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# Discomfort Glare from Headlamps: Interactions Among Spectrum, Control of Gaze and Background Light Level

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## ABSTRACT

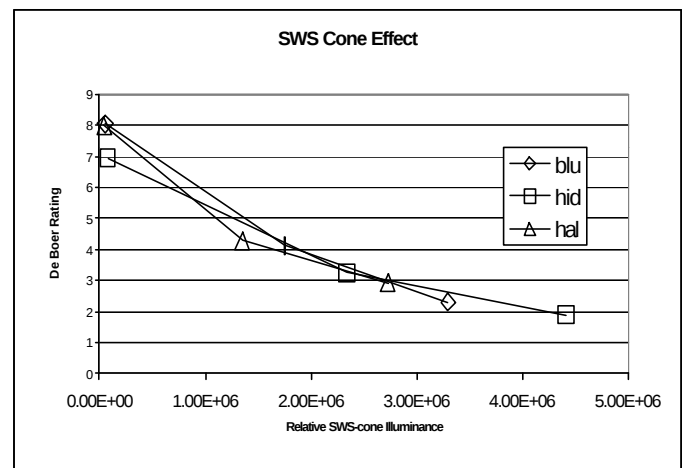
Discomfort glare while driving at night might have implications for long-term fatigue and ultimately, driving performance and safety. The intensity of oncoming headlights, their spectral power distribution, the location of the lights in the field of view, and the ambient illumination conditions can all impact feelings of discomfort while driving at night. Not surprisingly, light sources with higher intensities are perceived as more glaring. Similarly, perceptions of discomfort increase as the ambient lighting conditions are reduced, and as the glare sources are located closer to the line of sight. Recent research also appears to demonstrate the role of short-wavelength light in contributing to the discomfort glare response. The present paper outlines a laboratory study to probe the effects of ambient light level, spectral power distribution, and control of gaze on discomfort glare, and potential interactions among these factors.

## BACKGROUND

High-intensity discharge (HID) headlamps are becoming more widespread on vehicles in North America. These lamps not only produce more light than conventional halogen headlamps [1], they have a wider distribution of light [2,3], and a different spectral power distribution weighted more heavily toward short visible wavelengths ("blue" light) [4]. All of these factors have potential impacts in terms of disability and discomfort glare when these headlamps are viewed during the nighttime in oncoming traffic.

Flannagan [5] studied the impact of headlamp spectral power distribution (halogen and HID) on both disability glare (glare that impairs visual performance) and discomfort glare (glare that causes an annoying or painful sensation; disability and discomfort glare are often, but not necessarily, coexistent). He found no response difference between halogen and HID glare sources in terms of threshold light level for a target (disability glare). But for discomfort glare, the HID lamp was rated consistently 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; a relative characterization of the light source's ability to stimulate the rod photoreceptors in comparison with the cone photoreceptors of the eye) ratios for these two lamps was only 1.04, lending doubt to the hypothesis that rods contribute primarily to the discomfort glare response in a nighttime driving context.



**Figure 1.** Mean De Boer discomfort ratings (1=unbearable, 9=just noticeable) for halogen, blue-filtered halogen and HID headlamps, in the study by Bullough *et al.* [4], plotted as a function of the relative S-cone illuminance. The typical size of the standard deviation in that study was about one De Boer unit. The correlation between the mean ratings and the S cone illuminance is 0.97.

Similarly, Bullough *et al.* [4] measured contrast threshold (disability glare) and rated discomfort glare from three types of headlamps in a scale-model laboratory study: conventional halogen headlamps, blue-filtered halogen headlamps, and HID headlamps. These investigators similarly found no effect of glare source spectrum on contrast threshold, but found a significant effect of spectral power distribution on ratings of discomfort; one that was also not highly correlated with S/P ratio. The blue-filtered halogen lamp used by Bullough *et al.* [4] had a S/P ratio of approximately 2, higher than that of the HID headlamp (S/P of approximately 1.7) and the halogen headlamp (S/P of approximately 1.6). However, the blue-filtered halogen headlamp did not result in the greatest

degree of discomfort. Instead, the ratings of discomfort were highly correlated with the relative degree to which the sources stimulated the short-wavelength (S) cone photoreceptors (Figure 1) [4]. Such results do not necessarily imply that S cones are the primary mechanism for discomfort glare, but the high correlation between discomfort ratings and "S cone illuminance" at least provides the basis for this quantity as a convenient metric for estimating the possible degree to which a light source can cause discomfort glare. This finding is consistent with a model of brightness developed by Fotios and Levermore [6] which is based upon the responses of S cones. If, as seems reasonable to suppose, discomfort glare is a form of excess brightness, such a mechanism could be plausible.

The results of Flannagan [5] and Bullough *et al.* [4] were somewhat surprising considering the context of previous research in a street lighting context [7,8]. De Boer and Van Heemskerck Veeckens [7] and Ferguson *et al.* [8] compared nominally white street lighting sources with nominally yellow sources: incandescent versus yellow-filtered incandescent [7], and mercury versus low pressure sodium [8]. Berman [9] and Bullough and Rea [10] published typical S/P ratios for a number of light sources, including the sources used by De Boer and Van Heemskerck Veeckens [7] and Ferguson *et al.* [8]. When the ratios of the estimated S/P ratios [9,10] of the white and yellow sources were compared, they were highly correlated with the ratios of the luminances of the sources that resulted in equal visual discomfort, which is consistent with a role of rods in discomfort glare [10]. Indeed, Fry and colleagues [11,12] hypothesized that discomfort glare could perhaps be linked to the response of the pupillary reflex; this response is dominated by the rod photoreceptors [13,14].

However, there are some important differences between the studies by De Boer and Van Heemskerck Veeckens [7] and Ferguson *et al.* [8] and those conducted by Flannagan [5] and Bullough *et al.* [4]. The former investigators presumably permitted subjects to view the street lights directly in free gaze conditions and used relatively higher background light levels (above  $1 \text{ cd/m}^2$ ), while the latter investigators requested subjects to fix their gaze on a reference point in the field of view and used relatively lower background light levels ( $1 \text{ cd/m}^2$  and lower). Possibly, these differences in experimental conditions explain the apparent differences in results.

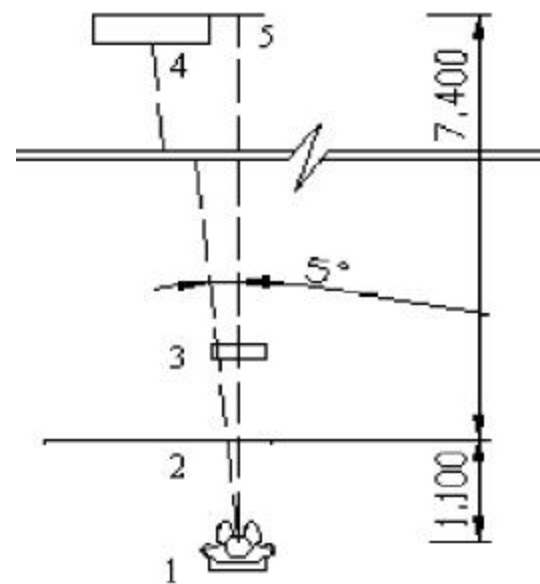
It therefore appeared to be useful to probe the potential effect of background light level and control of gaze on ratings of discomfort glare, in order to better understand whether these different conditions could impact sensitivity to discomfort glare under nighttime driving conditions.

## METHOD

Using apparatus and methods similar to those of Bullough *et al.* [4], two laboratory experiments were set up to investigate the impact of glare source spectral power distribution, background light level, and control of gaze (fixed or free) on subjective ratings of discomfort glare.

**APPARATUS** - Figure 2 shows the experimental setup for the study. The experiments were 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 on the wall facing the subjects was set to either  $0.1 \text{ cd/m}^2$  or  $3 \text{ cd/m}^2$ , as described below.

A subject 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 [15] (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.

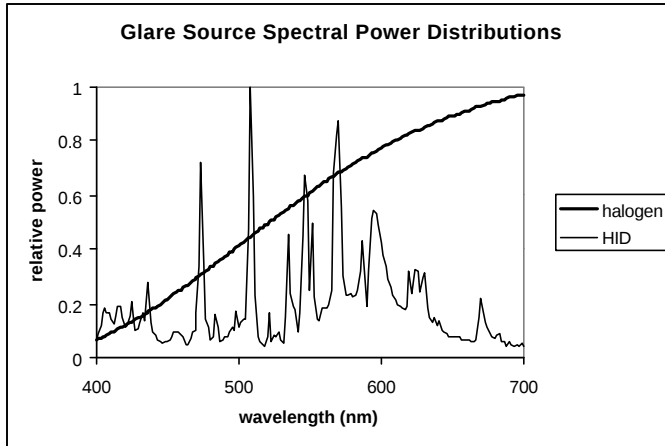


**Figure 2.** Plan view of discomfort glare experimental apparatus: (1) subject; (2) curtain; (3) ambient light source; (4) glare source; (5) poster providing focal point. Dimensions are given in mm.

A halogen headlamp was located between the board and the subject, 1.5 m in front of the subject. It was positioned on the floor, filtered with a diffuser, and aimed toward the poster to provide an ambient light level of  $0.1 \text{ cd/m}^2$  or  $3 \text{ cd/m}^2$  on the wall containing the poster. The subject could not see this lamp directly.

To the left of the poster, at a viewing angle of  $5^\circ$ , was the glare source. The glare source (either a halogen or HID

headlamp; spectral power distributions of these lamps are shown in Figure 3) 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 lx, 1.6 lx, or 0.04 lx.



**Figure 3.** Relative spectral power distributions of the halogen and HID glare sources.

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 in diameter. Although an actual halogen or HID headlamp was used behind the apparatus, the resulting glare source did not have a luminous intensity distribution matching an actual headlamp set; it simply provided one of the three illuminances listed above at the eye.

**PROCEDURE** - Each subject experienced an adaptation period upon entering the darkened laboratory for 3 to 5 minutes before participating in the experiment. For each subject, there were a total of 12 conditions (2 light sources, 3 glare illuminances and 2 background light levels). The subjects were shown each condition for about 4 seconds. Then they were asked to give a rating, using the De Boer scale, of how disturbing the glare source was. 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.

In the fixed-gaze experiment, subjects sat with their heads positioned in a chin rest and were instructed to look only at the focal point on the De Boer rating poster on the opposite wall. In the free-gaze experiment, subjects were permitted (but not required) to look directly at the glare source or at other locations in the field of view in order to make their assessment of discomfort glare.

**SUBJECTS** - Twenty-two subjects participated in the fixed-gaze experiment, ranging in age from 22 to 57 years, with a mean of 31 years, and a standard deviation

of 10 years. Eighteen subjects participated in the free-gaze experiment, ranging in age from 22 to 47 years, with a mean of 31 years, and a standard deviation of 7 years.

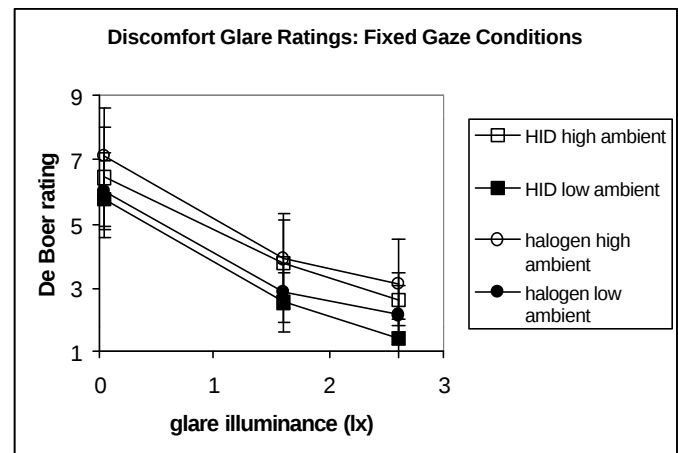
## RESULTS

**FIXED-GAZE EXPERIMENT** - The results of the fixed-gaze experiment are shown in Figure 4. This figure shows several clear trends:

- decreasing De Boer rating (increased discomfort) with an increase in the glare illuminance
- decreasing De Boer rating with a decrease in background ambient luminance
- decreasing De Boer rating as the spectral power distribution is changed from halogen to HID

Each of the three effects described above were found to be statistically significant ( $p < 0.05$ ) using a within-subjects analysis of variance (ANOVA).

The same ANOVA found that none of the two-way interactions (spectrum  $\times$  background light level, spectrum  $\times$  glare illuminance and background light level  $\times$  glare illuminance) were statistically significant; nor was the three-way interaction of spectrum, background light level and glare illuminance.



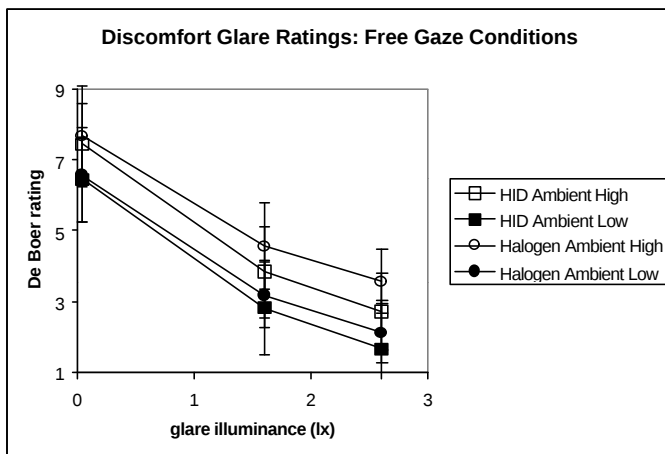
**Figure 4.** Mean discomfort glare ratings (1=unbearable, 9=just noticeable) and standard deviations for the two headlamps viewed at a fixed location of 5° off-axis, for two background luminances (0.1 and 3 cd/m<sup>2</sup>).

**FREE-GAZE EXPERIMENT** - The results of the free-gaze experiment are shown in Figure 5. Like Figure 4, this figure also shows several clear trends:

- decreasing De Boer rating with an increase in the glare illuminance
- decreasing De Boer rating with a decrease in background ambient luminance
- decreasing De Boer rating as the spectral power distribution is changed from halogen to HID

Each of the three effects described above were found to be statistically significant ( $p < 0.05$ ) using a within-subjects ANOVA.

The same ANOVA found that none of the two-way interactions (spectrum  $\times$  background light level, spectrum  $\times$  glare illuminance and background light level  $\times$  glare illuminance) were statistically significant; nor was the three-way interaction of spectrum, background light level and glare illuminance.



**Figure 5.** Mean discomfort glare ratings (1=unbearable, 9=just noticeable) and standard deviations for the two headlamps viewed under free-gaze conditions, for two background luminances (0.1 and 3  $\text{cd/m}^2$ ).

## DISCUSSION

The results of both studies were highly correlated with one another ( $r^2 = 0.99$ ), although on average, the ratings for the fixed-gaze experiment were about 0.4 De Boer units lower than those for the free-gaze experiment. When the mean ratings for each condition in the free-gaze experiment were compared to the mean ratings in the fixed-gaze experiment in a paired Student's *t*-test, it was found that the ratings for the fixed-gaze experiment were statistically significantly lower ( $p < 0.05$ ) than for the free-gaze experiment. In comparison, significant differences among subject groups with similar age distributions, as used in the present experiments, were not found in other studies where the experimental protocols and methods were similar [2,3,16].

Assuming therefore, as seems reasonable, that the subject groups in each experiment were indeed similar, the difference described above could perhaps imply that the free-gaze conditions were slightly less uncomfortable than the fixed-gaze conditions, even though in free gazing, one could look directly at the glare source. This might have been more than compensated for, however, by the subjects' ability to look away from the glare source once a glare assessment was made. Nonetheless, the very similar trends found in both experiments, and the relatively small size of the potential fixed/free-gaze effect, demonstrate that it might not be necessary to control the

direction of gaze in future study, at least under similar conditions to these experiments.

The lack of interactions between headlamp spectrum and background light level in both experiments indicates that differences in background light level, at least in the range between 0.01 and 3  $\text{cd/m}^2$ , does not differentially affect the spectral sensitivity of the discomfort glare mechanism. Similarly, the trends between the two experiments were highly correlated with one another, indicating that headlamp spectrum had no effect in one of the experiments that it did not have in the other.

What remains, then, is a difference between these results (and those of Bullough *et al.* [4], Flannagan [5] and others) and the earlier street lighting work by De Boer and Van Heemskerck Veeckens [7] and Ferguson *et al.* [8] that cannot be explained by the ambient light level nor by the subjects' ability to look directly at (or away from) the glare sources. It is altogether possible that the sources used in these earlier studies were somewhat different in construction from the modern sources characterized by Berman [9] and Bullough and Rea [10], leading to differences in the ratios of the S/P ratios from the values described above.

## CONCLUSIONS

The discomfort glare experienced by observers in the context of oncoming headlamps at night seems to be influenced by the short-wavelength content of the headlamp illumination under a range of background luminances that correspond to rural roadways to urban streets [17,18], and for viewing conditions ranging from fixed to free gazing. The use of S/P ratio or scotopic units to quantify the degree of discomfort glare is not recommended as it has no apparent relationship with this response.

The consistency of the results between the two studies described in this paper further demonstrate that fixed or free gaze is probably of little practical importance in the design of future experiments along these lines.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Jost, K. 1995. Anatomy of high-intensity discharge headlamps. *Automotive Engineering* (November): 38.
2. Van Derlofske, J., J. D. Bullough and C. M. Hunter. 2001. Evaluation of high-intensity discharge automotive forward lighting (SAE paper number 2001-01-0298). In *Lighting Technology*

- Developments for Automobiles* (pp. 1-7), SP-1595. Warrendale, PA: Society of Automotive Engineers.
3. Van Derlofske, J., J. D. Bullough and C. M. Hunter. 2002. Visual benefits of high-intensity discharge automotive forward lighting (SAE paper number 2002-01-0259). In *Advanced Lighting Technology for Vehicles* (pp. 51-56), SP-1668. Warrendale, PA: Society of Automotive Engineers.
  4. Bullough, J. D., Z. Fu and J. Van Derlofske. 2002. Discomfort and disability glare from halogen and HID headlamp systems (SAE paper 2002-01-0010). In *Advanced Lighting Technology for Vehicles* (pp. 1-5), SP-1668. Warrendale, PA: Society of Automotive Engineers.
  5. Flannagan, M. J. 1999. *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution*, Report No. UMTRI-99-36. Ann Arbor, MI: University of Michigan.
  6. Fotios S. A. and G. J. Levermore. 1998. Chromatic effect on apparent brightness in interior spaces II. *Lighting Research and Technology* 30(3): 97-110.
  7. De Boer, J. B. and J. F. T. van Heemskerck Veeckens. 1955. Observations on discomfort glare in street lighting. *Proceedings of the Commission Internationale de l'Éclairage*, Zurich, Switzerland.
  8. Ferguson, H. M., J. Reeves and W. R. Stevens. 1953. A note on the relative discomfort glare from mercury, sodium and tungsten light sources. *GEC Journal* (July).
  9. Berman, S. M. 1992. Energy efficiency consequences of scotopic sensitivity. *Journal of the Illuminating Engineering Society* 21(1): 3.
  10. Bullough, J. D. and M. S. Rea. 2001. Driving in snow: Effect of headlamp color at mesopic and photopic light levels (SAE paper 2001-01-0320). In *Lighting Technology Developments for Automobiles* (pp. 67-75), SP-1595. Warrendale, PA: Society of Automotive Engineers.
  11. Fugate, J. M. and G. A. Fry. 1956. Relation of changes in pupil size to visual discomfort. *Illuminating Engineering* 51(7): 537.
  12. Fry, G. A. and V. M. King. 1975. The pupillary response and discomfort glare. *Journal of the Illuminating Engineering Society* 4(4): 307.
  13. Alpern, M. and F. Campbell. 1962. The spectral sensitivity of the consensual lightreflex. *Journal of Physiology* 164: 178.
  14. Alpern, M. and N. Ohba. 1972. The effect of bleaching and backgrounds on pupil size. *Vision Research* 12: 943.
  15. De Boer, J. (ed.). 1967. *Public Lighting*. Eindhoven, Netherlands: Philips Gloeilampenfabrieken.
  16. Bullough, J. D. 2002. Modeling peripheral visibility under headlamp illumination. *Transportation Research Board 16th Biennial Symposium on Visibility and Simulation*, Iowa City, IA, June 2-4.

17. He, Y., M. S. Rea, A. Bierman and J. D. Bullough. 1997. Evaluating light source efficacy under mesopic conditions using reaction times. *Journal of the Illuminating Engineering Society* 27(1): 125-138.
18. Rea, M. S. (ed.). 2000. *IESNA Lighting Handbook: Reference and Application*, 9th ed. New York, NY: Illuminating Engineering Society of North America.

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