UMTRI-2005-2

BLUE CONTENT OF LED HEADLAMPS AND DISCOMFORT GLARE

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Report No. UMTRI-2005-2
February 2005

Technical Report Documentation Page

1. Report No. UMTRI-2005-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Blue Content of LED Headlamps and Discomfort Glare		5. Report Date February 2005
		6. Performing Organization Code 302753
7. Author(s) Sivak, M., Schoettle, B., Minoda, T., and Flannagan, M.J.		8. Performing Organization Report No. UMTRI-2005-2
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150 U.S.A.		10. Work Unit no. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address The University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety		13. Type of Report and Period Covered
		14. Sponsoring Agency Code

15. Supplementary Notes

The Affiliation Program currently includes AGC Automotive America, Autoliv, Automotive Lighting, Avery Dennison, Bendix, BMW, Bosch, DaimlerChrysler, DBM Reflex, Decoma Autosystems, Denso, Federal-Mogul, Ford, GE, General Motors, Gentex, Grote Industries, Guide Corporation, Hella, Honda, Ichikoh Industries, Koito Manufacturing, Lang-Mekra North America, Magna Donnelly, Mitsubishi Motors, Muth, Nichia America, Nissan, North American Lighting, OLSA, OSRAM Sylvania, Philips Lighting, PPG Industries, Reflexite, Renault, Schefenacker International, Sisecam, SL Corporation, Solutia Performance Films, Stanley Electric, Toyoda Gosei North America, Toyota Technical Center USA, Truck-Lite, Valeo, Visteon, 3M Personal Safety Products, and 3M Traffic Safety Systems.

Information about the Affiliation Program is available at: http://www.umich.edu/~industry/

16. Abstract

This study evaluated the effect of blue content of headlamps on discomfort glare, in order to provide guidance regarding spectral compositions that would minimize driver complaints. Three LED headlamps were tested (with correlated color temperatures of 4000, 4800, and 6600 K), as well as a tungsten-halogen headlamp and an HID headlamp. Subjects, seated in a stationary vehicle, rated discomfort from brief presentations of stimuli that produced illuminances of 0.25, 0.5, and 1 lux.

As predicted in our previous analytical study, we found that—when they appear bluer than current tungsten-halogen or HID headlamps—LED headlamps tend to produce more discomfort glare. The effect is probably due to the color appearance of the LED lamps used in this study rather than to any inherent characteristic of LED sources, and it could probably be altered or reversed with different sources. For the data reported here, ratings of discomfort glare were linearly related to the amount of blue content in the light output as weighted by the spectral sensitivity of the short-wavelength (blue) cone photoreceptors. Therefore, if this relationship is replicated and extended in future studies, it may provide an index of blue content that could be used heuristically to select colors of headlamps to minimize driver complaints about glare.

17. Key Words headlighting, LED headlamps, HID headlamps, discomfort glare, blue content, blue cones	18. Distribution Statement Unlimited

19. Security Classification (of this report) None	20. Security Classification (of this page) None	21. No. of Pages 21	22. Price

Acknowledgments

Appreciation is extended to the members of the University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety for support of this research. The current members of the Program are:

AGC Automotive America
Autoliv
Automotive Lighting
Avery Dennison
Bendix
BMW
Bosch
DaimlerChrysler
DBM Reflex
Decoma Autosystems
Denso
Federal-Mogul
Ford
GE
General Motors
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Solutia Performance Films
Stanley Electric
Toyoda Gosei North America
Toyota Technical Center, USA
Truck-Lite
Valeo
Visteon
3M Personal Safety Products
3M Traffic Safety Systems

We would like to thank JARI and Stanley Electric for lending us the LED headlamps and the associated equipment.

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Introduction

In the previous study in this series (Sivak, Schoettle, and Flannagan, 2003), we calculated the chromaticities of a sample of LED light sources that are being considered for use in headlighting, and compared them to the chromaticities of HID and tungsten-halogen headlamps. The results indicated that these particular "white" LED light sources are somewhat bluer than HIDs, and significantly bluer than tungsten-halogens. Because of the known increase in discomfort glare with bluish stimuli (Flannagan et al., 1989; 1991; 1992; Flannagan, 1999), we predicted that headlamps using LEDs with the chromaticities examined in that study would lead to more discomfort glare than the HID headlamps, and substantially more discomfort than tungsten-halogen headlamps. Our recommendation was that, to minimize discomfort glare, manufacturers should keep the blue content of LED headlamps as low as practicable, given other considerations.

Our findings received support from a study reported in 2004 (JARI, 2004). That study evaluated discomfort glare from three different LED headlamps (4000, 4800, and 6600 K). The main finding was that, for both younger and older observers, an increase in the correlated color temperature (which is strongly correlated with blue content over the range of interest) was associated with an increase in discomfort glare.

The present study was designed to replicate the main elements of the JARI study with U.S. observers, and to further explore the potential mechanisms underlying discomfort glare. For ease of comparison, the present study used the same LED lamps as the JARI study.

Method

Experimental setup

Schematic diagrams of the experimental setup and the subject's view are shown in Figures 1 and 2. Two subjects were seated in a stationary late-model sedan. Directly in front of the subjects was a rack with five headlamps, masked by a large, black board. The rack and black board were 40 m from the subjects. The center of the rack and the center lamp were aligned with the center of the subjects' vehicle. The other lamps were spaced laterally with their centers 42.5 cm (0.6° at 40 m) apart. The centers of all five lamps were 0.66 m above the ground, to correspond to the average mounting height of headlamps on cars in the U.S. (Schoettle, Sivak, and Nakata, 2002).

The five lamps used three different types of light sources—tungsten-halogen, HID, and LED. The optics of all lamps were reflector based. Three different LED lamps were used. They differed in their nominal color temperatures (4000, 4800, and 6600 K), but their physical dimensions and construction were the same.

The five lamps on the rack were individually adjusted in such a way that they each produced 1 lux at the eyes of the subjects. The adjustments and photometry were performed at night, just prior to each experimental session. Illuminance measurements were taken using a Minolta T-10 illuminance meter. The meter was positioned inside the vehicle, at the approximate position of the subjects' eyes. The readings therefore took into account windshield transmittance.

Subjects participated in pairs. One subject of each pair was seated in the driver's seat of the subject vehicle while the other was seated in the right front passenger seat. Subjects were balanced for age across the two seat locations. One experimenter was seated in the back seat of the subject vehicle, while another experimenter operated the lamps and was thus obscured from the subjects' view by the same black board that masked the rack.

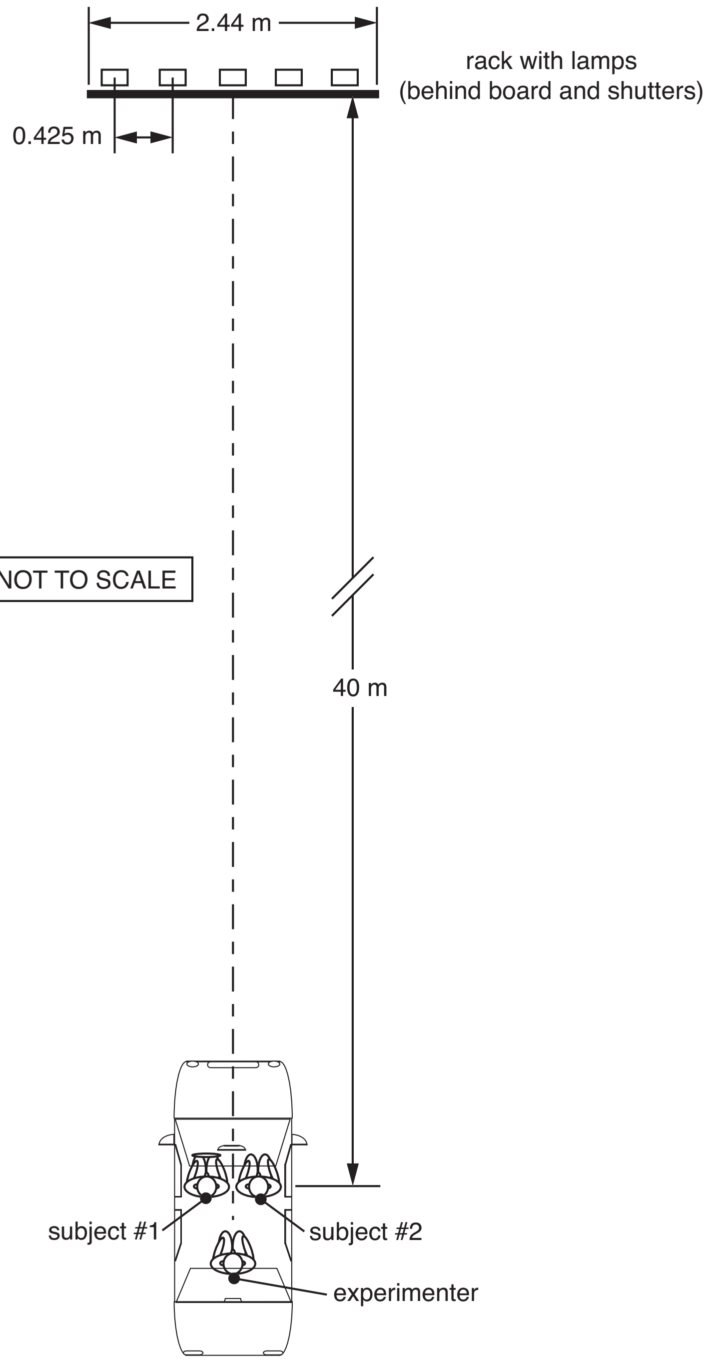

Figure 1. A schematic of the experimental setup.

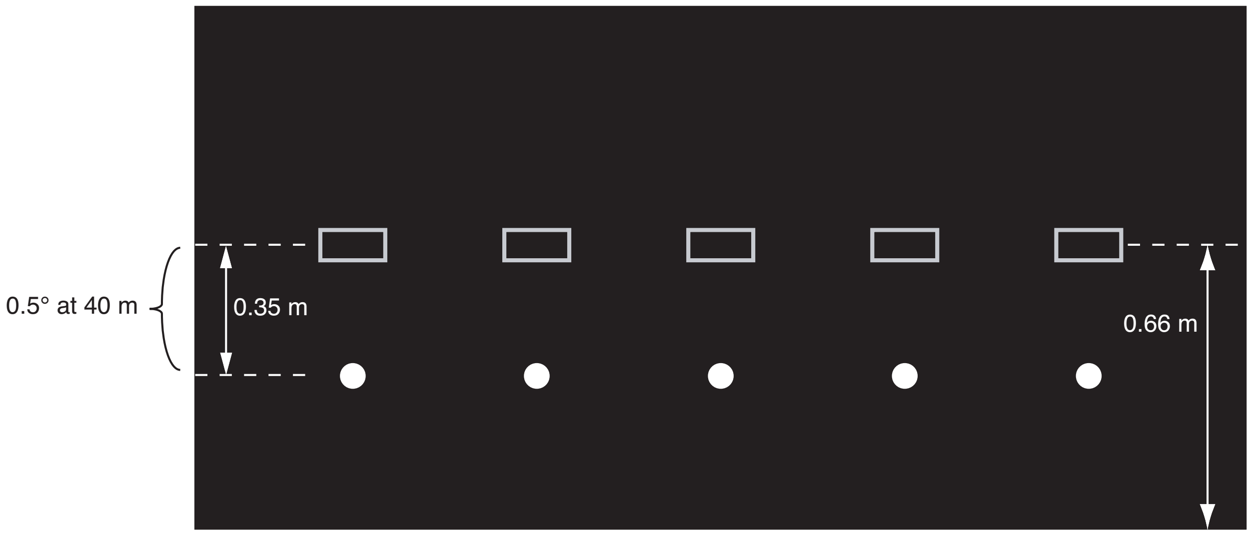

Figure 2. A schematic of the subject's view. The rectangles represent the lamp apertures and the circles the corresponding fixation points. (See text for details.)

The black board that was used to mask the lamps included five apertures, through which individual lamps were shown when corresponding shutters were lifted. Each aperture was 15 cm wide and 7 cm tall. The lamp apertures were not visible to the subjects when closed; they are indicated in Figure 2 only for illustration purposes. Until a test lamp was exposed, subjects saw only a large, black board with small white fixation dots illuminated by the subject vehicle low beams.

Task

Subjects rated the discomfort glare from the lamps when they were energized and presented one at a time on the rack ahead. To rate discomfort glare, subjects were asked to use the de Boer response scale. This scale has often been used to evaluate glare in night driving situations (Bhise, Swigart, and Farber, 1975; de Boer, 1967). It is a 9-point scale with qualifiers only for the odd points as follows: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (just noticeable). A copy of the de Boer scale was given to each subject to refer to throughout the session as needed. The actual subject instructions are in the Appendix.

Stimuli

Fifteen stimuli were used in the study. These stimuli were obtained by the orthogonal combination of three levels of illuminance at the subject's eyes from the lamps (0.25, 0.5, and 1 lux) and five lamp types (tungsten-halogen, HID, and three LED types).

The two lower levels of intensity were achieved by placing neutral density filters in front of the lamps. (These filters had transmittance of 50% and 25%, respectively.) No filters were used for the highest intensity level.

The lamps were connected to power supplies and were manually controlled as needed. The shutter covering each lamp's aperture allowed the lamps to be energized without this being visible to the subjects. To minimize the build-up of heat during the experimental session, the LED lamps were energized just prior to their use, and de-energized just following their use. To maintain stable color temperatures during the experimental session, the tungsten-halogen and HID lamps remained energized for the entire experimental session (about 45 minutes).

Ambient conditions

The study was run on fall nights with no precipitation. The tungsten-halogen low-beam headlamps of the subject vehicle were nominally aimed and energized at all times throughout each session. The ambient illumination was evaluated by measuring vertical lux at the subjects' eye position at the beginning and at the end of the session. The readings averaged 0.20 lux, with a minimum of 0.16 lux and a maximum of 0.27 lux.

Subjects

Twelve paid subjects participated in the study. There were 6 younger subjects (ranging from 25 to 30 years old, with a mean age of 28) and 6 older subjects (ranging from 64 to 79 years old, with a mean age of 71). Each age group included 3 males and 3 females. All subjects were licensed drivers.

Procedure

Subjects were tested in pairs. Each pair participated in a single session made up of 45 trials. The trials were presented in 3 blocks of 15 trials each (5 lamps times 3 lamp intensities). On each trial, one lamp was presented for three seconds. The presentation order was randomized within each block. The first block of 15 trials served as practice to allow subjects to familiarize themselves with the task. The subjects were not informed of the practice nature of the first block, nor were they informed that there were three separate blocks (repetitions) within the session. (Only the latter two blocks were analyzed, and they will be referred to from now on as the first and second blocks.)

For each trial, the subjects were instructed to look at one of the fixation points (see Figure 2). Each fixation point was positioned 0.5° (at the viewing distance of 40 m) below the center of the lamp to be presented on that trial.

The LED lamps were presented only at the three middle locations, and these locations were balanced for subject age and gender. The tungsten-halogen and HID lamps were presented only at the outermost locations, and were also balanced for subject age and gender. The six possible lamp-location combinations (see Table 1) were each used for two subjects. It took about 45 minutes to complete each session.

Table 1
Summary of lamp-location combinations. (Location A corresponds to the leftmost position from the subjects' view in Figure 2, while Location E corresponds to the rightmost position.)

Session	Location				
	A	B	C	D	E
1	TH	LED - 4000	LED - 4800	LED - 6600	HID
2	TH	LED - 6600	LED - 4000	LED - 4800	HID
3	TH	LED - 4800	LED - 6600	LED - 4000	HID
4	HID	LED - 4800	LED - 4000	LED - 6600	TH
5	HID	LED - 6600	LED - 4800	LED - 4000	TH
6	HID	LED - 4000	LED - 6600	LED - 4800	TH

Results

Basic findings

An analysis of variance was performed on the de Boer ratings of discomfort. The independent variables were headlamp type (tungsten-halogen, HID, LED-4000, LED-4800, and LED-6600), illuminance (0.25, 0.5, and 1 lux), subject age group (younger and older), and trial block (first and second).

As expected, the effect of illuminance was statistically significant, $F(2,20) = 103.7$, $p = .0001$, with the amount of discomfort monotonically related to the amount of illuminance (see Table 2).

The effect of lamp type was also statistically significant, $F(4,40) = 8.5$, $p = .0001$. Discomfort was lowest for the tungsten-halogen lamp, followed by the HID lamp, LED-4000, LED-4800, and LED-6600 (see Table 3).

Table 2
The effect of illuminance on de Boer ratings of discomfort glare.
(Lower de Boer units indicate more discomfort.)

Illuminance (lux)	Discomfort glare (de Boer units)
0.25	5.8
0.5	4.1
1	2.9

Table 3
The effect of lamp type on de Boer ratings of discomfort glare.
(Lower de Boer units indicate more discomfort.)

Lamp type	Discomfort glare (de Boer units)
Tungsten-halogen	5.3
HID	4.7
LED-4000	4.2
LED-4800	3.7
LED-6600	3.3

There was no statistically significant interaction of lamp type and illuminance, implying that the effect of lamp type was consistent across the three levels of illuminance (see Figure 3).

The effect of trial block was statistically significant, $F(1,10) = 21.5$, $p = .0009$, with the first block having higher de Boer ratings, indicating less discomfort (mean of 4.5), than the second block (mean of 4.0). The effect of subject age group was not statistically significant.

The only other statistically significant effect was the interaction of illuminance by trial block, $F(2,20) = 4.3$, $p = .03$. As shown in Figure 4, the increase in discomfort from the first to the second block was present primarily at the two lower illuminance levels.

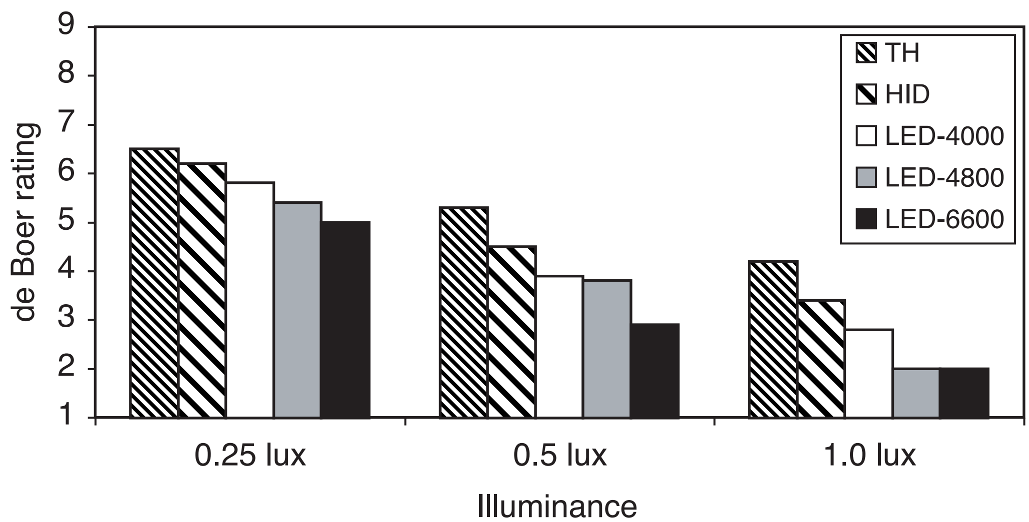

Figure 3. The effects of lamp type and illuminance on de Boer ratings of discomfort glare. (Lower de Boer units indicate more discomfort.)

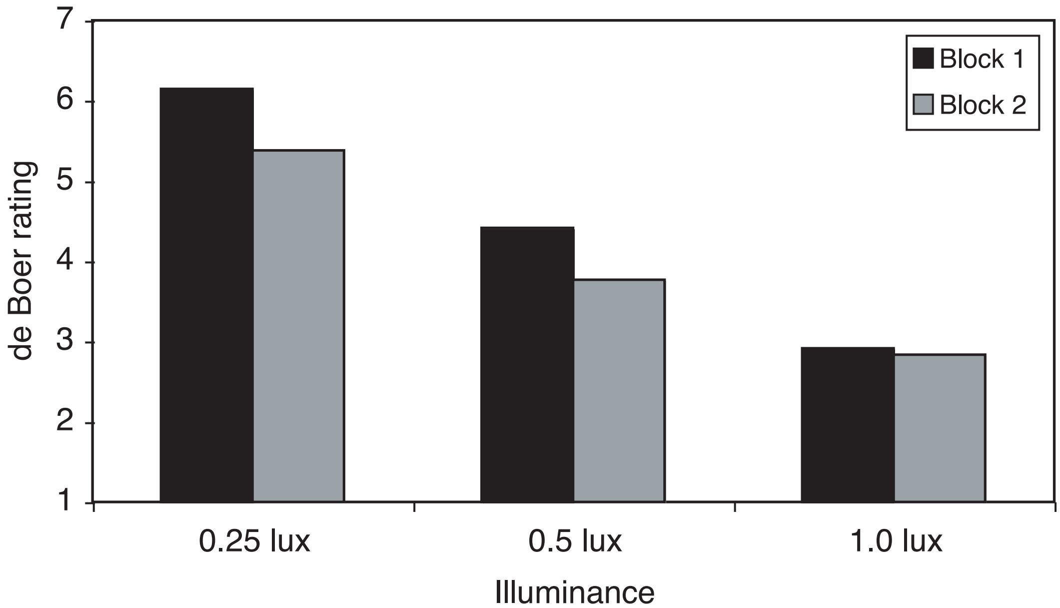

Figure 4. The effects of illuminance and trial block on de Boer ratings of discomfort glare. (Lower de Boer units indicate more discomfort.)

Blue-cone sensitivity function and discomfort ratings

As indicated in the Introduction, there is evidence that bluish light results in more discomfort than white light. The imprecise term "bluish" should be regarded here as a serviceable but rough approximation. It is not clear exactly what aspects of the spectral power distribution of light determine whether the average person will subjectively rate it as more or less glaring. The closely related issue of what visual mechanism or mechanisms may be responsible for the effect is also unclear.

Unfortunately, some of the simplest and most appealing hypotheses about visual mechanisms are in conflict with existing data. For example, the scotopic or "night" visual system has its peak sensitivity at about 507 nm, closer to the short-wavelength (blue) end of the spectrum than the photopic or "day" visual system, which peaks at about 555 nm. The scotopic system is dominated by the rod photoreceptors while the photopic system is dominated by the cones. The fact that the scotopic system is relatively more sensitive to blue light suggests the hypothesis that the rods might have a special, or even dominant, role in discomfort glare.

However, when that hypothesis was applied to the difference in discomfort glare between tungsten-halogen and HID headlamps, it significantly underpredicted the magnitude of that difference (Flannagan et al., 1993). More generally, any hypothesis that attributes discomfort glare to a single receptor system could not account for the fact that discomfort glare as a function of wavelength changes with light adaptation, in a way that is at least qualitatively consistent with mesopic vision (Flannagan, Sivak, and Gellatly, 1991).

Nevertheless, although it may not be possible to account for all aspects of discomfort glare in terms of a specific part of the visual system, it may be a helpful heuristic strategy to use what is known about the spectral sensitivities of the visual receptor systems to construct at least a partial explanation for the effects of wavelength on glare. The data reported here, as well as a wide range of previous findings about headlamp color (e.g., Schreuder, 1976), indicate that the tendency of headlamps to evoke complaints about glare is somehow connected to the blue content of the light. One simple index of blue content could be based on the spectral sensitivity of the short-wavelength, "blue" cones. Although the connection to a specific cone type should be considered speculative, this index has the potential advantage of having a simple relationship to a known property of the visual system. The blue cones are one of three cone types in the human retina. The 2° sensitivities of the three cone types across the visible spectrum are illustrated in Figure 5.

In this analysis, we first weighted the spectral power distributions of each lamp by the blue-cone sensitivity function, integrated over wavelength, and then compared the output of these calculations to the discomfort glare ratings. As shown in Figure 6, we found a strong, approximately linear relationship, with the power weighted by the blue-cone sensitivity function accounting for 99% of the variance in discomfort-glare ratings.

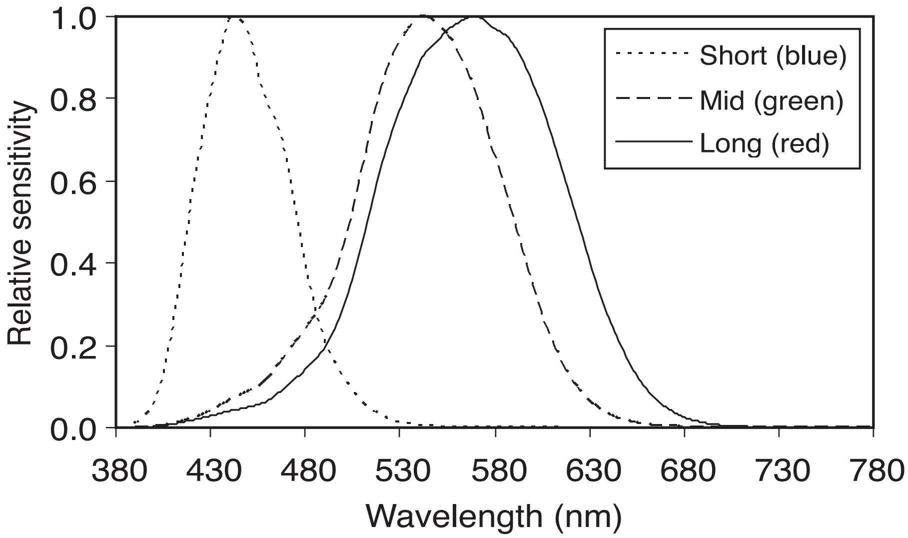

Figure 5. Relative sensitivities of the three cone types (Stockman, Sharpe, and Fach, 1999; Stockman and Sharpe, 2000).

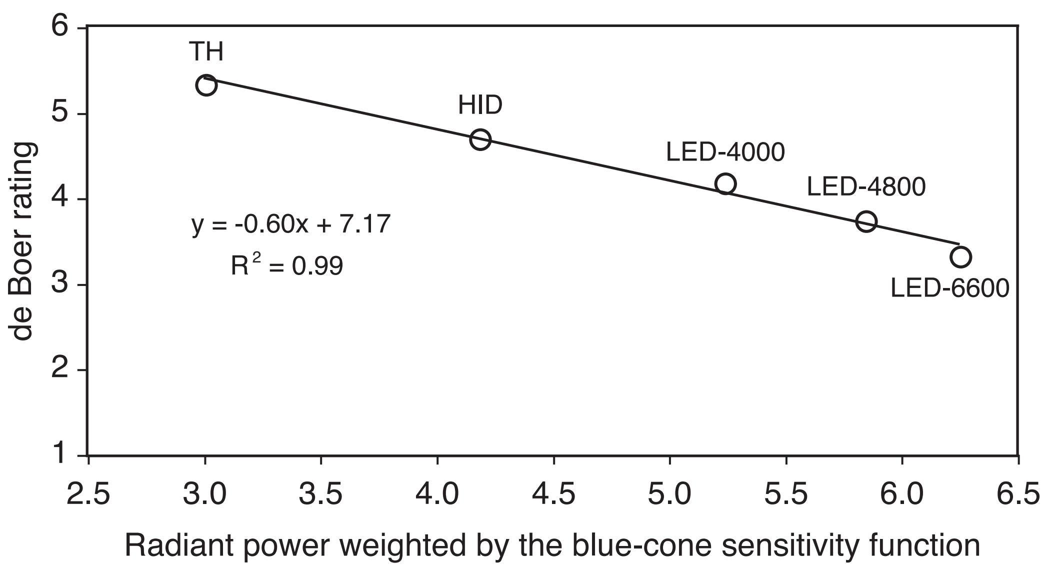

Figure 6. Relationship of the blue-cone-weighted power to de Boer ratings of discomfort glare. (Lower de Boer units indicate more discomfort.)

Discussion

Relation to prior research

As predicted in our previous analytical study (Sivak et al., 2003), we found that (1) when they are relatively blue, LED headlamps tend to produce more discomfort glare than either tungsten-halogen or HID headlamps, and (2) the discomfort from the headlamps tested is directly related to the amount of blue content in the light. Furthermore, our findings were consistent with the data of JARI (2004) performed under similar conditions.

Blue cones and discomfort glare

The most intriguing finding of the present study is that the radiant power weighted by the blue-cone sensitivity function was a strong predictor of discomfort glare. This relationship should be considered tentative, pending a replication with a wider variety of spectral compositions of headlamp illumination.

Stimulus size, stimulus uniformity, and discomfort glare

In a previous study, we found a small, but reliable effect of stimulus size on discomfort glare (Sivak, Simmons, and Flannagan, 1988). Specifically, we found that reducing the size (in terms of the subtended visual angle of the diameter) of a circular stimulus by half (from 0.6° to 0.3°), while keeping the illuminance constant, decreased the de Boer ratings by 0.2 units (indicating a slight increase in discomfort).

The effective stimulus size is related to stimulus uniformity. Consider an extreme example of a stimulus for which 99% of the intensity is emitted through the central 50% of the nominal area. In such a case, the effective size of the stimulus is likely to be only 50% of what it would be if the stimulus was completely homogenous.

We evaluated the uniformity of the five tested lamps by masking each lamp down to 25% of the area (down to 50% of each linear dimension), centered on the center of the lamp (see Figure 7), and then measuring the resulting light output. The results are shown in Table 5.

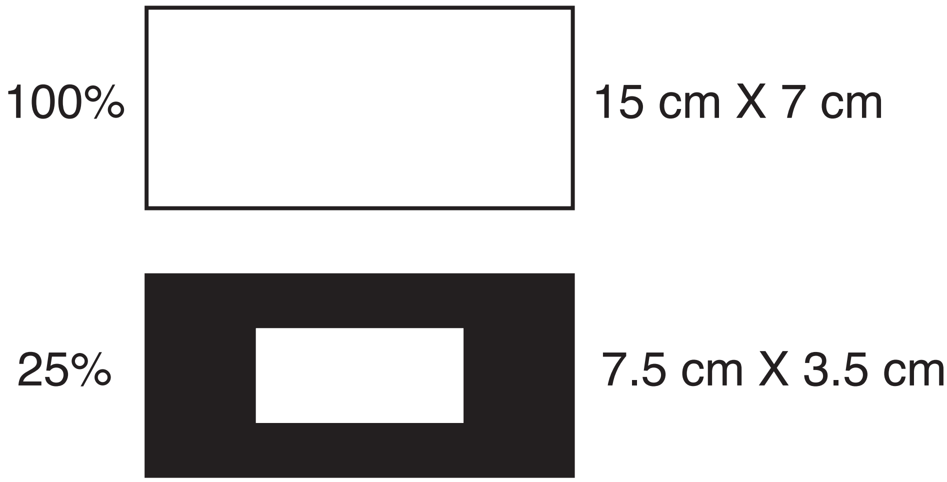

Figure 7. A schematic of the mask used to evaluate the light output from the central 25% of the lamp area.

Table 5
Percentages of the total light output from the central 25% of the area of each lamp.

Lamp	Lamp aperture	
	15 cm x 7 cm (0.2° x 0.1°)	7.5 cm x 3.5 cm (0.1° x 0.05°)
TH	100%	5%
HID	100%	5%
LED-4000	100%	56%
LED-4800	100%	50%
LED-6600	100%	58%

If the lamps were perfectly uniform, masking down the area to 25% of the full area would have produced 25% of the full light output. The results indicate that for both the tungsten-halogen and HID lamps, less than 25% of the output (5%) was due to the central 25% of the area. On the other hand, for all three LED lamps, more than 25% (50% to 58%, depending on the lamp) was due to the central 25% of the area.

The results in Table 5 indicate that the LED lamps might have been perceived as somewhat smaller than the tungsten-halogen and HID lamps. Consequently, a small part of the difference in discomfort between the tungsten-halogen and HID lamps on one hand and the LEDs on the other could be due to the effective stimulus size. Based on the results of Sivak et al. (1988) we estimate that this could be on the order of 0.1 de Boer units. Importantly, there is no indication in our data of differences in effective size either between the tungsten-halogen and HID lamps, or among the three LED lamps. Consequently, the effective stimulus size should have had no effect on either the differences in discomfort ratings between the tungsten-halogen and HID lamps, or the differences among the three LED lamps.

Potential benefits of bluish illumination

There have been some tentative indications that light with higher blue content can increase sensitivity to peripheral stimuli under light adaptation conditions similar to night driving (Sullivan & Flannagan, 2001; Van Derlofske & Bullough, 2003). Future studies in this line of research should attempt to better quantify both glare and detection as functions of wavelength in order to understand how these two possibly conflicting effects should be incorporated in the selection of headlamp color.

Summary

This study evaluated the effect of blue content of headlamps on discomfort glare, in order to provide guidance regarding spectral compositions that would minimize driver complaints. Three LED headlamps were tested (with correlated color temperatures of 4000, 4800, and 6600 K), as well as a tungsten-halogen headlamp and an HID headlamp. Subjects, seated in a stationary vehicle, rated discomfort from brief presentations of stimuli that produced illuminances of 0.25, 0.5, and 1 lux.

As predicted in our previous analytical study, we found that—when they appear bluer than current tungsten-halogen or HID headlamps—LED headlamps tend to produce more discomfort glare. The effect is probably due to the color appearance of the LED lamps used in this study rather than to any inherent characteristic of LED sources, and it could probably be altered or reversed with different sources. For the data reported here, ratings of discomfort glare were linearly related to the amount of blue content in the light output as weighted by the spectral sensitivity of the short-wavelength (blue) cone photoreceptors. Therefore, if this relationship is replicated and extended in future studies, it may provide an index of blue content that could be used heuristically to select colors of headlamps to minimize driver complaints about glare.

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Appendix

SUBJECT INSTRUCTIONS

Welcome to UMTRI and thank you for your participation in this study.

Tonight you will be viewing several different types of headlamps with varying levels of intensity. You will be asked to evaluate the glare that you experience from each headlamp.

Each headlamp will be presented for approximately 3 seconds. During the presentation of each lamp, we would like you to look at the small white circle below the active lamp for that trial. I will indicate which lamp will be active for each trial.

After each lamp is presented and the trial is complete, we would like you to rate your glare experience on the following 9-point scale:

1 Unbearable
2
3 Disturbing
4
5 Just Acceptable
6
7 Satisfactory
8
9 Just Noticeable

Throughout the entire session, we ask that you do not talk about your glare experience or impressions with the other subject until the session is over. The entire session will take about 45 minutes to complete.

When the session is complete, you will be able to discuss your impressions with each other, as well as ask me any questions that you might have. I will be able to answer any questions that you may have regarding the experiment or the technology involved. Please note though that I may need to defer answering certain questions until after the session to avoid affecting your responses during the trials.