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Determining Contrast Sensitivity Functions for Monochromatic Light Emitted by High-Brightness LEDs

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ABSTRACT

Light-emitting diode (LED) technology is becoming the choice for many lighting applications that require monochromatic light. However, one potential problem with LED-based lighting systems is uneven luminance patterns. Having a uniform luminance distribution is more important in some applications. One example where LEDs are becoming a viable alternative and luminance uniformity is an important criterion is backlighted monochromatic signage. The question is how much uniformity is required for these applications. Presently, there is no accepted metric that quantifies luminance uniformity. A recent publication proposed a method based on digital image analysis to quantify beam quality of reflectorized halogen lamps. To be able to employ such a technique to analyze colored beams generated by LED systems, it is necessary to have contrast sensitivity functions (CSFs) for monochromatic light produced by LEDs. Several factors including the luminance, visual field size, and spectral power distribution of the light affect the CSFs. Although CSFs exist for a variety of light sources at visual fields ranging from 2 degrees to 20 degrees, CSFs do not exist for red, green, and blue light produced by high-brightness LEDs at 2-degree and 10-degree visual fields and at luminances typical for backlighted signage. Therefore, the goal of the study was to develop a family of CSFs for 2-degree and 10-degree visual fields illuminated by narrow-band LEDs at typical luminances seen in backlighted signs. The details of the experiment and the results are presented in this manuscript.

Keywords: LED, signage, channel, letter, red, green, blue, backlighted, contrast sensitivity function, uniformity

1. INTRODUCTION

During the past few years, light-emitting diode (LED) technology has been rapidly advancing and has demonstrated significant benefits over conventional light source technologies in certain lighting applications, such as EXIT signs and traffic signals. In these applications, LEDs have shown energy savings of more than 80% compared with their incandescent counterpart. Such large energy savings are realized because colored signs and signals are created using optical filters over incandescent lamps that absorb and waste a significant portion of the radiant energy generated by the light source. Alternatively, LEDs are much more efficient in producing monochromatic light. Therefore, LEDs are becoming the preferred light source for applications that require colored light. However, since LEDs produce much less light per light source compared with traditional light sources, typically several LEDs are assembled into arrays to meet the light level requirements of applications. The discrete nature of LEDs could potentially create uneven light distributions. Additionally, depending on system design, different LEDs in the array could experience different degradation rates and contribute to the creation of non-uniform luminance patterns over time. Having a uniform luminance distribution is more important in some applications. One application where LEDs are becoming a viable alternative and luminance uniformity is an important criterion is backlighted monochromatic signage.[1]

Backlighted signs have been used outdoors for decades and are an important feature of storefronts that draw customers' attention, especially during evening hours. Corporations spend a great deal of money to design and manufacture signs that attract customers, making them an important selling point for a store. Perception of a retail establishment's quality may often be based on the illuminated signage in front of that store. For example, a store with certain letters or sections of its sign burned out may be perceived as lower quality because the sign has not been well-maintained. Similarly, non-uniform luminance distribution within a sign may also affect consumers' perceptions of the store.

Accepting the fact that LED systems are likely to produce non-uniform luminance patterns, the question becomes: How uniform should a luminance pattern be? Presently, there is no accepted metric that quantifies luminance uniformity. A recent publication by Simonson *et al.* proposed a method based on digital image analysis to quantify the beam quality of reflector lamps that are commonly used in interior lighting applications.[2] In that paper, it is explained that perceived beam quality depends on several factors including distance of the observer to the target field, background luminance, target pattern, and target color. In their study, Simonson and others demonstrated that a beam quality rating based on analyzing a digital image weighted by a contrast sensitivity function (CSF) correlated much better with human subject ratings, compared with analyzing the raw CCD camera image. To be able to employ such a technique to analyze colored beams generated by LED systems, it is necessary to have CSFs for monochromatic light produced by LEDs.

1.1 What is CSF?

CSF describes the sensitivity of the visual system as a function of spatial frequencies.[3] The size and contrast of a target come into play when assessing the sensitivity of the visual system. The contrast sensitivity curve (Figure 2) describes the window of visibility. The curve has points that show the threshold contrast at the respective spatial frequencies. Beyond these threshold points, an individual may not be able to see a particular spatial frequency. Contrast is derived from Michelson's formula, (L_{max}–L_{min}/L_{max}+L_{min}), and contrast sensitivity is the reciprocal of contrast. Spatial frequency is determined by the characteristics of the visual target and is expressed in cycles per degree. The reason for the typical shape of the curve is that the visual system is less sensitive to very low and very high spatial frequencies. There is an intermediate point at which the visual system has higher sensitivity than at either extreme. Usually, the CSF falls off rapidly after reaching a peak of about 3 to 5 cycles per degree.[3] With an increase in luminance, the peak value of the CSF will increase and at the same time, the peak also will shift toward higher spatial frequencies.[4] It has also been shown that there is an effect of field size on the CSF. Carlson showed that the absolute sensitivity to lower spatial frequencies increases with increasing field size.[5] This effect is diminished for higher spatial frequencies, and there is no significant difference among CSFs.[5] Kelly derived CSFs for short, medium, and long wavelength cone photoreceptors using gratings illuminated with red, green, and blue light sources. During the experimental sessions, subjects were adapted to an opponent color prior to viewing the test grating. Kelly concluded that under these conditions, there is a significant difference in the absolute heights and the position of the peaks of CSFs among the short, medium, and long wavelength cone photoreceptors.[6]

As mentioned earlier, to develop a metric that can quantify the luminance uniformity of backlighted signs, CSFs are needed. Although CSFs exist for a variety of light sources at visual fields ranging from 2 degrees to 20 degrees,[7] CSFs do not exist for red, green, and blue light produced by high-brightness LEDs at 2-degree and 10-degree visual fields and at luminance levels typical for backlighted signage. In reality, a person would look at a backlighted sign on a storefront within a range of 2-degree to 10-degree visual fields. For example, signage on large-scale department stores would be seen at about a 2-degree viewing angle when someone is far away from the store, such as driving along a nearby highway, and at about a 10-degree viewing angle when someone is closer to the store, such as walking toward the store from the parking lot. Therefore, the goal of the study was to develop a family of CSFs at 2-degree and 10-degree visual fields illuminated by red, green, and blue LEDs at typical luminances seen in backlighted signs.

2. EXPERIMENT

A human-factors experiment was designed for the purpose of developing a CSF for each of the sine wave grating patterns illuminated by red, green, and blue LEDs. The experiment comprised two parts: one, to replicate one of the existing CSFs for white light sources to use as a baseline for comparison, and another to determine the CSFs for monochromatic light produced by red, green, and blue LEDs. The second part of the experiment was conducted at two viewing distances corresponding to 2-degree and 10-degree visual field sizes.

2.1 Experimental Setup

The experimental setup (Figure 1) consisted of a 2 ft. x 2 ft. x 9 in. (61 cm x 61 cm x 23 cm) light integrating box built of 1/4-inch thick white foamboard. The sine wave grating patterns printed on white sheets were mounted at the rear of the box. These gratings were mounted such that they could be changed easily during the experiment. An array of high-brightness LEDs were mounted on a white foamboard panel that formed the front face of the integrating box. The LEDs faced the back wall of the box where the gratings were placed. Three separate front panels were built, each one with a different colored LED array (red, green, and blue). During the experiment, the respective front panel was mounted depending on the required color. The LED array was wrapped around an 8 in. x 11 in. (20 cm x 28 cm) aperture cut into the front panel. For the purpose of replicating one CSF for broad-band white light, two 40 W incandescent light sources were mounted inside the box, one on the left panel and the other on the right panel closer to the front side of the box. Both the LED and incandescent light sources were powered by a direct current power supply. The average luminance values of the illuminated gratings were measured before and after each subject's experiment. The average luminance $[(L_{max}+L_{min})/2]$ is the mean of the darkest and the lightest part of the gratings.

The target sine wave gratings were viewed by the subjects from a distance of 9.5 ft. (2.9 m) for the 2-degree visual field experiment and at a distance of 1.8 ft. (0.6 m) for the 10-degree visual field experiment. The variables of the sine wave gratings were their contrast and spatial frequency. The contrast of the grating is defined by $(L_{max}-L_{min})/(L_{max}+L_{min})$, where L_{max} is the luminance at the peak of the grating, and L_{min} is the luminance at the trough. The spatial frequencies of the gratings chosen were 1, 2, 3, 4, 6, 8, 10, 12, 14, 16, and 32 cycles per degree. These gratings were created using computer software and were printed on white sheets of paper. In one series of tests, an average target luminance of 45 cd/m^2 was maintained for all red, green, and blue target gratings. In a second series of tests, the average target luminance was based on the typical luminance of red, green, and blue backlighted signs (red: 125 cd/m^2, green: 35 cd/m^2, blue: 5 cd/m^2) determined during a field survey.

2.2 Experiment 1

The objective of the first experiment was to replicate an existing CSF for a broad-band white light source. Seven subjects, three females and four males in the age group of 20 to 30 years, participated in this experiment. Subjects were initially tested for color vision deficiencies, and only those with normal color vision participated in the experiments. During the first experiment, subjects viewed the target sine wave gratings illuminated by the incandescent light sources from a distance of 9.5 ft. (2.9 m). The visual field for this case was 2 degrees. The experiment was conducted at a luminance of 45 cd/m^2. A two-minute dark adaptation time was given to each subject at the beginning of the experiment. The target gratings were presented in a random order of contrast for a duration of two seconds for each spatial frequency. The subjects were asked whether they could see any vertical gratings during each grating presentation. If they did, that particular contrast value was recorded. The mean contrast value was obtained from the data for each spatial frequency. The reciprocal of the mean contrast value provided the value for the contrast sensitivity, which was then plotted against the spatial frequencies to form the CSF.

2.2.1 Results: 2-degree visual field

The result (Figure 2) is compared with the result obtained by Robson[8] for a white light source at a luminance of 20 cd/m^2 and at a 2.5-degree visual field. Figure 2 shows that the two CSFs are identical at higher spatial frequencies but deviate slightly in the lower frequency region. This small deviation could be due to the fact that the 2-degree visual field used in this study is smaller than the 2.5-degree field used in Robson's experiment, which in turn results in fewer cycles in the field of view. Past literature shows that at low spatial frequencies, the values of contrast sensitivity decrease when fewer cycles are presented in the field of view.[9] This analysis shows that the apparatus is adequate for developing CSFs for sine wave gratings illuminated by monochromatic red, green, and blue LEDs.

2.3 Experiment 2

The objective of the second experiment was to develop the CSFs for red, green, and blue light produced by high-brightness LEDs. The peak wavelengths of the red, green, and blue LEDs used in this study are 625 nm, 525 nm, and 475 nm, respectively. The procedure was very similar to Experiment 1. Fourteen subjects, an equal number of males and females in the age group of 20 to 30 years, participated in Experiment 2. The experiment was initially conducted for the 2-degree visual field. During this experiment all three colors were kept at an equal luminance, 45 cd/m^2. Then the experiment was repeated at different luminances: 125 cd/m^2 for red, 35 cd/m^2 for green, and 5 cd/m^2 for blue. Finally, the experiment was repeated for the 10-degree visual field by moving the subjects closer to the experimental apparatus.

2.3.1 Results: 2-degree visual field

Figure 3 shows the CSFs for the different colors, all measured at the same luminance level of 45 cd/m^2. The visual field was 2 degrees. At an equal luminance of 45 cd/m^2, the red, green, and blue CSFs overlapped in the higher spatial frequency region, but they separated out slightly at the lower spatial frequency region. Figure 4 shows the CSFs for each of the colors at different luminances. The visual field size was once again 2 degrees. As mentioned earlier, these were the typical luminance levels for the red, green, and blue backlighted signs surveyed. It appears that the peak values of the CSF increased with increasing luminance levels, and they also shifted to higher spatial frequency values. These results are consistent with CSFs found in the literature.[4]

2.3.2 Results: 10-degree visual field

Figures 5 and 6 illustrate the results for the 10-degree visual field at an equal luminance level of 45 cd/m^2 and at different luminance values of 125 cd/m^2 for red, 35 cd/m^2 for green, and 5 cd/m^2 for blue, respectively. In this case, the CSFs of all three colors overlapped. Neither luminance nor color variation seem to have an impact on the CSFs. For the 10-degree field of view, the peak values of the CSFs occurred at smaller spatial frequencies, 2 to 3 cycles per degree, compared with 6 to 7 cycles per degree for the 2-degree visual field results. Furthermore, the values of contrast sensitivity for the 10-degree case were greater at all spatial frequencies compared with the 2-degree case. This is again consistent with results seen from past studies.[5, 7, 10]

3. SUMMARY

To be able to employ digital image analysis to quantify the beam quality of colored beams generated by monochromatic LEDs, it is necessary to have appropriate contrast sensitivity functions (CSFs). Although CSFs exist for a variety of light sources at visual fields ranging from 2 degrees to 20 degrees, CSFs do not exist for narrow-band red, green, and blue LEDs at 2-degree and 10-degree visual fields and at luminance levels typical for backlighted signage. Therefore, an experiment was conducted, and a family of CSFs was derived for 2-degree and 10-degree visual fields illuminated by narrow-band LEDs at typical luminance levels.

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FIGURES

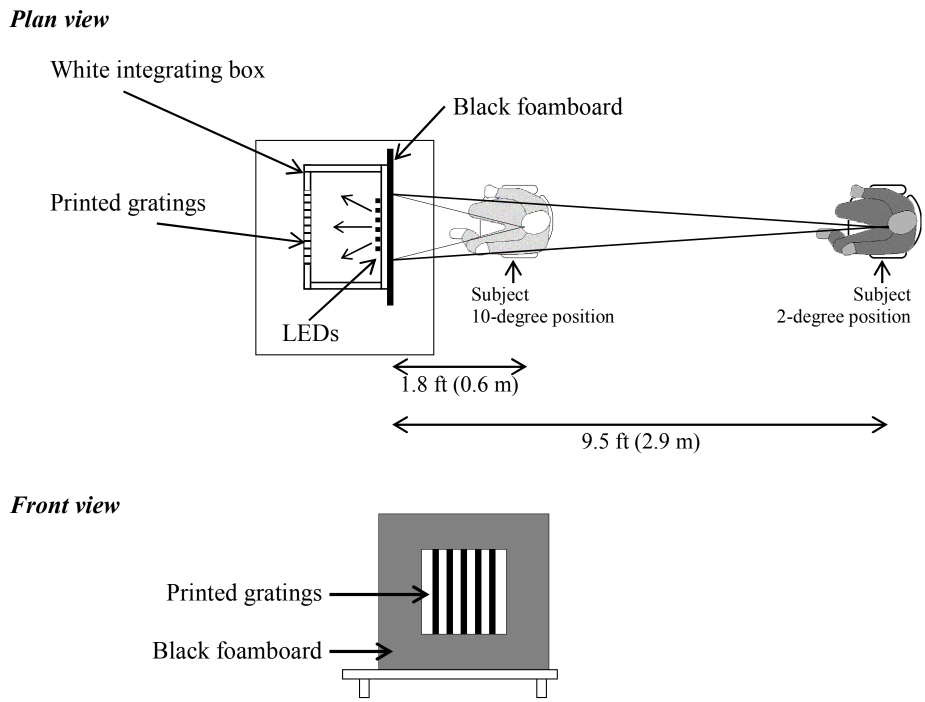

Figure 1: Experimental setup.

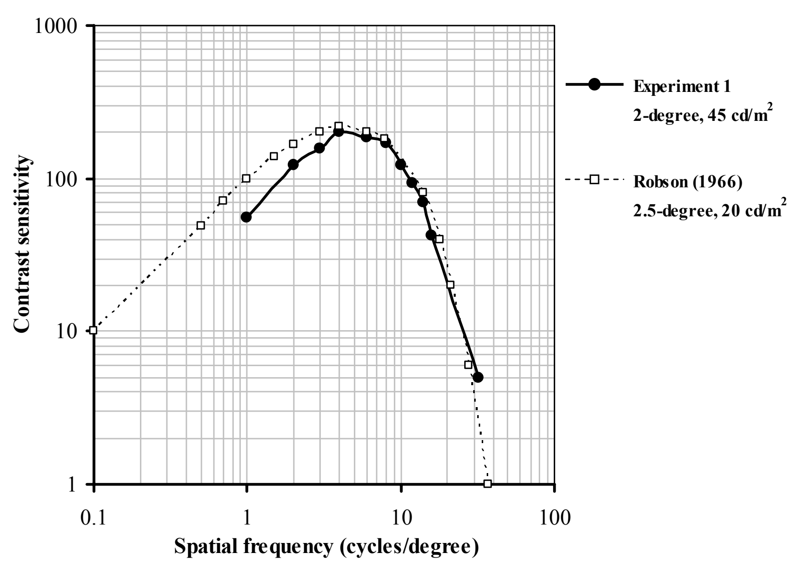

Figure 2: Baseline comparison between CSFs derived for incandescent light sources.

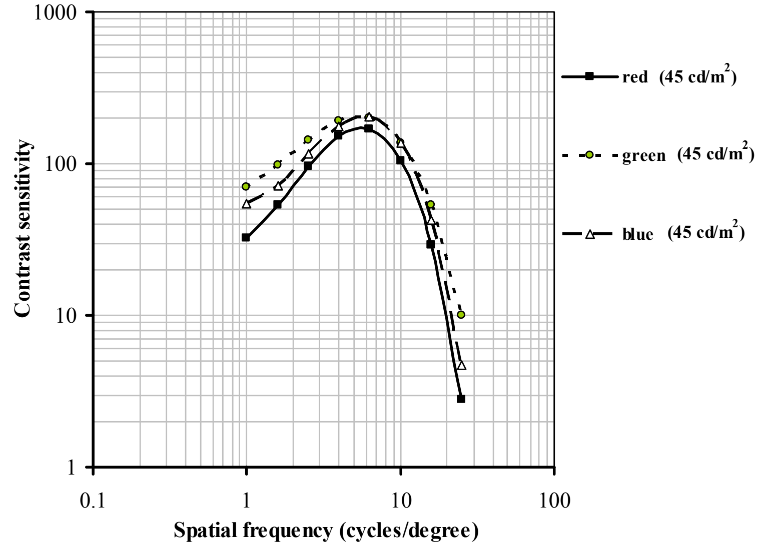

Figure 3. Contrast sensitivity functions derived for 2-degree sinusoidal gratings at a luminance of 45 cd/m^2 for red (625 nm), green (525 nm), and blue (475 nm) LEDs.

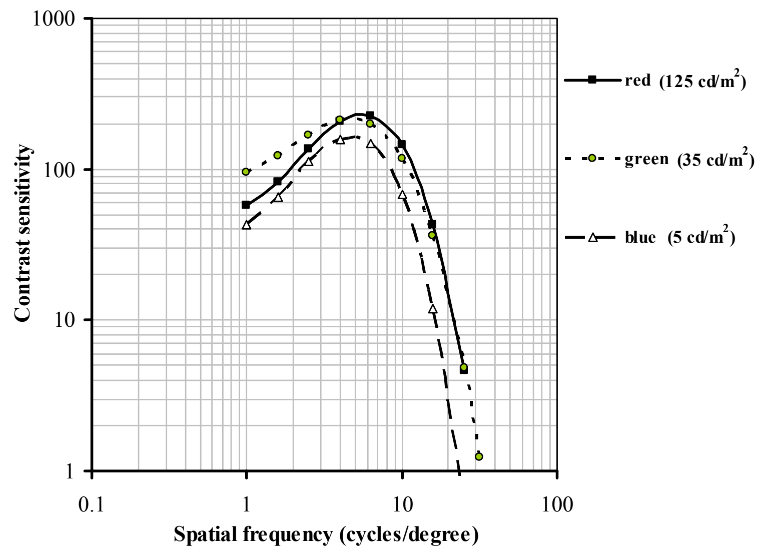

Figure 4: Contrast sensitivity functions derived for 2-degree sinusoidal gratings at typical luminance values (red: 125 cd/m^2, green: 35 cd/m^2, blue: 5 cd/m^2) for red (625 nm), green (525 nm), and blue (475 nm) LEDs.

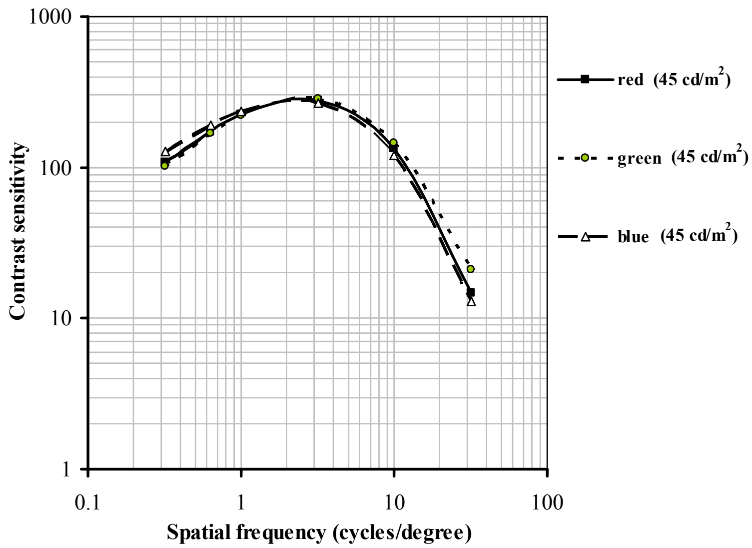

Figure 5: Contrast sensitivity functions derived for 10-degree sinusoidal gratings at a luminance of 45 cd/m^2 for red (625 nm), green (525 nm), and blue (475 nm) LEDs.

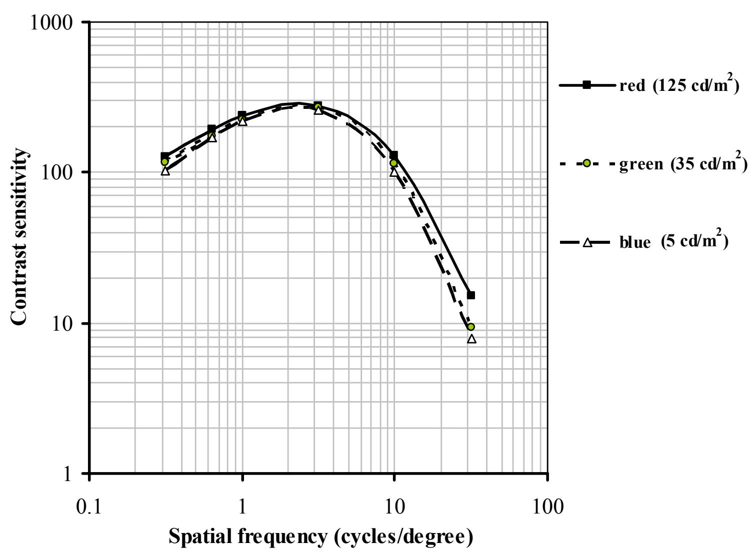

Figure 6: Contrast sensitivity functions derived for 10-degree sinusoidal gratings at typical luminance values (red: 125 cd/m^2, green: 35 cd/m^2, blue: 5 cd/m^2) for red (625 nm), green (525 nm), and blue (475 nm) LEDs.