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Relation Between Glare and Driving Performance

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The present study investigated the effects of discomfort glare on driving behavior. Participants (old and young; U. S. and Europeans) were exposed to a simulated low-beam light source mounted on the hood of an instrumented vehicle. Participants drove at night in actual traffic along a track consisting of urban, rural, and highway stretches. The results show that the relatively low glare source caused a significant drop in detecting simulated pedestrians along the roadside and made participants drive significantly slower on dark and winding roads. Older participants showed the largest drop in pedestrian detection performance and reduced their driving speed the most. The results indicate that the *deBoer rating scale,* the most commonly used rating scale for discomfort glare, is practically useless as a predictor of driving performance. Furthermore, the maximum U. S. headlamp intensity (1380 cd per headlamp) appears to be an acceptable upper limit.

INTRODUCTION

Automobile headlamps provide illumination for driving that enables efficient lane keeping, detection of potential obstacles such as other vehicles and pedestrians, and perception of traffic signs. There is an inherent conflict between the visibility that headlamps may provide for the user and the impairment caused by glare they may cause for oncoming drivers. Traditionally two types of glare have been recognized. The first type is *disability glare,* which causes reduced contrast sensitivity. Although there are large individual differences in people's sensitivity to disability glare, the average reduction in contrast sensitivity can be calculated objectively (see, e.g., Vos, 1984).

The subjective sensation of discomfort referred to as *discomfort glare* is determined subjectively, primarily by rating scales. While looking in the direction of the light source, participants indicate how annoying it is. Although there is no consensus about which rating scale should be used (see, e.g., Gellatly & Weintraub, 1990; Olson & Sivak, 1984; Sivak & Flannagan, 1994; Weintraub, Gellatly, Sivak, & Flannagan, 1991), the 9-point DeBoer scale is most widely used in the field of automotive and public lighting (DeBoer, 1967). This scale includes the following ratings: unbearable (1), disturbing (3), just admissible (5), satisfactory (7), and unnoticeable (9).

Glare is the blinding experience that results from a bright light source in the visual field of view. Car drivers may frequently experience blinding because of glare from oncoming cars when driving at night on a dark road. In general the effect of glare will increase when the source luminance increases, the background luminance decreases, and the angle between the line of sight and the direction of the light source decreases (see, e.g., Alferdinck, 1996; Alferdinck & Varkevisser, 1991). In the case of disability glare, there is a direct relation between the amount of glare and the contrast detection performance. With increasing glare there is a reduction in the ability to perceive small contrasts. This reduction may affect a number of visual tasks required in traffic such as detecting critical objects, controlling head-

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way, reading signs, and evaluating critical encounters. Discomfort glare is assumed to cause discomfort without necessarily impairing the vision of objects. This means that there may be aspects of lighting that do not affect the disability glare but increase discomfort glare. A good example is headlamp size which influences discomfort glare but not disability glare (Alferdinck, 1996; Sivak, Simmons, & Flannagan, 1990). It also has been shown that discomfort glare ratings may depend on task difficulty (Sivak, Flannagan, Ensing, & Simmons, 1991). Thus the same glare is judged more uncomfortable on a road with poor delineation (a more difficult task) than on one with good delineation. The relationship between discomfort glare and task difficulty suggests that driving behavior is affected by discomfort glare.

Even though some researchers have suggested that driving behavior may be affected by discomfort glare, no study ever directly addressed this issue. The main goal of the present study was to determine the relationship between actual driving behavior and the luminous output of headlamps that produce glare within the range that is assumed to cause only discomfort (but not disability) glare. There is consensus that glare within the range that causes discomfort does not significantly reduce the ability to perceive information. If a glare source causes only feelings of discomfort, as is generally agreed upon, then one expects that driving behavior is not affected by the presence of the glare source. However if the discomforting glare source results not only in feelings of discomfort but also in strategic adaptations to reduce discomfort, then one may expect to see changes in driving behavior.

Participants in the study drove an instrumented vehicle with a simulated light source mounted on the hood along an experimental stretch consisting of urban, rural, and highway roads. The light source on the hood was either off (control condition), or had one of three glare intensities: one corresponding to just admissible discomfort glare, one similar to the European beam, and one close to the U. S. beam (Economic Commission of Europe, 1976; Federal Motor Vehicle Safety Standard, 1991). Driving behavior in terms of speed and steering wheel reversal and the detection distance of particular objects was determined.

The widely used DeBoer rating scale was used as a measure for discomfort glare. Because the amount of discomfort glare experienced depends on age as well as on previous exposure to glare sources (Sivak et al., 1991), three groups of participants were tested: young drivers from the United States who had experience with U. S. headlamps, young drivers from the Netherlands who had experience with European headlamps, and old drivers from the Netherlands.

METHOD

Participants

In total 24 participants took part in the experiment. Eight were American students who had just arrived in Holland and had not yet driven in Europe. The U.S. participants consisted of 5 women and 3 men with an average age of 24.4 years (18–28 years). The young Dutch participants were 4 males and 4 female with an average age of 28.3 (between 23 and 34 years). The older Dutch participants were 4 men and 4 women with an average age of 62.3 years (57–69 years). All participants had their driving licenses for at least two years and had driven more than 10000 km a year.

Driving Route

The experimental track was 23.555 km long. The track was divided into nine different experimental sections, each representing a different type of road (e.g., residential urban area; wide road outside built-up area with and without street lighting, winding narrow road without lighting, and four-lane highway). Table 1 provides an overview of the characteristics of the road sections.

The ambient background luminance in the viewing direction of the driver was measured continuously along the experimental route. The average luminance background for each experimental section is given in Table 1.

Apparatus

Instrumented vehicle. The TNO Human Factors instrumented car ICARUS (Instrumented Car for Road User Studies) was used in the experiment. ICARUS is a Volvo 240 station wagon with dual controls and on-board

Table 1: Description of Experimental Sections

	1	2	3	4	5	6	7	8	9
Type	Residential	Outs b-up	Outs b-up	Outs b-up	Outs b-up	Outs b-up	Outs b-up	Outs b-up	Interstate
Curvature	90° corners	Curvy	Straight	Curvy	Curvy	Very curvy	Curvy	Curvy	Straight
Environment	Houses	Industrial	Woody	Woody	Woody	Woody	Woody	Woody	Woody
Speed limit	50 km	80 km	50 km	80 km	80 km	50 km	80	80 km	120 km
Number of lanes	2	2	2	2	2	1	2	2	4
Road width (m)	6.10	5.80	7.80	7.80	7.00	4.10	7.00	7.00	7.00
Lane width (m)	3.05	2.40	3.90	3.90	3.50	–	3.50	3.50	3.50
Road markings	No	Center, side	Center, side	Center, side	Center, side	No	Center, side	Center, side	Center, side
Shoulder	Pavement	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Emerg. lane
Sep. bike path	No	no	no	no	Yes	No	Yes	Yes	–
Intersections	P and NP	no	no	no	No	No	No	Yes (tr. lghts)	No
Public lighting	Both Sides	Right side	Left side	no	Left side	No	No	Right	No
Amb. luminance	0.2346	0.3377	0.1524	0.0903	0.1457	0.0825	0.1287	0.2173	0.1438

Note: Amb. Luminance = mean ambient luminance (cd/m^2); Outs b-up = outside built-up area; p = priority; np = non-priority; tr. Lghts = traffic lights; Emerg. lane = 3 m wide emergency lane.

Figure 1. The view from the position of the driver. To the left is an actual car, to the right is the lighting rig.

computers (for a detailed description, see Van der Horst & Godthelp, 1989). A lighting rig simulating the low-beam headlights of an oncoming car at a distance of 50 m at a fixed glare angle was mounted on the hood of the car. It should be emphasized that the lighting rig simulates the glare illuminance on the driver's eye of a continuous stream of oncoming cars. The advantage of using the lighting rig is that it is possible to present a constant and well-defined glare illuminance level to the driver's eyes for a period long enough to allow one to determine the effect of glare illuminance on driving behavior. It should be noted that an oncoming stream of vehicles would cause glare illuminance that is comparable to the constant illuminance used in the present study. The dimensions of the lighting rig are the dimensions of the oncoming car scaled down by a factor of 2.2/50 = 0.044.

Figure 1 gives a picture of the pattern of light produced by the lighting rig as it corresponds to a car at a distance of about 50 m. This point was chosen because it corresponds to the point B 50 L of the European beam pattern, the so-called glaring point in the beam pattern that causes the largest glare illuminance. For the U. S. beam pattern, the glaring point is similar to the European B 50 L.

In the experiment the four light levels were tested (lighting condition). The experimental luminous intensities were 0 (control), 350, 690, and 1380 cd per headlamp, corresponding to glare illuminance of, respectively, 0, 0.28, 0.55, and 1.1 lx at the observer's eye. Glare illuminance at the eye of the observer of 0.55 lx (690 cd per headlamp) is comparable to the European low-beam headlights; glare illuminance of 1.1 lx (1380 cd per headlamp) is close to what is the standard U.S. low beam. The two high-luminous intensities used represent the glare intensities of European and U.S. headlamps. The color temperature of the light of the lighting rig was about 3100 K, which matched very closely with the headlamp colors on the road.

Detection of wooden plates. Pedestrians were simulated by gray plywood boards, which is common in pedestrian visibility studies (Helmers & Rumar, 1975; Olson, Aoki, Battle, & Flannagan, 1990; Taniguchi, Kitagawa, & Jin, 1989). Plywood boards with the same dimensions as used in the study of Olson et al. were employed in this study, with a height of 76.2 cm (30 inches) and a width of 30.6 cm (12 inches). The reflection was 12.5 % (RAL color number 7031, blue-gray) which corresponds to dark clothing. Note that it is not necessary to use larger boards to simulate pedestrians because in practice, pedestrians are detected when the headlamps illuminate the lower part of the body (i.e., legs).

Six locations on the left and six locations on the right side of the road were marked. The distance between the locations was 80 m. According to a fixed schedule, either four or six plates were visible during a trial, half on the left and half on the right side. Plates were positioned about 1 meter from the right and left edge of the road. Before each trial participants were unaware of the number and locations of the plates.

Procedure

The experiment took place on 18 nights between 8.30 p.m. and 3:00 a.m. Each night two participants were tested. The complete experiment took place in dry and clear weather conditions.

Pretesting. Upon arrival participants first read and signed the informed consent form and read a form stating the purpose of the experiment. The straylight sensitivity of each participant was determined by means of the IJspeert, Waard, van den Berg, and de Jong (1990) straylight measurement device. Visual acuity was determined by means of the Landolt-C acuity test.

Before the experiment, participants had to judge nine different light levels by means of the DeBoer rating scale. Participants were seated in the experimental car, which was parked at the TNO parking lot. The immediate background was relatively dark. While seated in the instrumented vehicle, participants were asked to fixate a dot positioned straight ahead in the forward viewing direction. In random order different filters were positioned in front of the glare source, creating 9 light levels (40, 20, 10, 5.0, 2.5, 1.26, 0.63, 0.32, and 0.16 lx at the observer's eye). Each time a filter was placed in front of the glare source it was switched on for a few seconds, and participants were asked to indicate orally on the 9-point DeBoer rating scale how they judge the glare illuminance (e.g., disturbing, just admissible).

Experiment. Before the start of the experiment, participants were familiarized with the experimental car. They were told to drive as they normally would without endangering other vehicles or themselves. They were told to obey traffic laws and that the driving instructor would give directions and would indicate when to stop and start. Each participant took a test drive with the driving instructor until the instructor thought he or she controlled the car adequately.

Each participant drove the experimental track (divided into nine sections) four times. Each time, a different filter was placed in front of the light source of the lighting rig, creating the four different light intensities. The order of presentation was randomized by means of a Digram Latin square.

At the end of each experimental section, the car was stopped and participants were asked to indicate on the DeBoer rating scale how they judged the light source. While pointing at the DeBoer rating scale, the driving instructor asked, "Can you indicate on a scale from one to nine (see sheet at dashboard) what you thought about the light source on the road you just have been driving?" This procedure was done nine times during a drive (at the end of each section) and only when the glare source was lit (i.e., not during the control condition).

During Section 4 (a dark rural road) participants were required to detect plywood plates erected on both the left and right side of the road. Before Section 4 participants were told, "During the next part of the route there are several wooden plates positioned on the left and right side of the road. Try to detect these plates as soon as possible and hit the horn as soon as you have seen one." Between 4 and 6 objects were present at 12 possible locations (6 left, 6 right side of the road). The participant pressed the horn button upon detection of a plate, which started the time measurement in the on-board computer. The experimenter pressed a button as soon as the experimental car passed the object, which stopped the time measurement. By combining this time elapsed with the speed driven, the detection distance could be determined. After each drive the order and location of the wooden plates was changed according to a fixed schedule.

After each experimental drive, the participant who just drove took a rest and the other participant performed the experiment. Resting participants were allowed to watch television, eat, and drink nonalcoholic beverages.

Data Analyses and Design

The experiment involved a 2 within-subjects and a 2 between-subjects design. Within-subjects factors were glare source intensity (control, 350, 690, 1380 cd) and section (Sections 1 to 9). Between-subjects factors were age (young versus old) and nationality (U.S. versus Dutch). The latter two factors were not completely factorial because old U.S. participants were not tested in the present experiment. (It was impossible to find older Americans who just arrived in the Netherlands and were willing to participate.) The driving behavior dependent measures were driving speed (km/h) and steering wheel reversal (#/s). For the detection of wooden plates, detection distance (in meters) and missed targets (%) were determined. As a subjective measure for discomfort, the DeBoer rating scale was used (scale 1 to 9).

RESULTS

The data of one U.S. participant had to be discarded because the participant did not follow the instructions (i.e., gave discomfort ratings without judging the light source). In addition the participant was unable to handle the vehicle adequately. The acuity measures showed that older participants had significantly worse acuity than did young participants, 1.78 vs. 1.28; $t(14) = 2.31$; $p < .05$. In addition, there was a trend that older participants were more sensitive to straylight than were young participants, 11.8 for young versus 16.14 for old; $t(14) = 1.64$; $p = .065$.

DeBoer Rating

Before the experiment. The DeBoer rating at the TNO parking lot before the start of the experiment indicated no differences between young Dutch and U.S. participants or between young and old participants. As expected, the DeBoer rating depended on the glare illuminance on the eye of the observer, $F(8,168) = 109.9$; $p < .001$. Figure 2 presents the results. The expected ratings based on the models of Schmidt-Clausen and Bindels (1974), Sivak et al. (1990), and Alferdinck and Varkevisser (1991) are also given in this figure. The latter is calculated for a background luminance of 0.4 cd/m^2 using the Schmidt-Clausen and Bindels model. As is clear from Figure 2, participants rated a glare illuminance of about 3 lx as just admissible (5).

During the experiment. Overall there was a main effect on the DeBoer rating of intensity of the light source, $F(2,42) = 26.5$; $p < .01$, and of section, $F(8, 168) = 30.0$; $p < .01$. The results indicate that the highest light level of 1380 cd was rated as just acceptable (mean = 5.4); the level of 690 cd was rated between just acceptable and satisfactory (mean = 6.7); and the level of 350 cd was rated as satisfactory (mean = 7.0). Additional planned comparisons showed that all DeBoer ratings for the different glare source intensities differed significantly from each other (all $p < .05$). Overall there were no differences between the DeBoer ratings for U.S. (5.7) versus Dutch (6.2) and young (6.2) versus old (7.2) drivers.

Section 6 (narrow, dark, and winding road) was rated as the least acceptable of all sections (mean of 4.2, between disturbing and just acceptable). Section 2, which had the highest public lighting level (a wide, clearly lit road outside the built-up area), was rated as least problematic (mean = 7.2).

Behavioral Measures

For each experimental section the driving speed in the control condition and the background luminance level was plotted. To ensure that the analyses of driving behavior (driving speed and steering wheel reversal) were concerned with free driving behavior (not determined by characteristics of the vehicle, curves, traffic lights, other traffic, standing still at intersections, etc.) only portions without acceleration and decelerations (e.g., constant speed) were selected. In addition only portions within a section that had approximately the

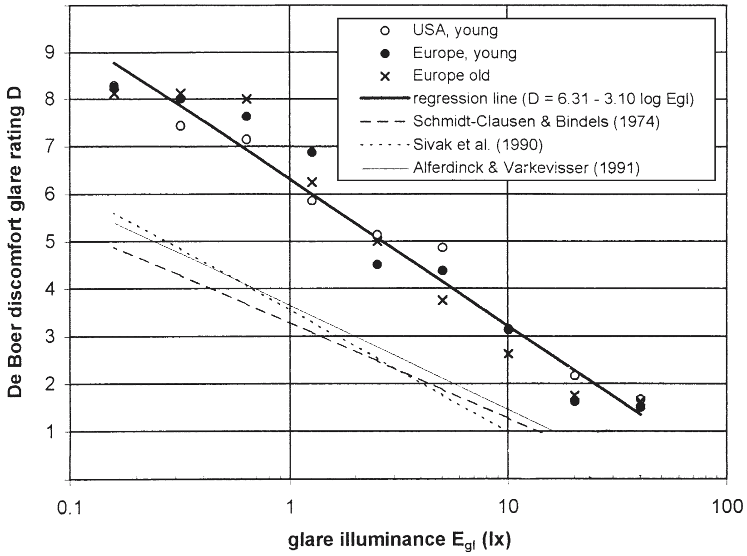

Figure 2. The DeBoer rating as a function of the glare illuminance on the eye of the observer. Also plotted are predictions from the model of Schmidt-Clausen and Bindels (1974), Sivak et al. (1990), and Alferdinck and Varkevisser (1991). The DeBoer scale runs from unbearable (1), disturbing (3), just admissible (5), satisfactory (7), to unnoticeable (9).

same low background luminance level were used in the analyses. This ensured that conclusions drawn from the analysis referred to section segments with approximately the same background luminance.

Driving speed. The mean driving speed per participant was determined for each of the selected sections. An ANOVA on mean driving speed with participant group, section, and glare source intensity as factors showed main effects of participant group, $F(2,21) = 3.96$; $p < .05$; section $F(8,168) = 436$; $p < .01$; and glare source intensity, $F(3,63) = 30.5$; $p < .05$. Planned comparisons showed that U. S. drivers drove significantly slower than Dutch drivers (69.5 km/h vs. 75.5 km/h; $p < .01$). There was also a trend that older Dutch drivers drove significantly slower than young Dutch drivers (75.5 km/h vs. 71.5 km/h; $p = .096$). An interaction of old/young with section ($p < .05$) indicated that the older driver drove especially slow on some sections (Section 4, dark wide road with pedestrian detection, and Section 9, highway driving).

Overall the presence of glare source had an effect on driving speed. Relative to the control condition, the presence of a glare source reduced speed about 2 km/h. There was, however, no significant difference in speed reduction among the glare source intensities. In additional analyses the mean speed collapsed over the three glare source intensities (350, 690, and 1380 cd) was calculated and compared with the control condition (no light). The speed reduction relative to the control was calculated. This measure was plotted against the average background luminance for the different portions for each of the sections (see Figure 3). The corresponding section numbers are indicated.

Note that Sections 6 and 7 give relatively large speed reductions whereas Section 4 and 5 with the same luminance background give relatively small speed reductions. The speed reduction induced by the glare source obviously did not depend only on the background luminance. If the driving task is relatively difficult (as driving the small winding road of Sections 6 and 7) the glare source causes relatively large speed changes. Figure 3 shows the regression between background luminance and speed reduction when Sections 6 and 7 are excluded from the analysis.

Steering wheel rate reversal. For each of the selected sections, the mean steering wheel rate reversals (SRR) per participant were determined. This measure was derived from steering

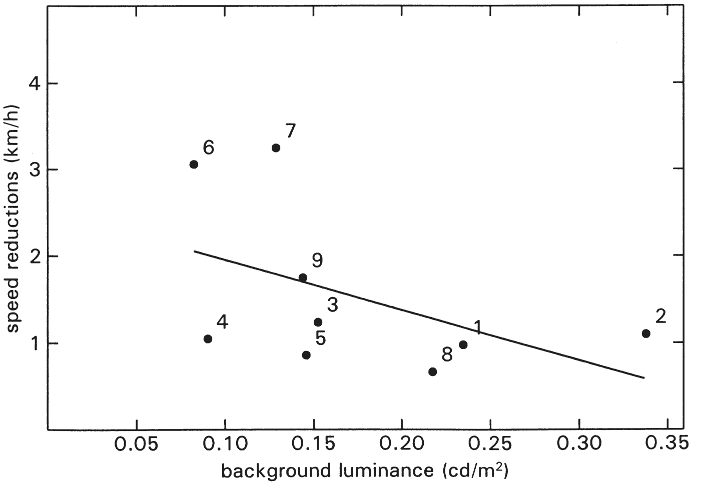

Figure 3. Speed reduction induced by glare source as a function of background luminance.

wheel movements analyzed in terms of number of reversals per second (e.g., Verwey & Veltman, 1996). A movement was defined as a change from a negative (clockwise movement) to a positive (counterclockwise) rotational velocity when the positive rotational velocity exceeded 3.0 °/s. An ANOVA showed only a main effect of section, $F(8,168) = 80.2$; $p < .01$. Analysis showed that during Section 7 the SRR was significantly larger when a glare source was present than when it was absent. This result indicates that participants made more steering wheel reversals because of the glare source.

High values of SRR are indicative of high driving task demands (Macdonald & Hoffman, 1980; Verwey & Veltman, 1996). The glare source may have made the driving task more difficult (i.e., it is harder to see where the road leads), causing participants to devote more attention to the steering subtask. Another reason there may have been more steering wheel reversals when the glare source was present is that the glare source changed the viewing point of the drivers away from the center of the road. This may have caused the steering movements to become less calibrated to the contours of the road so that more steering movements had to be made. Note that at Section 6, SRR did not reach statistical significance, probably because drivers had to make many steering reversals when negotiating this difficult section (about 25% more than in any of the other sections). Because the SRR was already so high, it is feasible that it was not possible to invest more reversal because the SSR was close to ceiling.

Detection of Wooden Plates

Distance. For those trials in which the driver detected the wooden plates, the detection distances (distance between the plate and car upon detection of the plate) were determined for plates erected along the right and left sides of the road. An ANOVA showed a main effect of target erected left versus right side of the road on detection distance, $F(1,21) = 109$; $p < .001$. Wooden plates erected along the right side were detected at 41.4 m. When presented on the left side in the direction of the glare source, they were detected on average at a distance of 20.5 m.

There was also a main effect of glare source, $F(3,63) = 9.4$; $p < .01$. When no glare source was present, on average participants detected the wooden plate at 35.4 m. With a light source of 350, 690, and 1380 cd, these distances were 33.3, 27.7, and 27.5 m, respectively. Planned comparisons showed that there were no differences between the control condition and the 350 cd condition. Glare source intensities of 690 and 1380 cd gave significantly shorter detection distances than did the control condition (all p's < .05). There is no significant difference

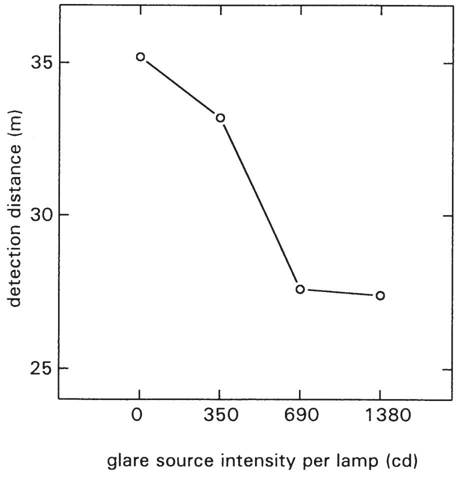

Figure 4. Detection distance as a function of glare source intensity

between these latter two light sources. Figure 4 illustrates the results.

There was no difference in detection distance between the U.S. and Dutch participants. However there was a trend that the detection distance for old drivers was shorter than for young drivers (old drivers at 25.8 m vs. young drivers at 34.2 m; $F(1,14) = 4.00$; $p = .063$).

Missed targets. Trials in which participants did not detect a wooden plate were counted as misses. There was a main effect of target erected left or right on missed targets, $F(1,21) = 202$; $p < .001$. When targets were presented on the right side, 3.5% were missed; when presented on the left side, 22.5% were missed. There was also a main effect of glare source, $F(3,63) = 2.8$ $p < .05$. The number of missed targets increased with increasing glare source intensity. Additional planned comparisons showed that there were no differences in missed targets between the control condition and glare source intensity of 350 cd. At glare source intensities of 690 and 1380 cd, there were significantly more targets missed than at control condition (all p's < .05). There were no differences between the 690 and 1380 cd in missed targets.

There was no effect of missed target between U.S. and Dutch participants. Older participants missed more targets at the higher glare illuminance levels than did younger participants (interaction old/young × glare source intensity, $F(3,42) = 3.4$; $p < .05$). As shown by Figure 5 old participants missed many targets at the higher glare levels (690 and 1380 cd).

The difference in targets missed between old and young drivers was large when the targets were presented on the left side of the road (in the direction of the glare source) and basically absent when presented on the right side (interaction left/right × young/old, $F(1,14) = 2.1$; $p = .073$). One way to explain this finding is that older drivers tend to look away from the glare source in order to reduce discomfort. This implies that the presence of a low-intensity glare source does not directly result in loss of vision but in a behavioral adaption (e.g., looking away from the source) that ultimately also results in worse performance in detecting objects.

DISCUSSION

The present experiment shows that a glare source that is assumed only to cause discomfort has an effect on actual driving behavior. Glare source leads drivers to choose a lower speed. Moreover when lane keeping became more difficult (e.g., driving on dark and winding roads), drivers slowed down even more.

The results with respect to the detection of the simulated pedestrians are important. With a glare illuminance of 0.55 lx (690 cd) and 1.1 lx (1380 cd), drivers detected the simulated pedestrians at significantly shorter distances than when the glare source was off or when the illuminance was 0.28 lx (350 cd). Similar results were found for the number of missed targets: At glare illuminance of 0.55 and 1.1 lx, participants missed more targets than when the glare source was off or had an illuminance of 0.28 lx. Even when the glare source illuminance is as low as 0.55 lx, there is a significant drop in object detection performance in terms of both detection distance and missed targets.

In a recent simulator study, Ranney, Simmons, and Masalonis (2000) also showed that glare slowed the detection of pedestrians along the roadside. Given the fact that Ranney et al. (2000) used glare sources between 1.4 and 3.0 lx, this finding is not surprising. Our results based on detection of simulated pedestrians in an actual driving environment indicate that a glare illuminance of only 0.28 lx or less may have no harmful effects on the detection of objects along the roadside. A glare illuminance of 0.55 lx (the maximum according to the European standard) or 1.1 lx (the maximum according to the U.S. standard) does reduce the ability to detect objects along the roadside.

Note that both EU and U.S. headlamp illuminances had a detrimental effect and that there was no reliable difference between a glare illuminance of 0.55 and 1.1 lx. It is crucial to stress the fact that the glare ranges used in the present experiment are expected to cause only discomfort glare and not an impairment of vision. This view is incorrect because even at these very low illuminances, object detection performance is impoverished.

The DeBoer rating before the experiment is unlike the predictions based on the models (see Figure 2). Overall participants rated the light sources as less annoying than what is predicted by any of the models. There is, however, an important difference between the way the DeBoer ratings were assessed in the present experiment and the way they were assessed in previous laboratory studies on which the model predictions are based. In all lab studies participants had to perform a task (e.g., a target detection task as in Schmidt-Clausen & Bindels, 1974 or a tracking task as in Alferdinck & Varkevisser, 1991) while giving the DeBoer rating. In the present study participants gave their DeBoer ratings while fixating a dot straight ahead. As discussed earlier, the difficulty of the task while giving the discomfort rating does play a crucial role and affects the absolute level of the DeBoer rating.

In the present study, before the actual start of the experiment participants gave their rating *without* an additional task. In the absence of an additional task participants rate the glare illuminance as much less annoying than when performing a relatively difficult lab detection task. The suggestion that task difficulty may be the reason for the discrepancy between model predictions and current ratings is corroborated

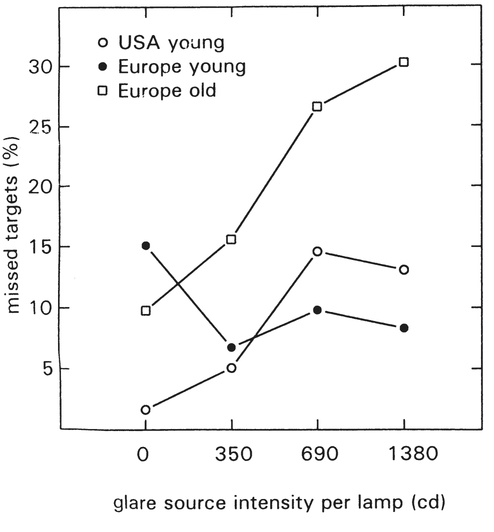

Figure 5. Percentage of targets missed as a function of glare source intensity for the different participant groups.

by the observation that the DeBoer ratings after driving the most difficult section (Section 6) were in line with the model predictions. For glare illuminance of 0.28, 0.55, and 1.1 lx, participants gave ratings of 4.8, 4.8, and 3.2, which are comparable to the model predictions.

To determine the relationship between the DeBoer measures and behavioral data, the change in driving speed relative to the control condition was correlated with the DeBoer ratings during the experiment. The correlation was relatively low, $r(67) = .16$. Only 2.7% of the variance in speed reduction could be explained by the score on the DeBoer rating scale. Even though the DeBoer ratings are well spread within the 1–9 scale, a lower DeBoer rating (i.e., more discomfort) was certainly not associated with a larger speed change.

The reduction in detection distance relative to the control was correlated with the DeBoer rating on the section during which object detection took place. Again, the relation was rather weak, $r(67) = .28$, suggesting that 8% of the reduction in detection distance could be accounted for by the DeBoer rating. One would expect that a strong reduction in detection distance would result in a low DeBoer rating – that is, drivers who do see the objects late would claim that the glare source is annoying. This relationship is rather weak.

The older participants missed many targets, yet their DeBoer ratings were always higher (indicating less annoyance) than those of young participants. This indicates that absolute levels of the DeBoer rating are hard to compare; even though one group of participants report experiencing less annoyance than another group of participants, the actual performance may be dramatically worse.

DeBoer ratings as measured in the present study do, however, show the same relationship among the variables influencing discomfort glare, as reported in previous laboratory studies. This suggests that we measured discomfort glare in the same way as was done in other (laboratory) studies. Besides the expected dependency on glare illuminance, the present study shows a large effect of task difficulty on the DeBoer rating.

As reported by Sivak et al. (1991), drivers experience more discomfort when performing a difficult driving task than when performing an easy one. In line with Schmidt-Clausen and Bindels (1974), the present study shows that the ambient luminance has only a small effect on the DeBoer rating. Also found by Alferdinck (1996), older participants with a higher straylight sensitivity do not report having more discomfort than do young participants. However unlike Sivak et al. (1991), the present study did not show that Americans who have experience with higher levels of glare illuminance report less discomfort glare than do Dutch participants who are used to lower levels of glare. A possible reason might be that for Americans, driving for the first time on public roads in Europe is relatively difficult. In the current study, the experience of being exposed to higher glare levels might be counteracted by the feelings of discomfort induced by the more difficult task. The finding that, overall, U.S. participants drove significantly slower than Dutch participants suggests that they experienced the task as being more difficult.

An important consideration is that a glare source that causes discomfort may not directly affect vision but may result in a behavioral adaptation to reduce the discomfort of the glaring source. This behavioral adaptation, such as looking away from the glare source or fixating more than usual to the right side of the road, may lead to worse object detection performance. This poorer detection performance is not a result of the glare source causing a luminous veil over the scene (as is the case with disability glare), but because of a strategic adaptation to cope with the discomforting glare source. The fact that drivers may be able to strategically adapt their behavior to reduce discomfort may also affect their rating of the extent of discomfort from the glare source. Indeed older drivers may have a strong tendency to adapt their behavior to reduce the discomforting effect of the glare source; as a consequence, this may result in less annoyance (higher DeBoer ratings) but also in worse object detection performance.

CONCLUSIONS

The present study indicates that only when roads are winding and dark and lane keeping becomes a problem do drivers slow down to compensate for the negative effects of a glare source. If the road is wide and fairly predictable, there is no behavioral adaptation because lane keeping is easy even when glare is present. This observation implies that in practice, drivers may or may not adapt their behavior under the influence of glare, depending on whether they expect there will be problems with respect to lane keeping. Thus a road that is wide without many curves may suggest to drivers that slowing down under the influence of glare is not necessary.

The effect of glare on target detection performance on dark road stretches is large, and even relatively low intensities of 690 cd per headlamp (intensities that are typically considered to cause only discomfort and not the impairment of vision) cause a severe performance decrement. It seems that this is a problem that cannot be solved by designing different beam patterns. Alferdinck and Padmos (1988) stated, "without permanent road lighting a pedestrian on the road is not sufficiently visible to a motorist, unless a pedestrian wears retroreflectors of sufficient quality" (p. 16).

Implications for Practice

The maximum U.S. headlamp intensity comparable to 1380 cd per headlamp is an acceptable upper limit. The finding that participants adapt their behavior in a safe direction by reducing speed and/or investing more effort independent of the actual glare illuminance indicates that a glare illuminance of 1.1 lx (the maximum U.S. level, comparable to 1380 cd per headlamp) is acceptable as a maximum upper limit. Drivers adapt their behavior adequately even though they are not capable of reporting this by subjective measures such as the DeBoer ratings.

Discomfort glare also has an effect on driving behavior for which drivers cannot compensate. Both European and U.S. glare illuminance levels (0.55 and 1.1 lx) cause dramatic drops in object detection performance (e.g., pedestrian detection) on dark roads, especially among older drivers. One may accept a high illuminance level for automobile headlamps as long as one realizes that glare illuminance levels within the range that is generally agreed to cause only discomfort in practice also causes a drop in object detection performance.

The Boer scale, the most commonly used rating scale for discomfort glare, is practically useless as a predictor of driving performance. There is no relationship between the DeBoer ratings and actual driving behavior, both within and between groups of participants. When drivers report hardly any discomfort, their actual driving behavior might be affected dramatically. The DeBoer rating may say something about the subjective annoyance a glare source may cause, yet, it cannot be used to predict the effects of discomfort glare on actual driving behavior. How drivers rate a particular glare illuminance level has nothing to do with the way they respond to such a glare source during actual driving.

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