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Toward the Development of a Field Methodology for Evaluating Discomfort Glare From Automobile Headlamps

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The aim of this research was to collect information and experimental data toward the development of a universally acceptable methodology for evaluating discomfort glare from vehicle headlamps. Three separate studies were performed: (a) an international survey of experts in headlighting and vision, soliciting opinions on desirable aspects of such a methodology; (b) a field evaluation of a proposed methodology at a speed of 50 km/hr (30 mph); and (c) a field evaluation at 100 km/hr (60 mph). The findings of this research suggest that the proposed methodology, which is easy to set up and implement, provides relatively reliable and valid measures of discomfort glare, and is time-efficient with respect to data collection.

The aim of this research was to collect information and experimental data toward the development of a methodology to evaluate discomfort glare from vehicle headlamps. The intended product of this research is a methodology that is valid, reliable, easy to set up and implement, time-efficient in respect to data collection, and universally applicable. Such a methodology is required for making progress toward potential harmonization of the differences between European and U.S. headlamp beam patterns (Olson, 1977).

This research consisted of the following three studies:

1. An international survey of experts in headlighting and vision, soliciting opinions on desirable aspects of such a methodology;
2. Field testing of a proposed discomfort-glare evaluation methodology at intermediate speeds (50 km/hr [30 mph]); and
3. Field testing of a proposed discomfort-glare evaluation methodology at high speeds (100 km/hr [60 mph]).

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STUDY 1: INTERNATIONAL SURVEY OF EXPERTS

Respondents

A written questionnaire was sent to 43 experts in headlighting and vision. The contacted persons represented academia, industry, and government. A total of 28 persons returned a completed questionnaire, a response rate of about 65%. Table 1 presents a tabulation by country of contacted and responding experts.

Questionnaire and Results

The questionnaire consisted of eight questions. Each question was presented in a four-alternative forced-choice format. The actual questions and the distributions of the responses are shown in Table 2.

TABLE 1
DISTRIBUTION OF CONTACTED AND RESPONDING EXPERTS BY COUNTRY

Country	Number Contacted	Number Responding
United States	10	10
Australia	4	4
West Germany	5	3
Sweden	4	3
Canada	5	2
The Netherlands	5	2
Japan	2	2
United Kingdom	4	1
France	1	1
Finland	1	0
Spain	1	0
Switzerland	1	0

Discussion

The analysis in Table 2 suggests that discomfort-glare evaluation on a straight roadway was the primary issue of concern, with 42% of the respondents rating this aspect as an essential component of a desirable methodology. Straight roadway was followed (in decreasing order of *essential* responses) by vertical misaim, field aspect, hills, and driver as the rater. These aspects were rated by at least one third of the respondents as being essential. On the other hand, the least important issues (again in decreasing order of importance) were sags, rapid evaluation, rater experience, rater sex, and rater education. These aspects were rated as being essential by fewer than 10% of the respondents. The preferred response scale was a 9-point scale; 43% of respondents selected this scale.

Based partly on the results of the survey of experts in Study 1, a methodology was developed for evaluating discomfort glare. This methodology was then tested under intermediate speeds (Study 2) and high speeds (Study 3).

STUDY 2: TESTING THE METHODOLOGY AT INTERMEDIATE SPEEDS

Experimental Design

Proposed methodology for evaluating discomfort glare. The following methodology for evaluating discomfort glare was tested:

1. The observer vehicle is driven at 50 km/hr (30 mph) on a straight, level roadway towards a stationary glare vehicle in the adjacent lane.
2. The lamps of the glare vehicle are on for the vehicle separation of 400 to 300 m (1,312 to 984 ft), and then again for the vehicle separation of 150 to 50 m (492 to 164 ft).
3. Glare is rated on the de Boer scale (de Boer, 1973). This 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).
4. Two ratings are obtained for each

TABLE 2
DISTRIBUTION OF RESPONSES TO THE SURVEY QUESTIONS

Question	% Responses			
	Not Important	Important	Very Important	Essential
How important is discomfort-glare evaluation in establishing headlighting performance standards?	7	22	37	33
How important is field as opposed to laboratory evaluation of discomfort glare?	0	18	46	36
How important is dynamic (all participants moving) as opposed to static evaluation of discomfort glare?	14	7	50	29
In a dynamic evaluation, how important is it for the rater to be a driver as opposed to a passenger?	11	30	26	33
How important is it to include the following situations in discomfort glare evaluation:				
Straight roadway	4	23	31	42
Left curves	12	23	35	31
Right curves	19	23	42	15
Hills	15	23	27	35
Sags	44	36	12	8
Horizontal misaim	19	46	19	15
Vertical misaim	8	19	35	38
How important is it to consider the following observer variables:				
Age	0	25	46	29
Sex	59	37	4	0
Education	74	22	4	0
Experience	30	48	19	4
How important is it for the discomfort-glare evaluation to be relatively rapid?	22	43	30	4
	9-point	3-point	2-point	Other or no preference
What is the preferred rating scale for discomfort-glare evaluation?	43	18	4	36

Note. The number of responses per question varied from 23 to 28.

run, one for the vehicle separation of 400 to 300 m (1,312 to 984 ft), and the other one for the vehicle separation of 150 to 50 m (492 to 164 ft). Subjects memorize the first rating, and record both ratings after the second exposure.

Test site. The test was performed on a flat and straight private road with no significant illumination. Each lane of this two-lane, asphalt roadway was about 3 m (10 ft) wide.

Test vehicles. The subjects were driving (and riding) in a 1983 General Motors full-size station wagon. The stationary glare car was a 1981 full-size Ford station wagon.

Rater position in the car. To investigate the potential effects of rater position in the car (and of driving load), each subject served as a driver, center-front passenger, and right-front passenger.

Illumination levels. On each trial, subjects were shown one of the following four glare stimuli: (a) standard U.S. high beams, (b) standard U.S. high beams filtered with neutral density filters having transmissivity of 18%, (c) standard U.S. low beams, and (d) standard U.S. low beams filtered with neutral density filters having transmissivity of 18%.

These four glare stimuli produced (at two vehicle separations) eight illumination levels ranging from 0.035 to 5.1 lux. These measurements were taken at the end of the glare exposure (i.e., at vehicle separations of 300 m [984 ft] and 50 m [164 ft] inside of the subject's car at the approximate location of the eyes of the center-front passenger. The measurements evaluated the sum of the illumination from the glare car and the ambient illumination. The headlamps of the subject's car were off during these measurements. (Because of the scattering of the light by the filters, the lux values for the filtered low beams are substantially above what would be predicted based only on the transmissivity of the filters.)

The particular illumination levels were selected because it was hoped that they will lead to responses covering the whole range of the response scale. (All eight illumination levels were produced from the same physical units—a total of two large rectangular sealed beams [No. 6052]. Consequently, subjects could not identify which stimulus was being shown based on the location, number, or size of the illuminated headlamps.)

Adaptation illumination. The adaptation illumination was measured inside of the subject's car (with the headlamps of the subject's car on and the headlamps of the glare car off) at the approximate position of the eyes of the center-front passenger. This illumination was approximately 0.055 lux.

Subjects. A total of 12 volunteers participated as subjects. To investigate the effects of age on discomfort-glare rating, the subject group consisted of both older and younger persons. Six subjects (three males and three females) were between 67 and 73 years of age, and six (four males and two females) were between 19 and 23 years of age.

Procedure. Three subjects were tested at a time. Each subject had a clipboard with a response sheet that had the response (de Boer) scale printed on the top, and each had a miniature flashlight to be able to record the responses without major changes in the level of dark-adaptation. The driver was instructed to drive at about 50 km/hr (30 mph). All subjects were asked to look straight ahead, but not directly into the headlights of the glare car.

Two experimenters ran the study. One was seated in the back seat of the subjects' car. His task was to signal, via a handheld radio, when the subjects' car passed four cones at four vehicle-separation landmarks (i.e., 400, 300, 150, and 50 m [1,312, 984, 492, and 164 ft]. Specifically, he indicated "on" at 400 m (1,312 ft), "off" at 300 m (984 ft), "on" at 150 m (492 ft), and "off" at 50 m (164 ft). The second experimenter, seated in the stationary glare car, turned the glare car's headlights on at 400 m (1,312 ft), off at 300 m (984 ft), on at 150 m (492 ft), and off at 50 m (164 ft). Additionally, this experimenter selected, for each trial, the beam to be shown and inserted/removed the filters.

Two replications of each stimulus were shown to each subject at each seating position and at each vehicle separation. (This allowed a more precise estimation of the discomfort and allowed for a test of the reliability of the responses.) This design resulted in 48 trials per subject (2 vehicle separations × 2 beams × 2 filters × 3 positions in the car × 2 replications). Each experimental session, including four practice trials and two short breaks for rotation of subjects' positions, lasted about 90 minutes.

Results

Analysis of variance. The results of the analysis of variance on discomfort-glare ratings (with illumination level, age, rater position, and replication as factors) were as follows:

Illumination level. The effect of illumination level (Table 3, column "All Subjects" — with entries in the decreasing order of the ratings) was statistically significant ($F[7,70]=143.17$, $p<.01$).

Age. The effect of age was statistically significant, with older subjects reporting *less* discomfort (M[mean glare rating]$=6.0$) than younger subjects ($M=5.3$) ($F[1,10]=4.91$, $p=0.05$).

Rater position. The differences among the ratings of drivers ($M=5.6$), center-front passengers ($M=5.5$), and right-front passengers ($M=5.8$) were not statistically significant ($F[2,20]=1.24$, $p>.05$).

Replications. The difference between the ratings for the first replications of each stimulus ($M=5.7$) and the second replications ($M=5.6$) was not statistically significant ($F[1,10]=1.65$, $p>.05$).

Interactions. From among all interactions, only two reached statistical significance: illumination level$\times$age (Table 3, columns "Older Subjects" and "Younger Subjects") ($F[7,70]=4.64$, $p<.05$) and replications$\times$age ($F[1,10]=8.56$, $p<.05$), with older subjects tending to report more glare for first replications and younger subjects for second replications.

Relation of glare ratings to illumination. Glare responses were significantly related to the illumination reaching the eyes of the observers, whether measured in lux ($r[574]=-.64$, $p<.01$) or the logarithm of illumination ($r[574]=-.71$, $p<.01$).

Glare angle/vehicle separation. The confounded effect of glare angle/vehicle separation, when controlling for the effect of the logarithm of the illumination reaching the

TABLE 3
MEAN GLARE RATINGS AT 50 KM/H (30 MPH)
BY ILLUMINATION LEVEL AND AGE

Illumination (lux)	Vehicle Separation	Beam	Filter	Mean Rating		
				All Subjects	Older Subjects	Younger Subjects
0.035	400-300 m[a]	low	yes	8.0	7.9	8.2
0.190	150-50 m[b]	low	yes	7.8	7.6	7.9
0.070	400-300 m	high	yes	6.6	7.3	5.8
0.070	400-300 m	low	no	6.6	7.2	5.9
0.370	150-50 m	low	no	6.4	6.8	5.9
0.700	150-50 m	high	yes	4.7	5.5	3.9
0.350	400-300 m	high	no	3.2	3.8	2.7
5.100	150-50 m	high	no	1.7	1.8	1.6

[a] 1,312-984 ft. [b] 492-164 ft.

eyes of the observer, was statistically significant. The ratings for the 0.6° glare angle (M=4.1) were more discomforting than for the 3.8° glare angle (M=7.1) ($F[1,573]$= 355.9, $p<.01$). The glare angle of 0.6° was always associated with the vehicle separation of 400 to 300 m (1,312 to 984 ft), and the glare angle of 3.8° was always associated with the vehicle separation of 150 to 50 m (492 to 164 ft). (The glare angles were computed for the center-front passenger at 300 m [984 ft] and 50 m [164 ft].)

Variance accounted. The results of stepwise regression analyses indicate that 51% of the variance of the glare ratings can be accounted for by the logarithm of illumination, 70% by the logarithm of illumination and age, and 72% by the logarithm of illumination, age, and glare angle/vehicle separation.

Discussion

The principal results of this study, applicable to the tested speed of 50 km/hr (30 mph), are as follows:

1. The proposed methodology provided relatively reliable measures, as there was no main effect of replications. However, interaction of replications×age was statistically significant. Specifically, there was a tendency for younger respondents to assign more discomforting responses to the second presentation of the stimulus. (This tendency was reversed for older subjects.)

2. Position in the car (and thereby also driving vs. nondriving) had no effect on glare ratings. This is an important finding, indicating that glare ratings could be obtained from up to three raters at a time, without a reduction in validity of the ratings.

3. There was, as expected, a main effect of age. However, this effect was in the unexpected direction: Older subjects reported *less* discomfort glare than did younger subjects (cf. Wolf, 1960). There are two possible *post hoc* explanations of the present finding. The first explanation is based on subject sampling. Specifically, although the sample of younger drivers might have been typical of their age group, the sample of older subjects was quite likely not representative. Since the study relied on volunteers who were willing to drive late at night on an unknown road, it is likely that the sample of older subjects was skewed towards more physically fit persons. The second possible explanation is based on the finding that older persons are more likely to respond to survey questions in a manner that they believe meets with the approval of others (Campbell, Converse, & Rogers, 1976). According to this hypothesis, older subjects would be more likely to report low levels of discomfort glare, because they may believe that those are the answers desired. This hypothesis is strengthened by the finding of a significant illumination×age interaction: Although for the six most discomforting stimuli older subjects did report less discomfort glare than did younger subjects, for the two least discomforting stimuli the effect was reversed. (For these latter stimuli the glare experiences are in the "desirable" [nondiscomforting] end of the response range. Consequently, adjustments of the responses toward the less discomforting end of the scale are not necessary for these stimuli.)

4. The methodology provided valid measures because (a) the measures were found to correlate significantly with the illumination reaching the eyes of the observers; and (b) when controlling for the effects of illumination reaching the eyes of the observer, the conditions with the smaller glare angle produced more discomforting responses.

STUDY 3: TESTING THE METHODOLOGY AT HIGH SPEEDS

Experimental Design

The experimental design was identical to the design in Study 2, except for the following:

Test site. A proving-grounds straightaway was the test site for this study. Each lane of this two-lane, asphalt roadway is about 3 m (10 ft) wide.

Test vehicles. The subjects were riding in a

1987 General Motors full-size station wagon. The stationary glare car was identical to the one used in Study 2.

Rater position in the car. Only the center-front and right-front passengers were raters in this study. (Because of the high speed in this study, the driver was a professional driver who provided no glare ratings.) The subjects remained in their original positions during the entire experimental session.

Illumination levels. The same combinations of beams, filters, and vehicle separations were used as in Study 2, resulting in approximately the same illumination levels as in Table 3. (Because the glare car, the body style of the subjects' car, and the width of the test road were the same as in Study 2, no separate photometry was performed in this study.)

Adaptation illumination. The adaptation illumination was comparable to the illumination in Study 2. (As indicated above, no separate photometry was performed in this study.)

Subjects. A total of eight volunteers participated as subjects: Four subjects (three males and one female) were between 64 and 73 years of age, and four (two males and two females) were between 20 and 21 years of age. (Four of the eight subjects also participated in Study 2.)

Procedure. Two subjects were tested at a time, one in the center-front position and one in the right-front position. The driver was instructed to drive at about 100 km/hr (60 mph).

The same vehicle separations were used as in Study 2 (i.e., 400 to 300 m [1,312 to 984 ft], and 150 to 50 m [492 to 164 ft]. Since the speed was about twice the speed in Study 2, the time duration of exposure to glare was about one half of the time duration in Study 2.

Three replications of each stimulus were shown to each subject at each vehicle separation. This design resulted in 24 trials per subject (2 vehicle separations $\times$ 2 beams $\times$ 2 filters $\times$ 3 replications). Each experimental session, including four practice trials, lasted about 45 minutes.

Results

Analysis of variance. The results of the analysis of variance on discomfort-glare ratings (with illumination level, age, rater position, and replication as factors) were as follows:

Illumination level. The effect of illumination level (Table 4, column "All Subjects") was statistically significant ($F[7,28]=42.75$, $p<.01$).

Age. The effect of age was statistically significant, with older subjects reporting *less* discomfort ($M=6.6$) than younger subjects ($M=5.5$) ($F[1,4]=8.08$, $p<.05$).

Rater position. The mean ratings of center-front passengers and right-front passengers were identical ($M=6.0$) ($F<1$).

Replications. The mean ratings for each of the three replications were identical ($M=6.0$) ($F<1$).

Interactions. From among all interactions, only two reached statistical significance: illumination level $\times$ age (Table 4, columns "Older Subjects" and "Younger Subjects") ($F[7,28]=2.69$, $p<.05$) and replications $\times$ age ($F[2,8]=7.60$, $p<.05$), with older subjects tending to report most glare for first replications and younger subjects tending to report least glare for first replications.

Relation of glare ratings to illumination. Glare responses were significantly related to the illumination reaching the eyes of the observers, whether measured in lux ($r[190]=-.61$, $p<.01$) or the logarithm of illumination ($r[190]=-.68$, $p<.01$).

Glare angle/vehicle separation. The confounded effect of glare angle/vehicle separation, when controlling for the effect of the logarithm of the illumination reaching the eyes of the observer, was statistically significant. The ratings for the 0.6° glare angle ($M=4.7$) were more discomforting than for the 3.8° glare angle ($M=7.3$) ($F[1,189]=$

TABLE 4
MEAN GLARE RATINGS AT 100 KM/H (60 MPH)
BY ILLUMINATION LEVEL AND AGE

Illumination (lux)	Vehicle Separation	Beam	Filter	Mean Rating: All Subjects	Mean Rating: Older Subjects	Mean Rating: Younger Subjects
0.035	400-300 m[a]	low	yes	8.2	8.2	8.2
0.190	150-50 m[b]	low	yes	7.9	7.7	8.1
0.070	400-300 m	high	yes	7.0	7.5	6.4
0.070	400-300 m	low	no	6.8	7.4	6.2
0.370	150-50 m	low	no	6.4	6.9	5.9
0.700	150-50 m	high	yes	5.5	6.8	4.2
0.350	400-300 m	high	no	3.8	4.9	2.8
5.100	150-50 m	high	no	2.5	2.9	2.0

[a] 1,312-984 ft. [b] 492-164 ft.

6.34, $p < .05$). (As in Study 2, the glare angle of 0.6° was always associated with the vehicle separation of 400 to 300 m [1,312 to 984 ft], and the glare angle of 3.8° was always associated with the vehicle separation of 150 to 50 m [492 to 164 ft]).

Variance accounted. The results of stepwise regression analyses indicate that 47% of the variance of the glare ratings can be accounted for by the logarithm of illumination, 63% by the logarithm of illumination and age, and 68% by the logarithm of illumination, age, and glare angle/vehicle separation.

Discussion

The principal results of this study, applicable to the tested speed of 100 km/hr, are as follows:

1. The proposed methodology provided relatively reliable measures, as there was no main effect of replications. However, interaction of replications × age was statistically significant.

2. The effect of age was statistically significant: Older subjects reported *less* discomfort glare than did younger subjects. However, illumination level × age was statistically significant.

3. The methodology provided valid measures, because (a) the measures were found to correlate significantly with the illumination reaching the eyes of the observers; and (b) when controlling for the effects of illumination reaching the eyes of the observer, the conditions with the smaller glare angle produced more discomforting reponses.

SUMMARY OF THE EXPERIMENTAL FINDINGS

The experimental part of this research tested a proposed methodology for evaluating discomfort glare under intermediate and high speeds. The principal findings of this research are as follows:

1. The proposed methodology is easy to set up and implement.

2. The proposed methodology provides

relatively reliable measures, as there was no main effect of replications in either of the two studies.

3. The proposed methodology provides valid measures of glare, because (a) the measures were found to correlate significantly with the illumination reaching the eyes of the observer and (b) the glare-angle effect (after controlling for the effect of illumination) was in the expected direction.

4. Discomfort-glare ratings were unaffected by the rater's position in the car. Consequently, the proposed methodology is time-efficient, since up to three raters can be used simultaneously.

5. Rater sampling appears to be an important consideration in using the proposed methodology, because the age effect was in the unexpected direction under both speed conditions.

6. The proposed methodology is relatively robust: Although there was a tendency for the intermediate-speed ratings to be more discomforting ($M=5.6$) than the high-speed ratings ($M=6.0$), this difference did not reach statistical significance when controlling for the effect of age ($F[1,17]=2.29$, $p>.1$).

CONCLUSIONS

The impetus for this research was the need for a universally acceptable methodology for evaluating discomfort glare from vehicle headlamps. The results are very encouraging: The proposed methodology, which is easy to set up and implement, provides relatively reliable and valid measures of discomfort glare and is time-efficient with respect to data collection. However, before this methodology can be recommended for general use, the following studies need to be performed:

1. A validation of the present unexpected age effect.

2. An evaluation of the effect of the first glare exposure on the rating of the second glare exposure and vice versa (because in the proposed methodology subjects make two ratings during each vehicle approach).

3. Cross-cultural replications of the basic findings.

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