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DISCOMFORT GLARE FROM HIGH-INTENSITY DISCHARGE HEADLAMPS:

Effects of Context and Experience

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16. Abstract

This study was designed to investigate further a difference in discomfort glare produced by tungsten-halogen (TH) and high-intensity discharge (HID) headlamps that we had found in a previous experiment. In a static field setup, 36 subjects, 24 in a younger group and 12 in an older group, made de Boer ratings of discomfort glare for TH and HID lamps. The lighting conditions were similar to those seen while driving on a dark, two-lane road when glare from an oncoming car is encountered.

The results replicated the difference between TH and HID lamps that we observed in the earlier study, and indicated that the difference is not reduced by several manipulations of context and experience that we introduced in the present study. Analysis of subjects' discomfort ratings indicated that when TH and HID lamps produce equal discomfort glare, the tungsten-halogen lamps produce more photopic lux at the eye of the observer. The magnitude of this difference was not affected by the type of headlamp (TH or HID) used on the car in which observers sat while viewing the glare stimuli, nor by whether the TH and HID lamps were presented in the context of headlamps that had been filtered to produce strongly saturated colors. For younger subjects, the magnitude of the difference did not change over the course of the experimental session, but for older subjects the difference became larger. During the early part of the experiment, in which the magnitude of the difference was the same for younger and older subjects, the average difference between TH and HID lamps in photopic lux corresponding to a criterion level on the de Boer scale was 0.165 log units (meaning that photopic lux for TH lamps would be 1.46 times greater than for HID lamps when discomfort glare was equal). The significance of these findings for possible effects of HID lamps in actual driving is discussed.

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Contents

Introduction

Tungsten-halogen (TH) and high-intensity discharge (HID) light sources vary markedly in spectral power distribution (SPD). The difference is illustrated in Figure 1, which shows a typical SPD in the region of the visible spectrum for each type of source. The SPD for the TH source is smooth, and has a strong concentration of power in long wavelengths. In contrast, the SPD of the HID source is characterized by strong lines, and the distribution of power is very different from that of the TH source. Most notably, the HID is weak above 600 nm, the region in which the TH source is strongest. Proposals to use high-intensity discharge (HID) sources in automotive headlamps have raised questions about the possible perceptual effects of these differences in spectral power distribution.

There have been two general areas of concern, color rendering and discomfort glare. We have recently addressed each of these areas with a series of studies. Our studies of the color rendering issue have led us to the tentative conclusion that HID sources should not cause a problem in automotive applications (Sivak, Flannagan, Traube, Battle, & Sato, 1993).

The work reported here addresses the issue of possible differences in discomfort glare from HID and TH headlamps. We have previously performed two laboratory studies (Flannagan, Sivak, Ensing, & Simmons, 1989; Flannagan, Sivak, & Gellatly, 1991) and one field study (Flannagan, Sivak, Gellatly, & Luoma, 1992) on this issue. The laboratory studies used monochromatic stimuli rather than actual headlamps. They suggested that, in the range of

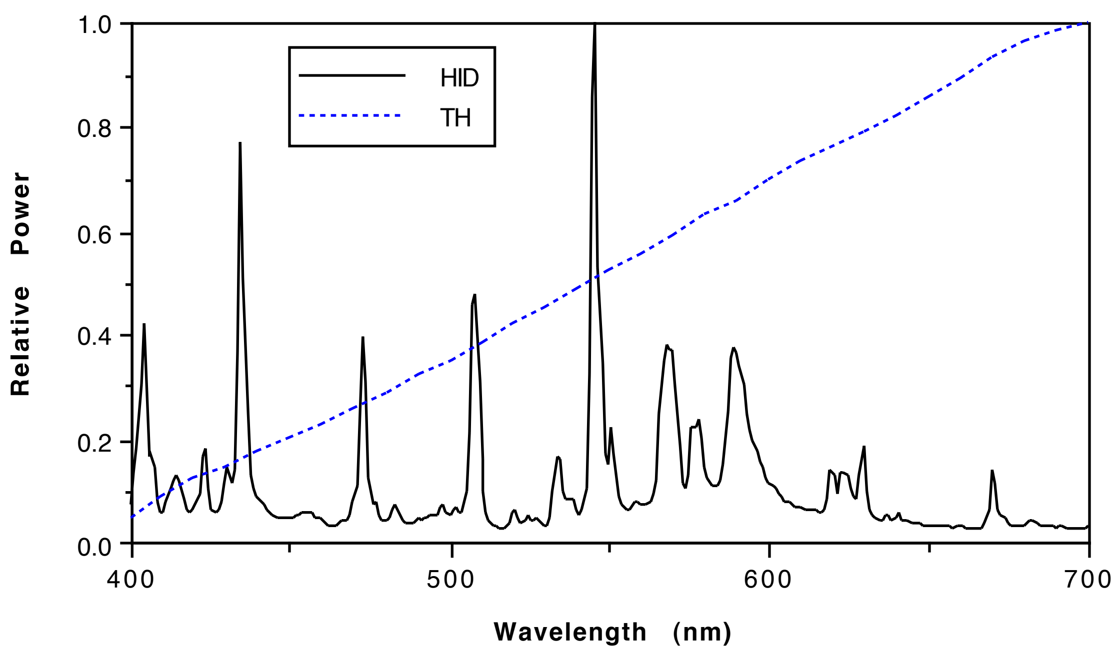

Figure 1. SPDs for a typical TH headlamp and for the HID headlamp used in the present study.

luminance that is characteristic of night driving, discomfort glare ratings were strongly influenced by rod photoreceptors, and that the scotopic luminous efficiency function might lead to better predictions of discomfort ratings than the more standard photopic luminous efficiency function. In the previous field study we measured the difference in discomfort glare ratings for actual HID and TH headlamps in an outdoor, static situation that was comparable in terms of lighting to a meeting between two cars on an unlighted, two-lane road.

Subjects' ratings of discomfort glare indicated that the HID lamps were more glaring than TH lamps when the two types of lamp produced equal photopic lux values at the subjects' eyes. We quantified the effect in terms of the difference in log photopic lux levels that would be necessary to produce equal discomfort glare ratings. That difference turned out to be 0.30 (corresponding to a factor of 2.00), or 0.22 (corresponding to a factor of 1.66) if one outlier subject was dropped. This difference was in the same direction as, but much larger than, a predicted difference based on the assumption (prompted by the laboratory data on monochromatic stimuli) that scotopic photometry would predict discomfort glare responses. The predicted difference in log photopic lux values was only 0.037 (corresponding to a factor of 1.09). Thus the field results indicated a possible problem with discomfort glare from HID lamps, but they were not fully consistent with the laboratory data on monochromatic stimuli.

The present study was our second field study using actual TH and HID headlamps. We had two principal goals. First, we wanted to test the robustness of the difference in discomfort glare properties that we had observed between TH and HID lamps. Although we believed that the first field study was methodologically sound, replication seemed appropriate considering both the potential importance of the issue of discomfort glare from HID lamps, and the fact that the field results differed from our expectations based on the laboratory results. Second, we wanted to test the hypothesis that the difference in discomfort glare was due to, or perhaps exaggerated by, the novelty of HID sources as automotive headlamps. Although both the HID and TH headlamps used in the previous field study are within the range of what is considered white by most casual observers, their colors are clearly discriminable. The HID lamps are usually described as relatively blue, and the TH lamps as relatively yellow. Given that the lamps are basically discriminable, if subjects for some reason had a tendency to be unusually critical of new or different lamps, the difference that we observed could have been partly or even entirely due to novelty.

We tested the novelty hypothesis with three extensions to the method of the previous field study, each designed to reduce any effect due to novelty. First, we lengthened the experimental sessions somewhat so that we could better assess the effects of experience. In the previous field study, the amount of experience that each subject had with the HID lamps had been limited to the number of trials needed to get reliable measurements. Each subject saw just

10 presentations of the HID lamps (mixed randomly with 10 presentations of the TH lamps) over a period of about 10 minutes. In the present experiment, each subject was given 80 total trials over a period of about 45 minutes.

Second, we included HID lamps as observer-car lamps. In the previous study, the car that subjects sat in during the experiment always had TH low beams on. In the present study, half the subjects had TH low beams as observer-car lamps, and half had HID low beams. Thus, for half the subjects the scene within which the glare stimuli appeared was constantly illuminated by HID lamps. This gave them considerable experience with the color of the HID lamps, as it was reflected from a relatively neutral pavement. The use of HID lamps on the observer car also allowed a test of whether it was the contrast between the HID glare lamps and the TH observer lamps used in the previous study, rather than novelty of the HIDs per se, that caused the observed difference.

Third, half the subjects in the present experiment saw only TH and HID glare stimuli (as did all subjects in the previous experiment). The other half saw the TH and HID glare stimuli mixed from trial to trial with glare stimuli of four additional colors that covered a much wider range of chromaticity. The additional colors were produced by using selective filters over the TH lamps to produce red, green, blue, and yellow stimuli of much higher saturation than would normally be considered realistic for headlamps. We will refer to these four lamps as the saturated-color (SC) lamps. In the context of these highly chromatic glare stimuli, the *relative* novelty of the HID lamps should have been greatly reduced.

Method

Subjects

There were 36 subjects: 24 in a younger group (aged 17 to 26 years with a mean of 21.0), and 12 in an older group (59 to 79 with a mean of 69.0). An effort was made to ensure that the sample would be approximately balanced by sex, but equal representation was not required. In the younger group there were 15 males and 9 females; in the older group there were 7 males and 5 females. The subjects were paid for their participation. All subjects were licensed drivers. None of them were previously familiar with HID headlamps.

Apparatus

Two cars were used in the study: one for observers to sit in (a 1990 Cadillac Sedan de Ville), and one to provide the glare stimuli (a 1992 Cadillac Eldorado). Each of the two cars was equipped with both HID and TH low-beam headlamps. The spectral power distributions for the four HID lamps were examined and found to be very similar. Figure 1 shows the spectral power distributions for one of the HID lamps, along with a typical distribution for a TH lamp.

All the lamps were mounted on bars attached to the fronts of the vehicles, just in front of the vehicles' standard lamps. Thus, in addition to its standard lamps, each vehicle had four lamps mounted on the bar: two HID lamps and two TH lamps. The lamps could produce both high and low beams, but only low beams were used in this study. One HID lamp and one TH lamp were mounted on each side of each car. Thus the cars had two-lamp systems of each type mounted in approximately the standard headlamp positions. On the driver side of each car, the TH lamp was outboard and the HID lamps was inboard, whereas on the passenger side, the TH lamp was inboard and the HID lamp was outboard. This allowed the separation between each same-type pair of lamps to be the same (1.2 m, center to center), but the midpoints of each same-type pair was offset slightly from the midline of the vehicle. The faces of the lamps were all 10 cm high and 10 cm wide.

Filters could be placed just in front of the headlamps of the glare car to adjust their effective intensity and/or chromaticity. The filters covered the faces of the lamps completely. There were two sets of filters: a set of four neutral filters that varied in density, and set of four selective filters that could be used to produce reasonably saturated red, green, blue, and yellow. The neutral filters were composed of one, two, three, or four layers of Lee Filters No.

210 (neutral density, nominal density 0.6). The colored filters were Lee Filters Nos. HT 019 (red), 124 (green), 118 (blue), and 101 (yellow).

The neutral density filters were used with both the TH and HID lamps. Their transmittances were measured for both types of lamp, and were the same within the error of measurement (as would necessarily have been the case if the filters were ideally neutral). The measured transmittances, averaged over the two lamp types, are shown in Table 1. The colored filters were used with the TH lamps to produce the set of SC lamps. The transmittances of the colored filters were measured only for the TH lamps, because in the experiment they were used only with those lamps. Those values are also shown in Table 1.

The chromaticity coordinates for the SC lamps, which were produced by using the TH lamps with each of the colored filters, were measured with a Pritchard 1980A photometer equipped with TF-80 tristimulus filters. They are shown in Table 2 and in Figure 2, which also shows the SAE white box (Society of Automotive Engineers, 1988) and locations of the unfiltered HID and TH lamps.

A sheet of rigid, opaque material was mounted on stands just in front of the headlamps of the glare car to be used as a shutter in controlling presentation of the glare stimuli. It was wide and high enough to block the direct view of the glare lamps from the observer car, as well as reflection from the intervening pavement. It could be quickly moved from a vertical position (blocking the view of the lamps) to a horizontal position (lying flat on the ground and allowing a full view of the lamps).

Table 1.

Densities and transmittance values for all of the individual filters used in the study. These values were measured using the TH lamps for the colored filters, and both the TH and HID lamps for the neutral filters.

Filter	Density	Transmittance
ND 1	0.58	.26
ND 2	1.20	.062
ND 3	1.83	.015
ND 4	2.43	.0037
Red	0.59	.26
Green	0.72	.19
Blue	0.81	.16
Yellow	0.11	.78

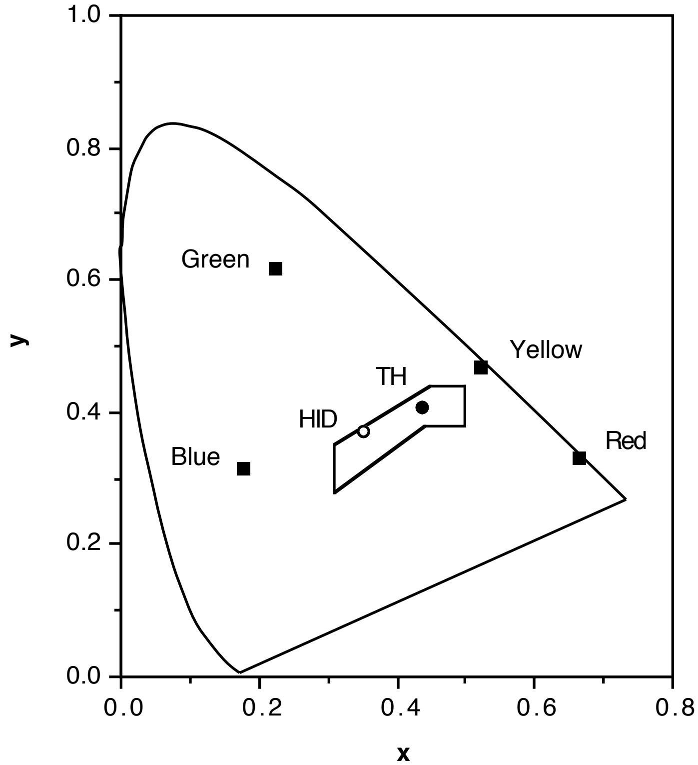

Figure 2. The CIE chromaticity diagram, showing the locations of the TH and HID lamps, as well as the four SC lamps produced by placing selective filters over the TH lamp.

Table 2.

Chromaticity coordinates for the TH lamps combined with each of the colored filters (the SC lamps), measured by means of a photometer equipped with tristimulus filters.

Filter	x	y
Red	.67	.33
Green	.22	.62
Blue	.18	.32
Yellow	.52	.47

Field Setup

Testing was conducted in a parking lot adjoining the UMTRI building. The area was dark, with no artificial lighting in or near the lot. The observer vehicle and the glare vehicle were placed in fixed positions to simulate a meeting on a two-lane road. The distance from the headlamps of the glare car to the subjects' eyes was 35 m. The intervening pavement was dry asphalt.

Stimuli

Sixteen different types of glare stimuli were presented to the subjects. Eight of these consisted of the TH and HID lamps presented with their normal chromaticities, each presented at four intensities. They were produced by combining each of the two lamp types with each of the four neutral density filters. The other eight stimulus types consisted of the four colors of SC headlamps, each presented at two intensities. These were produced by the TH lamps combined with the four colored filters, each of which was used alone or in combination with a two-layer (density 1.20) neutral density filter.

Because of the candela gradients in the beam pattern of the glare vehicle, lux values at the eye positions of the subjects could be affected by even slight changes in the positions of the observer and glare vehicles. Because data were collected in sessions on four separate evenings, and because the vehicles had to be moved between sessions, we collected photometric values at the beginning of each session. After the vehicles were positioned, and just before data collection began, the lux levels produced by the TH and HID pairs of lamps on the glare vehicle were measured at each of three positions across the front seat of the observer vehicle (at the approximate eye positions of subjects sitting in the left, center, and right of the front seat). These measurements were made for each of the two pairs of lamps individually, and with no filters on the lamps. Lamp aim (which could be adjusted more finely than the overall position of the glare vehicle) was adjusted so that the illuminance at each of the three positions, and by each of the two lamp types, would be as close as practical to 20 lx. In making the adjustments, we tried to make the effective intensities of the individual lamps appear approximately equal within each same-type pair (this was judged by eye by an experimenter sitting in the observer vehicle), but illuminance measurements were made only for the two TH lamps as a pair and the two HID lamps as a pair.

Even after these adjustments, there were measurable differences in the illuminance measurements taken at different positions in the observer vehicle, on different evenings, and for different lamp types. Therefore, lux values were recorded for each combination of those three factors, and were used in the data analyses discussed below. The geometric mean, over all seat positions and evenings, for illuminance by the TH lamps was 20.9 lx, with a range from 13.5 to 30.6 lx. The mean for the mean for the HID lamps was 18.7 lx, with a range from 15.0 to 21.5 lx. The mean values can be used, in combination with the filter transmittances described above, to calculate the ranges of illuminance for each lamp type that the average subject was exposed to. Those illuminance values are shown in Figure 3 for the TH, HID, and four colors of SC headlamps. We did not constrain the illuminance ranges to be exactly equal across lamp types, but we wanted to ensure that there was enough range within each lamp type, and enough overlap across lamp types, to allow us to perform certain interpolation analyses, which are described below.

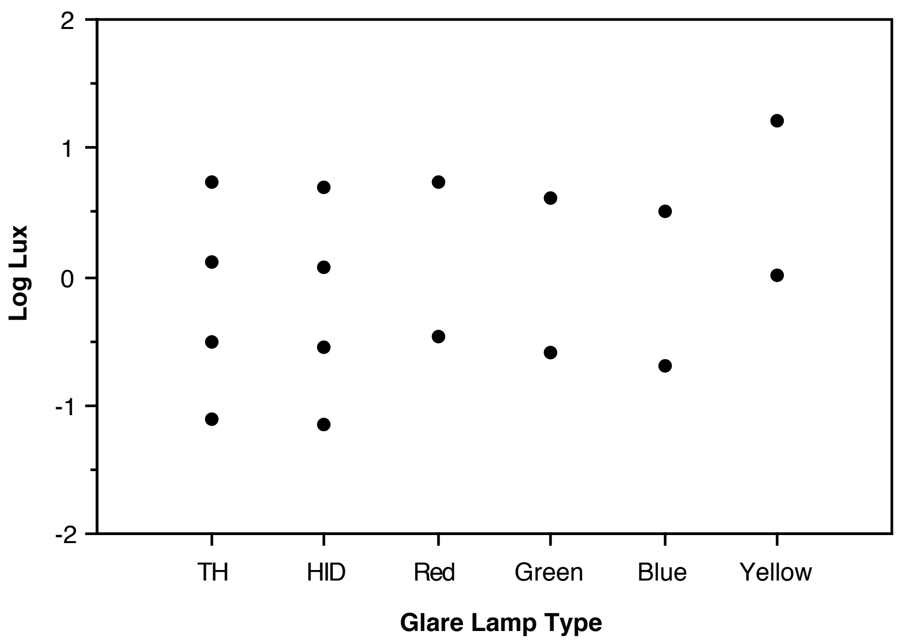

Figure 3. Ranges of illuminance at the eye for the six different lamp types. Values are based on the geometric averages of TH and HID unfiltered illuminance across all seat positions and nights, and on filter factors for the four neutral density filter sets and for the four colored filters.

Design summary

The between-subjects variables were age, sex, seat position, observer-car lamp type (TH or HID), and presence/absence of the SC lamps. The within-subject variables were glare lamp type (which for half the subjects included TH and HID, and for the other half included TH, HID, and the four colors of SC lamps), illuminance at the subject's eyepoint (which varied across four levels for the TH and HID lamps, and across two levels for each color of the

SC lamps, as shown in Figure 3), and amount of experience in the experimental session (represented by the blocks into which each session was divided).

Response scale

Subjects were asked to use the de Boer scale for their assessment of discomfort glare. This scale has been used extensively to evaluate glare in night driving situations (Bhise, Swigart, & Farber, 1975; de Boer, 1967). It 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).

Procedure

Subjects were run in groups of three. They received instructions in the UMTRI building and were then led outdoors to the test site. All headlamps on both vehicles were off at this time. The subjects were seated in the front seat of the observer vehicle; deciding among themselves who would sit in the driver-side, center, and right positions. One pair of headlamps on the observer vehicle (either TH or HID) was then turned on, and the subjects were allowed to adapt to these lighting conditions for 10 minutes. The observer-car lamps were left on throughout the session. For half of each age group (12 of the younger subjects and 6 of the older subjects) the observer-car lamps were TH; for the other half of each group they were HID. The engines of both vehicles were idling throughout the session.

After subjects had adapted for 10 minutes, a series of 80 trials was presented. The series took about 45 minutes to complete. At the beginning of each trial, the shutter was in its elevated (closed) position in front of the glare vehicle. An experimenter stationed at the glare vehicle turned on the appropriate lamps for that trial. For all except the first trial, this was done immediately after the previous trial; if the lamps required for a trial were the same as for the previous trial, those lamps were simply left on. Because the shutter was elevated, the subjects' view of the glare lamps was blocked when they were first turned on. This allowed time (about 30 s) for lamp output to stabilize before the glare stimulus was presented. During this time, two experimenters mounted the filters appropriate for that trial in front of the lamps. One experimenter then signaled the observer car by radio that a trial was about to be presented. Another experimenter then lowered the shutter for 5 seconds, presenting the glare stimulus. After the shutter was raised, the subjects recorded their estimate of the discomfort they experienced from the glare on a response sheet using the de Boer scale.

For half of the subjects the glare stimuli did not include the SC lamps. They saw only the eight combinations of the TH and HID lamps with the four densities of neutral filters. The stimuli were presented in 10 blocks, each of which included all 8 combinations. This blocking insured that each combination would appear equally often early and late in the session. Within each block of trials stimuli were randomized. The boundaries between blocks were not identified for the subjects; stimuli were presented in a single, continuous series of 80 trials.

For the other half of the subjects the glare stimuli included the same eight combinations of TH and HID lamps with neutral density filters, as well as the eight color-by-intensity combinations of SC lamps (four colors, each presented at two intensities; produced by using the TH lamps with four different selective filters, each used with and without the two-layer neutral filter). For these subjects, the stimuli were presented in 5 blocks, each of which included all 16 stimulus types, randomized within blocks.

Chromaticity range was crossed with observer-vehicle lamp and age. Thus six younger subjects and three older subjects were run in each combination of chromaticity range and observer-vehicle lamp.

Results and Discussion

Data treatment

We analyzed the results by using regression modeling to summarize relationships between de Boer ratings and log lux at the eyes of the observers. The modeling method is illustrated in Figure 4, which shows data for one subject. This person was a young female in the SC-lamps-absent condition. Although the modeling method could be demonstrated with any subject's data, this individual was selected as an example because the difference between her responses to the HID and TH lamps, quantified in the way that we are about to describe, was near the mean difference for all 36 subjects.

The de Boer ratings shown in Figure 4 are arithmetic means of the ten ratings that the subject gave for each of the eight combinations of lamp type and intensity shown in the figure. For both lamp types, de Boer ratings decrease (indicating *more* discomfort) as lux levels increase. The relationship is negatively accelerated, possibly because of a floor effect: the lower lux levels may have been too low to produce appreciable discomfort. Because the data from many subjects showed substantial quadratic trends, we decided to use second-order polynomial regression models to summarize each subject's data. The fits for these models were extremely good. Of the 72 models that were fitted (for 36 subjects times 2 types of lamp), 48 had r^2 values above .99, and only 4 had r^2 values below .95.

The regression models for the example subject are illustrated by the curved lines in Figure 4. These curves summarize the relationship between de Boer ratings and photopic lux for each lamp type. In Figure 4 the HID curve is below the TH curve, meaning that any particular lux value discomfort ratings will be numerically lower (indicating more discomfort) for the HID lamps than for the TH lamps.

Another way of summarizing this information is to calculate the lux values required for each lamp to produce a particular discomfort level. That is what we did for the main analyses of these data. As illustrated in Figure 4 by the horizontal line at a de Boer value of 5.0, and by the vertical arrows, the regression equations can be used to calculate log lux values that, if they had actually been presented, should have produced ratings of 5.0 for each lamp type. In this example those log values are 0.05 (1.12 lx) for the HID lamps, and 0.22 (1.66 lx) for the TH lamps. This means that in order to cause this subject to produce equal discomfort ratings, the TH lamps would have to be 1.66/1.12 = 1.48 times more intense than the HID lamps.

The choice of a value on the de Boer scale is somewhat arbitrary. As is suggested by the example data in Figure 4, within a broad range the value chosen has no substantial effect on comparisons between lamps. We chose 5.0 because it is a meaningful criterion in terms of the de Boer scale labeling (corresponding to “just acceptable” discomfort), and because it is comfortably within the ranges of responses made by all subjects (allowing relatively reliable interpolation).

We chose to use the regression models derived from subjects’ responses to calculate the difference in log lux values for the two lamp types corresponding to a fixed criterion on the de Boer scale. It is also possible to use the models in the reverse way, calculating the difference in de Boer rating that would be expected for the two different lamps if they were presented at the same photopic lux level. We chose the former because we decided that discussing differences in terms of the physical variable (lux, or actually log lux) rather than the psychological variable (de Boer rating) would make it easier to relate the sizes of the observed effects of lamp type to other factors. However, the choice of variable makes no difference in the conclusions that one reaches; the same information is available in either domain. As an example of the reverse form of calculation, for a physical criterion of 1.0 lx (log lx = 0), the expected de Boer ratings for this subject would be 5.25 for the HID lamps and 6.00 for the TH lamps, a difference of 0.75 units on the de Boer scale.

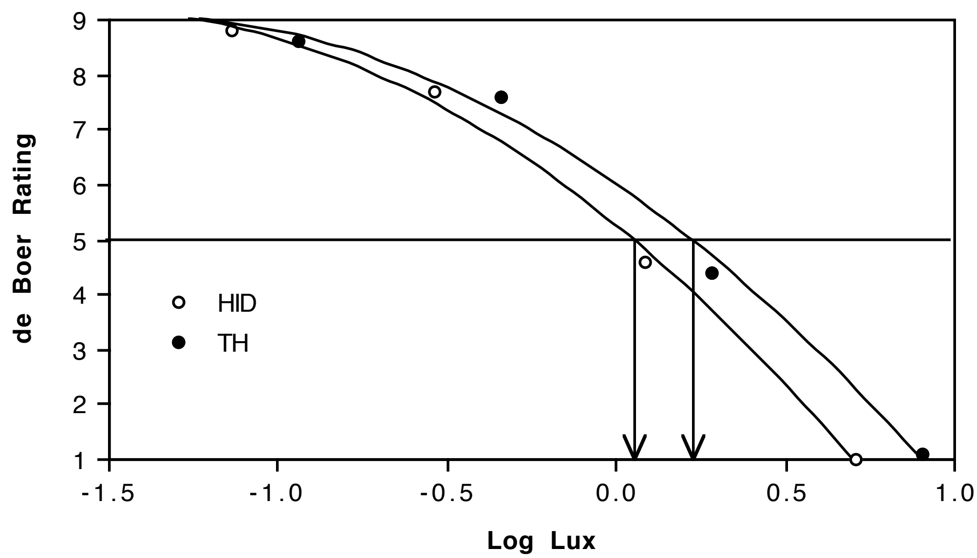

Figure 4. Mean de Boer ratings for HID and TH lamps, each at four levels of lux at the eye of the observer. Data are from one subject, a young female who was not shown the SC lamps, and for whom the difference between responses to HID and TH lamps was very near the average for the entire group of 36 subjects. The curves are the best fitting second-order polynomial regression lines for the two sets of data. The horizontal line at a de Boer value of 5.0 and the vertical arrows illustrate the modeling method that was used to compare the discomfort glare properties of the different lamp types (see text for details).

Analyses of variance

Log lux values corresponding to de Boer ratings of 5.0 were submitted to an analysis of variance with age, seat position, observer-car lamp type, presence/absence of SC lamps, and glare lamp type as factors. Three main effects were significant: age, $F(1,12) = 7.42$, $p = .018$; observer-car lamp type, $F(1,12) = 5.25$, $p = .041$; and glare lamp type, $F(1,12) = 40.21$, $p < .0001$. One two-way interaction was significant: the interaction of age and glare lamp type, $F(1,12) = 6.43$, $p = .026$.

The main effect of age was that the older subjects had greater overall sensitivity to glare than the younger subjects. For the older subjects the average log lux value corresponding to a de Boer rating of 5.0 was -0.089; the value for the younger group was 0.120. Thus, on average, lux values at the eyes had to be 1.62 times higher for the younger subjects than for the older subjects in order to evoke equal discomfort ratings. The effect of observer-car lamp type was such that subjects were less sensitive to glare when the observer-car lamps were HID than when they were TH. The average log lux values for those conditions were 0.133 and -0.032, respectively.

The main effect of primary interest, that of glare lamp type, was such that TH lamps were more intense than HID lamps when they evoked equal discomfort ratings. The log lux value (corresponding to our criterion level of 5.0 on the de Boer scale) for the TH lamps was 0.133, and the value for the HID lamps was -0.032. Thus the difference in log lux was 0.165, corresponding to a factor of 1.46.

The interaction of glare lamp type with age is shown in Figure 5. Although the effect of lamp type is present for both younger and older subjects, it is greater for the older subjects.

It is of particular interest whether the difference between TH and HID lamps is affected by presence/absence of the SC lamps or by observer-car lamp type. Those issues are addressed by the two-way interactions of glare lamp type with presence/absence of the SC lamps and with observer-car lamp, respectively. Neither effect was significant. The nonsignificant interaction of glare lamp type with presence/absence of the SC lamps, $F(1,12) = 1.17$, $p = .30$, is shown in Figure 6. The trend evident in that figure suggests that, if there is any effect at all of the presence of the SC lamps, it is to increase the difference between TH and HID lamps. The nonsignificant interaction of glare lamp type and observer-car lamp type, $F(1,12) = 0.28$, $p = .61$, is shown in Figure 7.

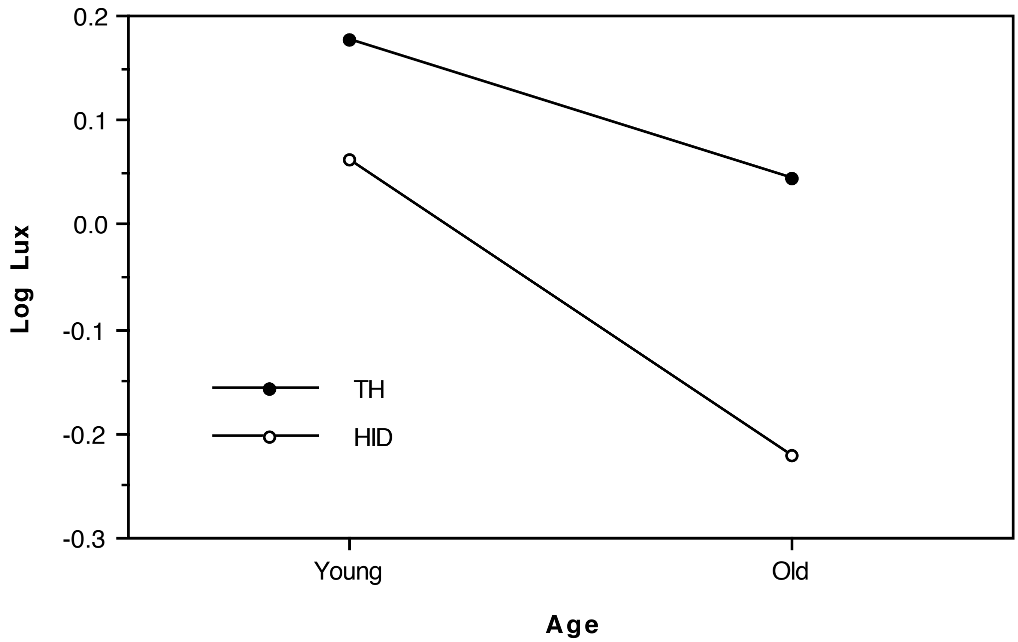

Figure 5. The interaction of age and glare lamp type. The dependent variable is log lux corresponding to de Boer ratings of 5.0.

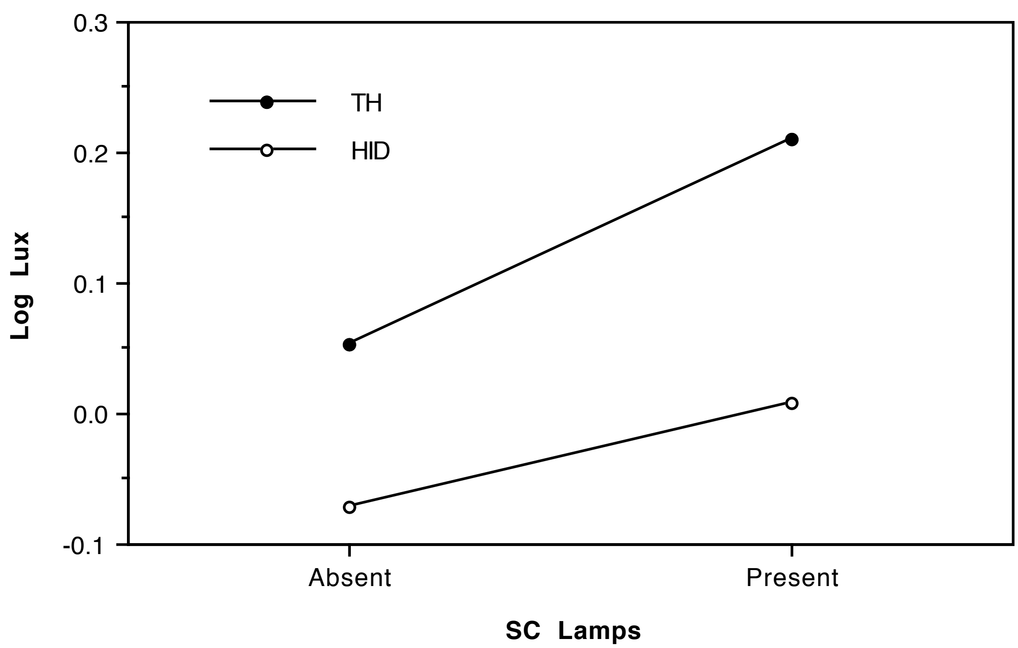

Figure 6. The nonsignificant interaction of glare lamp type with presence/absence of the SC lamps. The dependent variable is log lux corresponding to de Boer ratings of 5.0.

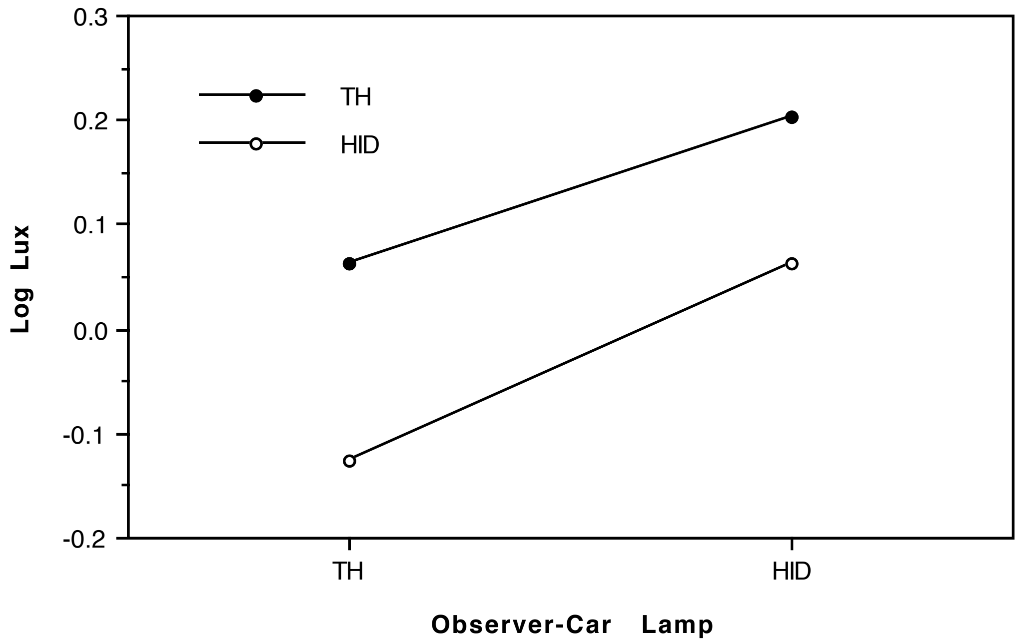

Figure 7. The nonsignificant interaction of glare lamp type (distinguished by the open and filled symbols) and observer-car lamp type (on the horizontal axis). The dependent variable is log lux corresponding to de Boer ratings of 5.0.

Effects of experience. In order to assess possible changes over time, we selected data from "early" and "late" periods of each subject's experimental session. These periods were defined as the first two fifths and the last two fifths of each session. We then fitted regression models as described above for each combination of subject, glare lamp type, and time period. As would be expected, the fits were not quite as good for this partitioning of the data as they were when data were not partitioned by time period. Nevertheless, the fits were very good. The mean r^2 was .97, and of the 144 models (36 subjects times 2 glare lamp types times 2 time periods) only 6 had r^2 values below .90. We calculated log lux levels corresponding to de Boer ratings of 5.0, and submitted those values to an analysis of variance with age, presence/absence of SC lamps, glare lamp type, and time in session as factors. Seat position was not included because it had proved to be unimportant in the analysis described above.[1]

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[1] The finding that position in the front seat has no effect on discomfort ratings is consistent with the results of our earlier field study (Flannagan et al., 1992), as well as with a methodological study in which we tested the effect of seat position (Sivak & Olson, 1988).

The analysis yielded two significant effects involving time: the two-way interaction of time with age, $F(1,28) = 5.97$, $p = .021$, and the three-way interaction of time, age, and glare lamp type, $F(1,28) = 7.87$, $p = .009$. As illustrated in Figure 8, the interaction of time with age is such that younger subjects tended to become less sensitive to glare over the course of the session, requiring higher lux values in the late period than in the early period to respond with a de Boer rating of 5.0, whereas older subjects became more sensitive.

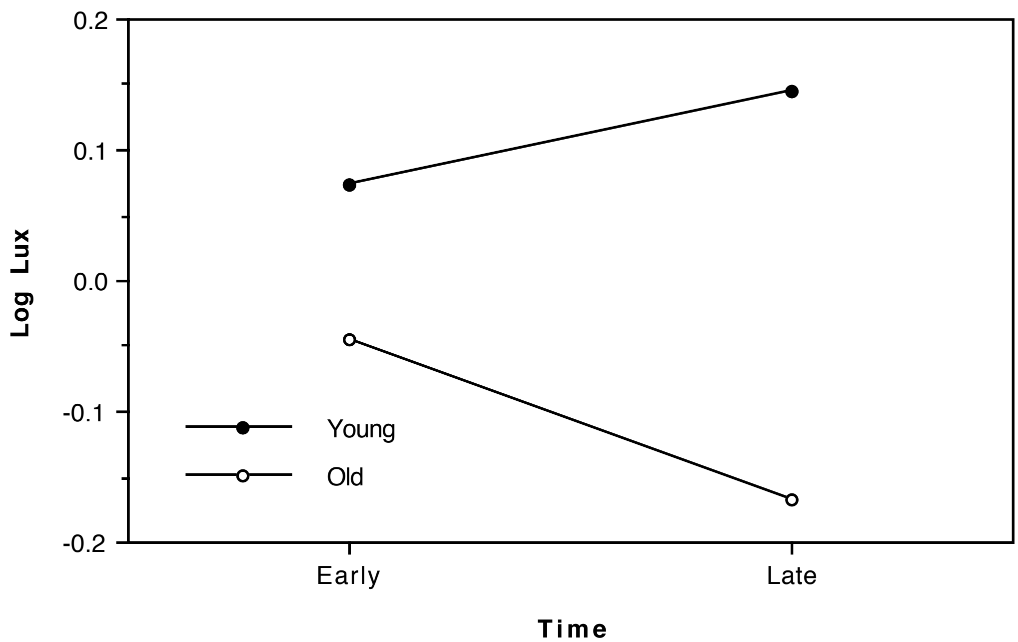

Figure 8. The interaction of age with time in session. The dependent variable is log lux corresponding to de Boer ratings of 5.0.

The significant three-way interaction, however, is of most importance for understanding the effects of glare lamp type in these data. This interaction is illustrated in Figure 9, and numerical values are given in Table 3. Figure 9 indicates that the overall increase in sensitivity among older subjects is due to the HID lamps. Like the younger subjects, they actually become slightly less sensitive to glare from the TH lamps over time, but for the older subjects this is more than offset by a large increase in sensitivity to the HID lamps.

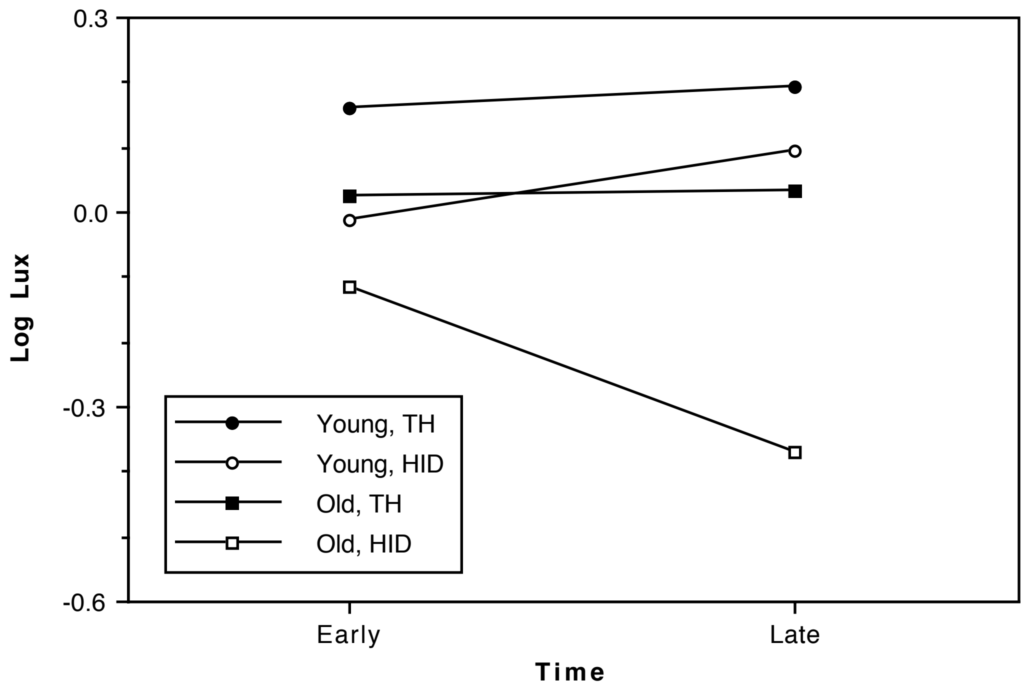

Figure 9. The three-way interaction of age, glare lamp type, and time in session. The dependent variable is log lux corresponding to de Boer ratings of 5.0.

Table 3

Log lux values corresponding to 5.0 de Boer ratings for each combination of subject age, glare lamp type, and time in session. Numbers in parentheses after the differences in log values are the factors corresponding to the log differences.

	Early in session	Late in session
Younger subjects		
TH	0.161	0.192
HID	-0.013	0.096
TH minus HID	0.174 (1.49)	0.096 (1.25)
Older subjects		
TH	0.025	0.032
HID	-0.115	-0.368
TH minus HID	0.140 (1.38)	0.400 (2.51)

The difference between log lux values for TH and HID lamps is about the same for younger and older subjects early in the experiment, but the results for younger and older subjects diverge later on. In our previous study (Flannagan et al., 1992) we did not find a significant effect of age, but the sessions in that experiment were shorter, perhaps too short for an effect of age to develop. Considering the differences in session lengths, the present results are consistent with the earlier study with regard to the effect of age. In the previous study, the sessions were about equal, in both time and number of trials, to the portions of the present sessions that we have designated as early.

Table 4 presents estimates from both studies of the magnitude of the difference between TH and HID lamps on log lux values corresponding to a criterion de Boer level.[2] The estimates from the previous study are shown both with and without an outlier subject (see the upper panel of Figure 11, which is described below in a note on individual differences). We have no reason to believe that this subject's data are invalid, but because she was an outlier it is interesting to consider what happens when her data are excluded. In either case, the 95% confidence intervals from the previous study lie entirely above zero (indicating significance at the .05 level for a test of the conventional hypothesis that the TH/HID difference is zero), and they include the mean difference for all subjects in the early portion of the current study.

Also included in Table 4 are predictions for the TH/HID difference in each study. These predictions are based on the assumption that discomfort glare is exactly determined by the scotopic luminous efficiency function. Our laboratory studies of discomfort glare suggested that that might be approximately true in a typical night driving environment (Flannagan et al., 1989; Flannagan et al., 1991). The predictions were derived by computing the difference in photopic photometric values that would exist when the TH and HID lamps were equated in scotopic photometric values. These calculations are straightforward given that the SPDs of the lamps are known. The prediction for the present study was derived from the SPDs in Figure 1, and the prediction for the previous study was derived using the slightly different SPD of the HID used in that study. For both studies the predicted differences between log lux for TH and HID are small, and in both studies the predictions are violated, as indicated by the fact that the 95% confidence intervals exclude the predicted values.

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[2]Because the criterion values were chosen to be near the middle of the ranges of de Boer values used by subjects in each of the two studies, and because those ranges were somewhat different, in the previous study we used a criterion de Boer value of 4.0, rather than 5.0 as used in the present study. The difference in criterion values affects absolute log lux values, but, as suggested by the example in Figure 4, it has a negligible effect on the *differences* in log lux values, such as those shown in Table 4. In fact, the value shown in the table for the present study changes only in the third significant digit (to 0.164) when a de Boer value of 4.0 is used.

Table 4

Estimates from two experiments of the difference in log lux values, corresponding to criterion de Boer ratings, for TH and HID lamps. Estimates from our earlier field study are shown with and without one outlier subject. The predictions are based on the assumption that discomfort glare under these experimental conditions is determined entirely by the scotopic luminous efficiency function (see text for details).

	Log Lux TH minus Log Lux HID		
		95% Confidence Interval Bounds	
	Mean	Lower	Upper
Previous field study			
All subjects (n=12)	0.300	0.076	0.525
Excluding outlier subject	0.221	0.064	0.378
Predicted	0.037		
Present field study			
All subjects (n=36), early in session	0.165	0.068	0.257
Predicted	0.060		

A note on individual differences. Although the mean difference in log lux between TH and HID lamps was significantly different from zero, the range of individual differences was large enough that for a few subjects there was nearly zero difference, or even a slight difference in the direction opposite the mean difference. Figure 11 shows a histogram of individual values of that difference (log lux TH minus log lux HID) for all 36 subjects during the early portion (first two fifths) of the current experiment, and a similar histogram for the 12 subjects in our earlier field study (Flannagan et al., 1992). We have chosen to show the individual differences in the early data because in that part of the experiment none of the between-subjects variables account for an appreciable amount of the variance between subjects. Thus all 36 subjects can be shown in a single histogram.

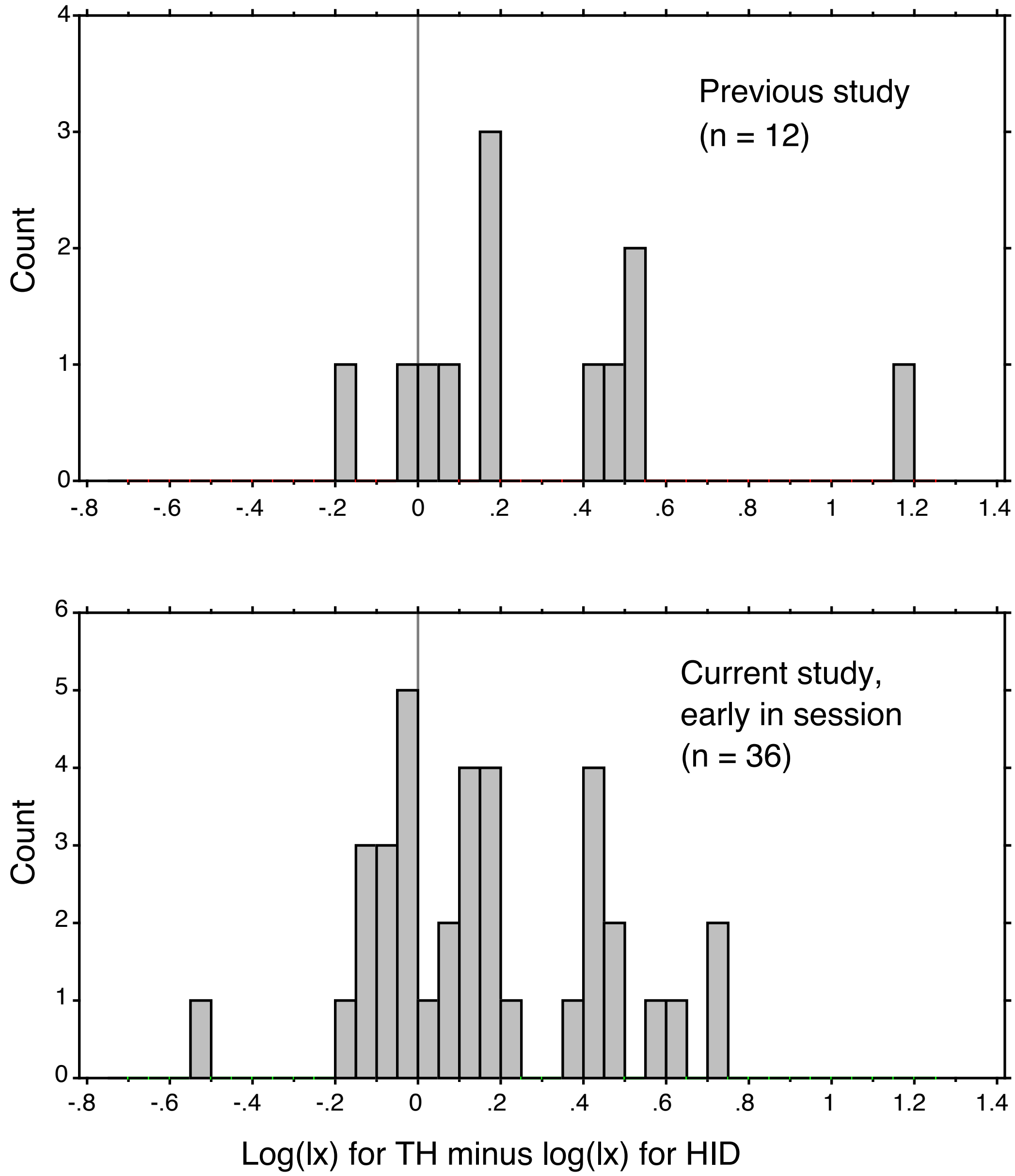

Figure 11. Histograms of values for individual subjects in two studies. Results from our earlier field study of discomfort glare (Flannagan et al., 1992) are shown in the upper panel, and results from the current study are shown in the lower panel. The variable on the horizontal axis is the difference between log lux values, corresponding to criterion de Boer ratings, for TH and HID lamps. The vertical axis is the count of individual subjects.

Discomfort glare from the saturated-color lamps. The SC lamps were included in this study so that we could observe the effects of their presence on discomfort glare ratings for the TH and HID lamps. However, because subjects rated discomfort glare from all of the lamp types that were used, we obtained information about the SC lamps as well. The data are not as clean as for the TH and HID lamps because only half the subjects saw the SC lamps, and because the number of trials for each of the four saturated colors was less than for either the TH or HID lamps, but some effects did emerge.

We applied the same sort of regression modeling to the ratings of the SC lamps that was described above for the TH and HID data. However, because only two intensity levels were presented for each color we used linear rather than quadratic models, and even for the linear models it was impossible to estimate any lack of fit. We fitted linear models for each combination of lamp and subject, and computed log lux levels corresponding to de Boer values of 5.0 as described earlier. One subject was an outlier with respect to log lux values for the SC lamps. For that subject, the mean log lux value for all four SC lamps was 3.5 standard deviations from the mean of that parameter for all 18 subjects who saw the SC lamps. His responses to the TH and HID lamps were well within the normal ranges. Because he was such a strong outlier, we have excluded him from the summary of responses to the SC lamps. Log lux values from the other 17 subjects were submitted to an analysis of variance with age and glare lamp type (TH, HID, and the four SC lamps) as factors. Age and the interaction of age and glare lamp type were not significant, but the main effect of glare lamp type was highly significant, $F(5,75) = 9.74$, $p < .001$. The main effect of glare lamp type is shown in Figure 10. Applying the Bonferroni multiple comparison method to the set of 15 possible pairwise comparisons among the glare lamp types, the two lamps with the highest mean log lux values (TH and red) were each significantly different from the two lamps with the lowest values (green and blue). No pairwise comparisons involving the lamps with intermediate values (HID or yellow) were significant.

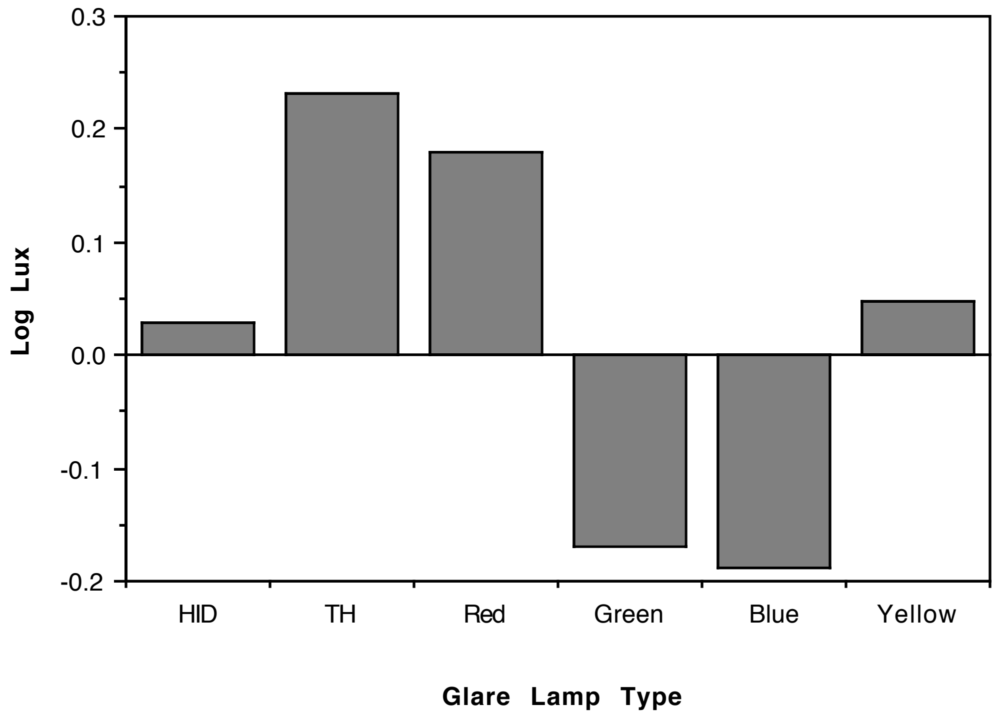

Figure 10. Mean log lux values for all glare lamp types. The dependent variable is log lux corresponding to de Boer ratings of 5.0. These values are based on 17 subjects who saw the SC lamps (one outlier has been excluded, see text).

Conclusions

The present study provides strong evidence that, for the average person, TH headlamps cause less discomfort glare than the HID lamps used in this study when both types of lamps produce the same level of photopic lux at the eye of the observer. This is consistent with the results of our previous field study (Flannagan et al., 1992), which used HID lamps similar in SPD to the ones used here. The present study indicates that this difference persists, and for older subjects increases, over a moderate amount of experience (an experimental session lasting about 45 minutes). The difference is not affected by the type of headlamp on the observer's car. Nor is it affected by whether the TH and HID lamps are presented in the context of lamps with more highly saturated colors.

In agreement with our previous field study (Flannagan et al., 1992), the present results indicated that the difference in discomfort glare properties of HID and TH lamps are not predictable from responses to monochromatic stimuli. Our previous laboratory work using monochromatic stimuli (Flannagan et al., 1989; Flannagan et al., 1991) led to predictions of much smaller differences than we actually observed between discomfort glare from TH lamps and the particular HID lamps that we used in the field studies.

The size and significance of the TH-HID difference.

Given that there is a difference between discomfort glare from TH and HID lamps, and that it is reasonably persistent, how large is the difference and how significant is it for the comfort and safety of driving? Unfortunately neither of these questions has a completely straightforward answer. However, we believe the following observations are significant.

First, it is an important question whether the results of our two field studies will generalize to most or all of the HID sources that are being considered or may be considered for use in headlamps. We have tested two types of HID lamps with very slightly different SPDs. It may be that the discomfort glare properties of HID headlamps are predictable from their chromaticities or perhaps even from their correlated color temperatures. If so, then our results would generalize to any HID lamps that are similar to the ones we used on those measures. However, there is no guarantee that that is the case.

Second, because of the interaction of lamp type with age and experience shown in Figure 9 and Table 3, no single number completely captures the difference in discomfort glare from TH and HID headlamps in the present data. However, if we assume that at least for the near future vehicles with HID headlamps will be relatively rare, so that the typical driver will have little experience with them, it may be valid to use the data from early in the sessions of the present experiment. For those data, there is no statistically reliable evidence for a difference due to age. Therefore, we can combine the younger and older subjects, as in Table 4. The estimate from early portions of the current experiment is not exactly the same as the estimates from the earlier study, but it is within the 95% confidence intervals from that study. As indicated by the widths of the confidence intervals, the estimate from the current experiment is more precise, primarily because of the larger number of subjects. The current estimate is a difference in log lux of 0.165, which corresponds to a factor of 1.46, meaning that an HID lamp producing a particular lux level at the eyes of an average observer would be judged to cause the same amount of discomfort glare as a TH lamp 1.46 times as intense.

How significant is such an effect? One way of judging its importance is to compare it to the current variability in headlamps. The variability that currently characterizes normal design and manufacturing can be regarded as a way of measuring how big a difference is worth worrying about in the collective wisdom of the industry. This assumes that the various formal and informal controls on variability during design and manufacturing will prevent unacceptably large differences between lamps, but will not overcontrol, producing variability that is substantially lower than necessary. The variation in glare levels actually encountered on the road is also affected by factors beyond the effects of headlamp design and manufacturing, such as headlamp aim and the amount of dirt on the lens. However, because the choice of a light source (TH or HID) is properly part of headlamp design, it seems useful to compare its possible effects to the current variability inherent in headlamps themselves.

A recent survey of 43 production headlamps for U.S. cars (Sivak & Flannagan, 1993) indicates that the standard deviation of log headlamp intensity at a test point relevant for glare from oncoming vehicles (0.5 U, 3.5 L) is 0.159. The log range for the sample at that point was 0.684 (226 to 1091 cd). Thus the difference in discomfort glare that might be expected because of a switch from TH to HID lamps is about the same as the standard deviation that currently characterizes the consistency of design and manufacturing of headlamps for the U.S. A change of about one standard deviation can be described as moderate in size. It is not small enough to dismiss, but neither is it so large that it dominates other considerations. Based on the current data, we estimate the effect on discomfort glare of a switch from TH to HID sources to be about the same as an increase in intensity of TH sources by a factor of 1.46. That difference seems large enough to justify some level of further research and attention, but not so large as to be a major impediment to the introduction of HID lamps.

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