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SUBJECTIVE AND OBJECTIVE ASPECTS OF HEADLAMP GLARE: EFFECTS OF SIZE AND SPECTRAL POWER DISTRIBUTION

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16. Abstract

In the formal study of glare, a major distinction has been made between subjective and objective effects of glare (referred to as discomfort glare and disability glare, respectively). Recently, both anecdotal reports and formal experiments have indicated that headlamp size and spectral power distribution affect discomfort glare, but no assessment has been made of whether these two factors also affect disability glare. Models of disability glare suggest that they should not. The present experiment was designed to provide empirical evidence about this issue.

Subjects were presented with glare stimuli that varied in size (0.3 or 0.6 degrees of visual angle) and spectral power distribution (tungsten-halogen or high-intensity discharge). Discomfort glare was measured by numerical ratings of subjective discomfort. Disability glare was measured by determining the luminance threshold for detecting a pedestrian silhouette presented near the glare source. Spectral power distribution affected discomfort glare, although, in contrast to previous studies, which had shown small but statistically significant effects, size did not affect discomfort glare. Neither variable affected disability glare.

These results indicate that, for size and spectral power distribution, effects on discomfort glare do not necessarily imply effects on disability glare. The fact that small, high-intensity discharge lamps do not seem to cause any special problems with disability glare under the conditions of this experiment is encouraging, particularly because disability glare is likely to have greater effects on safety than discomfort glare. However, given the importance of the issue, further studies of disability glare would be valuable. Also, even if effects on discomfort glare are not critical for safety, they are still of practical interest because driver comfort is important in itself, and they are of scientific interest because they have not been explained.

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Introduction

Two recent developments in headlighting have raised concerns about glare. One such development has been the use of projector optics, which results in headlamps that are smaller and brighter, as seen by oncoming drivers, than headlamps with more traditional optics. The other has been the use of high-intensity discharge (HID) sources, which have a blue-white color that is noticeably different from the relatively yellow light of tungsten-halogen (TH) headlamps. The two features have often been combined, producing lamps that are particularly likely to provoke complaints about glare.

There have been systematic studies of how glare is affected by lamp size (Alferdinck & Varkevisser, 1991; Sivak, Simmons, & Flannagan, 1990) and by the differences in spectral power distribution (color) between HID and TH lamps (Flannagan, Sivak, Battle, Sato, & Traube, 1993; Flannagan, Sivak, & Gellatly, 1991). These studies have served to demonstrate formally that those effects exist, and to quantify them reasonably well, but they have not generally succeeded in explaining them. For example, the effect of spectral power distribution cannot be explained in terms of any of the standard ways of quantifying light, including the photopic (daytime), scotopic (nighttime), or mesopic (mixed) luminous efficiency functions (Flannagan et al., 1993).

The present study was designed to investigate possible mechanisms of these glare effects by determining whether size and spectral power distribution affect objective as well as subjective aspects of headlamp glare. In the formal study of glare, a major distinction has been made between the extent to which glare stimuli diminish a person's objective ability to see (often referred to as disability glare) and the extent to which glare stimuli evoke reports of subjective discomfort (often referred to as discomfort glare). The mechanisms of disability glare are relatively simple and well understood, having to do with aspects of the eye itself. The mechanisms of discomfort glare, although they often appear to be quite systematic, are more complicated and less well understood, involving not just physiological aspects of the eye but also how people think about stimuli. People's subjective reactions to glare stimuli depend on many aspects of the stimulus situation and of their past experience—for example, the difficulty of a concurrent task (Sivak, Flannagan, Ensing, & Simmons, 1991) or the range of stimuli presented in a certain context (Olson & Sivak, 1983).

So far, all of the glare effects that have been attributed to lamp size and spectral power distribution have involved discomfort glare. It would not be right to dismiss these effects simply because they are subjective. Although there is as yet no formal evidence linking discomfort glare to objective driving performance, it seems reasonable to speculate that long exposures to high levels of discomfort glare might eventually produce objectively observable degradations in driving performance and safety. Also, although visual comfort should probably be considered secondary to safety, it should be given some weighting as a value in itself.

Whatever importance one puts on subjective aspects of glare, in order to explore possible mechanisms for the glare effects of lamp size and spectral power distribution, it is important to determine whether these variables also affect objective aspects of glare. In the present experiment we addressed that issue by presenting glare stimuli that varied in size and spectral power distribution, and by measuring both discomfort and disability glare. We presented the stimuli in a laboratory in which the lighting was controlled to simulate the visual conditions faced by a driver at night. Discomfort glare was measured by having the subjects make numerical estimates of subjective discomfort. Disability glare was measured by determining the luminance threshold at which subjects could detect a pedestrian silhouette near the source of glare.

Method

Subjects

Twelve people were paid to serve in the experiment. There were 6 younger subjects (ranging in age from 20 to 31, with a mean age of 24.8 years) and 6 older subjects (ranging in age from 61 to 77, with a mean age of 69.0 years). Each age group consisted of 3 males and 3 females. All were licensed, active drivers.

Experimental setup

The experiment was performed in a laboratory, with lighting controlled to represent the visual conditions faced by a driver using low beam headlamps on a roadway at night. At one end of the laboratory there was a chair for the subjects to sit in, and at the other end there was a set of equipment to provide glare stimuli and a pedestrian silhouette to be used in the visual threshold task. The subjects' view of those stimuli is shown in Figure 1.

The stimuli were 7.6 m from the subjects' eye position. The areas near the top of the stimulus configuration immediately around the glare stimuli and pedestrian silhouette were black, as shown in Figure 1. These areas were meant to simulate the dark areas beyond lighted pavement in a typical night driving situation. There was a rectangular white area below the glare stimuli and pedestrian silhouette that was meant to approximately represent the lighting effects of a road surface illuminated by typical low-beam headlamps. This surface was evenly illuminated to a luminance of 1.0 cd/m^2 by a tungsten lamp, a value that is reasonably representative of the visual adaptation conditions of a driver at night, using low-beam headlamps (Olson, Aoki, Battle, & Flannagan, 1990). The CIE 1931 chromaticity values of the surface were $x = 0.46$ and $y = 0.41$.

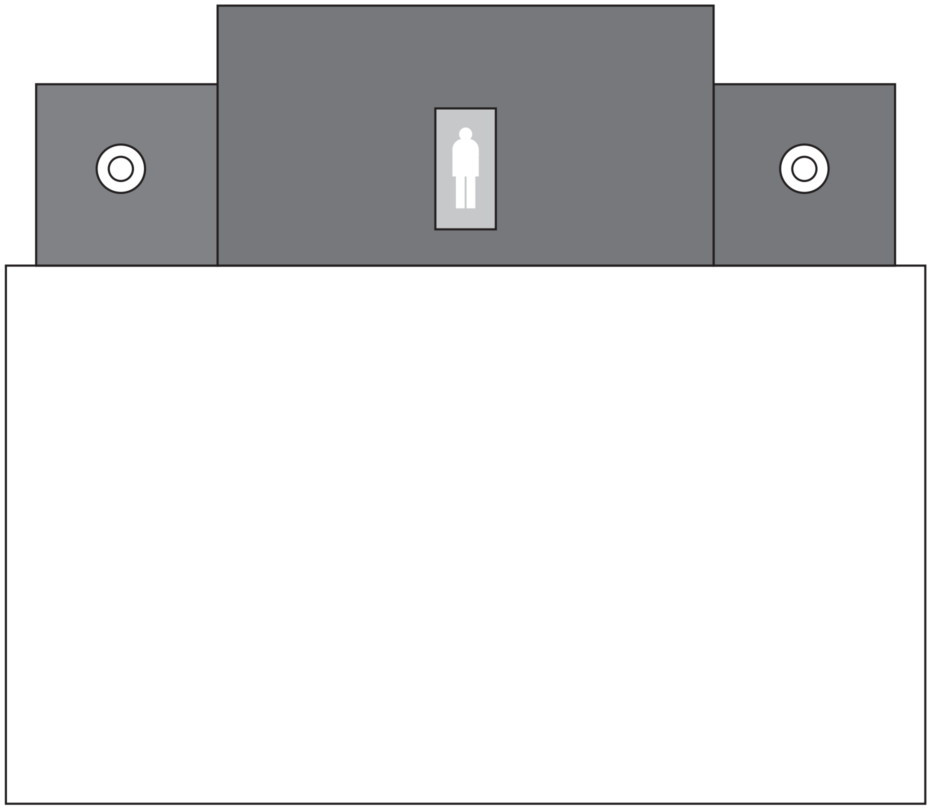

Figure 1. The subject's view of the glare sources and pedestrian silhouette. The glare sources appeared, as shown, to the right or left of the pedestrian. The larger glare stimuli are represented by the outer circles and the smaller glare stimuli are represented by the inner circles. The pedestrian appeared, as shown, in positive contrast against a neutral background within a small rectangular frame. The large white area below the pedestrian and glare stimuli was illuminated to a dim level representative of pavement illuminated by typical low-beam headlamps. The areas surrounding the glare stimuli and pedestrian were black.

Glare stimuli

The glare stimuli were 4 degrees of visual angle to the left and right of the pedestrian, and their diameters were 0.6 and 0.3 degrees. On either side, the glare stimuli could be TH or HID (the side on which each spectral power distribution appeared was balanced across subjects). Neutral filters with nominal densities of 0.3 and 0.6 were used, along with the unfiltered lamps, to produce three levels of intensity. Illuminance levels at the subjects' eye point were measured for each combination of spectral power distribution, size, and nominal intensity level (low, medium, and high). These values are given in Table 1.

The spectral power distributions of the TH and HID stimuli were measured at the subjects' eye point, and are shown in Figure 2. The CIE 1931 chromaticity values for the TH source were $x = 0.44$ and $y = 0.41$. The values for the HID source were $x = 0.38$ and $y = 0.36$.

Table 1
Illuminance of the subjects' eye position from each of the 12 glare sources defined by combinations of source type, size, and intensity.

Source type	Size (deg)	Nominal intensity	Illuminance (lux)
HID	0.3	low	1.32
HID	0.3	medium	2.72
HID	0.3	high	5.14
HID	0.6	low	1.36
HID	0.6	medium	2.77
HID	0.6	high	5.28
TH	0.3	low	0.87
TH	0.3	medium	1.88
TH	0.3	high	3.47
TH	0.6	low	0.97
TH	0.6	medium	2.04
TH	0.6	high	3.76

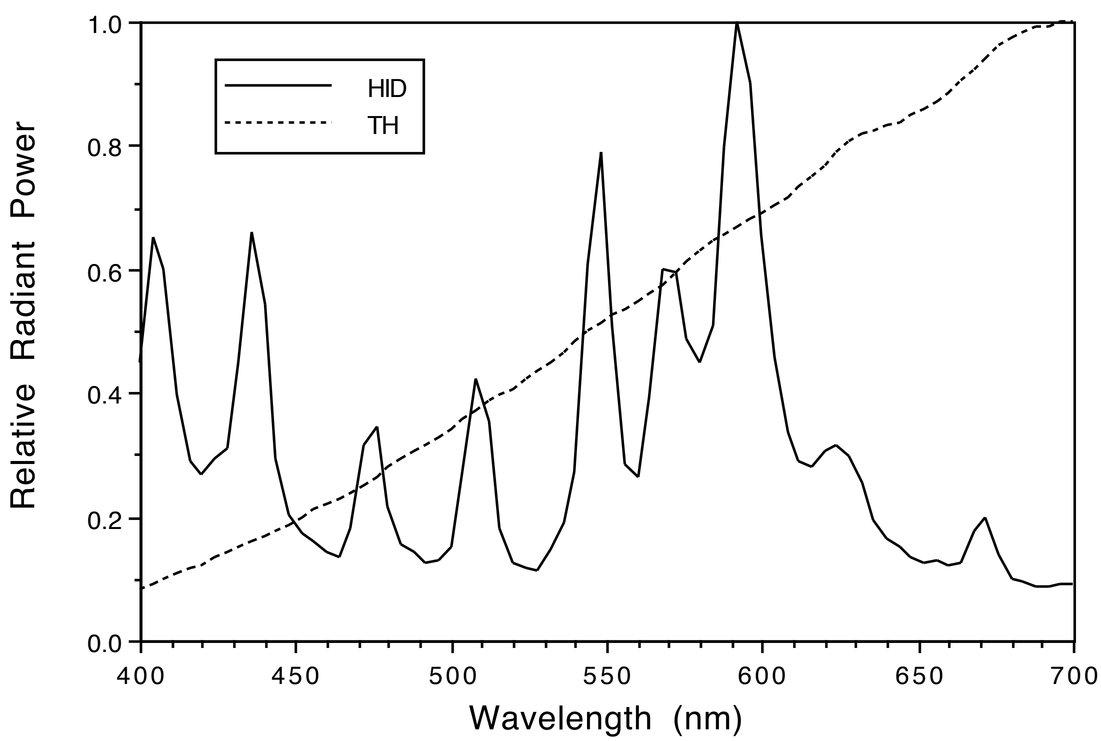

Figure 2. The spectral power distributions from the TH and HID sources used in the experiment.

Pedestrian stimulus

The pedestrian silhouette appeared within a small white rectangle in the middle of the stimulus configuration (shown as a light gray rectangle in Figure 1). The luminance of this area, due to ambient light, was 0.50 cm/m^2. The white rectangle was a translucent white diffusing panel, and the pedestrian figure was presented by backlighting the panel through an opaque cutout with a tungsten lamp. The luminance of the pedestrian figure was varied by controlling the voltage to the lamp. When the lamp was off the white panel was completely blank, and when the voltage was high enough the pedestrian figure appeared in positive contrast, as a white silhouette within a dimmer background. As seen from the subjects' position, the pedestrian was 1 degree of visual angle in height.

Procedure

Subjects were run individually. At the beginning of each session, instructions were read to the subject. The lights were dimmed to the low level that was meant to simulate night driving, and the subject's eyes were allowed to adapt to the lighting conditions for 10 minutes before data collection began. Subjects were asked to perform two tasks: a pedestrian-detection task designed to measure disability glare, and a numerical rating task to measure discomfort glare. The disability task was always performed before the discomfort task.

Both tasks consisted of a series of trials, on each of which glare was presented at one of the 12 combinations of spectral power distribution (TH or HID), size (small or large), and nominal intensity level (low, medium, or high). The TH and HID sources were always on the same side of the stimulus configuration for a given subject, but the sides on which they appeared were balanced across subjects. The order of the 12 glare conditions was randomized individually for each subject. For each subject, the same randomization was used for both the disability and discomfort tasks. Each task consisted of 24 trials, in which the random order of 12 glare conditions was used first forward then backward. This ensured that—on average—no glare condition tended to appear earlier or later than any other in the series of trials.

Each trial of the disability task began with the subject looking down at the white panel that was illuminated to the level that is typical of the light adaptation state of drivers using low beams at night (1.0 cd/m^2). At the beginning of the trial, the appropriate glare stimulus was presented by opening a shutter. An experimenter then instructed the subject to look up at the middle of the small white rectangle within which the pedestrian figure could be presented. The pedestrian figure was always visible when the subject first looked at it. The experimenter then lowered the luminance level of the figure until the subject reported that it was no longer visible.

That level was recorded, the luminance was lowered to zero, and then raised again until the subject reported that the figure was again visible. Two more such settings (descending and ascending) were made to complete the trial. When the trial was complete, the subject was instructed to look back down at the white panel until the next trial began.

The procedure for the discomfort task was very similar, except that the pedestrian figure never appeared. As in the disability task, subjects were instructed to look down at the large white adaptation panel between trials. At the beginning of a trial, before the glare stimulus was presented, the subject was instructed to look up at the small white rectangle within which the pedestrian figure had been presented. The appropriate glare stimulus was then presented by opening a shutter for two seconds. The subject then made a numerical estimate of the level of discomfort experienced from the glare, and again lowered his or her gaze to the white panel. The instructions to subjects concerning the numerical estimates were standard instructions for sensory magnitude estimation (e.g., Marks, 1974). The instructions were, in part:

> The way I would like you to make ratings is by picking numbers to represent how much discomfort you feel. For the first light that you see simply pick any number that seems right to you. This first rating may seem somewhat arbitrary. But for each subsequent trial, please try to choose numbers that are proportional to how much discomfort you feel, given the number that you picked for the first trial. If a light seems twice as discomforting as the first one, choose a number that is twice as big. If a light seems slightly less discomforting than the first item, choose a number that is slightly lower. Say the number out loud and I will record it. You can use any number that you want, except please do not use negative numbers or zero.

Results and Discussion

Data Treatment (Interpolation to Equate Glare Values Across Conditions)

As expected, both the threshold luminances for detection of the pedestrian target (the measure of disability glare) and the numerical estimates of discomfort generated by the subjects (the measure of discomfort glare) increased with higher glare illuminances. This is illustrated in Figure 3, which shows data from one subject for the larger TH and HID stimuli. As is evident in Figure 3, as well as in Table 1, the illuminance values for the TH and HID stimuli were not exactly matched. The HID values were generally higher than the TH values. Similarly, the illuminance values for the large and small versions of the TH and HID lamps were not exactly matched. However, the stimuli were designed so that the ranges of illuminance for all four combinations of size and source type would overlap considerably. This is important because our main interest is in measuring the effects of spectral power distribution and stimulus size, and those comparisons should not be contaminated by variations in illuminance values.

Ideally, we would be able to compare subjects' responses to two stimuli that varied in (for example) spectral power distribution but which had identical illuminance levels. By interpolation, we can effectively achieve that goal. Figure 3 illustrates the procedure. For each of the 12 subjects individually, we fitted regression models for each of the four combinations of size and spectral power distribution (i.e., 48 models for each of the two dependent variables). Two such models are shown in Figure 3. For the disability measure the models were linear relationships between luminance thresholds and illuminance; for the discomfort measure they were linear relationships between log discomfort ratings and log illuminance. Both of these cases are in reasonable agreement with the forms of the relationships that would be theoretically expected, but for present purposes the only requirement of the models is that they fit reasonably well empirically. The r^2 values for the models, which indicate proportion of variance in the data accounted for by the models, were quite good. The r^2 values for the disability measure ranged from .77 to 1.00 with a mean of .96. The fits for the discomfort case were not quite as good but were still adequate, with r^2 values ranging from .31 to 1.00 with a mean of .87.

Using the regression models, we interpolated detection threshold luminances corresponding to the mean illuminance level of all the glare stimuli (2.23 lux) for each subject for each of the four combinations of size and spectral power distribution (i.e., 48 values in all). Likewise, for the same 48 combinations of subjects and conditions, we interpolated discomfort ratings corresponding to the mean log illuminance level of all the glare stimuli (0.35 log lux). The interpolation method is illustrated in Figure 3 (for one subject, for the large TH and HID stimuli) by the vertical dashed line and the horizontal arrows. Note that in this case the interpolated glare rating is higher for the HID stimulus than for the TH stimulus. As will be evident in the summaries below, this was reasonably typical of the subjects as a group.

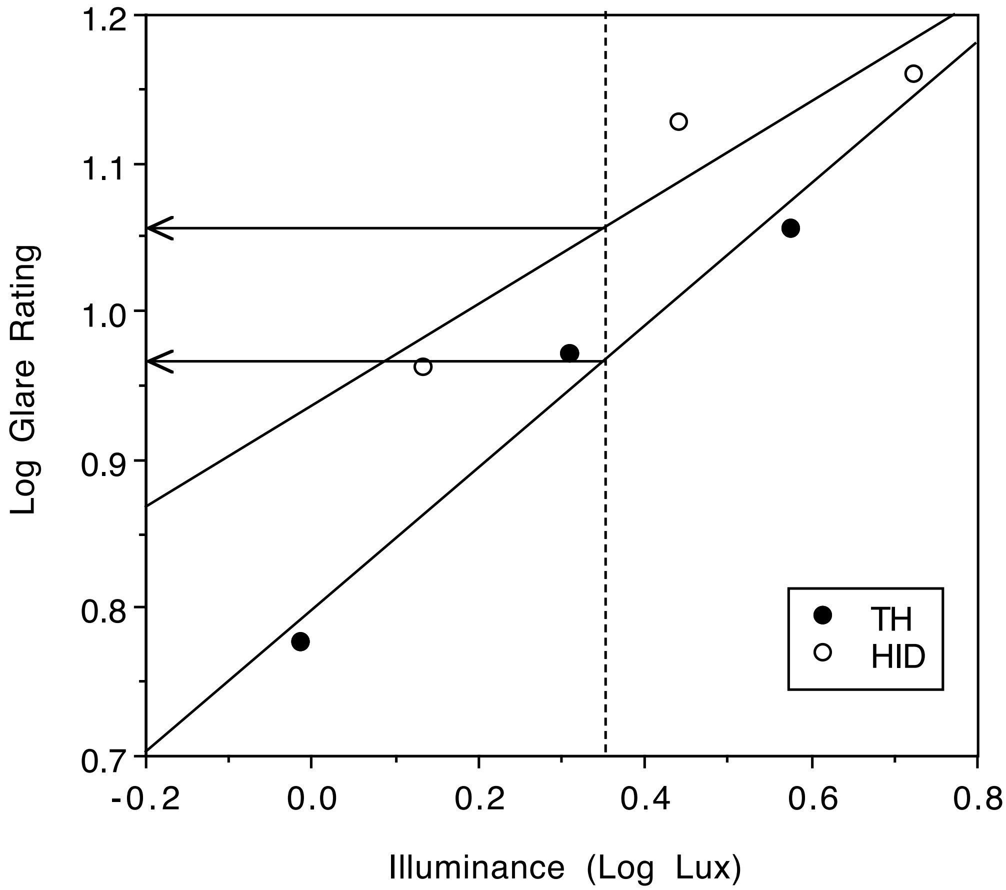

Figure 3. Log glare rating as a function of log illuminance, shown separately for TH and HID glare, for one subject with the larger glare stimuli. The diagonal lines are best fitting linear regression lines, fitted separately for the TH and HID stimuli. The vertical dashed line marks the mean of all the log illuminance values presented (0.35). The horizontal arrows illustrate the interpolation of glare rating values corresponding to that illuminance value. In this case, the rated discomfort for the HID stimulus would be higher than the rating for the TH stimulus, and the effect of source type for this particular subject is therefore reasonably typical of the mean effect over all subjects.

Effects on Disability and Discomfort Glare

The interpolated values of threshold luminance and log glare rating were summarized using two analyses of variance (ANOVAs), each of which had the same structure of independent variables—including subject age group (younger or older), glare-stimulus size (small or large), and glare-stimulus spectral power distribution (TH or HID). For the disability measure (interpolated threshold luminance) only the effect of subject age group approached statistical significance, $F(1,10) = 4.62$, $p = .057$. The not-quite-significant trend in the data was that, on average, older subjects had higher luminance thresholds (0.39 cd/m^2) than younger subjects (0.22 cd/m^2), as would be expected based on older people's generally poorer visual performance, especially at low light levels. Threshold luminance was not affected by size, spectral power distribution, or the interaction of those two variables.

In the case of the discomfort glare measure (interpolated log discomfort rating), age was statistically significant, $F(1,10) = 6.23$, $p = .032$, with older subjects giving generally higher log discomfort ratings (1.73) than younger subjects (1.30). That finding is consistent with the usual finding that older people have more problems with glare than younger people. However, in previous research the effect of age has been much more consistent for disability measures than discomfort measures, which is in keeping with the theoretical position that the mechanisms of disability glare are relatively simple compared with the mechanisms of discomfort glare.

Turning to the stimulus variables, the effect of size was not statistically significant, $F(1,10) = 1.70$, $p = .22$, but the effect of spectral power distribution was, $F(1,10) = 6.38$, $p = .030$. Interpolated log discomfort ratings were generally higher for the HID stimuli (1.54) than the TH stimuli (1.49). This difference in log ratings means that, on average, the interpolated discomfort ratings for the HID stimuli were 12% higher than for the TH stimuli. This is consistent with previous findings indicating that HID sources produce more discomfort glare than TH sources (Flannagan et al., 1993; Flannagan et al., 1991).

The failure to find an effect of size on discomfort ratings is somewhat surprising, given that a small but statistically significant effect had been demonstrated in two previous studies, using the same size stimuli (Alferdinck & Varkevisser, 1991; Sivak et al., 1990). One possible explanation is that in the present experiment subjects were strongly instructed not to look directly at the glare sources. Assuming they complied with instructions, the glare sources were always presented 4 degrees into the visual periphery, a location far enough out that visual acuity may have been too low for subjects to be sensitive to the difference in size. Subjects in both of the previous studies were also not supposed to look directly at the glare stimuli, but several differences in procedure make it somewhat more likely that they did occasionally get a better look at them than in the present study. In the Sivak et al. study the angle between the glare stimuli and where subjects were supposed to be looking (3.6 degrees) was similar to the angle in the present study. But in the Alferdinck and Varkevisser study, a range of angles was used: 1.72, 3.43, and 6.84 degrees. On at least some trials subjects were therefore looking relatively close to the glare stimuli. Also, in both of the previous studies the subject was performing a concurrent tracking task that, although it demanded some visual attention, also insured that subjects were moving their eyes at least to some extent. Finally, in both of the previous studies the glare stimuli always appeared to the left of where the subject was supposed to be looking. It may be that subjects found it easier to suppress a natural tendency to look toward the glare stimuli in the present experiment, in which the glare stimuli appeared on the right or left equally often, with the position varying randomly from trial to trial.

Summary and Conclusions

Subjects were presented with glare stimuli that varied in size (0.3 or 0.6 degrees of visual angle) and spectral power distribution (TH or HID). Discomfort glare was measured by numerical ratings of subjective discomfort. Disability glare was measured by determining the luminance threshold for detecting a pedestrian silhouette presented near the glare source. Spectral power distribution affected discomfort glare, although, in contrast to previous studies which had shown small but statistically significant effects, size did not affect discomfort glare. The HID stimuli evoked higher estimates of discomfort than the TH stimuli, as expected from previous research. Neither size nor spectral power distribution affected disability glare.

These results indicate that, for size and spectral power distribution, effects on discomfort glare do not necessarily imply effects on disability glare. One would expect there to be cases like this because the mechanisms of discomfort glare are believed to be much more complex than the mechanisms of disability glare. Discomfort glare is therefore more likely to be sensitive to a wide range of variables that are not likely to affect actual seeing ability, such as the difficulty of a concurrent task (Sivak et al., 1991) or the range of stimuli presented (Olson & Sivak, 1983). The fact that small, high-intensity discharge lamps do not seem to cause any special problems with disability glare under the conditions of this experiment is encouraging, particularly because disability glare is likely to have greater effects on safety than discomfort glare. However, given the importance of the issue, further studies of disability glare would be valuable. In particular, this experiment addressed the disabling effects of glare for concurrently presented stimuli; the aftereffects of glare would also be of interest. The concurrent effects of glare should probably be considered primary because there is virtually nothing a driver can do to avoid or reduce them. In contrast, the aftereffects of glare depend on the eye movement strategies of drivers.

Further studies of the discomfort glare effects might also be justified. Even if effects on discomfort glare are not critical for safety, they are still of practical interest because driver comfort is important in itself, and they are of scientific interest because they have not yet been explained. For example, a candidate explanation for the effect of spectral power distribution that might at first seem promising—differences in human spectral sensitivity at photopic, scotopic, and mesopic light levels—does not (at least not fully) account for the effect (Flannagan et al., 1993). This explanation seems promising at first because, in overall chromaticity, HID lamps are blue-white relative to TH lamps, and scotopic and mesopic spectral sensitivities are shifted toward the short-wavelength (blue) end of the spectrum. For a driver adapted to the relatively dark conditions of a road at night (scotopic or mesopic levels), HID lamps might therefore be more efficient in evoking visual responses (including glare) than would be predicted by photopic (daytime) photometry. However, actual calculations using spectral power distributions and the

CIE photopic and scotopic luminous efficiency functions show that, although the explanation is qualitatively in the right direction, it is rather far off quantitatively. If the spectral power distributions of the stimuli used here (shown in Figure 2), are equated in terms of photopic values (i.e., equal according to conventional photometry as used in most standards and regulations) the HID stimulus would be more luminous than the TH stimulus in terms of scotopic photometry, but only by 4%. That is in the right direction to account for the fact that the HID stimuli are judged to be more glaring, but (as in previous studies) the size of the scotopic difference is not nearly large enough to account for the magnitude of the difference in people's subjective responses to HID and TH lamps.

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