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JOINT EFFECTS OF WAVELENGTH AND AMBIENT LUMINANCE ON DISCOMFORT GLARE FROM MONOCHROMATIC AND BICHROMATIC SOURCES

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16. Abstract
Recent developments in headlighting and rearview mirror technology have increased the need to understand possible effects of the color of a glare source on discomfort glare. The present study addresses that need by partially replicating and extending a previous study in which subjects rated the discomfort glare experienced from monochromatic stimuli (Flannagan, Sivak, Ensing, & Simmons, 1989). In the present study five young subjects rated the discomfort glare experienced from monochromatic stimuli of 480 nm and 577 nm, as well as from a bichromatic mixture of those wavelengths that was balanced to appear white. Two levels of background luminance were used: 0.034 and 3.4 candelas per square meter.

Results are summarized in terms of discomfort glare efficiency functions, analogous to the photopic and scotopic luminous efficiency functions. At the dimmer background luminance level glare efficiency follows scotopic luminous efficiency. At the brighter background level glare efficiency shifts partially toward photopic luminous efficiency. Discomfort glare ratings for the bichromatic mixture agree well with predictions based on an additive combination of responses to the monochromatic stimuli, although the precision of the data is such that we cannot rule out the possibility of a substantial departure from additivity.

These results suggest that the glare properties of colored sources can be predicted by using an efficiency function similar to the scotopic luminous efficiency function. The possible consequences of this for glare from high intensity discharge (HID) headlamps are discussed. Calculations indicate that the glare properties of most HID headlamps should be similar to those of tungsten-halogen. Primarily because of uncertainty about the state of dark adaptation of drivers at night, these laboratory results should be supplemented with data from field conditions.

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glare, discomfort glare, color, wavelength, headlamps, mirrors, headlighting, photopic vision, scotopic vision

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INTRODUCTION

This study was an extension of previous work in our laboratory on the discomfort glare properties of monochromatic light sources (Flannagan, Sivak, Ensing, & Simmons, 1989). The motivation for that study, and this extension, was to provide information about the possible perceptual effects of two recent innovations in automobile vision-related equipment: high intensity discharge (HID) headlamps, and colored rearview mirrors. Both of these innovations change the spectral distribution of the light reaching a driver's eyes. That may have several perceptual consequences, including changes in a driver's seeing ability, but our concern in this research was with possible effects on discomfort glare.

Our previous work had shown that the discomfort glare produced by monochromatic sources, under conditions designed to simulate the visual environment of a driver at night, was substantially different from that predicted by standard photometry based on the photopic (daytime) luminous efficiency function, $V(\lambda)$. The results were better predicted by the scotopic (nighttime) luminous efficiency function, $V'(\lambda)$. The stimulus conditions in the previous study involved a single, rather low, background luminance of 0.034 cd/m^2.

The finding that discomfort glare properties were well predicted by the scotopic efficiency function, together with the well established shift from scotopic to photopic efficiency with increasing luminance, suggested to us that the effect of wavelength on discomfort glare would vary with background luminance. The primary purpose of this study was to test that possibility. We therefore used two levels of background luminance in a procedure similar to that of the previous study.

Additivity of discomfort glare

A secondary purpose of this study was to test whether results based on monochromatic lights are applicable to more complex sources. We used monochromatic sources for this research in order to produce results with the most general applicability. However, it is clear that in any realistic driving situation drivers will be exposed to lights consisting of relatively complex mixtures of wavelengths. The relevance of our results depends on whether the properties of such lights can be predicted from simple combinations of the effects of monochromatic lights. It is known that for some stimulus conditions and some visual tasks responses to wavelength mixtures are at least approximately predictable from additive combinations of the effects of isolated wavelengths, while under other conditions additive predictions are violated (Le Grand, 1972). When violations of additivity are found the evidence for their existence is unambiguous. But it is impossible to prove conclusively that additivity holds comprehensively for a given visual response, because there will always be an infinite variety of possible violations to be ruled out. Nevertheless, we wanted to perform at least a partial test of the validity of additive predictions in the present context. In the present study we therefore presented subjects with both monochromatic glare stimuli and bichromatic mixtures of those monochromatic lights, balanced so as to appear white.

Selection of background luminances

The way in which background luminance may alter the effect of wavelength on discomfort glare is partly illustrated in Figure 1, which shows how the background luminance levels used in this and the previous study are related to the scotopic, mesopic, and photopic ranges of luminance. The boundaries of those ranges are not firmly established, but the figure follows conventionally cited numbers (e.g., Wyszecki & Stiles, 1982, p. 406). In the photopic range, above about 3.0 cd/m^2, the efficiency of light of varying wavelength in producing a visual response is characterized by the function $V(\lambda)$. That function, illustrated in Figure 2, was officially adopted by the *Commission Internationale de l'Eclairage* (CIE) in 1924 (CIE, 1926). In the scotopic range, below about 0.001 cd/m^2, visual response is characterized by the function $V'(\lambda)$, also illustrated in Figure 2. $V'(\lambda)$ was adopted by the CIE in 1951 (CIE, 1951). Between those boundaries, in the so-called mesopic range, visual response is not well characterized by either $V(\lambda)$ or $V'(\lambda)$ or even by a simple combination of them. The CIE has not adopted an efficiency function for this range.

The lower of the two background luminance levels used in the current study was the same as the single level in the previous study: 0.034 cd/m^2. As illustrated in Figure 1, this level is near the middle of the mesopic range. It is a level that we have often used in laboratory simulations of night driving because it is the level of background luminance against which critical stimuli, such as pedestrians, will often first be detected in night driving with low beam headlamps in an otherwise dark environment. However, it may be too dark to represent properly the level of light adaptation that determines the effects of wavelength on discomfort glare for a typical night driver.

On the basis of a recent study, Olson and his coworkers (Olson, Aoki, Battle, & Flannagan, 1990) argued that the proper estimate for the adaptation luminance of a driver at night, on a road without fixed lighting, using typical U.S. low beam headlamps, was 1.0 cd/m^2. That level is also shown in Figure 1. For the higher level of background luminance in the present study we chose 3.40 cd/m2. That is two log$_{10}$ units above the lower level, reasonably close to Olson's estimate, but slightly higher so that the background conditions in the present study bracket Olson's estimate, as shown in Figure 1.

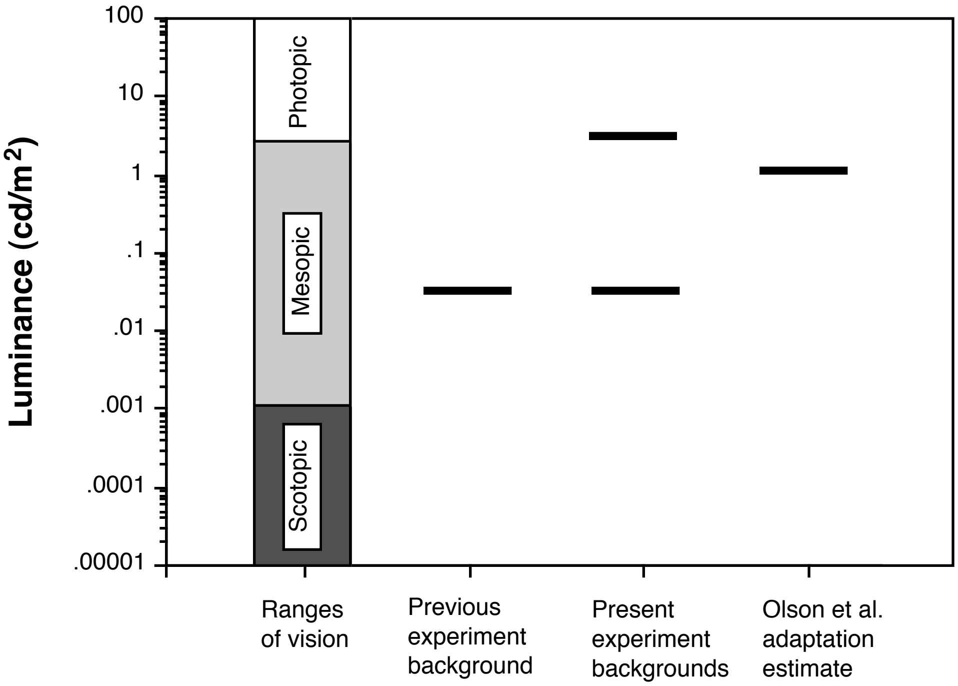

Figure 1. Relationships among scotopic, mesopic, and photopic ranges of vision, background luminance levels used in this and a previous experiment, and an estimate of the level of light adaptation for a driver at night using low beam headlamps.

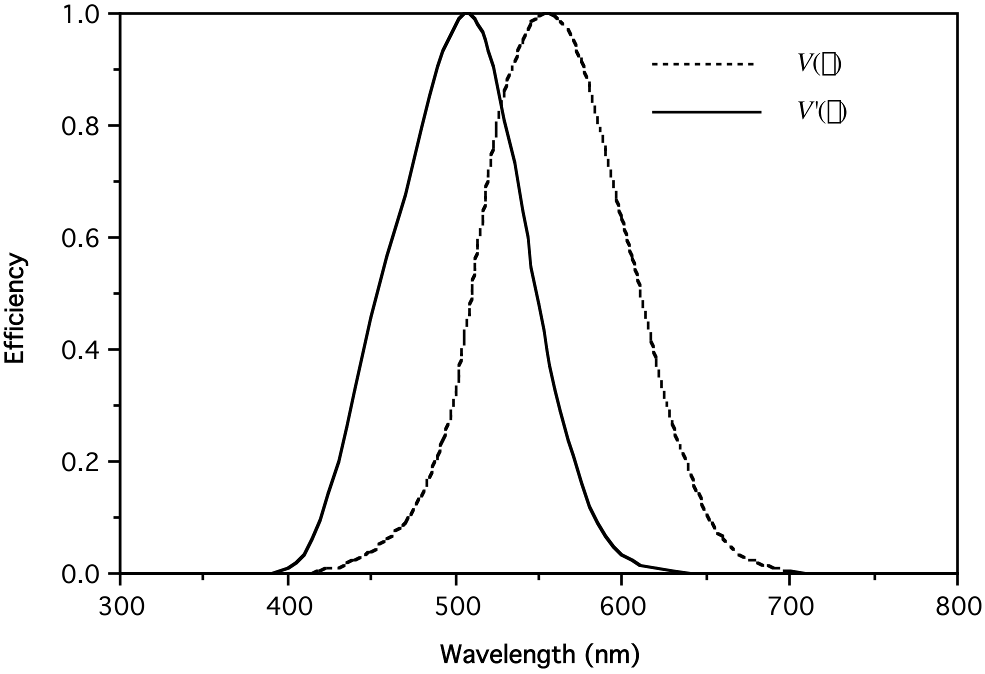

Figure 2. The scotopic (nighttime) luminous efficiency function, $V'(\lambda)$, and the photopic (daytime) luminous efficiency function $V(\lambda)$.

METHOD

Subjects

Five subjects, two female and three male, participated in the study. They ranged in age from 22 to 24, with a mean age of 22.8. One subject wore clear contact lenses; the others wore no vision correction. All subjects had color vision that was normal by the standard of a simple test using 6 Ishihara Pseudo-Isochromatic Plates (Titmus Vision Tester, Model OV7-M, Test 3).

Tasks

The subjects were asked to perform two tasks concurrently. The primary task was to make numerical ratings of the discomfort caused by glare stimuli that appeared periodically in the near visual periphery. The secondary task involved continuous compensatory tracking and was designed to mimic approximately the perceptual, cognitive, and motor demands of actual driving. The tracking task was presented as a dynamic simulated road scene on a computer-driven monitor. Deviations of the road's center were based on a mixture of sine waves generated so that the road appeared to be curving unpredictably. The subject's task was to keep the road centered on the screen by use of a standard steering wheel.

Apparatus

A schematic diagram of the experimental setup is shown in Figure 3. The subject was seated in a mockup of an automobile. Directly in front of the subject, at a distance of 3.3 m, was a television monitor with a screen 48 cm wide and 38 cm high. A computer controlled the images displayed on the monitor in response to movements of the steering wheel in the automobile mockup. The glare source was 2.7 m from the subject and 7.0 degrees of visual angle to the right of the center of the monitor screen. A panel showing a 9-point rating scale for discomfort glare, printed in black letters on a white background, was positioned 2.41 m from the subject. The letters were 1.9 cm high and subtended 27 minutes of visual angle from the subject's eye point. The panel was offset so that it appeared to the left of the monitor. The monitor, glare source, and rating-scale panel were all seen against a large white panel that was illuminated indirectly (and approximately uniformly) by incandescent desk lamps directed at the wall behind the subject. Two levels of background brightness could be provided by turning on all or just some of these lamps.

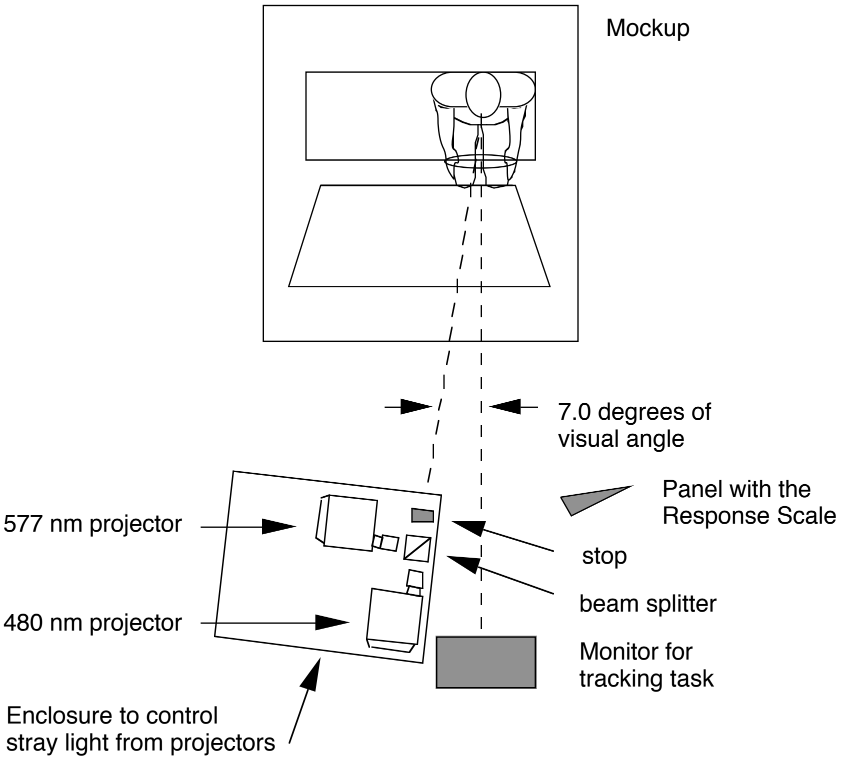

Figure 3. A schematic diagram of the experimental setup. Sizes and distances are approximately to scale.

Glare could be provided by either of two slide projectors, or by both of them in combination. The projectors were positioned with their optical axes at 90 degrees so that their outputs could be combined by a cube beam splitter as shown in Figure 3. Because of small errors in the alignment of the projectors and the beam splitter, the images of the two projector lenses did not perfectly overlap from the subject's point of view. In order to mask the areas that did not overlap, a round stop 19 mm in diameter was added in the position shown.

Each projector was fitted with an interference filter that remained inserted throughout the experiment. The interference filter in the projector that was at 90 degrees to the subject's line of sight had peak transmittance at 577 nm and a half-height bandwidth of 9.8 nm. The interference filter in the projector that was aligned with the subject's line of sight had peak transmittance at 480 nm and a half-height bandwidth of 7.1 nm. In addition to the interference filters, which were permanently inserted, each projector could be fitted with neutral density filters and opaque inserts that were mounted so that they could be changed easily from trial to trial.

When stimulus conditions called for monochromatic glare, an opaque insert was used to block completely the output from the projector that was not needed. One of four levels of output from the projector that supplied the desired wavelength was selected by inserting either no additional filter, or one of three neutral density filters with nominal densities of 0.7, 1.3, or 2.0. There were separate sets of these neutral density filters for each projector, but they were nominally identical. The relation between the intensities of the 480-nm and 577-nm projectors, when no neutral density filters were inserted, was set to the point described below in the Stimuli section by adjusting the voltage to the bulb of each projector. The voltage to the 480-nm projector bulb was 83.3 and the voltage to the 577-nm projector bulb was 105.4. The bulbs were CBA projector bulbs (120 V).

When stimulus conditions called for bichromatic glare, each projector was fitted with a neutral density filter in order to achieve the desired balance of wavelengths, and to reduce slightly the overall intensity of the combined output of the two projectors. Those filters had nominal densities of 0.1 and 0.6 for the 480- and 577-nm projectors, respectively. Any of four levels of bichromatic glare was then selected by inserting into each projector either no additional filter, or one of the three neutral density filters used for selecting levels of monochromatic glare (nominal densities of 0.7, 1.3, or 2.0).

Stimuli

Twelve different glare conditions were presented to subjects: four intensities for each of three wavelength compositions (480 nm, 577 nm, or bichromatic). Within each wavelength composition the four intensity levels were spaced approximately equally on a logarithmic scale (i.e., each step in intensity was approximately a fixed percentage change). Across wavelength compositions the step sizes were also approximately equal, so that for all three wavelength compositions the extents of the logarithmic ranges from least intense to most intense glare were about the same. The locations of these ranges, however, were selected on the basis of pilot testing in order to produce about the same range of discomfort ratings across all three wavelength compositions. The resulting ranges are unequal in terms of radiometric units, as shown in Table 1. The values for the monochromatic conditions were measured with a Pritchard 1980A photometer using a photopic filter, taking into account the deviations of the filter from $V(\lambda)$ at 480 and 577 nm. The values for bichromatic conditions are sums of values measured for each component individually.

The ratio of 480-nm to 570-nm irradiance values for the bichromatic stimuli was 0.87. This proportion appears white. Its location on the 1931 CIE chromaticity diagram is shown in Figure 4. The locations of all possible mixtures of 480 nm and 577 nm light are shown by the dashed line in the figure. The mixture that we chose was intended to have a chromaticity similar to a 4500 K blackbody radiator because that has been proposed as the center of a range to be used as a chromaticity standard for HID headlamps. It also lies approximately between two common chromaticities of light, exemplified by standard illuminants A (similar to many incandescent sources) and D_{65} (similar to many conditions of natural daylight).

The luminances and chromaticities of the background for the dim- and bright-background conditions are shown in Table 2. The chromaticities were measured with a Spectra Pritchard 1980A photometer equipped with TF-80 tristimulus filters.

Table 1

Irradiance values at the subject's eyepoint for the fifteen glare conditions (mW/m^2).

	Wavelength composition		
Nominal intensity level	480	577	bichromatic
1 (lowest)	0.0153	0.0601	0.0260
2	0.108	0.452	0.191
3	0.423	1.54	0.694
4 (highest)	2.45	8.78	3.98

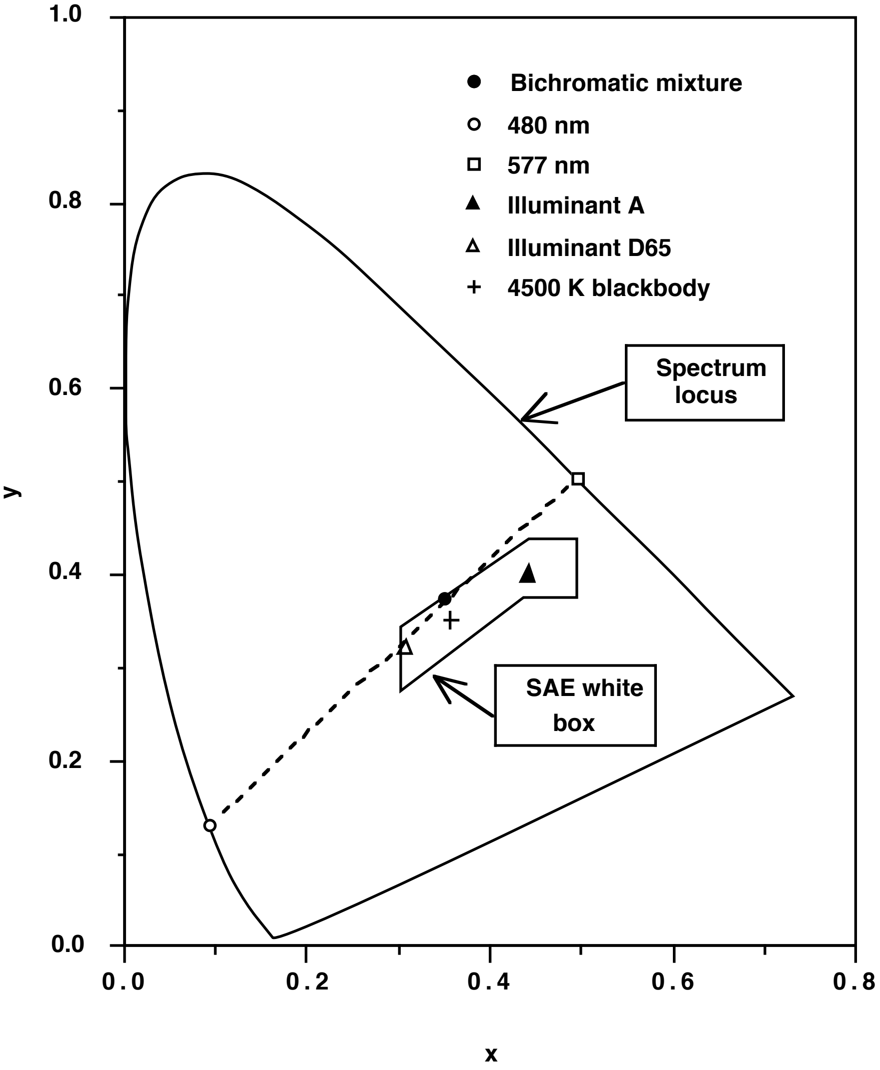

Figure 4. Chromaticities of the 480-nm, 577-nm, and bichromatic (white) glare stimuli used in this experiment, showing their relationships to several chromaticity landmarks: all possible mixtures of 480 and 577 nm (the dashed line), the spectrum locus, the SAE white box, standard illuminants A and D_{65}, and a 4500 K blackbody radiator. Note that the bichromatic glare stimulus used in this experiment lies just inside the SAE white box, and near the 4500 K blackbody radiator.

Table 2

Background luminances and 1931 CIE chromaticity coordinates for bright- and dim-background conditions.

Background condition	Luminance (cd/m^2)	Chromaticity x	Chromaticity y
dim	0.034	.48	.41
bright	3.4	.51	.41

Design

Trials were run in blocks of twelve. Each block consisted of all combinations of glare wavelength composition and intensity (3 X 4), individually randomized. Each subject was given ten blocks of trials, the first six with the dim background and the last four with the bright background.

Response scale

Subjects used 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 tested individually. After the subject was seated in the automobile mockup, the overhead fluorescent lights that normally illuminated the laboratory were turned off, leaving the lower of the two levels of incandescent background lighting described above. The subject was then given several minutes of practice on the tracking task. After the subject had become comfortable with that task, the glare-assessment task was explained. Subjects were told that they would periodically see brief (2.0 second) flashes of light to the right of the monitor. They should continue to watch the tracking task and not look directly at the light. After each light went off, they should refer to the response chart and select the appropriate scale number to describe the discomfort that they experienced from the glare. Glare stimuli were presented regularly, at intervals of approximately 15 seconds.

Each subject was given 120 trials, presented in 10 blocks of 12 trials. After the first six blocks, background luminance was increased to the higher level. The timing of the session varied slightly across subjects. The interval between when the overhead lights were turned off and data collection began averaged 11.5 min over all subjects. The duration of the first six blocks averaged 19.7 minutes. The interval between when the background luminance was increased and data collection resumed averaged 4.3 min, and the duration of the final four blocks averaged 12.5 min.

RESULTS AND DISCUSSION

The results are summarized in complete, though raw, form in Figure 5. Mean discomfort glare ratings over all subjects are shown for each combination of wavelength composition, irradiance, and background luminance. In all conditions numerical ratings decrease (indicating *more* discomfort on the de Boer scale) as irradiance at the eye point increases. For each of the six combinations of wavelength composition and background luminance, there is a marked curvilinear relationship between discomfort ratings and the logarithm of irradiance (note that the horizontal axis of Figure 5 is logarithmic). This is surprising in light of much previous work in which the relationship has been found to be linear, including the modeling work of Schmidt-Clausen and Bindels (1974).

It is possible that the curvilinear relationships observed here are due to ceiling effects caused by the way subjects use the de Boer scale. Perhaps at low levels of irradiance subjects would have liked to report even less discomfort (higher numbers) than they did, but the scale did not permit it. Support for this idea can be seen in Figure 6, which shows the data from the 480-nm, dim-background condition of the current study along with data from our previous study on this topic, which included discomfort glare ratings to 480-nm stimuli (Flannagan et al., 1989). The previous data are from the younger of two groups used in that study. That group was comparable in age to the subjects of the current study. They made discomfort ratings using the same scale, and background brightness was the same as the dim level of the current study. As can be seen in the figure, the four levels of irradiance used in the previous study were about one and a half $\log_{10}$ units higher than in the current study. At those higher levels, subjects' ratings are close to the lower numerical limit of the scale, and show an opposite curvilinear relationship with the logarithm of irradiance—what could be called a floor effect in contrast to the ceiling effect observed at lower irradiance values.

In order to develop the analysis of wavelength effects presented below, we summarized the data in Figure 5 by equations that expressed discomfort ratings as continuous functions of irradiance. We chose to use linear equations and to drop the lowest irradiance level of each wavelength composition, thus greatly reducing the apparent ceiling effect. This is partly justified by the simplicity of following previous work that has indicated linear relationships between irradiance and discomfort; and also by the fact that these equations were applied only in the middle range of discomfort ratings, where the relationships appeared to be approximately linear. We performed linear regressions of discomfort ratings on the logarithm of irradiance for each combination of wavelength composition, background luminance, and subject (always excluding the lowest of the four irradiance levels). The linear fits were very good. Figure 7 shows a histogram of the 30 r^2 values for those models.

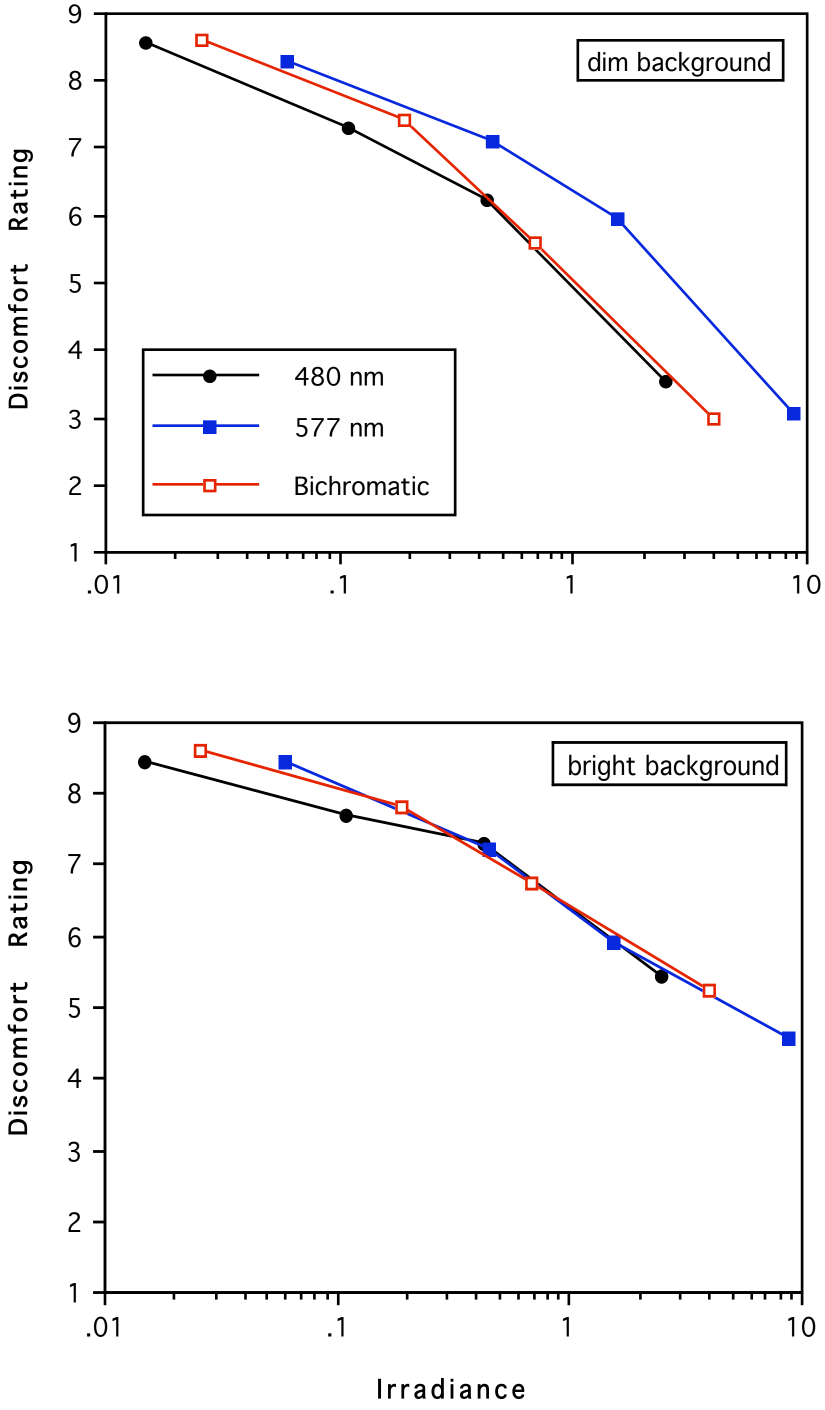

Figure 5. Mean discomfort ratings (de Boer scale), over all five subjects, as functions of irradiance at the subjects' eyes (mW/m^2) for each wavelength composition. Results are shown separately for the dim background (0.034 cd/m^2, top panel) and for the bright background (3.4 cd/m^2, bottom panel).

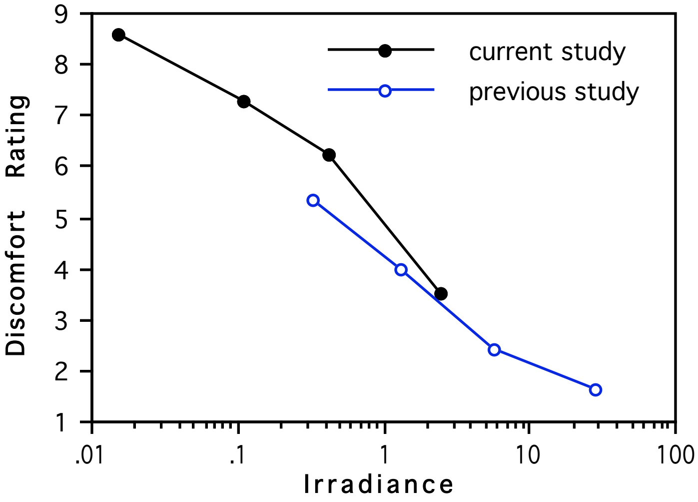

Figure 6. Discomfort ratings for 480-nm stimuli as a function of irradiance at the subjects' eyes (mW/m^2). Note that the vertical axis shows the full range of ratings allowed by the de Boer scale (i.e., 1 to 9). Data from the current study are those from the dim-background condition. Data from the previous study are from the younger of two age groups used in that study. See text for details.

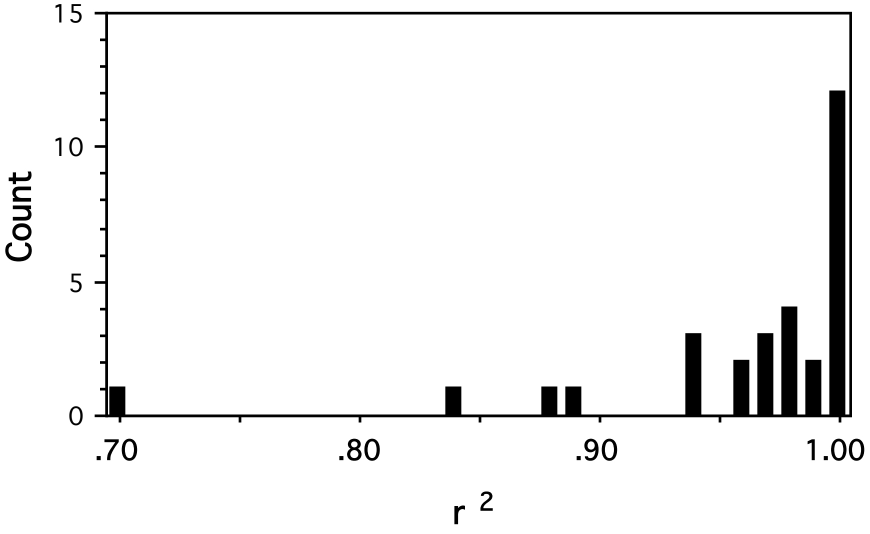

Figure 7. Histogram of r^2 values for models of discomfort ratings as linear functions of the logarithm of irradiance. Models were fit individually for each combination of glare-source wavelength composition, background luminance, and subject (3 X 2 X 5, yielding 30 models in all).

Each of the 30 linear models thus obtained was then used to calculate the irradiance value that should have produced a de Boer rating of 6.0 (a value chosen to be approximately in the middle of the range of the actual ratings that were used to estimate the parameters of the equations). This allows us to compare the physical intensities of stimuli that, according to the models, would give rise to the same sensory response. (See Marks, 1988, for a more detailed discussion of this type of modeling in psychophysics.)

The 30 calculated irradiance levels are summarized in Figure 8 and Table 3, averaged over the five subjects. Values are shown for each combination of wavelength composition and background luminance. An analysis of variance yielded significant effects of background, $F(1,4) = 1.53$, $p < .05$; wavelength composition, $F(2,8) = 9.03$, $p < .01$; and the interaction of background and wavelength composition, $F(2,8) = 2.65$, $p < .01$. The effect of background is such that, when background luminance is increased, it takes more glare irradiance to produce the same level of discomfort. This effect is in agreement with previous findings (Schmidt-Clausen & Bindels, 1974).

The effect of wavelength composition is primarily that considerably more irradiance is required for 577-nm stimuli than for either 480-nm or bichromatic stimuli to produce equal discomfort levels, and the character of the interaction is such that this difference is strongest at low background brightness. At the brighter background level there is little effect of wavelength composition.

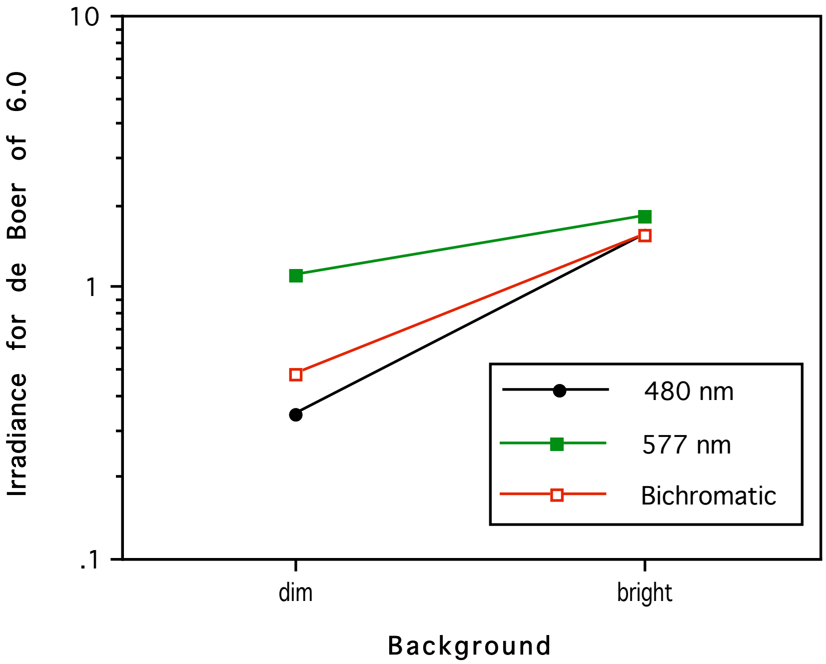

Figure 8. Irradiances (mW/m^2) needed to evoke de Boer ratings of 6.0 for each combination of background and wavelength composition. Irradiances are based on linear models for the relationship between discomfort rating and log irradiance, fitted for individual subjects (see text for details). The numerical values for this graph are given in Table 3.

Table 3

Irradiances (mW/m^2) needed to evoke de Boer ratings of 6.0 for each combination of background and wavelength composition. Irradiances are based on linear models for the relationship between discomfort rating and log irradiance, fitted for individual subjects (see text for details).

	Wavelength composition		
Background condition	480	577	bichromatic
dim	0.343	1.114	0.478
bright	1.574	1.824	1.567

Glare efficiency of monochromatic stimuli

The data in Table 3 can be used to generate two points on an action spectrum for discomfort glare, i.e., the efficiency of light for producing discomfort glare as a function of wavelength. Such a function is analogous to $V(\lambda)$ or $V'(\lambda)$, the luminous efficiency functions for photopic and scotopic vision. Each of these functions describes the effect of light of varying wavelength on a particular human response. For the luminous efficiency function that response can be described generally as brightness, which is actually measured in several specific ways (Le Grand, 1972). For the new function the response is the rating of discomfort glare, a sensation that can be distinguished (at least formally) from brightness.

In order to construct an action spectrum, stimuli that differ in wavelength are equated in their sensory effects and their physical magnitudes are compared. (In the present case physical magnitudes were never actually adjusted to produce equal sensory effects, but the regression analysis permits us to infer what physical magnitudes would be perceived as equal.) The ratio of the efficiencies of two perceptually matched stimuli is then the inverse of the ratio of the physical magnitudes required to achieve the match. It is convenient to assign the value 1.0 to the efficiency of the wavelength at which the least physical magnitude is required. Other efficiency values are then scaled so that they are expressed as proportions of the maximum efficiency. For example, if three times as much physical magnitude is required at a particular wavelength to produce the same sensory effect as produced by a certain amount of the most efficient wavelength, then the efficiency of the less efficient wavelength is 0.33.

Table 4 shows the discomfort glare efficiencies for each of the monochromatic stimuli at each background luminance. These efficiencies were calculated from the irradiances in Table 3 simply by taking the inverses of the irradiances and dividing all four results by the maximum inverse value. That maximum was for the 480-nm stimulus with a dim background (the condition that required the lowest irradiance to produce a de Boer value of 6.0). The discomfort glare efficiency for that condition is therefore 1.0, and all other efficiencies are less than 1.0.

Table 4

Relative discomfort glare efficiencies for each combination of background and single wavelength. The maximum efficiency measured in this experiment (at 480 nm with the dim background) has been set arbitrarily to 1.0 and the other values are scaled as fractions of that maximum efficiency.

Background condition	Wavelength	
	480	577
dim	1.000	0.308
bright	0.218	0.188

It should be noted that assigning the value of 1.0 to the most efficient of the conditions tested here is arbitrary and is done only for convenience in comparing the values. There is no reason to believe that the small set of conditions tested here included the wavelength (or background luminance) in which discomfort glare would be produced with maximum efficiency. In contrast, the CIE definitions of scotopic and photopic luminous efficiency were based on sets of data that comprehensively tested the effects of wavelength on luminance. Scotopic and photopic luminous efficiency were found to peak at 507 and 555 nm, respectively; and the functions *V'*(□) and *V*(□) were scaled so that they would have maximum values of 1.0 at those points.

Figure 9 shows the efficiencies from Table 4 in a form that makes it easy to compare the relative efficiencies of the 480- and 577-nm stimuli at each background level to the relative efficiencies predicted by the scotopic and photopic luminous efficiency functions. Efficiency at 480 nm is plotted on the horizontal axis and efficiency at 577 nm is plotted on the vertical axis. The slope of the resulting vector gives a graphic indication of the relative efficiency at each background level. The dotted lines show the locations where relative discomfort glare efficiencies would match relative luminous efficiencies defined by *V'*(□) and *V*(□). The values of *V'*(□) at 480 and 577 nm are 0.793 and 0.1436, respectively, yielding a slope of 0.181. The values of *V*(□) at 480 and 577 nm are 0.1390 and 0.8983, respectively, yielding a slope of 6.46.

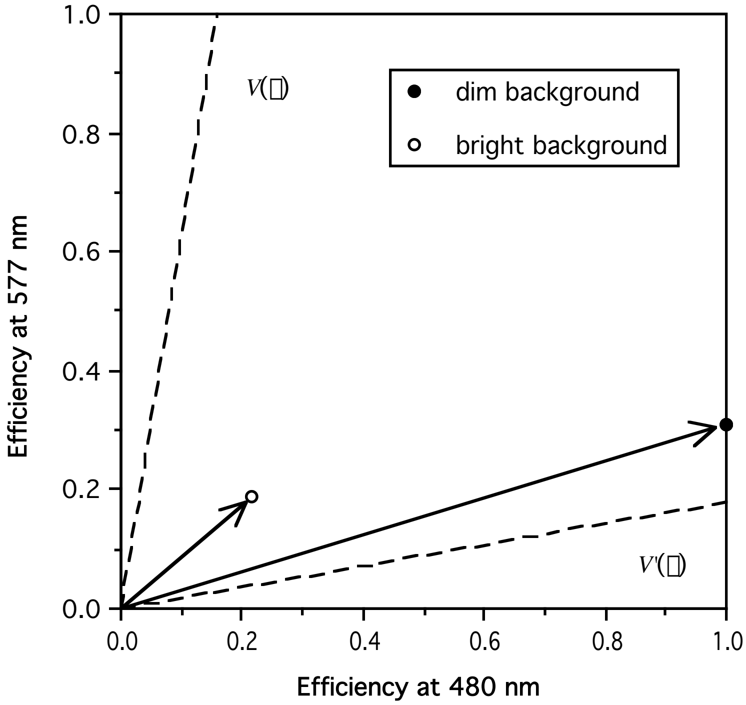

Figure 9. Relative glare efficiencies for producing discomfort glare of stimuli at 480 nm and 577 nm. Two dashed lines based on the relative photopic and scotopic luminous efficiencies at 480 nm and 577 nm are plotted for comparison. For graphing purposes the values of glare efficiency have been arbitrarily scaled so that the maximum value measured in this experiment (efficiency at 480 nm with the dim background) is 1.0. When the background is dim, relative discomfort glare efficiencies are roughly in agreement with scotopic luminous efficiencies. When the background is brighter the discomfort glare efficiencies shift toward, but do not reach, the photopic luminous efficiencies. See text for details.

Note first that the vector for the bright background is shorter than the one for the dim background. This reflects the fact that the glare light required to produce a particular de Boer rating is greater (i.e., discomfort glare efficiency is lower) when the background is brighter. The most important aspect of Figure 9, however, is the correspondence between the slopes of the vectors representing the data and the slopes of the lines based on $V'(\lambda)$ and $V(\lambda)$. Note that when the background is dim the relative-efficiency vector lies close to the $V'(\lambda)$ line. The slope (577-nm efficiency divided by 480-nm efficiency) is 0.308. This is consistent with the results of our previous study, in which the effect of wavelength on glare with a dim background was similar to scotopic luminous efficiency. For the brighter background the vector is about halfway between the $V'(\lambda)$ and $V(\lambda)$ lines. The slope is 0.862, which is fairly close to 1.0, indicating that when the background is at the brighter level (3.40 cd/m^2) the 480-nm and 577-nm are about equally efficient in producing discomfort glare.

This shift toward predictions based on the photopic luminosity function is qualitatively consistent with what would be expected if discomfort glare was related to luminosity. As noted in the Introduction, there are no conventionally established luminous efficiency functions for the mesopic region. However, some work by Kokoschka (cited in Wyszecki & Stiles, 1982) suggests that with increasing luminance in the mesopic region (luminances ranged from 0.001 to 10.0 cd/m^2) there is a reasonably smooth shift from performance in agreement with the scotopic luminous efficiency function to performance in agreement with the photopic luminous efficiency function. The present data show a qualitatively similar shift in that performance with the dim background is similar to scotopic luminous efficiency and performance with the brighter background is between scotopic and photopic luminous efficiency.

However, note that Figure 1 indicates that the present dimmer background is roughly in the middle of the mesopic range of vision, and that the brighter background is fully in the photopic range. As noted earlier, the limits for the ranges of vision used in Figure 1 are not firmly established; but based on those limits the simplest prediction would be that the dim background should yield performance somewhere between scotopic and photopic predictions, and the brighter level should yield fully photopic performance. In contrast, the present results are closer to what might have been expected if the two background luminances had been at the low end and at the middle of the mesopic range. Further research could more fully explore the effect of background luminance and perhaps determine the cause of this discrepancy. It would be of at least academic interest, for example, to determine whether even higher background luminances, above the range usually encountered in night driving, would yield a discomfort glare efficiency function in full agreement with the photopic luminosity function.

Figure 10 shows the efficiency values from Table 4 plotted in a different way, in order to allow comparison to discomfort glare efficiency values that were derived in a similar way from our earlier study (Flannagan et al., 1989). Figure 10 shows five types of visual efficiency as functions of wavelength: scotopic and photopic luminous efficiency, discomfort glare efficiency at 480 and 577 nm with bright and dim backgrounds (from the present experiment), and discomfort glare efficiency at 480, 505, 550, 577, 600 and 650 nm with the dim background (from the previous experiment). The data from the previous experiment are from the younger of two age groups used in that study. The younger group, which consisted of eight subjects, was similar in age to the group in the present study, ranging from 20 to 29 years old, with an average age of 22.6.

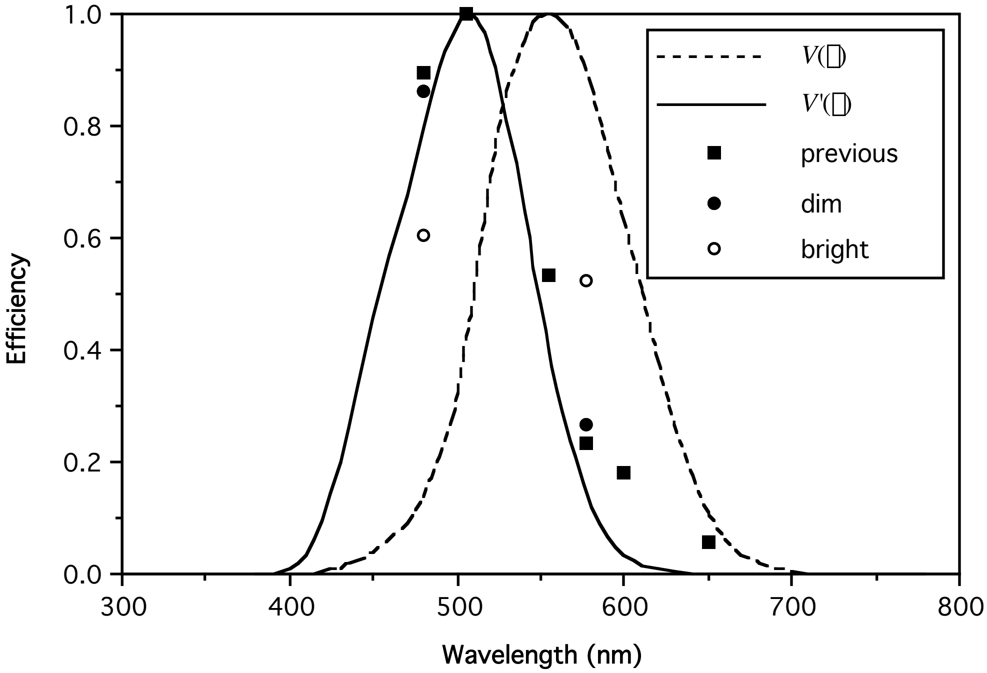

Figure 10. The scotopic and photopic luminous efficiency functions; and three sets of discomfort glare efficiency values: from a previous experiment, and from the dim- and bright-background conditions of the present experiment.

For graphing purposes, an arbitrary scaling factor had to be applied to each of the three sets of discomfort glare efficiencies in Figure 10. In the case of the data from the previous study, we assigned a value of 1.0 to the efficiency at 505 nm. Although it is possible that discomfort glare efficiency with the dim background level actually is maximal at or near 505 nm, we do not mean to make that claim by the way we have scaled the data in Figure 10. It was necessary to make an arbitrary decision about scaling in order to display these data along with the familiar forms of $V(\lambda)$ and $V'(\lambda)$. Although 505 nm is very close to the peak of the $V'(\lambda)$ function at 507 nm (and indeed was chosen for that reason), these data are from only six widely spaced wavelengths and so they cannot establish where discomfort glare efficiency actually peaks. Putting aside the problem of overall scaling, the meaningful aspect of the discomfort glare efficiency values from the previous study is their contour, which closely follows the scotopic efficiency function.

For both the dim-background and bright-background data from the present study, similar arbitrary scaling parameters had to be selected. Because these data are from only two wavelengths, we have even less basis to select a maximum efficiency value. We therefore scaled the present data so that, for each background condition separately, the average of the two glare efficiency values equaled the average of the glare efficiency values for 480 and 577 nm from the previous experiment. As with the previous data, the arbitrary scaling factor is necessary to allow graphing in this form, and it is actually the ratios between pairs of values plotted in Figure 10 which are meaningful. Data from the dim-background condition of the present experiment match the old data reasonably well, and the shift toward photopic performance with a brighter background that was seen in Figure 9 can be seen in a different form in Figure 10.

Predictions for the bichromatic stimuli based on monochromatic efficiencies

Because most practical light sources—including proposed HID headlamps and reflected glare from colored rearview mirrors—involve complex mixtures of wavelengths, it is important to know whether the discomfort glare properties of such sources can be predicted from discomfort glare efficiencies derived from subjects' responses to monochromatic stimuli. In applications of standard photometry it is assumed, usually implicitly, that an analogous form of prediction is valid. The scotopic and photopic luminous efficiency functions are derived from subjects' responses to monochromatic stimuli, but they are routinely applied to complex sources by defining the luminance of a complex source as a simple sum of the luminances of a set of arbitrarily narrow-band components into which it can be divided. Such a definition is valid to the extent that human perception follows the propositions sometimes referred to as Abney's laws (Wyszecki & Stiles, 1982). Under some circumstances, and for certain tasks, human perception does follow Abney's laws; but under other circumstances it does not (Alman, 1977; Richards & Luria, 1964). Among the results most relevant to our present purposes are those of Guth and his coworkers (Guth, Donley, & Marrocco, 1969) who extensively investigated responses of the human visual system to monochromatic and bichromatic lights. They found that responses to mixtures of two wavelengths were usually, though not always, weaker than would be predicted from responses to the component wavelengths presented separately.

The inclusion in this experiment of stimuli that were mixtures of 480- and 577-nm light, balanced to appear white, allows a limited test of whether the additivity implied by Abney's laws holds for discomfort glare. Le Grand (1972) claimed that additivity holds generally in scotopic vision. If so, the similarity of our results for discomfort glare to $V'(\lambda)$ suggests that additivity may hold for glare as well. Assuming simple additivity, the irradiance levels of the 480- and 577-nm stimuli that were required to produce a particular level of discomfort glare can be used to predict the irradiance level of the mixture that should be equally glaring. Specifically, for each row of Table 3 separately, the first two numbers (which are irradiance levels of the monochromatic stimuli corresponding to a discomfort rating of 6.0) can be used to generate a prediction for the irradiance level of the bichromatic mixture which should produce a discomfort rating of 6.0. That number can then be compared with the third value in the row, which is the level of irradiance that corresponded to a discomfort rating of 6.0 according to the actual[1] responses to the bichromatic stimuli.

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[1] Strictly speaking, all of the irradiance values discussed in this section might be referred to as predicted values, because they may never have been actually presented to the subjects. They are

The irradiance levels required for a particular criterion response (in this case a rating of 6.0) can be used to establish equivalent unit amounts for each of the monochromatic stimuli. For example, as shown in Table 3, 0.343 mW/m^2 of the 480-nm stimulus and 1.114 mW/m^2 of the 577-nm stimulus each corresponded to de Boer ratings of 6.0 in the dim-background condition, and thus can be considered equivalent unit amounts. If discomfort glare is additive the criterion response should be produced whenever a unit amount of glare stimulus is presented, even if that unit is composed of a fraction of a 480-nm unit and a complementary fraction of a 577-nm unit. Thus if $E_{e,480}$ and $E_{e,577}$ represent the irradiances of 480-nm and 577-nm radiation combined in a mixture (using the lowercase *e* subscript as a reminder that these are radiometric quantities), that mixture should produce the criterion response whenever

$$\frac{E_{e,480}}{0.343} + \frac{E_{e,577}}{1.114} = 1.0$$

We know that in this experiment the ratio of irradiance components in the mixture was always:

$$\frac{E_{e,480}}{E_{e,577}} = 0.87$$

We can solve these equations for $E_{e,480}$ and $E_{e,577}$. Because those values are the irradiances of the two components of a mixture that has the overall irradiance value needed to produce the criterion response, the prediction for the overall irradiance value will be simply the sum of those components:

$$E_{e,480} = 0.253 \text{ mW/m}^2$$

$$E_{e,577} = 0.291 \text{ mW/m}^2$$

$$E_{e,mix} = E_{e,480} + E_{e,577} = 0.544 \text{ mW/m}^2$$

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all irradiance values that, according to a linear relationship between discomfort and the logarithm of irradiance, correspond to 6.0 on the de Boer scale. To simplify terms we will use "actual" to refer to irradiance values of the white stimulus predicted relatively directly, on the basis of responses to other levels of the white stimulus itself, reserving the term "predicted" for irradiance values of the white stimulus predicted relatively indirectly, on the basis of responses to the monochromatic stimuli.

Applying the same computations to the data from the bright background yields:

$$E_{e,480} = 0.791 \text{ mW/m}^2$$

$$E_{e,577} = 0.909 \text{ mW/m}^2$$

$$E_{e,mix} = E_{e,480} + E_{e,577} = 1.700 \text{ mW/m}^2$$

The actual values for irradiance of the bichromatic stimuli, from the rightmost column of Table 3, were 0.478 and 1.567 for the dim and bright backgrounds, respectively. Both are somewhat less than the predicted values of 0.544 and 1.700, meaning that the effectiveness of the mixture in producing discomfort glare is slightly greater than predicted on the basis of the monochromatic results. Because the amount of discomfort glare that subjects experience has been shown to be linearly related to the logarithm of irradiance (Schmidt-Clausen & Bindels, 1974), it is useful to quantify the difference between predicted and actual values in logarithmic units. For the dim background, the actual value is less than the prediction by a factor of 1.14, or 0.056 $\log_{10}$ units. For the bright background the difference is a factor of 1.085, or 0.035 $\log_{10}$ units. These differences are too small for us to conclude that additivity has been violated. On the other hand, because experimental data always involve at least a small amount of statistical error, it is never possible to prove that additivity holds exactly. By examining the variability across individual subjects in how well prediction works we can determine how much precision these data provide.

We applied the calculations outlined above to the results from each subject in each background condition to obtain individual additive predictions. In Figure 11 those predictions are compared with the actual irradiance values needed to obtain a de Boer rating of 6.0 for the bichromatic stimuli. Each data point in the figure represents one subject in one of the background conditions. Predicted irradiance values are plotted on the horizontal axis, and actual values are plotted on the vertical axis; both on logarithmic scales. If additivity held perfectly, all the points would lie on the diagonal line. If actual values tended to be higher or lower than the additive predictions, the points would generally lie above or below the central diagonal. The fact that the points are centered on the central diagonal is therefore support for additivity. The formally proper statement to make about the data in Figure 11 is that they do not allow us to reject the hypothesis that discomfort glare from the bichromatic stimuli follows additive predictions.

However, there is quite a bit of scatter in Figure 11. This means that a substantial deviation from additivity may exist, but may have escaped detection because of the variability of the data. This uncertainty can be quantified by confidence intervals on the differences between actual and predicted values. On the basis of the between-subjects variability shown in Figure 11, 90% confidence intervals for the differences in $\log_{10}$ irradiance (actual minus predicted) are, for the dim background, -0.192 to 0.085, and for the bright background, -0.238 to 0.198. For example, in the underadditive direction (in which mixtures are less effective than predicted from the individual effects of their components and thus require more irradiance to produce the criterion response) these data allow the possibility that the actual mixture irradiance required exceeds the predicted value by as much as a factor of 1.22 in the case of the dim background and 1.58 in the case of the bright background.

In spite of this fairly wide range of uncertainty, the best estimate based on these data is still that additivity does hold, at least approximately. Therefore it remains reasonable to use additive modeling to make tentative predictions about real-world stimuli with complex spectra. In the next section of this report we discuss such predictions for the case of HID headlamps.

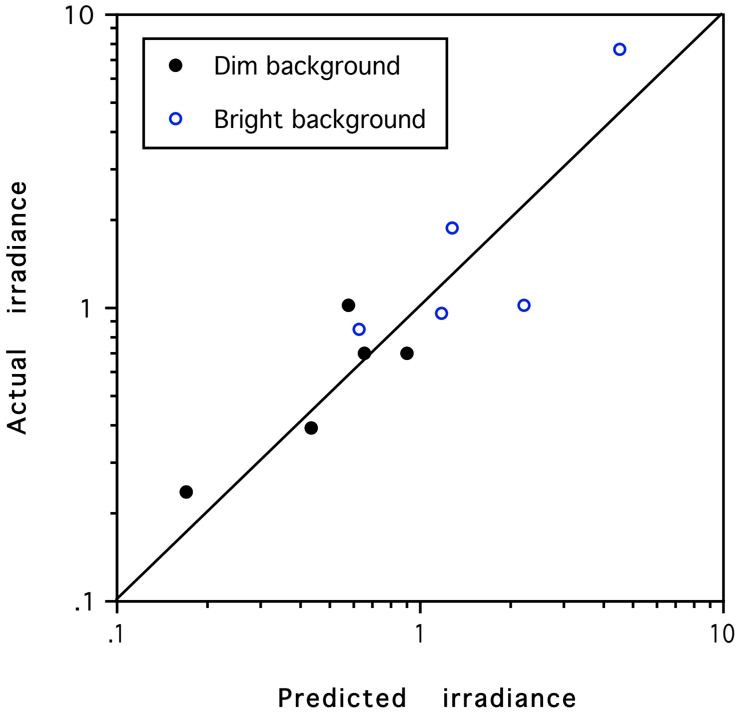

Figure 11. A comparison between actual and predicted values for irradiance by the bichromatic stimuli (mW/m^2) needed to produce a de Boer rating of 6.0. Predicted values are based on responses to the monochromatic stimuli. Actual values are based on responses to the bichromatic stimuli. Values are shown for each of the five subjects in each of the two background luminance conditions. See text for details.

Potential consequences for discomfort glare properties of HID sources

The results of our studies indicate that the discomfort glare properties of a light source are not perfectly predicted by photometry based on the photopic luminous efficiency function. Better prediction can be achieved if the spectral power distribution of the source is weighted by the scotopic luminous efficiency function (or perhaps by a function similar in form to both the photopic and scotopic functions, but lying in between them). When comparisons are made between levels of two or more sources with identical spectra, this difference may not be important. The effect of using a different efficiency function would be simply to change all measurements by a common factor. Thus the ratios of the measurements (which are usually of more importance in psychophysics than simple differences) would be unaffected. Furthermore, measurement of discomfort glare is influenced at least to some extent by the range of stimuli used (Lulla & Bennett, 1981; Olson & Sivak, 1983), so that the meaning of absolute values of measurements is already questionable. The question of what efficiency function to use in measuring discomfort glare therefore may not be crucial when the sources of interest have the same spectra. But when they differ in spectra the choice of an efficiency function can affect even their relative values.

Given two alternative efficiency functions and a set of light sources, it is straightforward to calculate how much of a difference the choice between the functions would make in measurements of the sources. In order to quantify how much discomfort glare might differ from the predictions of conventional, photopic photometry, we made those calculations for a set of spectra of proposed HID lamps, using the scotopic and photopic luminous efficiency functions. Our results do not tell us exactly the proper efficiency function for discomfort glare. We have measured the efficiencies of, at most, six wavelengths at a time; and we know that the proper function depends on background adaptation level, but we do not know exactly what background adaptation level is appropriate to obtain results that are valid for a typical night driving situation. Nevertheless, the evidence does indicate that the glare efficiency function is similar to the scotopic luminous efficiency function, although perhaps modified in the direction of the photopic luminous efficiency function. The scotopic function therefore seemed to us a good choice to use in these calculations. It is defined throughout the range that we needed to do the calculations and it matches our glare results reasonably well. Also, our results suggest that it represents a worst case; that is, the greatest extent to which discomfort glare efficiency may differ from the photopic luminous efficiency of conventional photometry.

The HID spectra that we used are shown in Figures 12 through 19. They include seven spectra that we used in a previous report (Simmons, Sivak, & Flannagan, 1989), referred to there and here as HID-1 through HID-7, as well as the spectrum of a Philips D1 bulb. We also used the spectrum of a tungsten-halogen headlamp, shown in Figure 20.

Table 5 shows the results of calculations involving those spectra. Details of the calculations were as follows: We actually used the scotopic and photopic efficacy functions, illustrated in Figure 21, rather than the efficiency functions. Because actual units (and even dimensionality) do not matter for present purposes, we arbitrarily scaled the power spectra of the sources so that when convolved with the scotopic efficacy function they each yield values of 1.0, as shown in the second column in Table 5. We then convolved the same power spectra with the photopic efficacy function, obtaining the results shown in the third column. Each of those numbers indicates the factor by which measurement in photopic units of a source with the relevant power spectrum would differ from measurement in scotopic units. Note that the values are all less than one. Inspection of Figure 21 shows that this will not be the case for all sources, but it will usually be true if there is substantial power below 555 nm. The fact that photopic values will be smaller for all of the sources considered here is mostly attributable to the greater absolute sensitivity of rods compared to cones, and is not particularly relevant to present purposes. The fourth column of Table 5 was obtained simply by dividing the values in the preceding column by the value for the tungsten-halogen source (0.675). The resulting values thus indicate how much difference the choice of weighting function makes for each source, scaled to the corresponding change for the currently standard headlamp source (tungsten-halogen). The final column gives the common logarithms of those values.

The significance of the numbers in the fourth column is as follows: If discomfort glare is exactly predicted by the scotopic luminosity function, and if an HID and a tungsten-halogen source are set to cause equal discomfort glare, then the number in the fourth column for that HID is the factor by which photopic photometric measurements (e.g. photopic lux at the eye of the observer) for that HID will differ from those of the tungsten-halogen source. For example, if HID-1 were equated with a tungsten-halogen source in terms of discomfort glare, and the tungsten-halogen source were delivering 1.0 photopic lux at the eye of the observer, then we would expect the HID-1 source to be delivering 1.050 times 1.0, or 1.050 photopic lux at the eye of the observer. This would mean that, because of its spectral distribution, HID-1 should cause slightly less discomfort glare than conventional tungsten-halogen headlamps when equated in terms of conventional photopic photometry.

Note that most of the HID sources considered here are similar to HID-1 in that they should be less glaring than tungsten-halogen at equal photopic lux levels. Only one lamp, HID-3, is substantially in the other direction. Perhaps the most important aspect of these numbers, however, is that none of the predicted differences from tungsten-halogen lamps is large. According to the Schmidt-Clausen and Bindels model of discomfort glare (Schmidt-Clausen &

Bindels, 1974), discomfort on the de Boer scale is linearly related to the logarithm of illuminance at the eye. The full equation for the model is:

$$W = 5.0 - 2 \log_{10} \frac{E_B}{C_{poo}\left[1 + \sqrt{\frac{L_U}{C_{pL}}}\right]\theta^{0.46}}$$

where W is a discomfort glare rating on the de Boer scale, E_B is the illumination at the observer's eye point in lux, C_{poo} is a constant equal to 3.0 x 10^{-3} lux $min^{-0.46}$, L_U is the luminance to which the observer is adapted in candelas per square meter, C_{pL} is a constant equal to 4.0 x 10^{-2} cd m^{-2}, and θ is the visual angle in minutes between the glare source and the observer's visual fixation point. Inspection of the equation shows that a change in illumination of the eye of one common log unit should result in a change of two units on the de Boer scale. The values in the rightmost column of Table 5 indicate that the source that should be most different from tungsten-halogen is HID-3, and according to the Schmidt-Clausen and Bindels model that difference should correspond to a difference of 0.288 units on the de Boer scale. The predicted differences for two of the sources correspond to less than one tenth of a de Boer unit: 0.042 units for HID-1, and 0.070 for Philips D1.

Table 5

Relative consequences of photopic and scotopic measurement for a variety of light sources.

Source	Relative scotopic units	Corresponding relative photopic units	Photopic-to-scotopic ratios scaled to t-h	Log_{10} of scaled ratios
Tungsten-halogen	1.000	0.675	1.000	0.000
HID-1	1.000	0.709	1.050	0.021
HID-2	1.000	0.812	1.203	0.080
HID-3	1.000	0.484	0.717	-0.144
HID-4	1.000	0.867	1.284	0.109
HID-5	1.000	0.841	1.246	0.096
HID-6	1.000	0.873	1.293	0.112
HID-7	1.000	0.852	1.262	0.101
Philips D1	1.000	0.623	0.923	-0.035

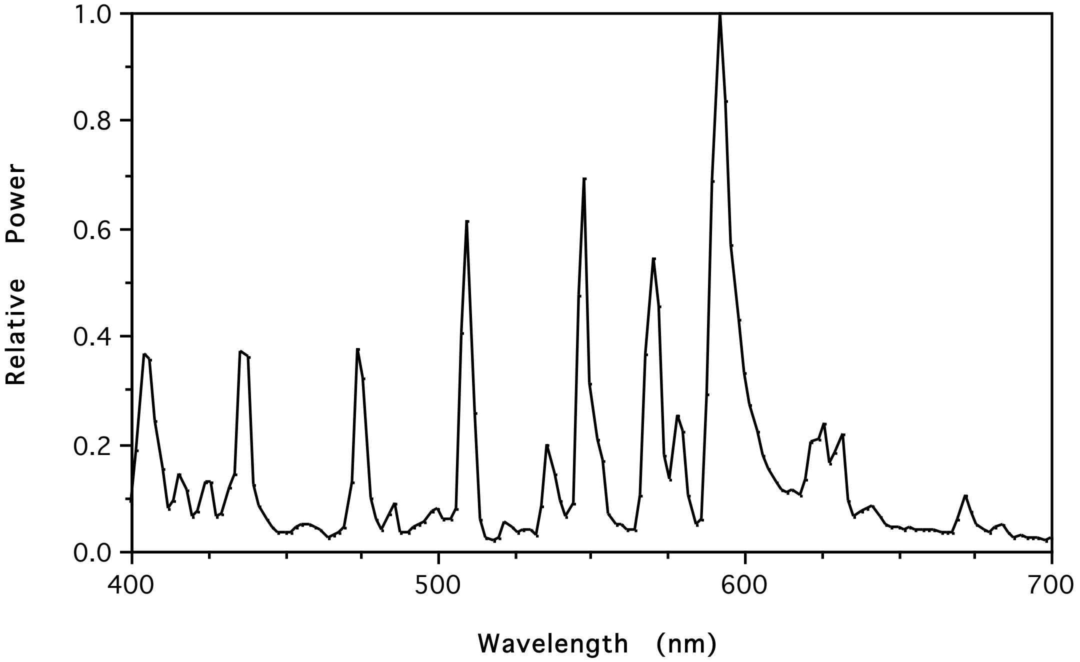

Figure 12. Relative spectral power distribution of HID-1.

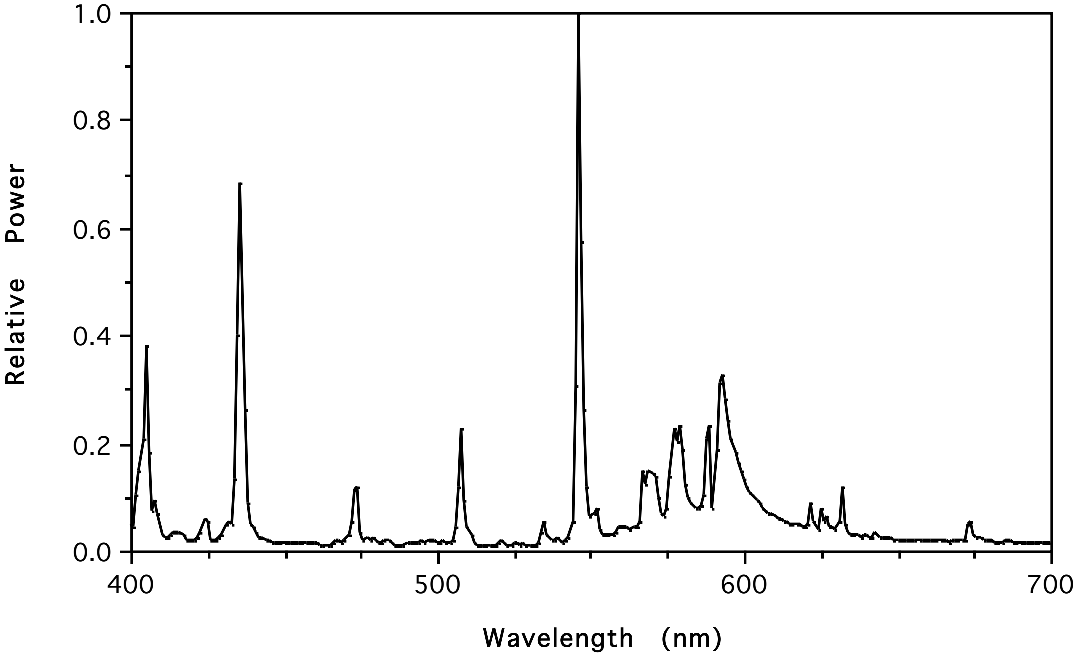

Figure 13. Relative spectral power distribution of HID-2.

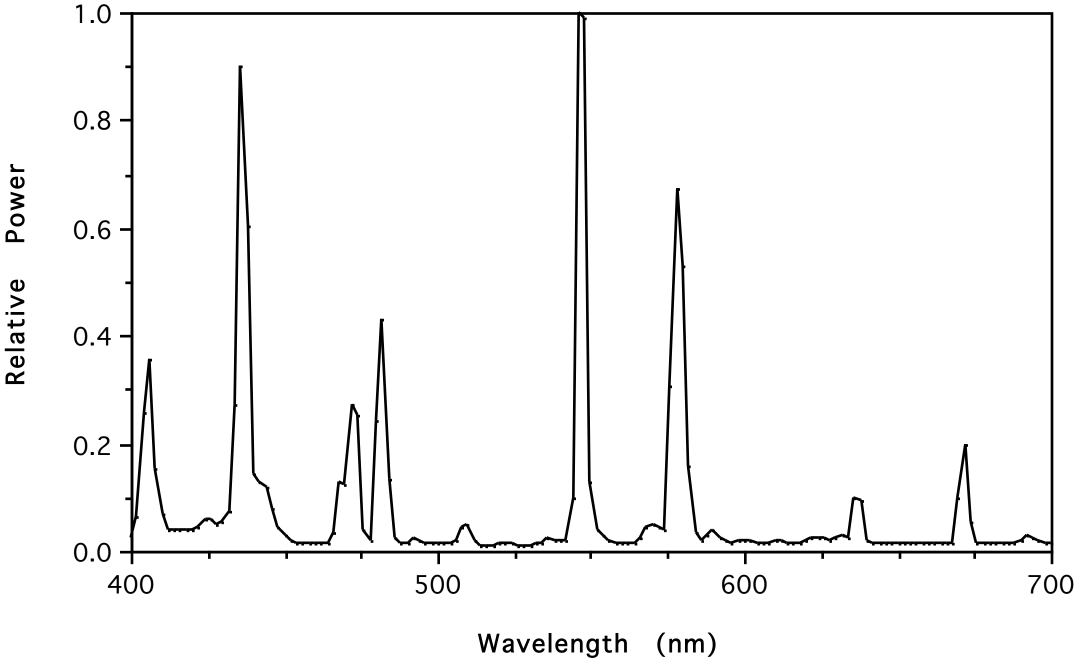

Figure 14. Relative spectral power distribution of HID-3.

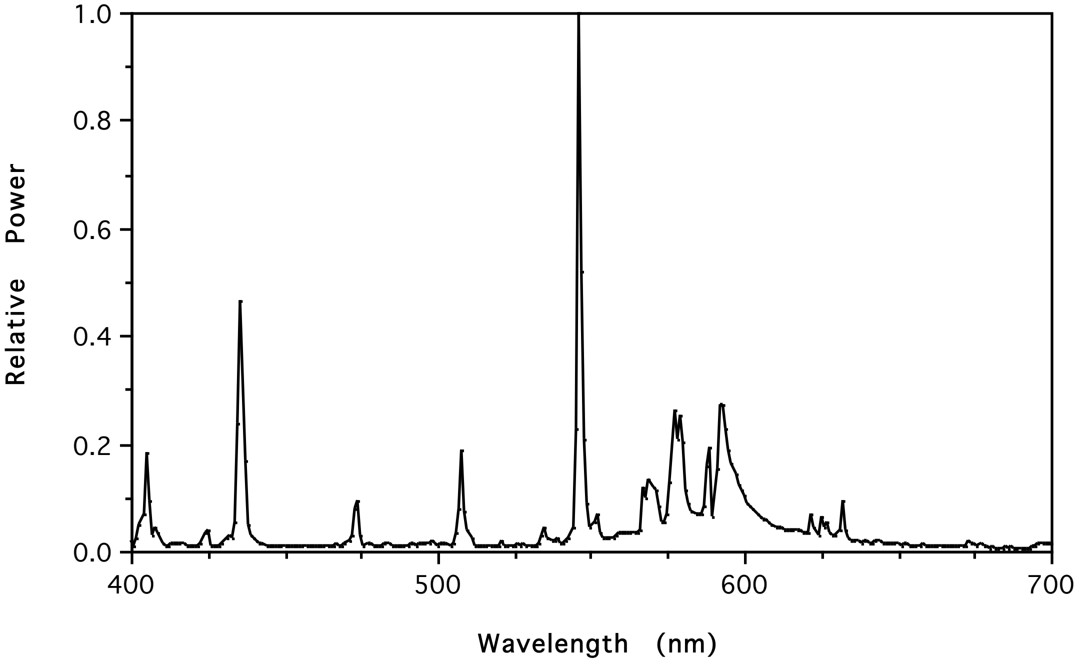

Figure 15. Relative spectral power distribution of HID-4.

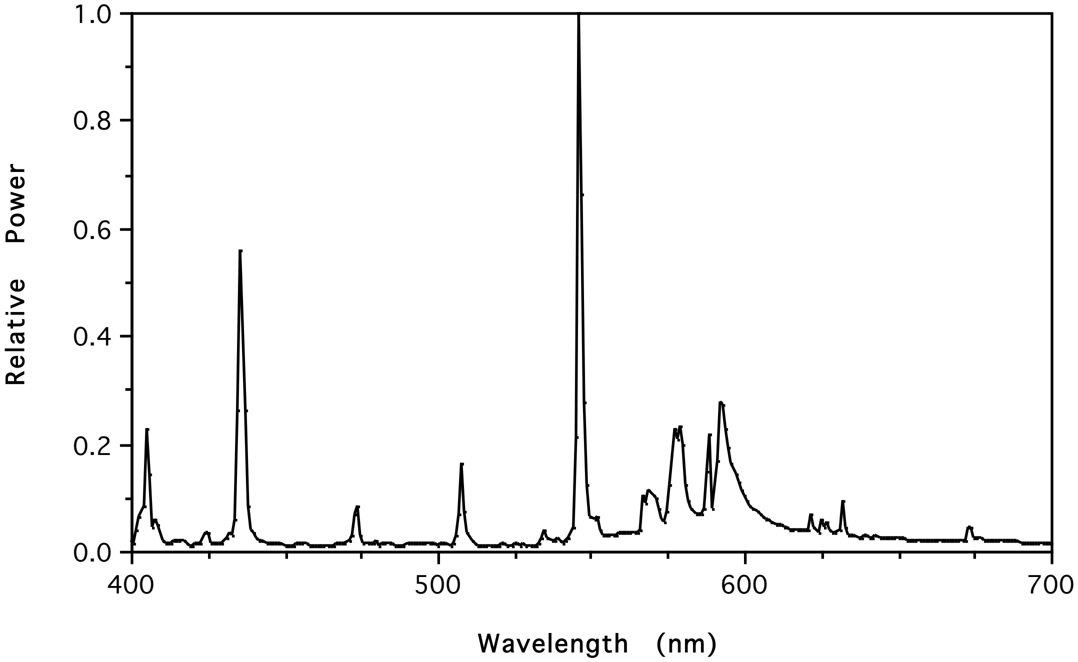

Figure 16. Relative spectral power distribution of HID-5.

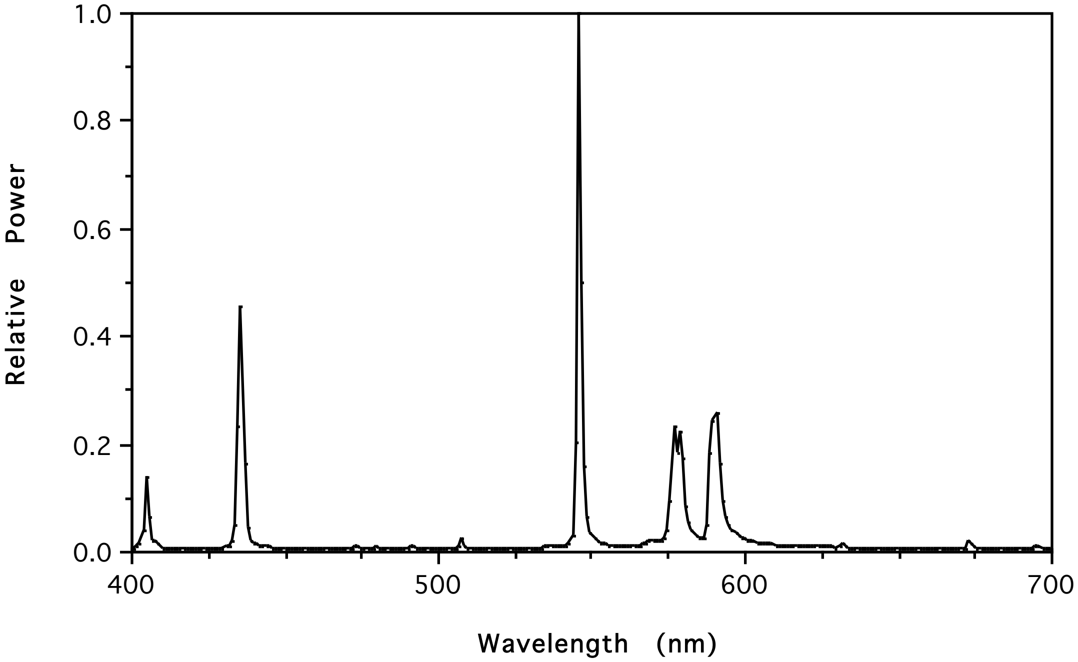

Figure 17. Relative spectral power distribution of HID-6.

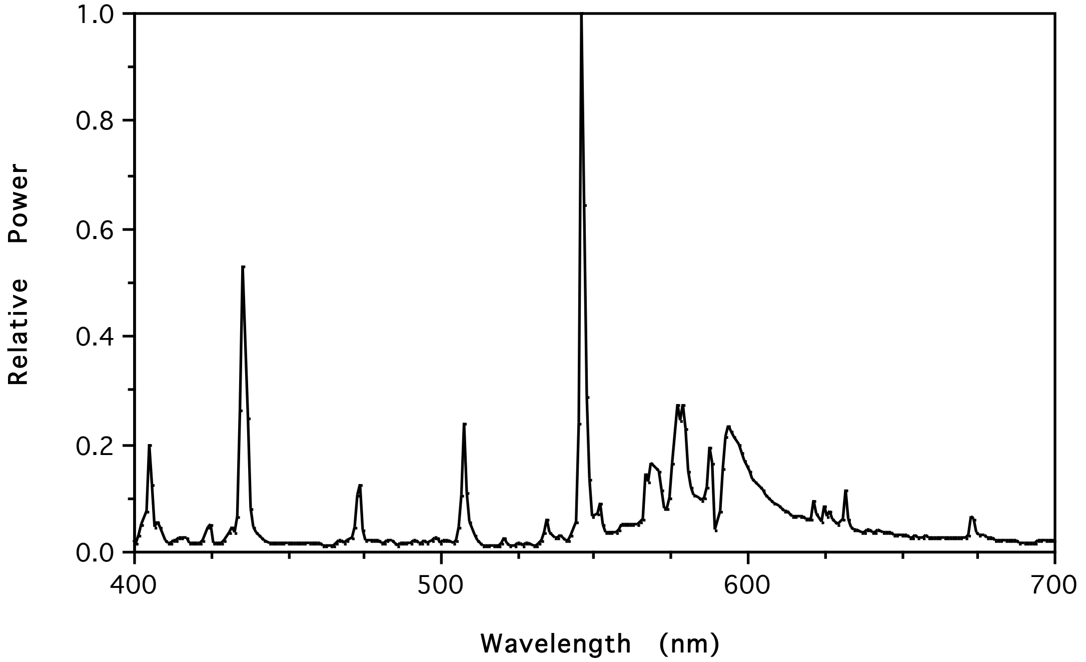

Figure 18. Relative spectral power distribution of HID-7.

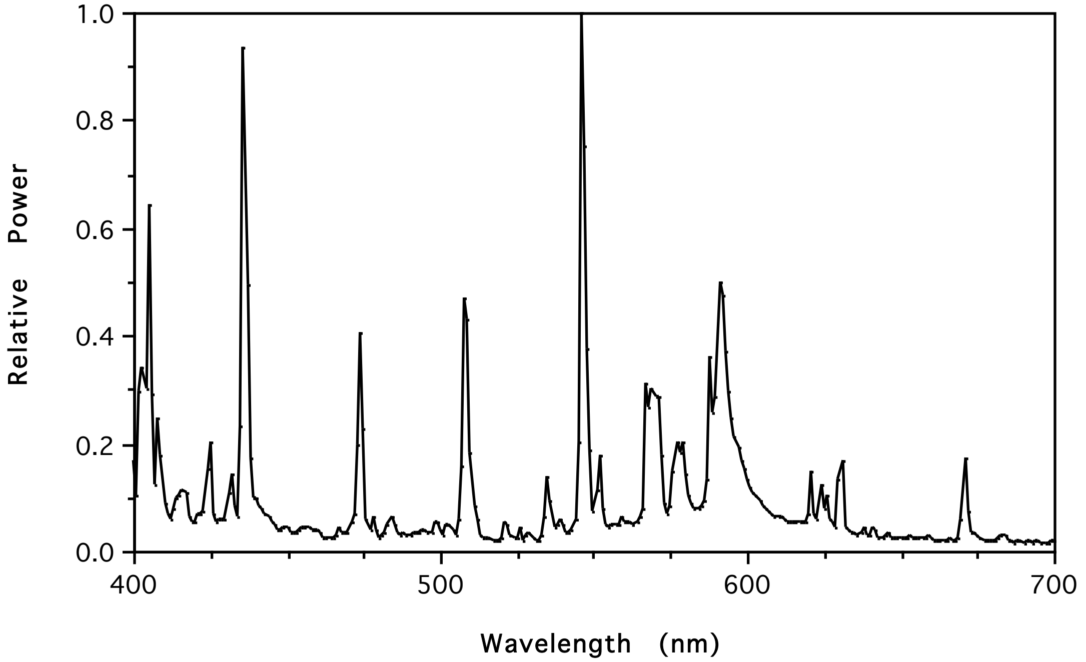

Figure 19. Relative spectral power distribution of Philips D1.

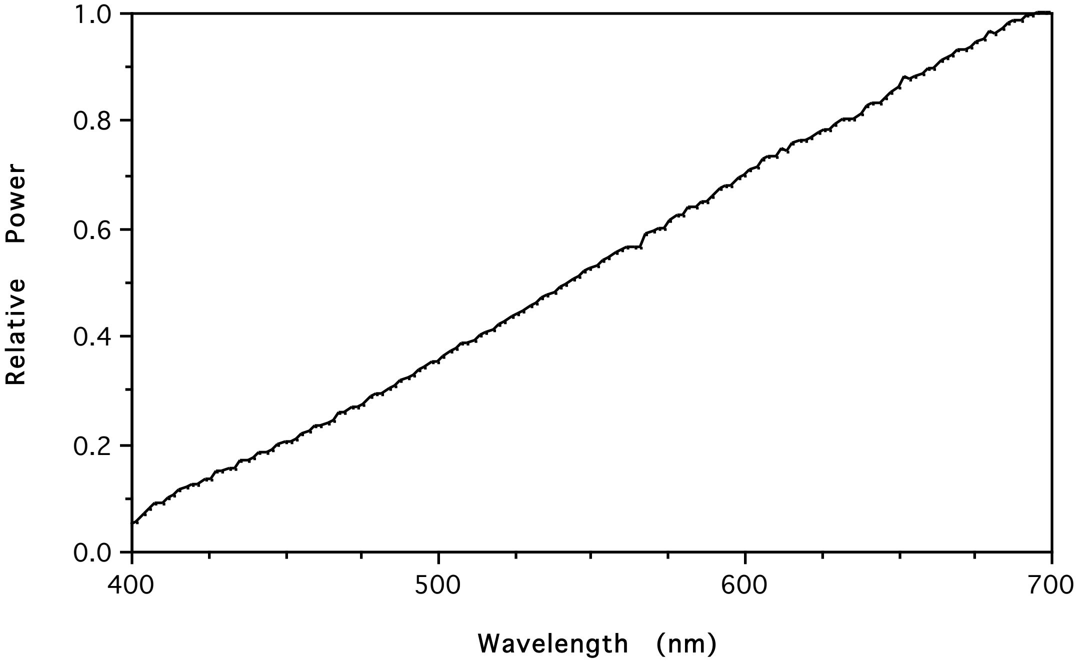

Figure 20. Relative spectral power distribution of a tungsten-halogen bulb.

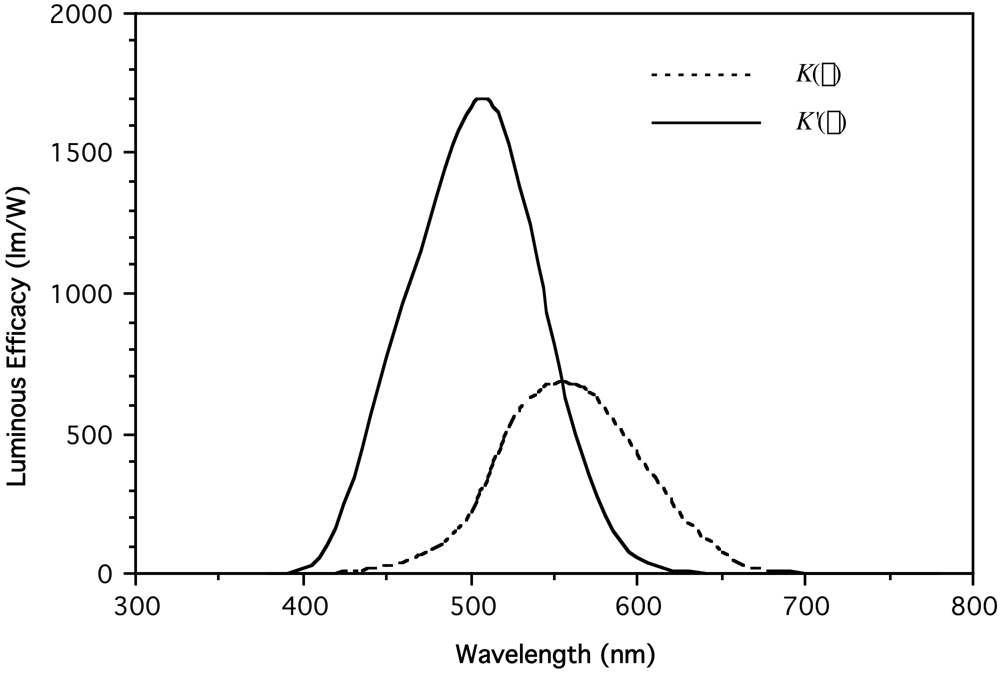

Figure 21. The scotopic and photopic luminous efficacy functions.

SUMMARY AND CONCLUSIONS

The results of the experiment presented here confirm and extend the results of our earlier study of the discomfort glare effects of the wavelength of monochromatic stimuli (Flannagan et al., 1989). As in the earlier study, discomfort glare from monochromatic stimuli differed from predictions based on conventional, photopic photometry. Discomfort glare under dim ambient conditions (0.034 cd/m^2 background) was well predicted by the scotopic luminous efficiency function. At a higher ambient level (3.40 cd/m^2), which may be more representative of the typical night driving environment, discomfort glare appeared to be predicted by a function that lies between the photopic and scotopic luminous efficiency functions.

Under both the dim- and bright-background conditions of this experiment, subjects' discomfort glare ratings for a light source that was a mixture of 480 and 577 nm, and which appeared white, were well predicted by an additive model based on their ratings of the monochromatic components. Although the precision of the data leaves open the possibility that moderately large violations of additivity exist, it is not unreasonable to use discomfort glare ratings of monochromatic stimuli to make tentative predictions about the discomfort glare properties of more complex sources.

Using the scotopic luminous efficiency function as an estimate for the discomfort glare efficiency function, and the Schmidt-Clausen and Bindels (1974) model for discomfort glare, we can make tentative predictions about how de Boer ratings would be affected by any specific design for HID headlamps or colored rearview mirrors. When we generated such predictions for a variety of HID headlamps matched to conventional tungsten-halogen in photopic lux, the predicted differences were not large. The largest difference from tungsten-halogen for the lamps considered here was 0.288 units on the de Boer scale. Interestingly, most of the HID lamps considered here were predicted to be less glaring than a photopically matched tungsten-halogen source. That suggests the possibility that HID sources, with the proper spectral power distributions, could provide some benefit in reducing discomfort glare. But again, the predicted differences were not large.

The goal of this research is to understand and predict the glare properties of innovations such as HID headlamps and colored rearview mirrors in actual driving environments. Our current state of knowledge is limited because the data obtained here were primarily from monochromatic stimuli presented under laboratory lighting conditions. Because the glare properties of complex light sources may not follow the predictions of additive models, and because the state of light adaptation of a typical driver at night may be different from that of the subjects in our experiments, it is important to validate these results under field conditions.

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