

Effect of different colored background lighting on LED discomfort glare perception

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ABSTRACT

In the past decade, there has been increased interest in energy-efficient lighting as energy resources become higher in demand. Street lighting and outdoor lighting are applications that are rapidly changing from the incumbent high-pressure sodium (HPS) to newer technologies such as light-emitting diode (LED) or induction-type lamps. There is evidence that certain populations believe LED streetlights and area lights to produce more glare than HPS luminaires. A number of differences exist between new and traditional light sources besides efficiency. These include spectral power distribution (SPD), source luminance, beam intensity distribution, and the number of sources needed to achieve intended light levels. Many field studies and laboratory studies have shown a relationship between glare and SPD, with most studies suggesting that sources more weighted in short wavelengths have an increased likelihood of discomfort glare. A study to assess the effect of different SPDs on perception of discomfort glare was conducted. Subjects were shown a white-light LED array against a luminous background with one of three different SPDs (blue, white, or yellow). As well, different intensities of light from the array and from the background were used. For the range of conditions evaluated, the presence of any luminous background significantly reduced the perception of discomfort glare from the LED array. The blue background reduced perception significantly less than the white or the yellow backgrounds. The implications for solid-state lighting systems such as outdoor array lighting are discussed.

Keywords: Discomfort glare, LED, outdoor lighting, white background, colored background, spectral power distribution, short wavelength, HPS

1. INTRODUCTION

In recent years, technological advancements and an increased need for energy efficiency have led to greater interest in using white light-emitting diodes (LEDs) for many general illumination applications. One general lighting application in particular, outdoor lighting, recently has been targeted for transformation to LEDs because of the technology's promises for lower energy use, longer life, better color rendering, easy tunability and acceptance of controls, and the potential for lower light levels because of increased mesopic efficacy due to its spectral composition. Lighting for streets, roadways, parking lots, and general outdoor areas is now rapidly switching from traditional high-pressure sodium (HPS) and metal halide (MH) light sources to arrays of high-power white LEDs.

However, there is anecdotal evidence that certain populations believe LED streetlights and area lights to produce more glare than HPS luminaires. A number of differences exist between new and traditional light sources besides efficiency. These include spectral power distribution (SPD), source luminance, beam intensity distribution, and the number of sources needed to achieve intended light levels. Research in the areas of vehicle headlamp design and outdoor lighting has shown that light sources with a greater amount of short-wavelength content, such as the phosphor-converted white LED, may produce more discomfort glare than light sources with more long-wavelength content.¹⁻³ Previous research also has shown that the presence of a luminous field surrounding a bright light source can reduce the viewer's perception of discomfort glare.⁴⁻⁶ This interaction is not well understood but has practical significance for luminaire design. LEDs of different luminous intensity and spectral power distribution (SPD) could be incorporated into the design of an outdoor lighting luminaire to create a luminous surround that reduces the perception of discomfort glare from the luminaire's white LED sources.

This paper describes an investigation of the connection between glare perception and the SPD of a luminous area surrounding a white LED array. This study considered background spectrum, brightness perception, and the effect of a luminous background on an LED array glare stimulus.

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2. BACKGROUND

2.1 Definition of discomfort glare

Discomfort glare is one of two primary types of glare, the other being disability glare. While disability glare can be measured directly and is well defined, discomfort glare is more difficult to define and measure. Discomfort glare is typically identified when observers complain of or state annoyance by a bright light source in their field of view.⁷ A discomfort glare rating system, called the de Boer rating scale, was developed in the 1960s and consists of a scale from 1 to 9 that can be used to rate the discomfort glare from a light source (Fig. 1).^{8,9}

de Boer rating scale

- 1 Unbearable
- 2 –
- 3 Disturbing
- 4 –
- 5 Just acceptable
- 6 –
- 7 Satisfactory
- 8 –
- 9 Unnoticeable

Figure 1. The de Boer rating scale.⁹ Every odd number in the scale is described by a vocabulary word to help subjects use the scale in a consistent manner.

2.2 Previous findings on glare and SPD

For light source SPD, previous studies have found no effect on disability glare but a strong effect on ratings of discomfort glare.^{1,10,11} In one study, Flannagan et al. looked at six narrow-band light sources and found the highest de Boer ratings (i.e., less discomfort) with a 577 nm stimulus and the lowest de Boer ratings (i.e., more discomfort) with a 480 nm stimulus.¹¹ Other studies have investigated discomfort glare from vehicle headlamps, which have begun to undergo technological changes in the past decade from halogen to high-intensity discharge (HID). HID headlamps have both increased luminance and a greater amount of short-wavelength content than traditional halogen headlamps; however, when the automobile industry introduced HID headlamps in the United States and received complaints from drivers about glare from the new car headlamps, it was unclear which of these factors (luminance or SPD) made the greatest contribution to observers' perceptions of discomfort glare from oncoming headlamps.¹⁰

Experimentally, HID light sources are perceived as producing more discomfort glare than halogen sources.^{3,10} Flannagan speculated that the glare perception difference might be a result of the different scotopic-to-photopic (S/P) ratios of these sources, but upon investigation found that S/P ratio was not a good predictor of discomfort glare.³ Bullough et al. confirmed this finding through experiments showing HID headlamps (S/P ratio 1.67) to produce the highest perception of discomfort glare, unfiltered halogen lamps (S/P ratio 1.62) to produce the lowest perception of glare, and blue-filtered halogen headlamps (S/P ratio 2) to produce a discomfort glare perception between the HID and the unfiltered halogen lamps.¹⁰ Fotios and Levermore have described the human visual system as having certain inputs and pathways to the brain that might explain some effects of SPD on brightness perception.¹² More recently, Bullough et al. have shown that discomfort glare can be estimated by using a function to weigh the contribution from the short wavelength sensitive cones.^{1,2}

3. EXPERIMENT

3.1 Subjects and experimental conditions

The study undertaken here was designed to evaluate the impact of different luminous background SPDs on subjective ratings of discomfort glare from the white LED array. Ten subjects (aged 23 to 52 years, median 39 years; 5 females) participated in the experiment. From the subject's location 3 m away from the apparatus, the LED array subtended a 2° visual angle, while the overall source including the background subtended 4° . The direct illuminances from the white LED array were 4, 6, 8, 10, and 12 lx at the eye, which were combined with three different colored luminous backgrounds (yellow, white, and blue), as well as a no-background setting where the background was dark, for a total of 20 combination conditions. At the lowest setting of 4 lx from the LED array, the background contributed 3 lx, or 42% of the light reaching the eye (a total of 7 lx). At the highest setting of 12 lx from the LED array, the background contribution of 3 lx made up 20% of the light reaching the eye (a total of 15 lx).

3.2 Apparatus

The experimental apparatus was built from a half-cylindrical light box that acted as an integrating chamber (Fig. 2). The background light surrounding the white light LED array was created by red (peak wavelength 635 nm), green (peak wavelength 525 nm), and blue (peak wavelength 465 nm, CIE 1931 $xy = 0.141, 0.044$) LEDs on the inside of the half-cylinder. The yellow background conditions (CIE 1931 $xy = 0.459, 0.497$) were created by mixing red and green LEDs, while the white background condition was created by using phosphor-converted white LEDs (CIE 1931 $xy = 0.325, 0.325$). The light was seen through a diffusing acrylic sheet mounted in the face of the apparatus. The white light LED array, which acted as the glare source for this experiment, was composed of nine phosphor-converted 6500 K, 3-W LEDs each fitted with a 10° beam lens mounted directly into the diffusing sheet so that the background light glowed uniformly around and between the sources making up the LED array. The CIE 1931 chromaticity of the white LED array was $x=0.28, y=0.32$.

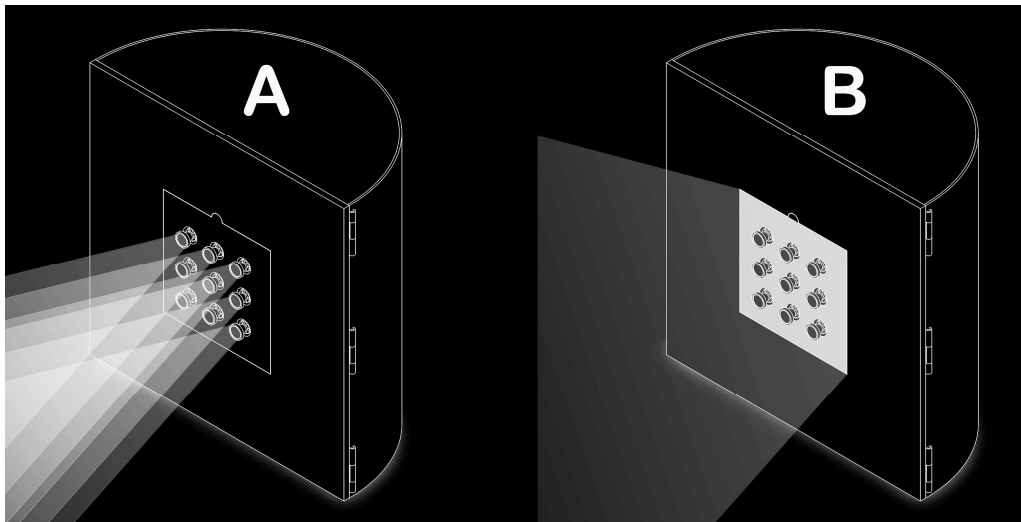


Figure 2. Illustration of experimental apparatus showing the white LED array (A) and the luminous background (B).

3.3 Protocol

The experiment was conducted in a dark, windowless laboratory. Subjects sat in a chair and were asked to rest their chins on a chin rest. The chin rest, located 3 m away from the apparatus, ensured that subjects' eyes were located at the same height as the center of the LED array. Each subject was tested individually and was allowed to hold a printed sheet showing the de Boer discomfort glare rating scale to use as a reference. At the beginning of each experimental session the room lights were turned off and the subject was allowed to adapt to the low light level of 0.2 lx for five minutes. Each LED array/background combination was presented in random order to each subject, and each subject saw a

different order than any other subject. For each condition, the subject rated his or her discomfort using the de Boer scale. Once the subject rated the condition, the apparatus was covered with an opaque shield for a period of 6 to 10 seconds while the experimenter switched to the next lighting condition. This process was repeated until all conditions were presented.

4. RESULTS

The results from the experiment are shown in Figure 3. The increasing illuminance levels of the LED array glare source are noted along the x-axis, while the y-axis plots the de Boer rating values, with 1 being the most glaring (unbearable) and 9 being the least glaring (unnoticeable). An analysis of variance (ANOVA) was conducted to compare the different conditions.¹³

The results show that there was a significant ($p < 0.05$) decrease in glare perception when a luminous background (blue, white or yellow) was added to the LED array (for the experimental geometry used and a 3 m distance). No significant difference was found between the white and yellow background conditions; however, a significant difference was found between the yellow and blue luminous backgrounds ($p < 0.05$). The blue luminous background condition was rated as being more glaring than the white or yellow luminous background conditions (but still significantly less glaring than the no background condition).

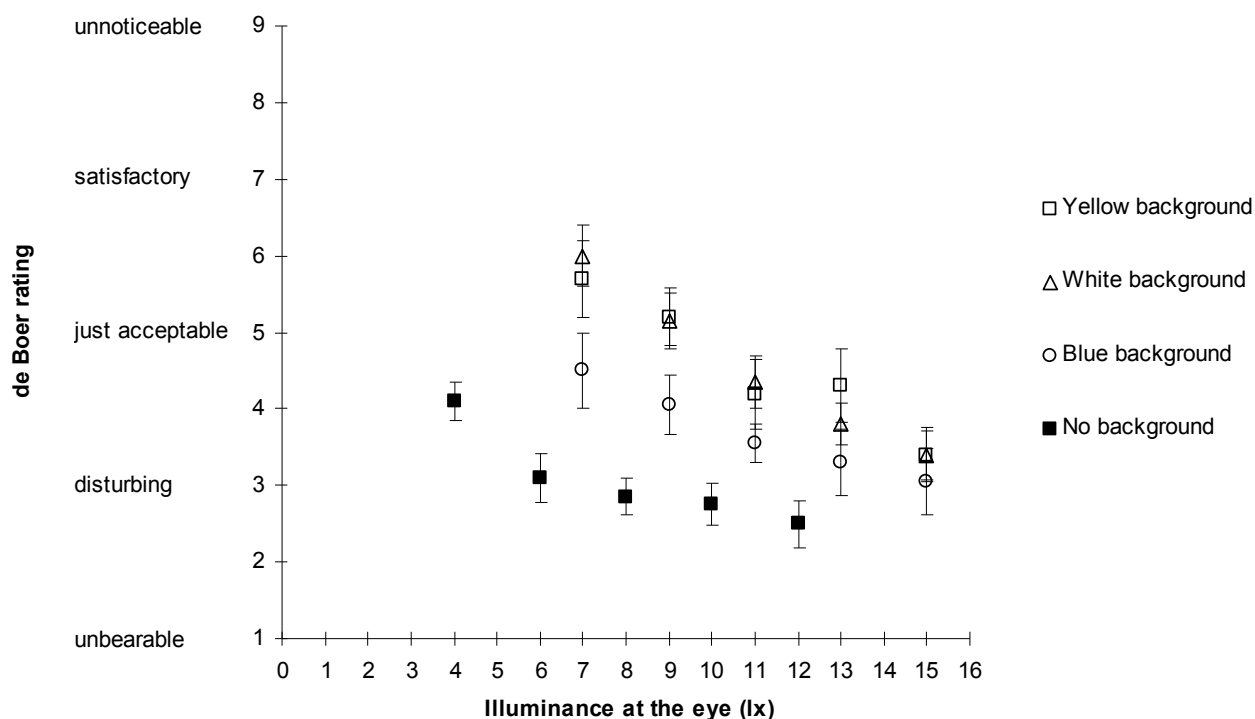


Figure 3. Mean de Boer ratings (\pm standard error of the mean) for the different experimental conditions.

5. DISCUSSION AND CONCLUSIONS

The results of this experiment confirmed that the perception of discomfort glare from an LED array can be decreased with the addition of a luminous surround. In this study, all three of the luminous background conditions (blue, white and yellow) showed a decrease in discomfort glare perception as compared with the no-background condition. Additionally, it was found that in certain cases the discomfort glare rating for the blue luminous background condition, was worse (rated as producing more glare) than the white or the yellow background conditions. There is evidence indicating that the effect of the SPD of the background is related to the viewing size of the source.

A possible application of the results could be in outdoor area lighting, where issues of glare could be overcome by adding a luminous background, or fill light, to a luminaire that utilizes an LED array. This type of design would create a wash of white light directly from an LED array on the ground beneath the luminaire. However, if a person were to look up at the fixture, the source itself could appear to have a yellow, blue, or white surround, making the array appear less glaring.

A limitation of this study is that the experiment was conducted entirely in a laboratory environment, where the ambient light was controlled and very dark. In an actual installation, the surrounding area's lighting conditions could influence the perception of the light source.^{4,5} Additionally, this study did not address discomfort glare from several LED luminaires in the field of view at once, although Bullough et al.⁵ found this not to be an issue.

Another limitation in this study lies with the de Boer rating scale itself. Some argue that the de Boer scale is counterintuitive, and that the higher numbers should equal increased amounts of glare.⁸ De Boer claimed that the scale represents a figure of merit, where the lower the number, the worse the glare.⁹ This convention might cause confusion among the subjects. It is necessary for the person administering the study to confirm the ratings given by the subject by clarifying the vocabulary words associated with the number. Regardless, the results from using this rating scale were shown in this study to be repeatable and consistent.

The results from this study have reproduced and extended findings from prior research that more information is needed than the photopic illuminance from a glare source and from the immediate surround to correctly characterize and predict discomfort glare.^{1,5,11} These findings reinforce conclusions from previous studies, which showed that the SPD of a source can have a significant effect on levels of discomfort glare.

ACKNOWLEDGMENTS

The authors are grateful to all the observers who participated in the experiment, to Martin Overington and Terence Klein for their assistance with the experimental setup, and to Jennifer Taylor for invaluable help preparing this manuscript.

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