UMTRI-89-30

EFFECT OF WAVELENGTH ON DISCOMFORT GLARE FROM MONOCHROMATIC SOURCES

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Report No. UMTRI−89−30
November 1989

Technical Report Documentation Page

1. Report No. UMTRI-89-30	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECT OF WAVELENGTH ON DISCOMFORT GLARE FROM MONOCHROMATIC SOURCES		5. Report Date November 1989 6. Performing Organization Code 302753
7. Author(s) Michael Flannagan, Michael Sivak, Michael Ensing, Carole J. Simmons		8. Performing Organization Report No. UMTRI-89-30
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute Ann Arbor, Michigan 48109-2150 U.S.A.		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address The University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes
As of November 1, 1989 members of the Industry Affiliation Program included GE Lighting, GTE Products Corp., Ichikoh Industries, Ltd., Inland/Fisher Guide Division of General Motors, Koito Manufacturing Co., Ltd., Stanley Electric Co., Ltd., and Valeo Automotive

16. Abstract
New developments in headlighting and rearview mirror technology have increased the need to understand possible effects of color of a glare source on experienced glare. To address this need, a laboratory experiment was performed in which 16 subjects, 8 younger and 8 older, gave numerical ratings of the discomfort glare they experienced from monochromatic stimuli of 480, 505, 550, 577, 600, and 650 nm, which had been approximately equated in lux values.

Results showed strong differences in discomfort glare as a function of wavelength, with minimal discomfort in the middle of the visible range at about 577 nm, and increased discomfort toward both extremes of the visible range. The effect of wavelength was different for young and old subjects.

These results suggest that the proper choice of color for headlamps or rearview mirrors may provide substantial reductions in discomfort glare. However, conclusions must be tentative because most practical stimuli will have complex, rather than monochromatic, spectra. Also, the relationship between wavelength and visibility in the night driving environment is uncertain. It probably is not well described by standard photopic photometry. Reductions in discomfort glare are truly beneficial only if they can be accomplished without a compensatory reduction in visibility. If the visibility provided by light sources is affected by wavelength in the same way as glare, then wavelength selection to reduce glare may not be able to provide a net improvement.

17. Key Words glare, discomfort glare, color, wavelength, headlamps, mirrors, headlighting		18. Distribution Statement Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 23	22. Price

Reproduction of completed page authorized

ACKNOWLEDGEMENTS

Appreciation is extended to the current members of the University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety for support of this research:

GE Lighting
GTE Products Corp.
Ichikoh Industries, Ltd.
Inland/Fisher Guide Divisions of General Motors
Koito Manufacturing Co., Ltd.
Stanley Electric Co., Ltd.
Valeo Automotive

CONTENTS

ACKNOWLEDGEMENTS ii

INTRODUCTION 1

METHOD 4

RESULTS 12

DISCUSSION 18

REFERENCES 20

INTRODUCTION

The issue of how the color of a light source affects its glare properties has been of concern in automotive applications for many years. Much of the past work on the problem has centered on an evaluation of the yellow headlights which have been used in France. Devaux (1956), for example, strongly advocated the use of yellow headlights, claiming that, among other advantages, they produced less glare than white headlights. In a comprehensive review of the relative merits of yellow and white headlights, Schreuder (1976) concluded that yellow headlights had some advantage over white headlights in terms of the discomfort aspects of the glare they produced, but that the difference was probably not of consequence for driving safety. He also concluded that in terms of disability aspects of glare, the effect of glare on an observer's ability to see and respond to visual targets, yellow and white headlights were probably not different.

Recent developments in automotive technology have increased the importance of understanding how color may affect glare. The planned use of high intensity discharge (HID) lamps as headlights is one such development. HID lamps have spectral power distributions that are very different from current tungsten-halogen headlights, and they offer much greater flexibility in headlight color. A second development that motivates gaining an understanding of color and glare is the growing use of rearview mirrors with selective spectral reflectance functions. An understanding of the relationship between color and glare may allow designers to choose HID lamps or mirror colors in such a way as to decrease glare effects while maintaining or increasing visibility levels.

Although there has been previous interest in the effects of color on glare, much of it has been tied to specific light sources (such as the French yellow headlight). In addition, many reports of previous work on this issue have been inadequate in terms of coverage of procedures and photometry. It seemed to us that a new and comprehensive approach to the problem was called for in order to satisfy current needs.

The color of a glare source could affect discomfort aspects of glare, disability aspects, or both. Traditionally these have been considered separable effects (e.g. Holladay, 1926; Hartmann, 1962; Adrian, 1968). This is the first of what we expect will be numerous studies devoted to this general problem, and for several reasons we decided that discomfort effects should be the first subject of our laboratory work. First, assessing discomfort involves simpler methods than assessing disability. In order to measure disability, observers must be presented not only with a glare source, but with a visual task for which disability can be measured. When the color of the glare source is manipulated, the chromatic qualities of the visual task become important, raising further technical questions. In contrast, discomfort has traditionally been measured in a simpler procedure not involving a secondary visual task (however, see Sivak, Flannagan, Ensing, & Simmons, 1989). Second, disability glare may be well accounted for in terms of scattering of light that results in a veiling luminance (Stiles, 1929; Fry, 1955). If that is the case, then color effects on disability glare should be predictable with a simple physical model provided that the colors of the targets of interest are known. This suggests that, in order to design a study of the effects of color on disability that would be of value for driving safety applications, a comprehensive survey of the colors of important highway targets would be necessary. Third, previous evidence, while inconclusive, suggested that wavelength effects were more likely for discomfort than for disability aspects of glare (Schreuder, 1976).

We decided to vary color in this experiment using a series of monochromatic lights across the visible spectrum. Although monochromatic sources are not realistic candidates for use as headlamps, this seemed a good approach for an initial study because it achieved the simplest possible manipulation of color, and because it allowed for future work to test predictions of the glare properties of lights with more complex spectral power distributions by additive models based on responses to the monochromatic stimuli.

In order to measure the effects of wavelength itself on glare it is necessary to vary wavelength while equating stimuli in all other respects. One way in which stimuli could be equated would be to adjust stimuli of all wavelengths to have equal radiometric levels. However, it is well known that the human visual system does not respond with equal strength across the visible spectrum. Human vision is much more sensitive in the middle of its range than at the extremes, as characterized, for example, by the CIE luminous efficiency function. That suggests a second option, which is to equate stimuli of different wavelengths in terms of their photometric levels. Unfortunately even that option is not completely satisfactory because the measurement of photometric levels must be based on one particular weighting of the influence of different wavelengths. Typically that weighting is the 1924 CIE luminous efficiency function, and that option is useful for many applications of photometry. However, the standard CIE function is not appropriate for all cases, especially when lower light levels and rod vision may be important (Kinney, 1967). We nevertheless chose the CIE function as a adequate default basis for equating our stimuli, reasoning that however discomfort glare varied as a function of wavelength, it would probably follow the CIE function reasonably closely. We also varied the glare stimulus levels at each wavelength over three orders of magnitude to insure that we would get a good assessment of glare effects even if they departed markedly from the CIE function.

METHOD

Subjects

Sixteen subjects—four older males, four older females, four younger males, and four younger females—participated in this study. The ages of the eight younger subjects ranged from 20 to 29 with a mean of 22.6, and the ages of the eight older subjects ranged from 60 to 78 with a mean of 67.8. The subjects were paid for their participation. All subjects had color vision that was normal by the standards of a simple test using 6 Ishihara Pseudo-Isochromatic Plates (Titmus Vision Tester, Model OV7-M, Test 5).

Tasks

The subjects were asked to perform two simultaneous tasks. 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 presented on a television monitor. Deviations of the road's center were based upon a mixture of sine waves generated so that the road appeared to be curving in an unpredictable manner. The subject's task was to keep the road centered on the screen by use of a steering wheel.

Equipment

Schematic diagrams of the experimental set-up and the subject's view are shown in Figures 1 and 2. The subject was seated in a mock-up of a 1985 Chrysler Laser. Directly in front of the subject, at a distance of 3.96 m, there 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 mock-up. The glare source was 2.69 m from the subject and 7 degrees of visual angle to the right of the center of the monitor screen. The glare source consisted of a slide projector fitted with an electromechanical shutter. The intensity and wavelength of the glare were selected by inserting interference filters and neutral density filters into the slide bracket of the projector.

Six interference filters were used, with peak wavelengths at 480, 505, 550, 577, 600, and 650 nm; bandwidths at half maximum ranged from 7.1 to 11.4 nm. The interference filters were mounted on carriers that allowed them to be slipped easily in and

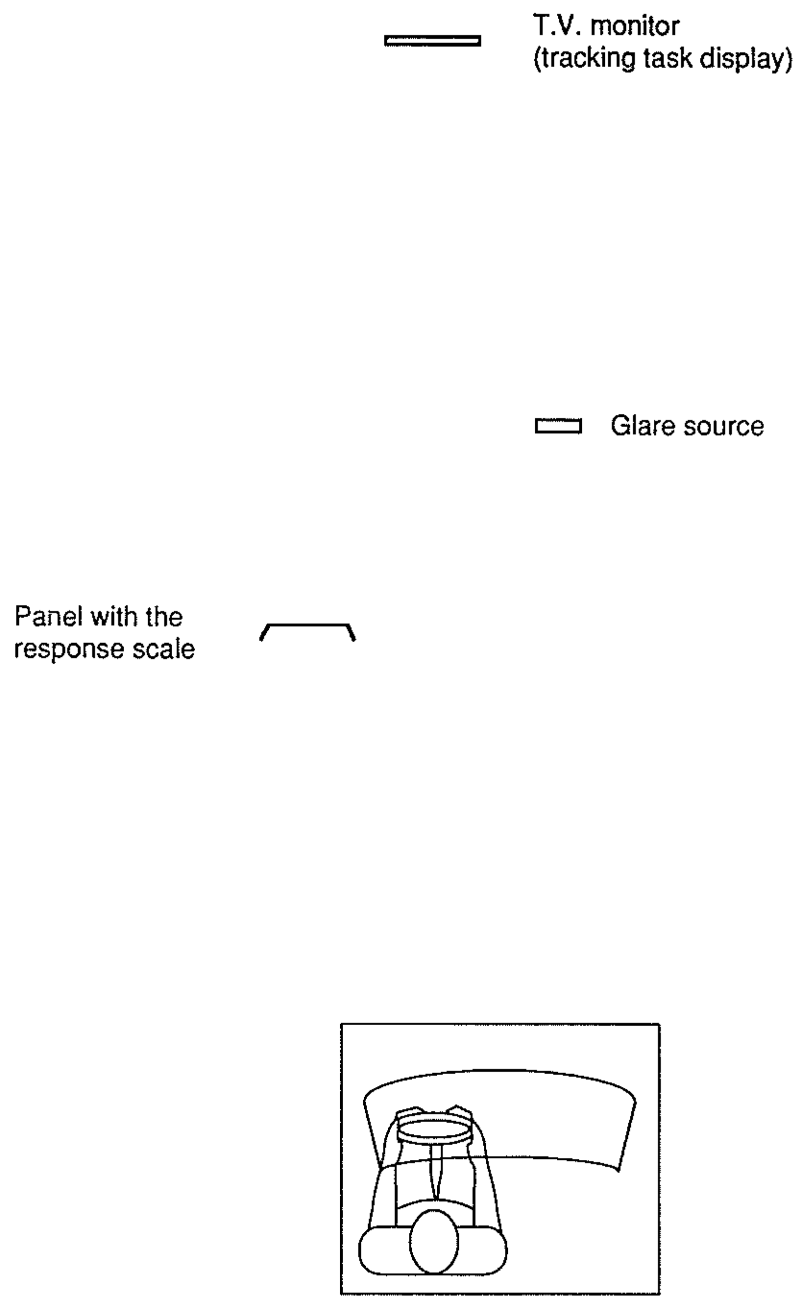

Figure 1. A schematic diagram of the experimental set-up.

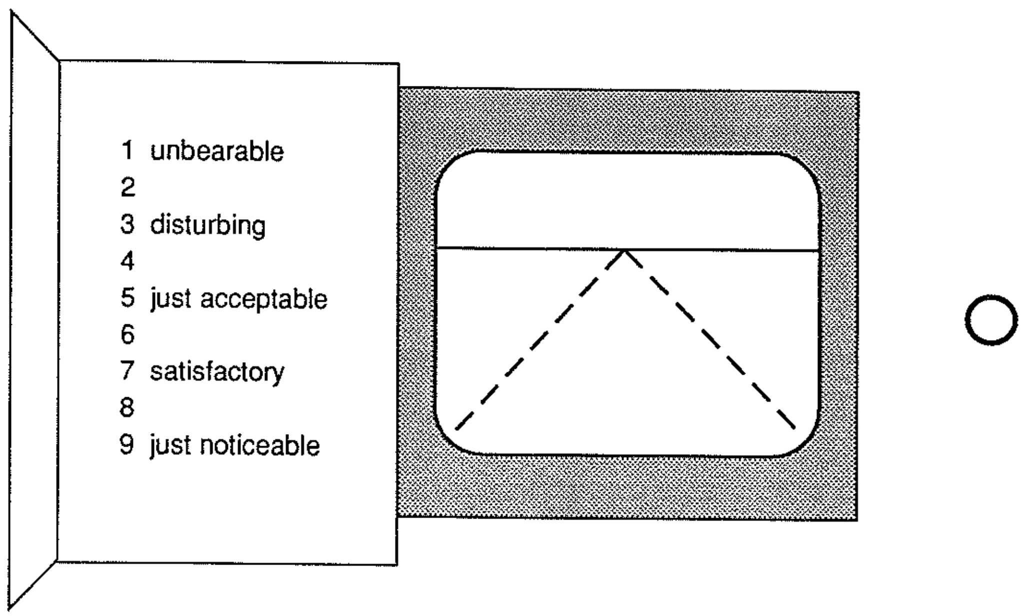

Figure 2. A schematic diagram of the subject's view.

out of the projector's slide bracket. The carriers were also fitted with varying numbers and densities of neutral density filters selected to compensate approximately for the spectral distribution of the incandescent projector lamp and for the profile of the CIE photopic luminous efficiency function. Thus the addition of those neutral density filters resulted in approximately equal light intensities (as measured using the photopic luminous efficiency function) at all wavelengths.

The highest levels of glare were produced by inserting into the projector only the carriers that held the interference filters and their accompanying compensatory neutral density filters. The lower levels were produced by also inserting one of three additional carriers that held more neutral density filters. These filters were selected to provide four levels of illuminance that would form approximately equal log steps between 0.03 and 3.0 lux.

A large panel with a 9-point rating scale for discomfort glare, printed in black letters on a white background, was posted at a distance of 2.0 m from the subject. The letters were 1.9 cm high and subtended approximately 33 minutes of arc. This chart was offset so that it appeared to the left of the monitor screen.

Ambient illumination was provided by a 25 W lamp positioned behind a set of baffles on top of the Laser mock-up so that most of the subject's field of view was illuminated indirectly by light scattered from the rear part of the room. From the subject's viewpoint, the rating scale, monitor, and glare source were all seen against a background of white cloth that was roughly homogeneous.

Photometry

The actual glare stimulus illuminances resulting from each combination of filters were measured at the eye point of the subject with a Pritchard photometer (Model PR-1980A) equipped with an IB-80 illuminance baffle. Measurements were taken using the filter supplied with that instrument that was designed to match the spectral response of the CIE photopic luminous efficiency function. Values were then corrected for the slight deviations of the filter from the true luminous efficiency function based on a calibration of the filter at 10 nm intervals performed by Photo Research. For this correction it was assumed that the stimuli were monochromatic at their peak wavelengths. The actual bands were sufficiently narrow that this approximation is reasonable.

The lux values produced at the subject's eyepoint by each combination of the six interference filters (with accompanying compensatory neutral density filters) and the three additional neutral density filters (including no additional filter for the highest illuminance levels) are given in Table 1. Corresponding irradiance levels, calculated from the illuminance levels, are given in Table 2. As can be seen in Table 1, the actual stimulus values deviated somewhat from the ideals of equal lux values across wavelengths and equal log steps between illuminance levels. For simplicity, we will discuss the manipulation of illumination in terms of four nominal illuminance levels corresponding to the columns of Table 1, but it should be remembered that the actual illuminance levels are not identical for all wavelengths. Because of the practical difficulty of equalizing illuminance values exactly, we decided to equate them approximately and then assess the effect of wavelength for a constant illuminance value by means of a regression analysis that is described in detail below.

Three widely separated points on the background areas of the subject's field of view were photometered to assess the ambient conditions. The luminances and chromaticity coordinates of those points are presented in Table 3. The average of the luminance values is 0.034 cd/m^2.

At the beginning and end, and sometimes in the middle, of each day's data collection, glare illuminance levels and background luminance levels were checked. Over the course of data collection all of these measurements had coefficients of variation (standard deviation divided by the mean) under 0.045 and the mean coefficient of variation was 0.023.

Response scale

Subjects were asked to use a 9-point scale for their assessment of discomfort glare. This scale, which is a minor modification of a scale used by de Boer (1967), has qualifiers only for the odd points as follows: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (just noticeable).

Table 1
Photopic illuminance values (lx) at the subject's eyepoint.

Wavelength	Nominal illuminance level			
	1	2	3	4
480	0.0307	0.124	0.546	2.67
505	0.0359	0.145	0.639	2.96
550	0.0380	0.151	0.666	3.03
577	0.0404	0.162	0.697	3.19
600	0.0371	0.149	0.655	2.99
650	0.0408	0.168	0.734	3.26

Table 2
Irradiance levels (mW/m^2) at the subject's eyepoint.

Wavelength	Nominal irradiance level			
	1	2	3	4
480	0.323	1.310	5.75	28.13
505	0.129	0.520	2.30	10.64
550	0.056	0.222	0.98	4.46
577	0.066	0.264	1.14	5.21
600	0.086	0.346	1.52	6.94
650	0.558	2.293	10.04	44.57

Table 3
Luminance and chromaticity coordinates for three background points.

Luminance (cd/m^2)	Chromaticity coordinates	
	x	y
0.045	0.50	0.43
0.024	0.49	0.42
0.033	0.49	0.43

Procedure

Subjects were tested individually. After the subject was seated in the automobile mock-up, the overhead fluorescent lights that normally illuminated the laboratory were turned off, leaving the low level of incandescent 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 while doing the tracking task they would periodically see brief (2 second) flashes of colored 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 10 seconds.

Each subject was given 120 experimental trials, presented in 5 blocks of 24 trials. Each block consisted of a full set of the 24 combinations of the 6 wavelengths and the 4 illuminance levels in a random order. Subjects were offered short (1–2 min) breaks between blocks. No change in room lighting was made during the breaks.

The intervals between when the room lights were turned off and data collection began, and between the beginning and end of data collection, varied slightly across subjects. The interval before data collection began averaged 6.8 min, and data collection itself averaged 31.4 min.

RESULTS

Glare ratings were submitted to an analysis of variance that included the following factors: wavelength, illuminance level, block (the 5 blocks of 24 trials that made up each session, therefore any block effects may reflect effects of time), age of the observer, and sex of the observer. There was no effect of sex of the observer. The mean rating by older subjects (4.42) was somewhat lower that that for younger subjects (5.06), in the direction of greater discomfort for the older subjects, but the effect was not significant, $F(1,8) = 1.57$, $p > .20$. There was no effect of block, $F(4,32) = 0.89$, $p = .48$, and no interaction of block with wavelength, $F(20,160) = .86$, $p = .63$. The possibility of block effects was of interest because subjects' dark adaptation may have continued to change during data collection. However, no effects of such a change were reflected in the glare ratings.

As expected, illuminance level had a strong effect on glare ratings, $F(3,24) = 158.48$, $p < .0001$. Figure 3 shows the means for each nominal illuminance level as a function of log illuminance. The values of illuminance in this graph are the means of actual illuminance levels for each nominal illuminance level in Table 1. Glare ratings were quite linear with log illuminance, with the linear trend accounting for 99.6 % of the variance in mean glare ratings.

The effect of wavelength on glare ratings was also very strong, $F(5,40) = 100.12$, $p < .0001$. The main effect of wavelength is shown in Figure 4. DeBoer ratings are highest (indicating least discomfort) for the 577 nm stimuli, and decrease toward both ends of the spectrum. The lowest DeBoer ratings (greatest discomfort) are given for the 480 nm stimuli.

There was a significant interaction between wavelength and intensity, $F(15,120) = 6.08$, $p < .0001$. The form of the interaction can be seen in Figure 5, which shows average DeBoer ratings for each combination of nominal illuminance level and wavelength. In spite of the significant interaction, the effect of wavelength on glare ratings appears to be about the same at all nominal intensities. A substantial part of the interaction appears to be that the ratings for the highest intensity level (4) are not as low in the short-wavelength region as they might be expected to be from the contour of the wavelength effect at the other three illuminance levels. Because the ratings for short wavelengths at the highest illumination level are near the lower limit of the numbers subjects were permitted to use, the interaction may be largely a floor effect rather than a real aspect of subjects' experience of glare.

Wavelength also had a significant interaction with age, $F(5,40) = 4.18$, $p = .0038$. That interaction is shown in Figure 6. The main effect of age mentioned above can also be seen, though that effect (tested by a relatively large between-subjects error term) was not significant. The effect of wavelength is stronger for the young subjects than the older subjects.

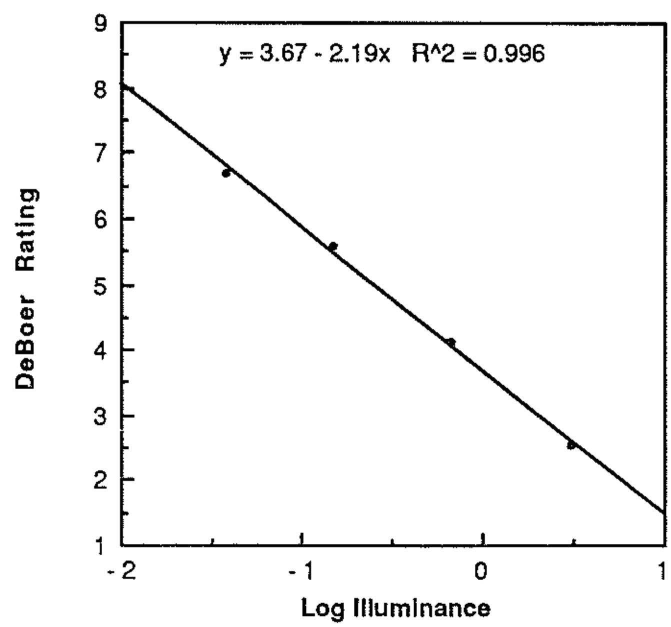

Figure 3. Discomfort glare ratings as a function of log illuminance.

Wavelength effects adjusted for illuminance

The effects of wavelength reported above do not reflect the pure influence of wavelength. This is because the actual illuminance values varied within the nominal illuminance levels as shown in Table 1. The following analysis was performed to assess the pure effect of wavelength.

As shown in Figure 3, mean DeBoer ratings for each nominal illuminance level were linear with the log of the mean luminance for each level. That linear effect also holds when the data are broken down by wavelength and subject. Linear regressions of DeBoer ratings on actual illuminance levels were performed for each of the 16 subjects at each of the 6 wavelengths. All of the data were quite linear; the median percent of variance accounted for by a linear model was 95.3. One of the 96 regressions is shown in Figure 7

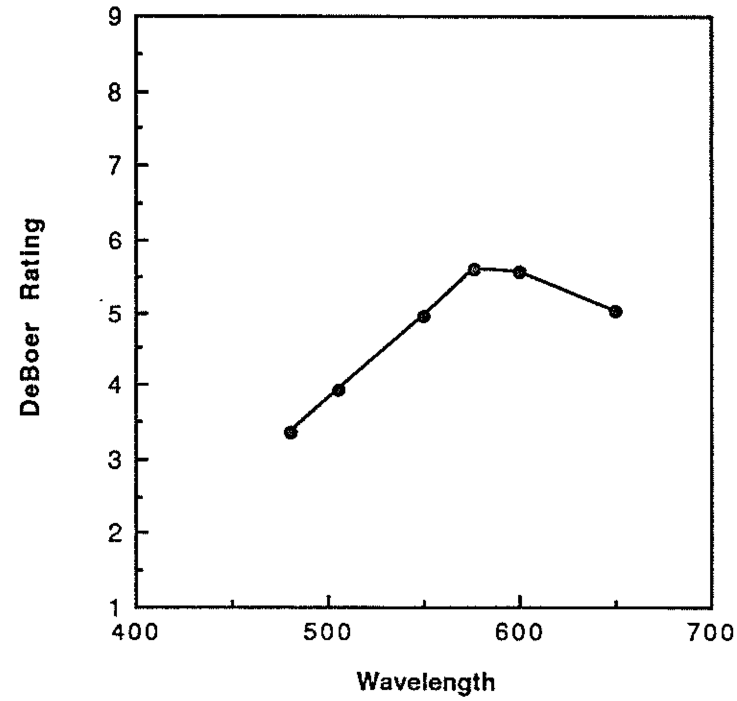

Figure 4. The main effect of wavelength on discomfort glare ratings.

as an example. The data are from one subject at one wavelength (480 nm); each of the plotted points is based on 5 trials.

The 96 regression equations were then used to obtain predicted DeBoer ratings for each subject at each wavelength for a luminance of 0.3 lx. That value was chosen because it was near the middle of the range of the actual illuminance values, where the confidence intervals for the regression models are narrowest. The vertical and horizontal lines in Figure 7 illustrate how one of the 96 predicted DeBoer ratings was generated. The vertical line has been placed at -0.52 (the log of 0.3); the horizontal line shows the projection onto the vertical axis of the intersection of the vertical line and the regression line. The predicted DeBoer rating for combination of wavelength and subject represented in Figure 7 is therefore 4.10.

The DeBoer values obtained from the regression models are thus predictions of how each subject would respond to stimuli of each wavelength if the stimuli could be perfectly equalized in illuminance level at 0.3 lx. Those values were submitted to an analysis of variance that included wavelength and age as factors. The results were almost identical to the summaries of raw ratings given above. The main effect of wavelength is significant, $F(5,70) = 121.23$, $p < .0001$, and is shown in Figure 8 (which should be compared to

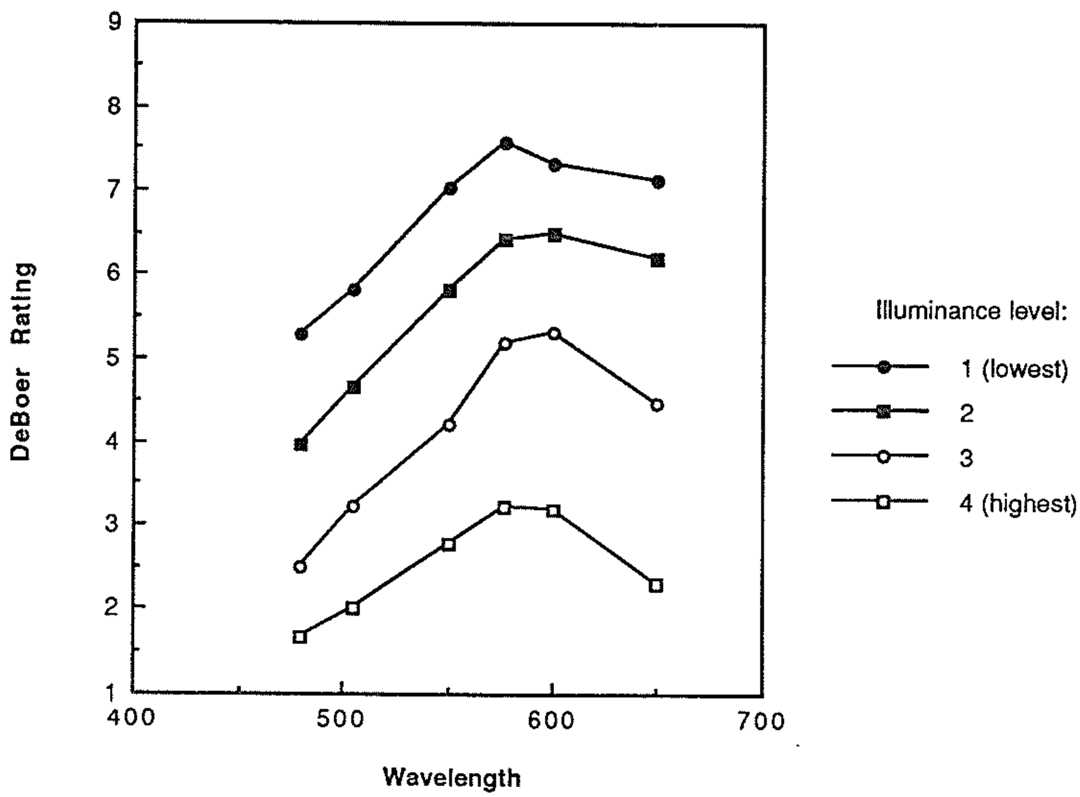

Figure 5. The interaction of wavelength and nominal illuminance level.

Figure 4). The interaction of wavelength with age is also significant, $F(5,70) = 4.49$, $p = 0.0013$, and is shown in Figure 9 (which should be compared to Figure 6).

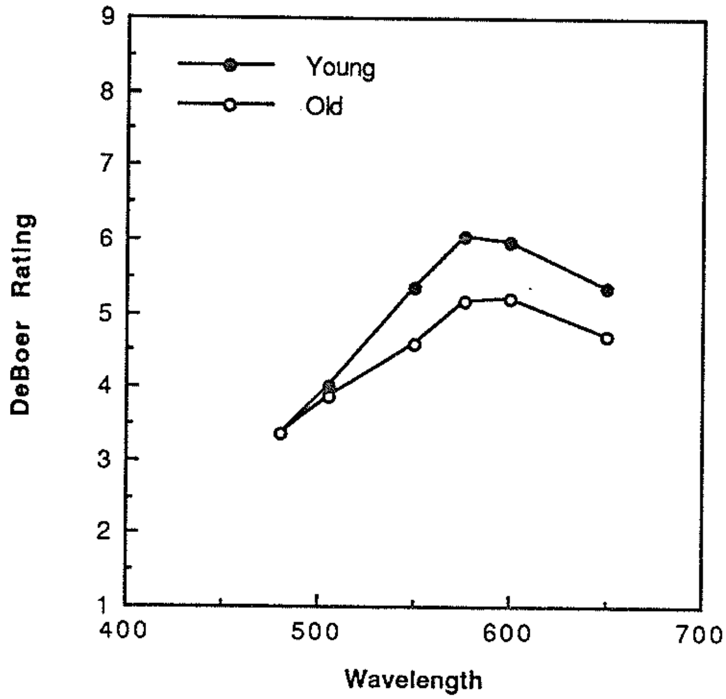

Figure 6. The effect of wavelength on discomfort glare ratings for young and old subjects.

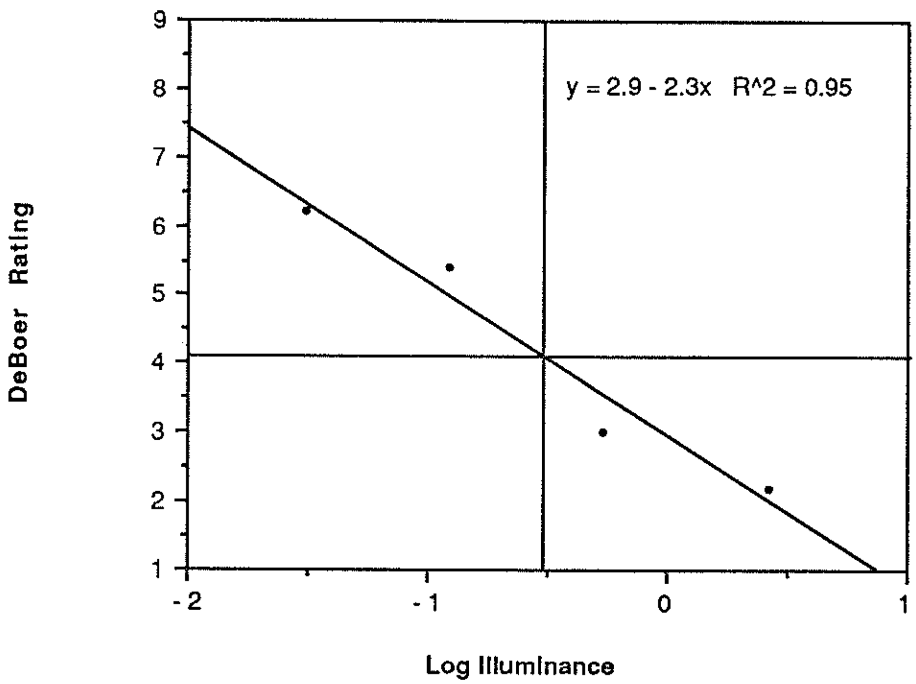

Figure 7. Regression of glare ratings on illuminance for one subject for 480 nm stimuli.

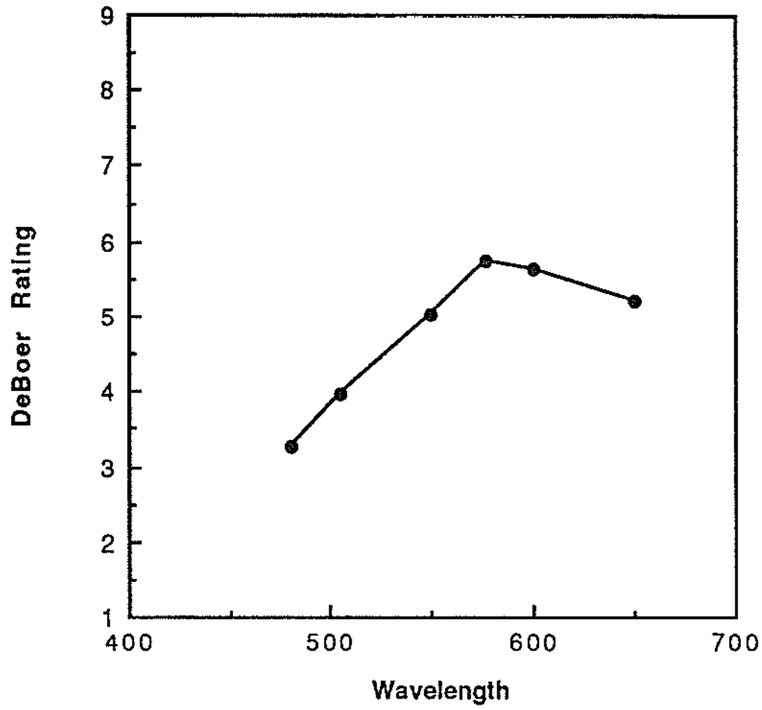

Figure 8. The main effect of wavelength on discomfort ratings predicted for 0.3 lx stimuli.

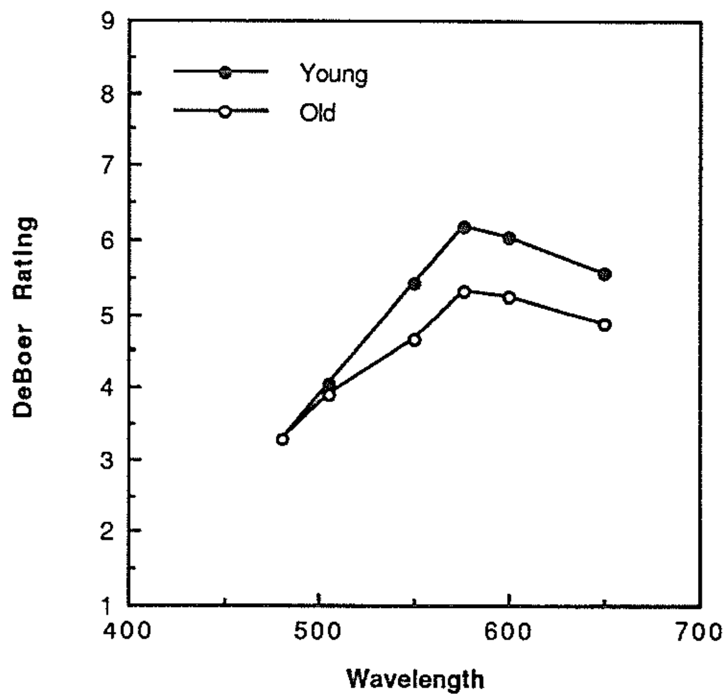

Figure 9. Predicted discomfort glare ratings for young and old subjects at each wavelength for 0.3 lx stimuli.

DISCUSSION

General

It is clear that discomfort glare is not equal for stimuli equated in illuminance (i.e. equal lux values based on the CIE photopic luminous efficiency function). Differences due to wavelength are in fact quite large, with a maximum of 2.9 DeBoer units separating stimuli of wavelengths 577 and 480 nm for the younger group of subjects. Furthermore, the effect of wavelength varies markedly with age. Relative to the glare they experience at longer wavelengths, older subjects have less trouble with shorter wavelengths than younger subjects. This may be due to yellowing of the lens with age. From about the age of 20 the human lens begins to absorb more light at all wavelengths, but it also absorbs relatively more short wavelength light (Said & Weale, 1959).

Practical implications

Recommendations for automotive applications based on this work must be tentative because of its preliminary and exploratory nature. Nevertheless, some interesting possibilities are suggested by these results. It may be that discomfort glare can be minimized by limiting the amount of light at the extremes of the visible spectrum, especially in the short wavelengths. Interestingly, older drivers might be less affected by that sort of manipulation of spectral power distribution than younger drivers. The principle reservation that should be kept in mind about this strategy for reducing glare is that we do not know how it would affect the visibility provided by the remaining light. A reduction in glare is only of interest if it can be achieved without an offsetting reduction in visibility. It may be that the ability of drivers to see important targets is affected by wavelength in a way that parallels the effects of wavelength on glare. If that is the case, then reducing glare by selecting middle wavelengths would not be more beneficial than reducing it by use of a neutral density filter.

A second major reservation about conclusions from these data concerns the uncertainty of making inferences about light sources with complex spectra from responses made to monochromatic stimuli. Practical light sources for automotive applications will almost certainly have complex spectra, and therefore will have color appearances very different from monochromatic stimuli. It is not known if glare properties of complex sources can be predicted by additive models based on monochromatic data, but additivity does fail markedly for brightness judgments (Alman, 1977), which may be closely related.

Future research

Several lines of research seem important for evaluating and extending the results of the present study. First, it would be valuable to account for the effects of wavelength on discomfort glare in terms of other visual responses, including heterochromatic brightness matching and scotopic or mesopic efficiency. Also, the interaction of wavelength and age that we observed might be accounted for in terms of changes in absorption in the lens or other known physiological effects of age. Knowing the the relationship between those factors and discomfort glare could help determine whether reducing glare by wavelength selection can result in a net benefit when visibility is considered. Second, visibility as a function of wavelength, especially with respect to targets that are important for driving, should be assessed directly. Third, the data collected here should be extended to other levels of dark adaptation. That would provide valuable information about the role of rods in determining glare effects at different wavelengths. Fourth, this work should be extended to stimuli with more complex spectral power distributions so that additivity of responses to single wavelengths can be checked, and so that implications for likely real-world light sources can be assessed.

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