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ABSTRACT

Illumination from high intensity discharge (HID) headlamps differs from halogen headlamp illumination in two important ways: HID headlamps have higher overall light output and a spectral power distribution that differs from halogen headlamps. These differences have been hypothesized to result in superior visibility with HID headlamps and most particularly in the periphery. These same factors, though, have also been conjectured to result in increased glare for drivers facing HID headlamps in oncoming driving situations. The present paper outlines a series of experimental investigations using halogen, HID, and blue-filtered halogen illumination to measure their relative impact on discomfort glare and disability glare under conditions matching those that might be experienced by oncoming drivers at night. Discomfort glare is determined using the scale devised by de Boer; disability glare is determined by measuring subjects' contrast sensitivity under different lighting conditions. The results are compared with predictions of existing glare models and with research on the possible role of rod photoreceptors or short-wavelength cones in glare-related responses.

BACKGROUND

In recent years, high-intensity discharge (HID) headlamps have become widespread in the automobile industry. Compared to the traditional halogen headlamp sources, HID headlamps generate more light. Generally, this light is distributed to peripheral areas. At present, glare is an important issue facing HID headlamps. Compared to traditional halogen headlamps, HID headlamps have a greater proportion of their spectrum in the short wavelength area, which may make them more efficient for peripheral vision but also perhaps more glaring to oncoming drivers during night time driving conditions [1]. Besides the spectrum difference, the fact that there is more light at wider periphery angles, particularly toward the oncoming driver, means such headlamps might dazzle oncoming drivers compared to the traditional halogen headlamps. The use of projector optics to reduce headlamp size may lead to even more glare issues.

Hamm [2] and Van Derlofske *et al.* [3] performed an experiment comparing halogen headlamps and HID headlamps. They concluded that HID headlamps increased visibility for drivers using them: HID headlamps produced higher illumination, which enables driver to react more quickly and to targets at greater distances.

At the same time, however, the high illumination level of HID headlamps may cause feelings of discomfort to oncoming drivers. Some people claim that the color appearance of HID headlamps, which is white-blue, would be preferred by drivers to the traditional yellowish halogen headlamps. The Road Research Laboratory in the United Kingdom performed a study of drivers' preference for white or yellow headlamps of equal intensity [4]. Drivers overwhelmingly preferred to drive with white headlamps, but by a small amount, they preferred oncoming drivers to have yellow headlamps. These results broadly support the idea that visibility is better with white headlights, but that oncoming yellow headlights are less glaring [5]. This survey happened when halogen lamps began to replace incandescent lamps in forward lighting technology. The incandescent lamps appeared more yellowish than the halogen lamps. At that time there was a large number of glare complaints, but these objections went away as people got used to the new halogen sources. Now at another time of technological development, history seems to be repeating. From the introduction of HID headlamps in the U.S., there have been many complaints about oncoming glare. Are these headlamps really more glaring or have they attracted attention simply because they are new?

Glare is the blinding or annoying experience that results from a bright light source in the visual field of view, such as driving toward sunset on a clear day. In general, the effect of glare will increase when the glare source's luminance increases, the background luminance decreases, and the angle between the line of sight and the direction of the light source decreases. Generally, two types of glare are recognized: discomfort glare and disability glare [6].

Discomfort glare is a sensation of annoyance or distraction caused by high luminances in the field of view

[6]. Discomfort glare is often measured by means of a subjective rating scale. A nine-point, De Boer scale is most widely used in the field of automotive and public lighting [7]. Discomfort glare does not necessarily impair the visibility of objects. In case of disability glare, visibility is reduced by scattered light in the eye. The glare sources get scattered in the eye which is perceived as a luminous veil over the scene. This veil reduces the contrast of the objects and hence their visibility. Disability glare may be well accounted for in terms of scattering of light that results in a veiling luminance [8].

For disability glare there is a direct relation between the magnitude of the veiling luminance and one's contrast detection performance [9]. With increasing glare, there is a reduction in the ability to perceive low contrast objects. This reduction may affect a number of visual tasks required in traffic, such as the detection of critical objects, headway control, reading of signs, and evaluation of critical encounters.

Flannagan [10] investigated whether spectral power distribution affects objective as well as subjective aspects of headlamp glare. The author used a halogen and an HID lamp, and found no response difference in terms of threshold light level for a target (disability glare). But for discomfort glare, the HID lamp was rated significantly more glaring than the halogen lamp. The author calculated the scotopic (rod-stimulating) content of each source to see if it explained these findings, but found that the ratio of the scotopic/photopic (S/P) ratios for these two lamps was only 1.04, which meant their scotopic content was very similar. The S/P ratio is defined as the ratio of a source's light output as determined using the scotopic luminous efficacy function, to the source's output as determined using the photopic luminous efficacy function.

METHOD

In order to further investigate the properties of oncoming light sources in terms of discomfort and disability glare, two experiments were conducted to measure subjective responses and measures of visual performance under three different types of headlamps:

- halogen headlamps (S/P ratio: 1.62)
- HID headlamps (S/P ratio: 1.67)
- blue-filtered halogen headlamps (S/P ratio: 2.00)

The blue-filtered halogen headlamp was used to provide a glare source with a much higher S/P ratio than the halogen and HID headlamps, which have similar S/P ratios.

DISCOMFORT GLARE STUDY - The experiment was conducted in the Levin Laboratory at the Lighting Research Center, which had an all-black environment. The distance between the subject and the light sources was 8.5 m, but simulating an approaching vehicle 50 m away. The ambient light level was set to 0.1 cd/m^2.

The apparatus is shown in Figure 1. A subject with his or her chin on a chinrest sat behind a set of black curtains and a board which limited the subject's field of view. There was a poster 8.5 m away directly in front of the subject. The nine-point De Boer rating scale (1=unbearable, 9=just noticeable) was presented on the poster. The poster was black with white letters. The letters were 1.9 cm high. There was a focal point on the poster directly in front of the subject at the same height as the glare source aperture.

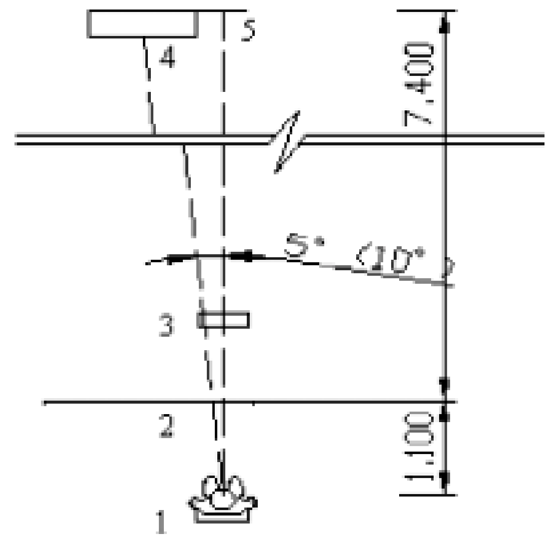

Figure 1. Plan view of discomfort glare experimental apparatus: (1) subject; (2) curtain; (3) ambient light source; (4) glare source; (5) poster providing focal point. Dimensions are given in mm.

A halogen headlamp was located between the board and the subject, 3.5 m in front of the subject. It was positioned on the floor toward the poster to provide an ambient light level of 0.1 cd/m^2 on the wall hanging the poster. The subject could not see this lamp directly.

To the left of the poster, at a viewing angle of 5^o or 10^o, was the glare source. The glare source (either the halogen, HID or blue-filtered halogen headlamp) was placed behind a black screen. Only a small round aperture in the screen allowed light from the glare source to be seen by the subject. Using neutral density filters, the illuminance from the glare source at the subject's eyes was adjusted to be either approximately 2.6 lux, 1.3 lux, or 0.04 lux. The glare source was moved to one of two positions in order to provide viewing angles of 5^o and 10^o.

Overall, the apparatus simulated viewing an actual headlamp from a distance of 50 m, corresponding to the visual angle subtended by a 12.5-cm headlamp from 50 m. Thus, the aperture size used in the apparatus was 2.1 cm.

Each subject experienced an adaptation period upon entering the darkened laboratory for 3 to 5 minutes before participating in the experiment. Subjects were asked to look at the fixation point throughout the experiment. For each subject, there were a total of 18 conditions (3 light sources, 3 light levels and 2 off-axis angles). The subjects were shown each condition for about 4 seconds. Then they were asked to give the rating according to the De Boer scale of how disturbing was the glare source. The order of the conditions was randomly selected for each subject. Because there were lamp changes in the experiment, it was necessary to have a warm-up period of about 1 minute for each light source.

Twenty-six subjects (15 males and 11 females) participated this experiment, ranging from 22 to 58 years of age. The mean age was 33 years, and the standard deviation was 10 years.

DISABILITY GLARE STUDY - The disability glare experiment used much of the same apparatus as the discomfort glare experiment (Figure 2).

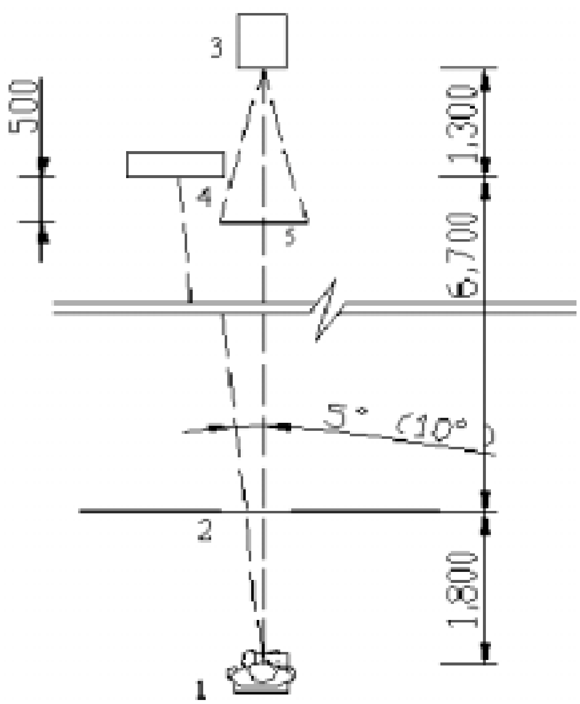

Figure 2. Plan view of discomfort glare experimental apparatus: (1) subject; (2) curtain; (3) projector for target; (4) glare source; (5) display screen for target. Dimensions are given in mm.

The experimental conditions also included the two off-axis viewing angles, three light levels and three light sources that were used in the discomfort glare experiment. The difference between the two experiments was the target. A screen was located 8 m directly in front of the subject. An image was projected on the screen from behind using a liquid-crystal display projector containing a metal halide reflector lamp. The projector was connected to a computer, and the projected image was created with LabView software. The image was a dark gray background with a small gray square as the target in the center. The target subtended 19 minutes of arc in the visual field against a background that subtended 6.9^o horizontally and 4.2^o vertically. This gray background had a luminance of 0.12 cd/m^2, close to the level used in the discomfort glare experiment.

The target was located at the same height as the glare source aperture. Changing the value of the projected image pixels would increase or decrease the brightness of the gray target. The pixel intensity value had 256 possible values ranging from 0 (black) to 255 (white). The subject sat 8.5 m from the glare source with a curtain positioned 1.8 m in front of him or her. Two buttons (marked “yes” and “no”) were fixed onto the desk at which the subject sat, which were in turn connected to the computer. The brightness of the target would change according to which button the subject pressed as described below.

For each subject, there was a 3 to 5 minute dark adaptation period before the experiment. The image was directly in front of the subject, with a background luminance of 0.12 cd/m^2. The initial target luminance was 3.7 cd/m^2. The glare source was presented when the experiment began. The subject was asked to press the button according to the visibility of the target. If it was distinguishable, the subject pressed “yes” and if it was not, the subject pressed “no.” The initial luminance target was much higher than its background, making it well above the visual threshold. The target luminance decreased each time the “yes” button was pressed, until the target could not be distinguished and the “no” button was pressed. At this time the luminance increased, and the steps were repeated according to the subject’s response.

The program was a single-staircase algorithm. Each subject had to respond at least 8 times (4 times “yes” and 4 times “no”), before finishing each condition. The result was a pixel brightness value, which could be converted into luminance. The first “yes” and “no” responses served as possible error responses and were not counted in the final value. The final luminance value was the average of the remaining 6 "yes/no" values. Subjects could observe the target as long as they needed to give a response.

8 subjects (5 males and 3 females) who participated in the discomfort glare experiment took part in this experiment, aged from 22 to 46 years. The mean age was 30 years, and the standard deviation was 7 years.

RESULTS

DISCOMFORT GLARE STUDY - The results of the discomfort glare study are shown in Figures 3 (for the 5^o viewing condition) and 4 (for the 10^o viewing condition). Three significant effects were found, according to these results, using a within-subjects analysis of variance:

- illuminance at the eye ($p<0.01$)
- lamp type ($p<0.01$)
- viewing angle ($p<0.01$)

There was also a significant interaction of lamp type and illuminance at the eye ($p<0.01$). No other interactions were statistically significant.

The HID glare source resulted in consistently lower (more glaring) De Boer ratings than the halogen and blue-filtered halogen at all illuminances, and the halogen glare source had the highest (least glaring) ratings. Of interest, the blue-filtered halogen glare source tended to be relatively more glaring at the highest illuminance, and relatively less glaring at the lowest illuminance (this accounts for the interaction between lamp type and illuminance).

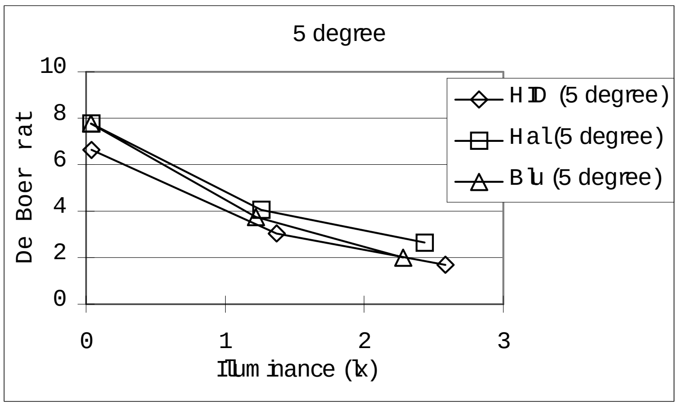

Figure 3. De Boer discomfort ratings (1=unbearable, 9=just noticeable) for the three glare sources at a viewing angle of 5°, as a function of illuminance at the eye. Typical standard deviation is one De Boer unit.

DISABILITY GLARE STUDY - The results of the disability glare study, in terms of threshold contrast under the various glare conditions, are plotted in Figure 5. They clearly show an effect of illuminance and of viewing angle for the glare source. A within-subjects analysis of variance found both of these to be significant main effects ($p<0.01$). There was also a significant interaction ($p<0.01$) between illuminance and glare source viewing angle. Unlike the results of the discomfort glare study, the effect of lamp type was not significant ($p>0.05$).

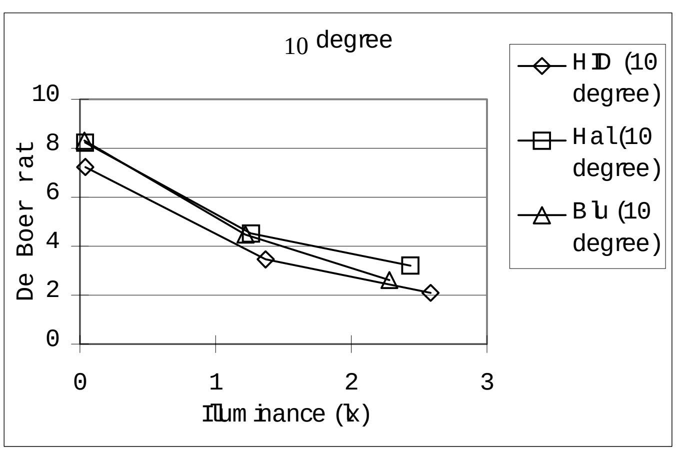

Figure 4. De Boer discomfort ratings (1=unbearable, 9=just noticeable) for the three glare sources at a viewing angle of 10°, as a function of illuminance at the eye. Typical standard deviation is one De Boer unit.

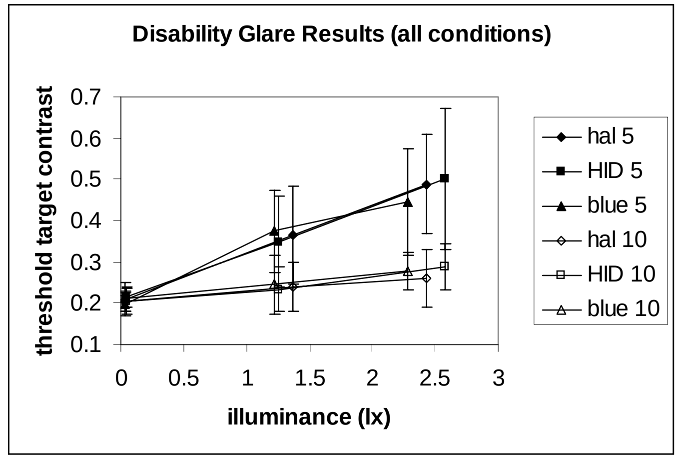

Figure 5. Threshold contrast and standard deviations as a function of glare illuminance for all lamps and viewing angles (5: 5°; 10: 10°).

DISCUSSION

The relative influences of lamp spectrum, light level and viewing angle appear to be much different for discomfort glare than they are for disability glare. The spectral composition of the glare source significantly impacted the discomfort ratings, but photopic measures of illuminance were adequate to characterize the impact of glare on threshold contrast, at least for foveal vision.

The data show that discomfort glare, for the experimental conditions used in this study, is not influenced by the scotopic content of the glare source, which is consistent with the findings of Flannagan [10]. The S/P ratios of the halogen and HID lamps were nearly the same, yet these lamps resulted in the least and most discomfort glare, respectively. According to the curves in Figures 3 and 4, for example, the illuminance from the halogen lamp needed to be about 25%-50% higher than from the HID lamp to elicit a De Boer rating of 4. The blue-filtered halogen lamp, having the highest S/P ratio of the three sources, had intermediate discomfort glare ratings. Based on these results, it seems unlikely that the scotopic content of a light source will predict its impact on discomfort glare under all viewing conditions.

A recent report by Fotios and Levermore [11] described the potential influence of short-wavelength-sensitive (SWS) cones in the brightness response. In order to determine whether SWS cones might play a role in discomfort glare under the viewing conditions used in this study, the De Boer ratings from Figures 3 and 4, averaged for the 5° and 10° viewing angles, were plotted as a function of relative SWS-cone illuminance. The SWS-cone illuminance is calculated by convolving the spectral power distribution of a light source with a luminous efficiency function having a peak at 440 nm, in contrast with the 555-nm peak of the photopic luminous efficiency function. It thus gives greater weight to sources having more energy in the 400-460-nm region of the visible spectrum. As seen in Figure 6, the ratings are correlated quite highly with the relative SWS-cone illuminances (r^2 = 0.974). This correlation provides insight that SWS cones might be contributing to discomfort glare under these viewing conditions, and the potential role of SWS cones should be explored in future research.

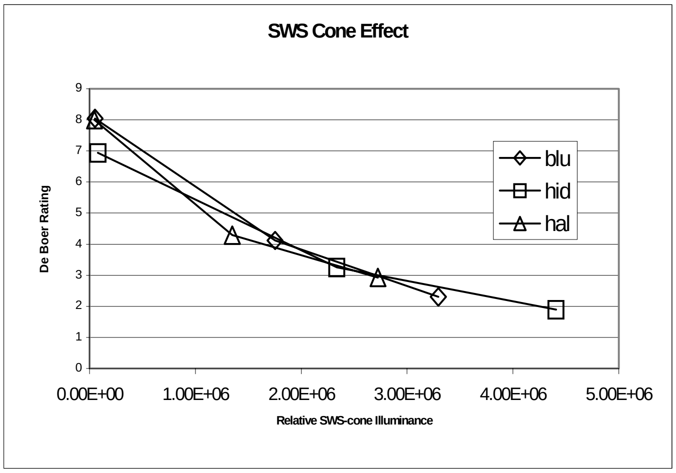

Figure 6. De Boer discomfort ratings (1=unbearable, 9=just noticeable) averaged for both viewing angles, plotted as a function of the relative SWS-cone illuminance.

CONCLUSIONS

For the same illuminance at the eye, HID headlamps seem to produce greater discomfort glare than halogen headlamps, despite their similar scotopic content. A possible mechanism involving SWS cones has been explored, but it must also be noted that the relative role of SWS cones or rods might be dependent upon the particular viewing conditions experienced by a driver. Indeed, it is well known that SWS cones tend to have relatively slow responses, so in a situation where a glare source is continually moving, as might be found in a real driving situation, the influence of SWS might be expected to decrease. Future work should investigate these possibilities.

It is also important to acknowledge that disability glare, as measured using a threshold contrast technique, was insensitive to spectrum once the photopic illuminance was held constant. In other words, even if one might experience greater discomfort in the presence of HID headlamp glare, it is possible that no deterioration of driving performance would be experienced, as long as the glare illuminance is controlled.

It is hoped that the data presented in this paper will contribute to the ongoing dialogue about the relative impact of light output, spectrum, discomfort glare and disability glare in forward lighting systems.

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