

Headlamp Parameters and Glare

John Van Derlofske, John D. Bullough, Peping Dee, Jie Chen and Yukio Akashi
Transportation Lighting Group, Lighting Research Center, Rensselaer Polytechnic Institute

Copyright © 2004 Society of Automotive Engineers, Inc.

ABSTRACT

New headlamp sources and optical designs are creating new glare scenarios on today's roadways. Recent evidence suggests that the spectral content of vehicle forward lighting may play a role in the glare that it produces. Additionally, there is concern that the decreasing size of some headlamp systems may be contributing to glare. This paper describes a field experiment designed to take a fresh look at headlamp glare, both disability and discomfort, by exploring the role of illuminance, spectrum, and size and determining the relative magnitude of each as it affects oncoming glare.

Subjects seated in a test vehicle were exposed to small targets at various angles. Test glare headlamps were positioned 50 m in front of the subject at an angle of 5°, simulating oncoming traffic. The glare intensity at the subject's eye, the spectrum of the glare source (among high intensity discharge, halogen, and blue filtered), and the glare source size were systematically varied. Target reflectance was also varied between 20% and 40%. The time of response to target presentation, as well as the number of targets missed, were collected as a measures of performance. Additionally, subjective ratings of discomfort were also collected from the subjects after every test condition.

The results show that illuminance at the eye is the dominant factor in glare produced by an oncoming headlamp under these conditions, both for on- and off-axis visual performance and discomfort. Further, for varying glare illuminances, there was found an interesting interaction between target contrast and discomfort ratings. Light source spectrum did not play a significant role in causing disability glare, but did significantly impact discomfort. Headlamp size had no significant impact on discomfort or disability glare. The impacts of these results on new light sources for vehicle forward lighting, such as HIDs and LEDs are discussed.

INTRODUCTION

When developing new headlamps to improve safety there is always a balancing act that must go on between maximizing the visual performance of the driver while minimizing glare to oncoming drivers. This struggle is acutely evident when new lamp sources or designs are being introduced, such is currently the case with HID headlamps, or will be the case with LED headlamps.

In the late 1960s Hemion estimated that approximately 1% of accidents could be attributed, at least in part, to headlamp glare.[1] Generally, two types of glare are recognized: disability and discomfort. Disability glare is defined by the direct reduction of visual performance.[2] Light from glare sources gets scattered in the eye and results in diminished visibility. Discomfort glare is a sensation of annoyance that is typically measured by means of a subjective rating scale. Discomfort glare does not directly affect visibility adversely but may have impacts that adversely effect driver behavior. Glare source illuminance, spectrum, and extended size are factors that may influence disability and discomfort glare.

BACKGROUND

Illuminance

Headlamp glare reduces visual performance relative to the level of that achievable without glare.[3][4] This effect has been shown to be consistent with predictions of veiling luminance over the field of view that adds to the visual noise and causes contrast reduction.[5]

Typical glare illuminances from oncoming headlights range from 0 to 10 lx in normal driving conditions.[6] Bhise *et al.* cite research stating that 0.1 lx at the eye is the threshold for glare, when the illuminance begins to become uncomfortable.[7] An illuminance of 1 to 3 lx is sufficient to cause drivers to flash their own headlights to signal to oncoming drivers.[7][8] A value of 3 to 10 lx is close to the illuminance at which discomfort becomes unbearable.[6][9][10][11][12][13][14]

Spectrum

It has been found that source spectrum has little effect on disability glare.[12][14][15] This is not surprising since disability glare is a foveal effect, where sources matched for photopic illuminance will produce similar effects. Spectrum does, however, appear to play an important role discomfort glare under nighttime driving conditions. This is a phenomenon that has been appreciated since at least the 1930s, when it was reported that discomfort glare was caused more by "blue" than by "yellow" light.[16] The effect of spectrum on discomfort glare for nearly monochromatic, highly saturated colors has shown that yellow sources are perceived as less glaring (from a visual comfort perspective) than green or blue sources.[17][18] For nominally white light sources, such as halogen and HID headlamps, a series of studies has confirmed that typical HID headlamps, viewed in an oncoming situation, result in greater discomfort than typical halogen headlamps.[12][14]

Size

The effects of headlamp size on disability glare have not been studied in great detail. Flannagan compared glare sources subtending 0.3 and 0.6 degrees and found no difference between them in terms of disability glare.[12]

More research has been conducted on the effects of source size on discomfort glare. It appears the effect of size is small, when compared to that of the illuminance produced at the eye.[19] Alferdinck and Varkevisser investigated a large range of source sizes (from 0.0006 to 0.15 degrees) and showed that the maximum difference in discomfort attributable to size was equal to about 1 De Boer unit.[6] Flannagan found no effect of size when going from 0.3 to 0.6 degrees, while another study using the same sizes showed a very small effect of size.[12][20]

It is interesting to compare these results to those of Bhise *et al.*, who field-tested two- and four-headlamp systems producing the same glare illuminance.[7] Dimming requests from other drivers were greater with the four-lamp systems, even though their luminance was reduced because the overall glare illuminance was the same. This may imply that other psychological factors could play into driving behaviors associated with discomfort. Drivers might have interpreted the four-lamp array as a vehicle with its high-beam headlights switched on and responded to that.

SCOPE OF PAPER

The goal of this research is to examine the effects of illuminance at the eye, source spectrum, and source size on the glare produced by oncoming headlamps under driving conditions.

This paper is divided into two main sections. The first reviews the experimental methods employed in the

study. This includes a description of the experimental geometries, procedures, and subjects used.

The second section presents the experimental results and presents brief discussions examining the implications. This includes both reaction time and missed signals as a function of target location, target contrast, and glare condition as well as subject discomfort evaluation as a function of the same conditions. Potential implications driving safety and on the development or refinement of forward lighting standards are discussed.

METHODS

EXPERIMENTAL GEOMETRY

The study had three primary components: for a constant glare source spectra and source size, glare was measured for different illuminances at the eye, for a constant glare illuminance at the eye and source size, glare was measured with three different glare source spectra: HID, halogen, and blue-filtered halogen, for a constant illuminance at the eye and a constant spectra, glare was measured for different light source sizes.

The experimental geometry is shown in Figures 1 through 3. Subjects were seated in a black 1995 Mercury Tracer and performed a tracking task cognitively similar to driving. The purpose of the tracking task was to ensure that angular distance to target locations remained constant. It has been shown that fixed gaze position does not have a significant effect on subjects' ratings of discomfort.[21]

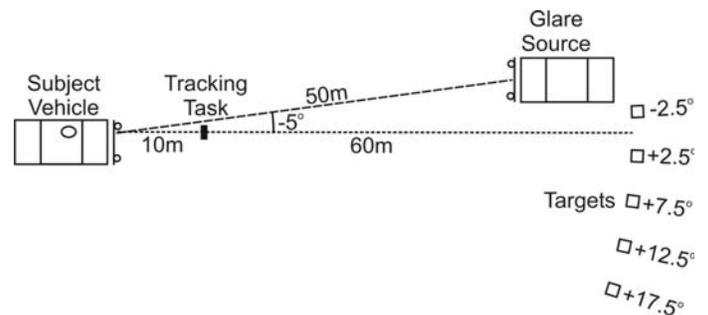


Figure 1. Schematic view of the experimental layout.



Figure 2. Daytime view of the experimental layout approximately from the subjects' viewing location.



Figure 3. Nighttime view of the glare headlights, the three centermost targets, and the tracking task.

Five 20 × 20 cm targets consisting of square-shaped arrays of flip dots were positioned on the roadway 60 m in front of the subject, separated by 5° intervals (Figures 1 - 3). The leftmost target was 2.5° to the left of the line of sight and the rightmost target was 17.5° to the right of the line of sight. The flip dots on the targets were painted black on one side and white on the other. When activated, the targets flipped (within 20 ms) to the white side. The average reflectance of the square target was 40%; a neutral density filter placed in front of the target reduced this reflectance to 20%.

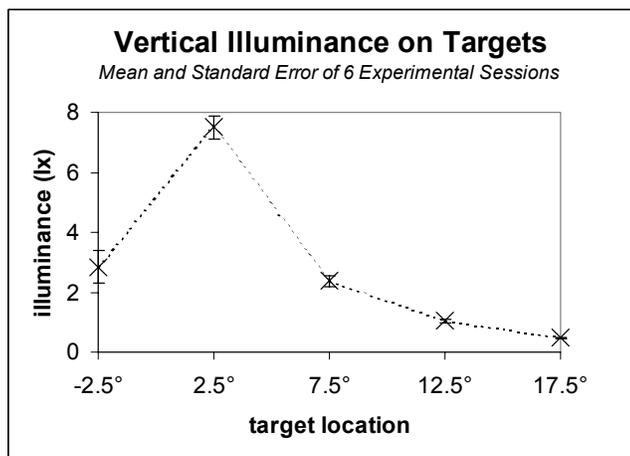


Figure 4. Target vertical illuminances from the subject's vehicle headlights.

A set of halogen, low-beam, optically aimable headlights was positioned in front of the subjects' vehicle. During each session the headlights were aimed. Figure 4 shows the vertical illuminances on the small targets from the subject's headlamps

The glare headlights were positioned 50 m in front of the subject, centered 5° to the left of the line of sight. This position simulated oncoming traffic from a distance of 50 m with a lateral separation of 4.4 m, as might be found on a two lane road. The glare headlights were then tilted slightly using wooden shims to achieve the desired conditions band to ensure that the apparent brightness of the headlamps was the same. The glare headlamps

were never tilted more than 1° in order to modulate the luminous intensity.

The photometric characteristics of the glare sources were as follows: for the illuminance study: 0.2, 1 and 5 lx from HID headlights having a luminous area of 26 cm², for the spectrum study: 1 lx from halogen, HID and blue-filtered halogen headlights, all having a luminous area of 26 cm², and for the size study: 1 lx from HID headlights having luminous areas of 9, 26 and 77 cm².

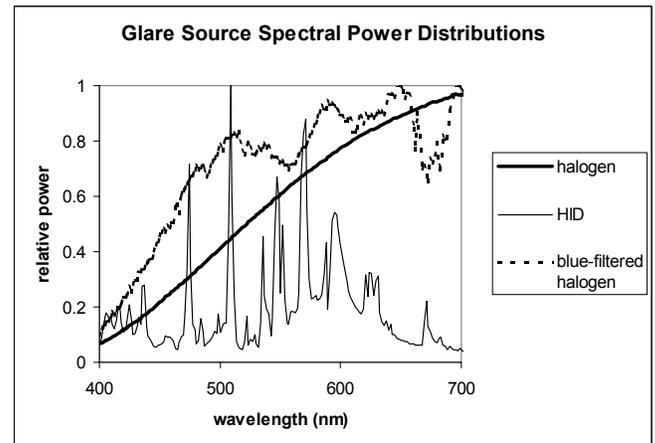


Figure 5. Spectral power distributions (SPDs) of the glare sources.

Figure 5 shows the SPDs of the three sets of headlamps used in the spectrum study (the HID was used in the other two studies as well). The blue-filtered halogen was created by filtering the halogen headlamps with theatrical gels (Roscolux 003 and 061). The relative scotopic content of each of these sources, or their ability to stimulate rod photoreceptors, can be quantified using the ratio of their scotopic to photopic light output, or S/P ratio. The resulting S/P ratios of the sources are: halogen: 1.62, HID: 1.67, and blue-filtered halogen: 1.95.

Similarly, it is possible to estimate the potential of these sources to stimulate the short-wavelength cones (SWC), using a luminous efficiency function based on the spectral sensitivity of the SWC photoreceptor. The resulting short-wavelength-cone-response to photopic ratios, or SWC/P ratios, are: halogen: 67, HID: 102, and blue-filtered halogen: 86.

PROCEDURE

Between four and six subjects participated during each evening session; sessions lasted approximately two to three hours and started after sunset when ambient light levels on the pavement were between 0.1 and 0.2 lx.

Each subject was given the opportunity to practice the tracking task and target detection task to ensure familiarity with the apparatus and procedure and to reduce learning effects during the study. During each session, each subject performed a total of six sets of trials, one for each combination of target reflectance and

either glare illuminance, glare spectrum or glare source size. The order of lighting conditions was randomized during the evening session in order to further reduce learning effects. For each set of trials, subjects performed the visual tracking task and were exposed 20 random order target presentations, four for each of the five targets. The subjects were asked to release a button on the as soon as a target was detected. Each of the target presentations was separated by a random interval between 2 and 4 s; thus, each set of 20 trials took about 1 min. Reaction times longer than 1 s were considered missed targets. After completing the 20 trials, an experimenter asked the subject to rate the level of discomfort experienced by the subjects, using the nine-point De Boer scale.

A total of 31 subjects participated in the study. Ten subjects ranging in age from 17 to 32 years (mean 24 years, median 24 years, standard deviation 6 years) participated in the glare illuminance study. Eleven subjects ranging in age from 24 to 62 years (mean 38 years, median 33 years, standard deviation 12 years) participated in the spectrum study. Ten subjects ranging in age from 22 to 34 years (mean 28 years, median 30 years, standard deviation 5 years) participated in the glare source size study. All subjects had drivers' licenses and wore corrective lenses if needed. One subject in the glare illuminance study had undergone LASIK surgery within the past year.

RESULTS AND DISCUSSION

DISABILITY GLARE

Glare Illuminance

The reaction time and missed target data for the glare illuminance study are shown in Figure 6. The reaction time data, with missed signals averaged in as a reaction time of 1000 ms, are shown in the upper graph. The lower graph of Figure 6 shows the overall percentages of missed targets for each condition. Also shown in this graph are two thick, smooth curves. These curves are predictions for are the predictions of missed targets under conditions without glare.[22] This model is based on field research that used experimental geometries and target characteristics similar to those in the present study.[23][24]

The data shown in Figure 6 show the effect of target location on detection performance, with the far-peripheral targets (12.5° and 17.5°) and the target closest to the glare source (-2.5°) being very difficult to detect. The data also show the impact of target reflectance on performance, with the low reflectance targets resulting in poorer visual performance. For the low reflectance targets, a clear effect of increasing reaction time and increasing number of missed signals with increasing glare illuminance can be clearly seen.

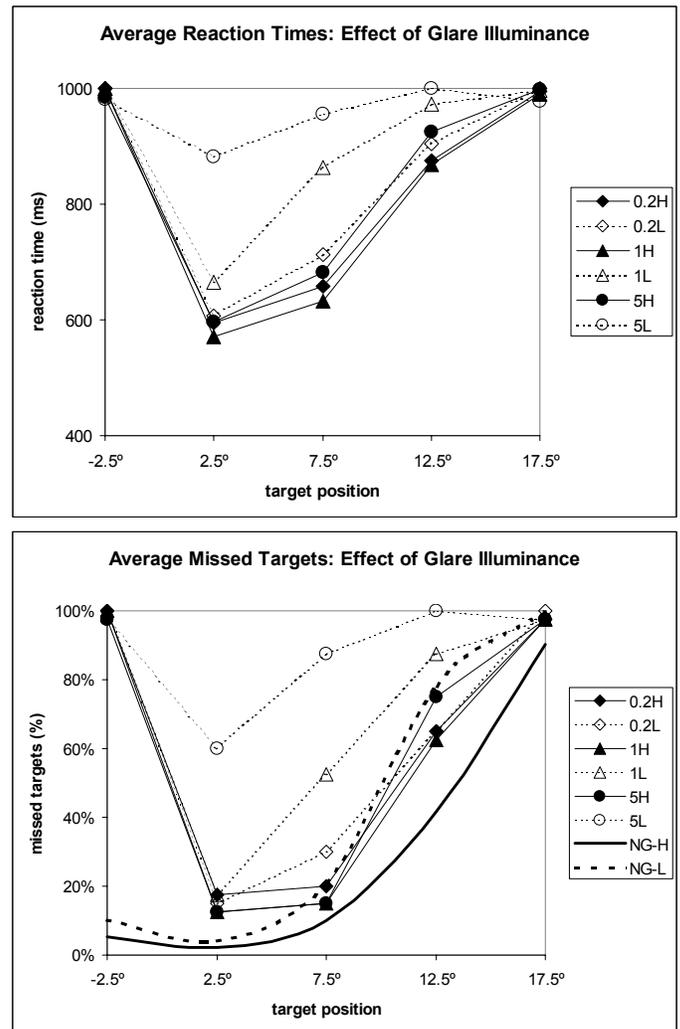


Figure 6. Reaction times and missed targets for the illuminance study. Top: average reaction times with missed target trials assigned a value of 1000 ms. Bottom: overall missed target percentages, as well as predicted missed target percentages without glare. Figure legends: 0.2, 1 and 5 refer to glare illuminances (in lx); NG refers to predicted responses without glare; H and L refer to high (40%) and low (20%) target reflectances.

Using a repeated-measures analysis of variance on the data, there were statistically significant ($p < 0.01$) effects of target position, target reflectance, glare illuminance, as well as statistically significant ($p < 0.01$) two- and three-way interactions among all of these variables.

The results of the target detection study clearly show an effect of glare illuminance on target detection. However, the practical significance of this effect is dependent upon the characteristics of the objects that must be detected. Figure 7 shows the interaction between target reflectance and glare illuminance on reaction. It is very interesting to note how the impacts of headlamp glare on visual performance can vary. The higher reflectance (40%) targets are not, on average, significantly affected by headlamp glare even up to 5 lx at the eye. However, while only 1 lx at the eye greatly impairs detection of the low reflectance (20%) targets.

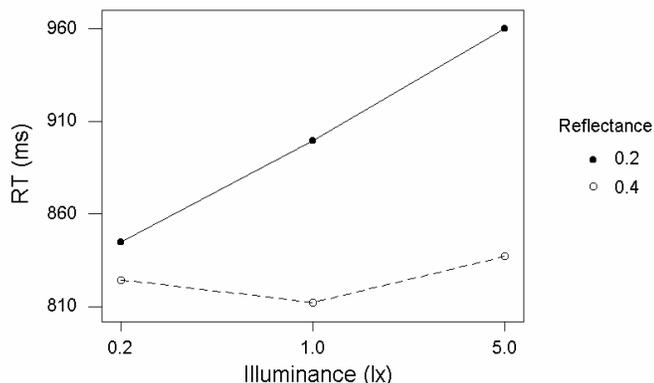


Figure 7. Interaction between glare illuminance and the target reflectance on reaction time averaged across all target locations.

Another point of interest is that even relatively low amounts of headlight glare (0.2 lx) can significantly impacted detection of the target located closest to the glare source. For the target at -2.5° , nearest to the glare source, the percentage of missed targets was very high regardless of target reflectance, significantly larger than predicted for the no glare condition using the model developed by Bullough.[22]

These results raise questions regarding the range of conditions for which disability glare formulae apply. Equation 1 provides the luminance of a uniform veil over the retina that would result in equivalent visual performance in the presence of glare.[5]

$$L_v = \frac{9.2E}{\theta(\theta + 1.5)} \quad (1)$$

In Equation 1, L_v is the resulting equivalent veiling luminance (in cd/m^2), E is the glare illuminance at the observer's eye (in lx), and θ is the distance (in degrees) between the observer's line of sight and the glare source. Clearly the glare formula in Equation 1 is not sufficient to explain the detection performance to the -2.5° target. However, Equation 1 predicts the impact of disability glare on foveal (on-axis) visibility, but not on peripheral visibility. The results in Figure 6 demonstrate that using such formulae to predict peripheral detection can be problematic, because some the visibility of some targets, those closest to the glare source as well as those furthest from the line of sight, are greatly affected by glare while others were not.

Glare Spectrum

The reaction time and missed target data for the glare spectrum study are shown in 8.

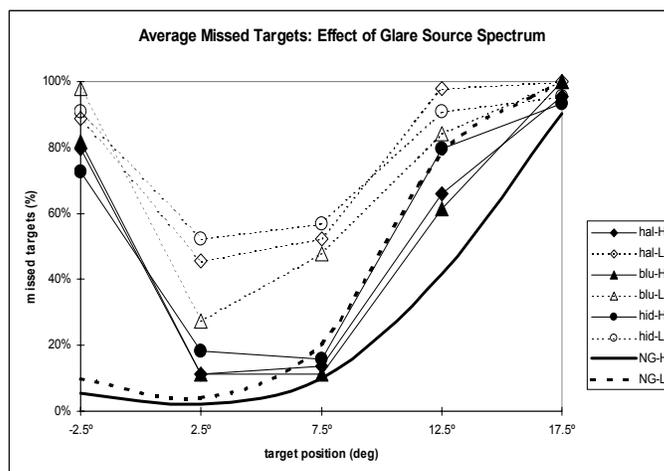
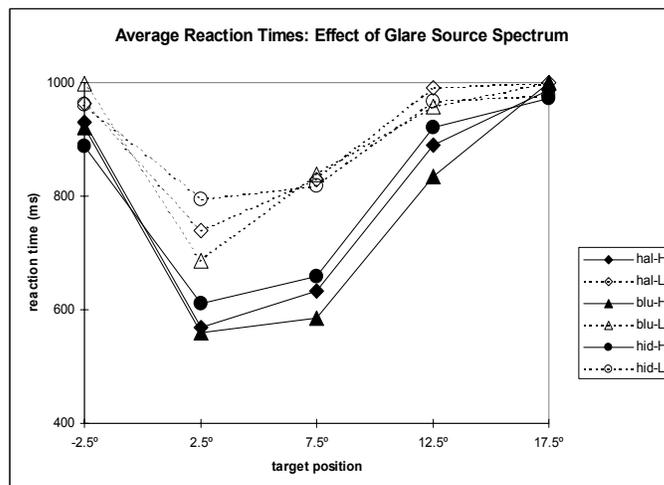


Figure 8. Reaction times and missed targets for the spectrum study. Top: average reaction times with missed target trials assigned a value of 1000 ms. Bottom: overall missed target percentages, as well as predicted missed target percentages without glare. Figure legends: glare spectra denoted by hal (halogen), blu (blue-filtered halogen) and hid (HID); NG refers to predicted responses without glare; H and L refer to high (40%) and low (20%) target reflectances.

The data shown in Figure 8 demonstrate clear effects of target location and reflectance, but show no strong effect of glare spectrum on either reaction times or missed targets. A repeated-measures analysis of variance on the data showed that there were statistically significant ($p < 0.01$) effects of target position and target reflectance, as well as a statistically significant ($p < 0.01$) two-way interaction between target position and reflectance.

The lack of effect of spectrum on the detection of peripheral targets is somewhat surprising. Based on studies of peripheral spectral sensitivity at mesopic light levels it was found that sources with greater scotopic content resulted in improved peripheral visual performance.[25][26] Using the scattering theory of disability glare, and considering that the equivalent veiling luminances for the glare illuminances ranged from 0.06 to $1.4 \text{ cd}/\text{m}^2$. Even taking into account the increase in adaptation brought on by the subject vehicle headlamps the resulting equivalent veiling luminances would still keep observers in the mesopic region of

adaptation. Thus glare sources with higher scotopic content might have been expected to result in reduced visual performance.

The source in this study with the highest S/P ratio is the blue-filtered halogen. This source results in slight, but not statistically significant, better performance than the other two. Thus, these data provide no basis to challenge the use of standard $V(\lambda)$ photometry to quantify the impact of headlamp disability glare.

Glare Source Size

The reaction time and missed target data for the glare source size study are shown in Figure 9.

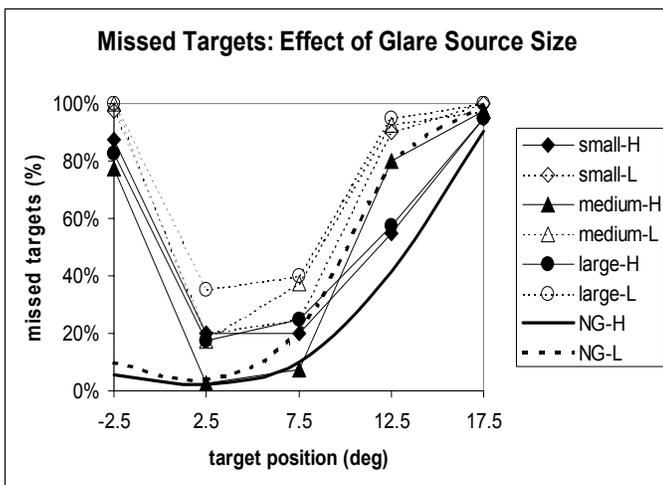
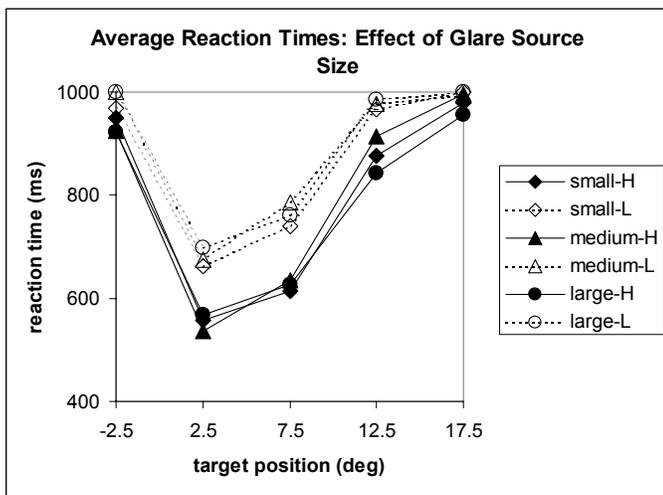


Figure 9. Reaction times and missed targets for the size study. Top: average reaction times with missed target trials assigned a value of 1000 ms. Bottom: overall missed target percentages, as well as predicted missed target percentages without glare. Figure legends: glare source size denoted by small (9 cm^2), medium (26 cm^2) and large (77 cm^2); NG refers to predicted responses without glare; H and L refer to high (40%) and low (20%) target reflectances.

The data shown in Figure 9 demonstrate that, as in the glare illuminance and glare spectrum blocks, large effects of target location and reflectance can be seen.

However, they show no apparent effect of glare source size on either reaction times or missed targets. Using a repeated-measures analysis of variance on the data, there were statistically significant ($p < 0.01$) effects of target position and target reflectance, as well as a statistically significant ($p < 0.05$) two-way interaction between target position and reflectance.

Despite a nearly log-unit variation in the sizes of the glare sources, there was effectively no difference in visual performance. The data in Figure 9 demonstrate that, down to a headlamp size of 9 cm^2 , conventional photometry based on illuminance at the eye, is sufficient to characterize the impact of headlamp glare on visual performance, at least under the range of conditions corresponding to those used in the present study.

DISCOMFORT GLARE

Glare Illuminance

Figure 10 shows the average De Boer ratings for each lighting condition in the glare illuminance study. The graph shows clearly the trend of decreased ratings (increased discomfort) with increasing illuminance. Figure 10 also shows a separation between the high and low reflectance targets, with the low reflectance targets resulting in greater discomfort. An analysis of variance of these ratings showed statistically significant ($p < 0.01$) effects of glare illuminance and of target reflectance, as well as a significant ($p < 0.05$) two-way interaction between these factors.

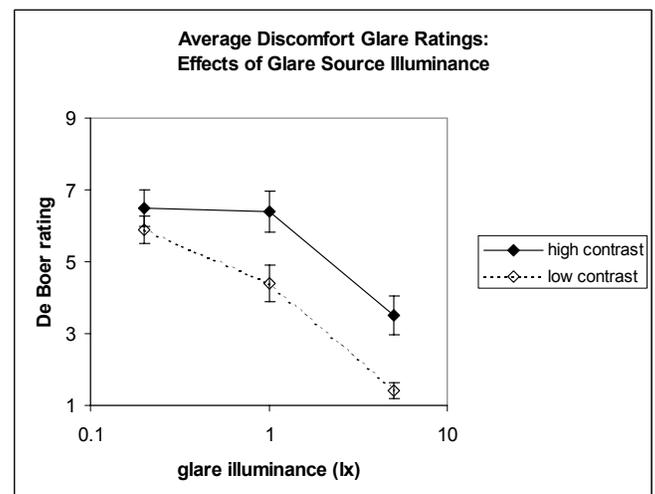


Figure 10. Average De Boer ratings (and standard errors) in the glare illuminance study.

Both the dependence of glare ratings on the illuminance from the glare source and the differences in terms of target reflectance were predicted by the literature.[27] In particular the 5 lx condition elicited very low De Boer ratings with the low-reflectance target resulting in an average rating of just over 1. Of interest, the equation by Schmidt-Clausen and Bindels for predicting ratings of discomfort glare on the De Boer scale gives the resulting

predictions: 0.2 lx: De Boer rating of 5.2, 1 lx: De Boer rating of 3.8, and 5 lx: De Boer rating of 2.4.[9]

Olson and Sivak reported that discomfort ratings in field studies tended to be more tolerating of glare than discomfort ratings in controlled laboratory studies.[10] For the high reflectance targets in the present study this also appears to be the case; all of the ratings with those targets are higher than would be predicted by Schmidt-Clausen and Bindels.[9] However, for the low-reflectance targets, the ratings were more closely in line with the predictions of Schmidt-Clausen and Bindels.[9]

Glare Spectrum

Figure 11 shows the average De Boer ratings for the glare spectrum study block. An analysis of variance on these ratings shows a statistically significant ($p < 0.05$) main effect of glare spectrum but no significant effect of target reflectance; nor was there an interaction between these factors.

As found in previous laboratory studies the HID glare source was found somewhat more glaring than the other two glare sources.[12][14] It is important to note, however, that the magnitude of the spectral effect on discomfort glare appears to be much smaller than that of glare illuminance.

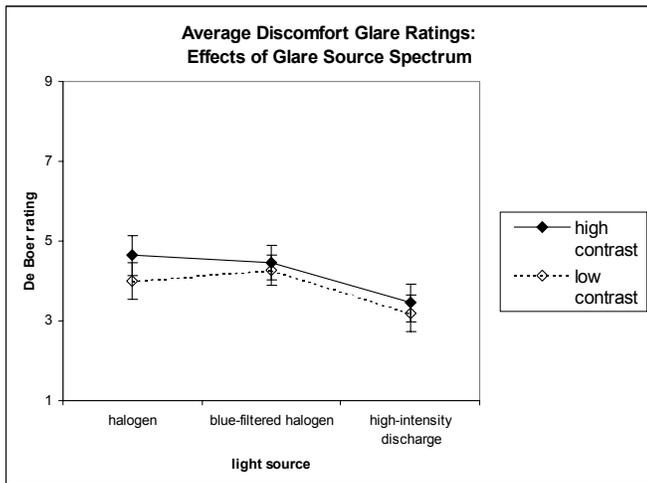


Figure 11. Average De Boer ratings (and standard errors) in the glare spectrum study block.

Glare Source Size

Figure 12 shows the average De Boer ratings for the glare source size study block. An analysis of variance on these ratings shows no statistically significant main effects: neither size nor target reflectance.

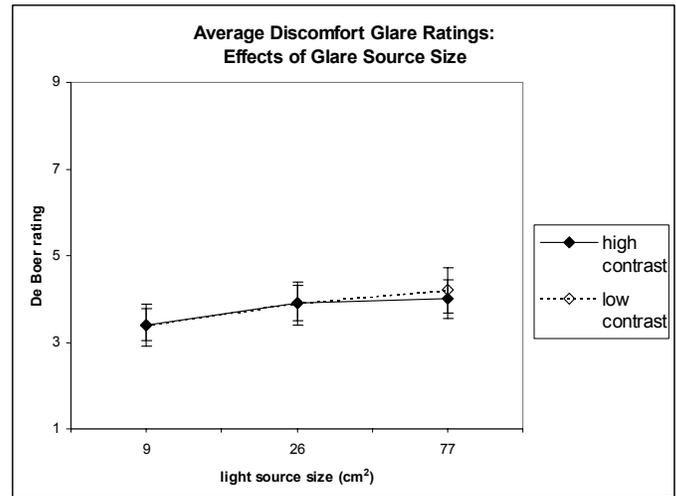


Figure 12. Average De Boer ratings (and standard errors) in the glare source size study.

Some previous research predicted a small dependence of glare source size on visual discomfort; while a very slight trend can be found in agreement with this prediction in Figure 12, this effect is not statistically significant, and is probably of no significance for real driving conditions.[6][28]

Target Reflectance

For the illuminance study the low reflectance targets elicited lower ratings (more glaring) than the high reflectance target conditions. This effect was not significant for the spectrum study, however, the average ratings are consistently more glaring for the low reflectance target. For the size study there was essentially no effect of target reflectance at all. The range of conditions experienced by subjects in the illuminance study was much wider, as evident by the wide range of discomfort ratings given, than in the other two blocks. The spectrum study had the next largest range of conditions. While no disability glare difference was found for the size study.

The impact of target reflectance on discomfort glare ratings might, therefore, might be a function of the range of conditions experienced. This opens up the intriguing possibility, for example, that higher levels of discomfort glare might be tolerable in an interstate highway driving scenario (a relatively more monotonous condition) than driving on a road through various types of countryside and with more curves or hills. This idea is consistent with the findings of Sivak *et al.* and of Theeuwes *et al.*, who found discomfort (as measured through the De Boer rating scale) to be increased when the task being performed was more complex and difficult.[26][29]

CONCLUSIONS

The present study reinforces the idea that disability glare and discomfort glare are discrete phenomena. Additionally, from the perspective of disability glare, the different technologies such as HID, halogen, and even

LED, employed in automobiles would be equivalent to one another at reducing peripheral visual performance when equated for the glare illuminance they provide at oncoming drivers' eyes. Nor is the size of the headlamp's illuminated area (within the range employed in this study) a factor impacting disability glare in this study. Thus, conventional photometry based on luminous intensity using the photopic luminous efficiency function appears to be appropriate for characterizing disability glare from headlamps.

The same is not true for discomfort glare. Two sources having the same standard $V(\lambda)$ photometric properties will not necessarily produce the same amount of discomfort. In the present study as well as in previous studies, HID headlamps were consistently found more glaring in terms of discomfort than halogen headlamps. Interestingly, blue-filtered halogen headlamps are not seen as more uncomfortable than conventional halogen lamps, despite their higher scotopic light output and "bluer" appearance.

ACKNOWLEDGMENTS

This research was conducted with support from the National Highway Traffic Safety Administration under the supervision of Michael Perel. Stephen Israel, commissioner of the Schenectady County Airport, is acknowledged for his generous cooperation in allowing use of the runway facility at the airport. Richard Pysar, Nishantha Maliyagoda, Yimin Gu and Martin Overington from the Lighting Research Center developed and refined the test apparatus used in this study.

REFERENCES

- Hemion RH. 1969. A Preliminary Cost-Benefit Study of Headlight Glare Reduction, Report AR-683. San Antonio, TX: Southwest Research Institute.
- Rea MS (editor). 2000. IESNA Lighting Handbook: Reference and Application, 9th edition. New York, NY: Illuminating Engineering Society of North America.
- Ranney TA, Simmons LA, Masaloni AJ. 1999. Prolonged exposure to glare and driving time: Effects on performance in a driving simulator. *Accident Analysis and Prevention* 31: 601-610.
- Akashi Y, Rea MS. 2001. The effect of oncoming headlight glare on peripheral detection under a mesopic light level. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 9-22).
- Fry GA. 1954. Evaluating disability effects of approaching automobile headlights. *Highway Research Bulletin* (89): 38-42.
- Alferdinck JWAM, Varkevisser J. 1991. Discomfort Glare From D1 Headlamps of Different Size, Report IZF 1991 C-21. Soesterberg, Netherlands: TNO Institute for Perception.
- Bhise VD, Farber EI, Saunby CS, Troell GM, Walunas JB, Bernstein A. 1977. Modeling vision with headlights in a systems context. *Society of Automotive Engineers Congress and Exposition*, Detroit, MI: Society of Automotive Engineers (Paper 770238).
- Rumar K. 2001. Intensity of high-beam headlights. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 829-848).
- Schmidt-Clausen HJ, Bindels JTH. 1974. Assessment of discomfort glare in motor vehicle lighting. *Lighting Research and Technology* 6(2): 79-88.
- Olson PL, Sivak M. 1984. Discomfort glare from automobile headlights. *Journal of the Illuminating Engineering Society* 13(3): 296-303.
- Flannagan MJ, Sivak M, Gellatly AW, Luoma J. 1992. A Field Study of Discomfort Glare from High-Intensity Discharge Headlamps, Report UMTRI-92-16. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Flannagan MJ. 1999. Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution, Report UMTRI-99-36. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Lehnert P. 2001. Disability and discomfort glare under dynamic conditions: The effect of glare stimuli on human vision. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 582-592).
- Bullough JD, Fu Z, Van Derlofske J. 2002. Discomfort and disability glare from halogen and HID headlamp systems. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0010).
- Fu, Z. 2001. Effects of headlamp spectrum on discomfort and disability glare. Masters Thesis. Rensselaer Polytechnic Institute: Troy, New York.
- Bouma PJ. 1936. The problem of glare in highway lighting. *Philips Technical Review* 1: 225-229.
- Flannagan M, Sivak M, Ensing M, Simmons CJ. 1989. Effect of Wavelength on Discomfort Glare from Monochromatic Sources, Report UMTRI-89-30. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Bullough JD, Boyce PR, Bierman A, Hunter CM, Conway KM, Nakata A, Figueiro MG. 2001. Traffic signal luminance and visual discomfort at night. *Transportation Research Record* (1754): 42-47.
- Völker S. 1999. The effect of discomfort glare on the development of headlamps. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 765-773).
- Sivak M, Simmons CJ, Flannagan MJ. 1990. Effect of headlamp area on discomfort glare. *Lighting Research and Technology* 22(1): 49-52.
- Bullough JD, Van Derlofske J, Fay CR, Dee P. 2003. Discomfort glare from headlamps: Interactions among spectrum, control of gaze and background light level. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2003-01-0296).
- Bullough JD. 2002. Modeling peripheral visibility under headlamp illumination. *Transportation Research Board 16th Biennial Symposium on Visibility and Simulation*, Iowa City, IA, June 2-4.
- Van Derlofske J, Bullough JD, Hunter CM. 2001. Evaluation of high-intensity discharge automotive forward lighting. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2001-01-0298).
- Van Derlofske J, Bullough JD, Hunter CM. 2002. Visual benefits of high-intensity discharge forward lighting. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0259).
- He Y, Bierman A, Rea MS. 1998. A system of mesopic photometry. *Lighting Research and Technology* 30(4): 175.
- He Y, Rea MS, Bierman A, Bullough J. 1997. Evaluating light source efficacy under mesopic conditions using

- reaction times. *Journal of the Illuminating Engineering Society* 26(1): 125-138.
27. Theeuwes J, Alferdinck JWAW. 1996. *The Relation Between Discomfort Glare and Driving Behavior*, Report DOT HS 808 452. Soesterberg, Netherlands: TNO Human Factors Research Institute.
 28. Manz K. 2001. The influence by size of headlamp on discomfort glare. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 618-634).
 29. Sivak M, Flannagan MJ, Ensing M, Simmons CJ. 1991. Discomfort glare is task dependent. *International Journal of Vehicle Design* 12: 152-159.

CONTACT

John Van Derlofske Ph. D., Head of Transportation Lighting, Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY, 12180, (518) 687-7100, vandej3@rpi.edu.