As seen in Figure 4, the subjects voted equally for the two cabinets showing no preference for either cabinet. Statistical analysis showed no significant difference, thus verifying the null condition. This test demonstrated that the two scenes in the experimental setup were identical.

The results shown in this section are the average values of the two experiments since experiment 1 and 2 gave very similar results. Both experiments giving similar results indicated that the color of the magazine nor the font size used for the reading task had any significant influence subject rating. Figure 5 illustrates the results of the side-by-side comparison experiment in which halogen was the reference light source. The

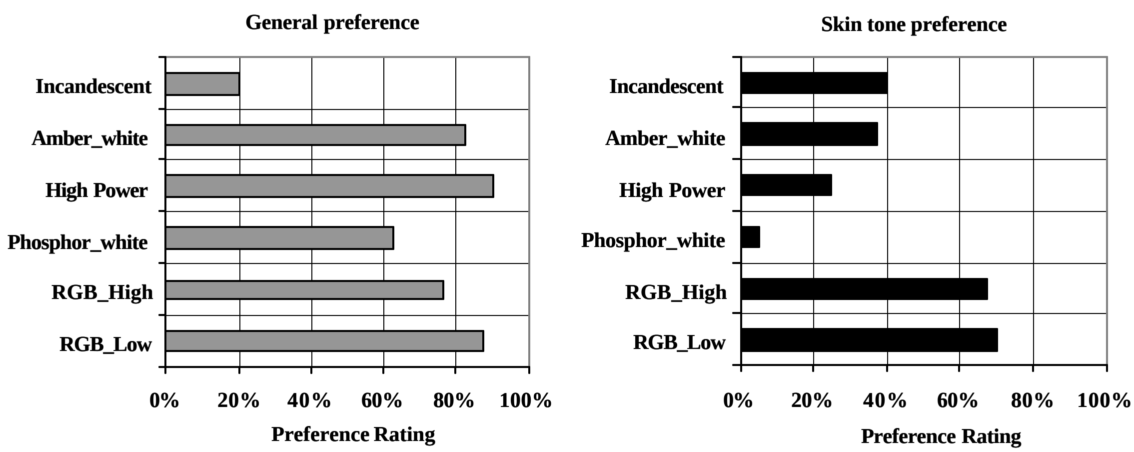

Figure 5: Side-by-side evaluation results for general preference and skin tone preference.

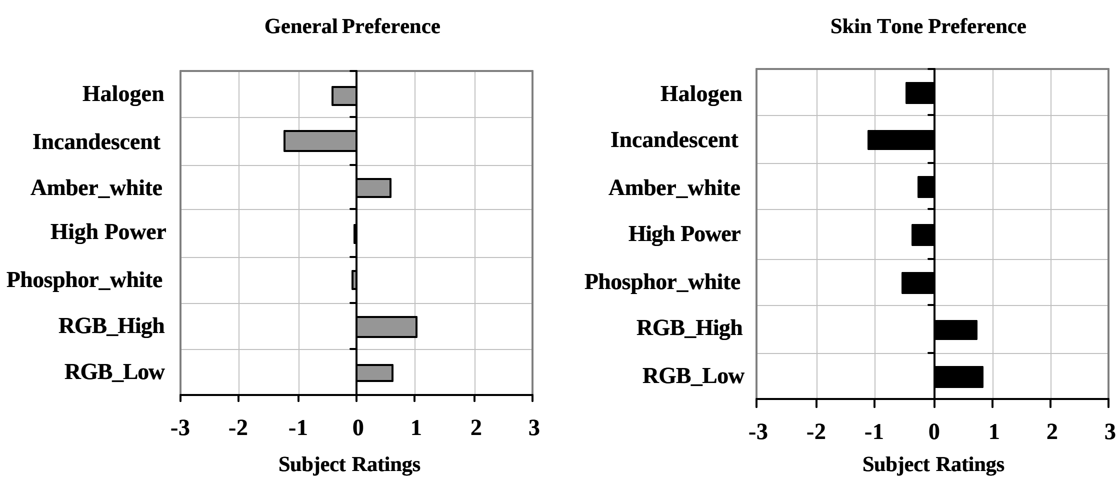

Figure 6: Individual evaluation results for general preference and skin tone preference.
Subject rating –3 means strongly disliked, +3 means strongly liked, and 0 means neutral.

questionnaire queried the subjects for their preferences for the color appearance of the overall scene, individual objects, and for font readability when illuminated by the different light sources. Since the general preference correlated well with the average preference for the individual object color preference and the reading task, only the general preference rating is shown in this paper. The graphs show the percentage of people who preferred the test light source as compared to the reference halogen source. For example, a rating of 90% for the high power LED light source indicates that 90 % of the subjects preferred this source while the remaining 10% preferred the halogen source. A rating of 50% indicates equal preference for the test light source and the reference light source. These results show that all of the LED-based light sources scored above 50%, therefore they were more preferred compared to the halogen light source in terms of general preference for object color appearance. Although phosphor-based LED light sources (high-power, phosphor white, amber white) showed a high percentage of preference for overall color appearance, they render human skin tones poorly, so their rating was much lower than for halogen light source. In terms of skin tone preference, the two RGB mix color white LED reading lights performed much better than the standard halogen reading lights.

Figure 6 illustrates the mean ratings of subject preference for a given lighted scene while viewing the scenes one at a time. The subjects expressed their preferences for the lighting on a -3 to +3 scale where -3 indicated strongly disliked, and +3 indicated strongly liked. Zero indicated a neutral response, indicating that the lighting was just acceptable for the aircraft reading light application. Here again only the general preference rating is shown because the general preference correlated well with the average preference for the individual object color preference and the reading task. As seen in figures 6 all the LED based reading lights were either just acceptable or more liked for general color appearance. Both halogen and incandescent reading lights were disliked. As in the side-by-side experiment, both RGB systems were liked very much for skin tone appearance. All other light sources were disliked.

This study shows that RGB mix white LED light sources have the best overall characteristics to be used as reading or task lights. The results demonstrate that the subject preferences during the side-by-side evaluation and individual evaluation are about the same for the RGB low CRI LED reading light and the RGB high CRI LED reading lights. This shows that, although the two RGB mix LED reading lights had significantly different CRI values, 25 and 63, subject preference was same for the two. This verified the hypothesis.

Figure 7 illustrates the overall color preference for the different light sources. In this graph the light sources were ranked in the increasing order of their CRI value. As it can be seen from this graph, people's preference for color does not correlate well with the CRI value of the source. In fact, in this particular case it has a negative correlation. The lower CRI valued RGB mix color white light source had a greater preference rating compared to higher CRI valued halogen sources. The authors wish to caution the readers that, in general, one cannot compare CRI values at different CCT values. The only reason it is done here is to illustrate a point that is discussed in the next section.

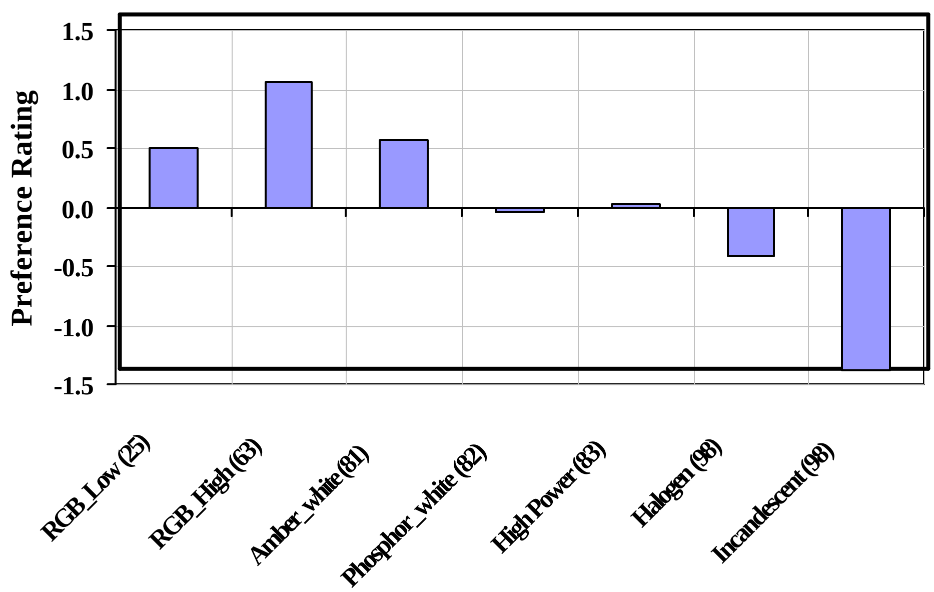

Figure 7: Average preference rating for the different light sources when viewed individually. Values within parenthesis indicate the respective CRI values.

DISCUSSIONS

It is a common belief that a light source with high CRI would render colors better than a source with low CRI and would be more preferred by people. Although commonly used, CRI is a metric that is often misunderstood and misused. The expectation is that CRI indicates the extent of the color rendering properties of a light source. However, in reality the CRI of a light source is a measure of the degree to which the perceived object colors illuminated by a test source conform to those of the same objects illuminated by a standard source such as an incandescent light source [2].

Recently, other publications have pointed out the inadequacies of the CRI metric [3-5]. In 2001 Tarczali et al conducted an experiment and concluded that CRI was not able to characterize the color rendering properties of modern light sources correctly [4]. In a 1999 publication, van Tright clearly explains all the major shortcomings of the CRI metric [3].

In the development process of a new light source such as the solid-state white light sources, one may have to sacrifice luminous efficacy to gain high CRI [6]. Contrary to general belief, this study showed that a low CRI LED light source was more preferred than a high CRI halogen or incandescent light sources. In addition the study described in this manuscript has shown that CRI has no correlation to peoples' color preference. Therefore, the authors of this manuscript do not recommend the use of CRI as a target metric in the development of solid-state light sources because it could negatively impact overall performance. A better metric is long overdue to quantify light source color rendering and preference properties.

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