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DISCOMFORT GLARE AND BRIGHTNESS AS FUNCTIONS OF WAVELENGTH

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16. Abstract

This study evaluated discomfort glare and brightness as functions of wavelength. Thirty-six different stimuli were presented in a laboratory setting. The stimuli were defined by a combination of wavelength (480, 505, 550, 577, 600, and 650 nm), illuminance (4.2, 0.6, and 0.1 lx average levels), and visual eccentricity (0° and 10°). The task involved rating either discomfort glare or brightness.

The results indicate that both discomfort glare and brightness are U-shaped functions of wavelength. The least discomfort glare and brightness were experienced at 577 nm. The greatest discomfort glare and brightness was at 480 nm, followed by 650 nm. In contrast to previous research, there were no differences between the two levels of visual eccentricity for either discomfort glare or brightness. Over all conditions, discomfort glare was highly correlated with brightness (r = .98), indicating that the sensation of brightness under the present conditions is not differentiated from the sensation of discomfort glare.

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CONTENTS

INTRODUCTION

The presence of a bright light in the visual field can result in a phenomenon called glare. The traditional view (e.g., Holladay, 1926) is that glare has two separate effects on the observer. One aspect–disability glare–refers to an objective impairment in visual performance. Disability glare is thought to be primarily the consequence of veiling luminance from light scattering in the optic media (Stiles, 1929). The other aspect of glare–discomfort glare–refers to a subjective impression of discomfort. Discomfort glare, believed to be more complex, is thought to be related to the degree of brightness inhomogeneity between the glare source and its background (Schmidt-Clausen and Bindels, 1974). The physiological origin of this phenomenon is not know. Furthermore, the nature of the relationship between discomfort and disability glare is not clear. Nevertheless, the concept of two separate effects of glare is dominant in the contemporary research of headlamp performance (e.g., Bhise et al., 1977).

Efforts to develop common worldwide headlighting standards for automobiles (for a recent review see Sivak and Flannagan, 1994) have repeatedly been stymied by international differences in tolerance for discomfort glare (Sivak, Olson, and Zeltner, 1989). This is the case despite the fact that the available methods for evaluating discomfort glare are less than satisfactory. The most frequently used rating scales for discomfort glare in the automotive context are based on the so-called de Boer scale (de Boer, 1967). This 9-point scale, with qualifiers only for the odd points, has several minor variations (Gellatly and Weintraub, 1990). The original qualifiers were in Dutch; the qualifiers that have been most frequently used in the U.S. (e.g., Bhise, Swigart, and Farber, 1975) are as follows: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (just noticeable). Gellatly and Weintraub (1990) evaluated this version of the de Boer scale with respect to its compatibility with population stereotypes of U.S. observers. The subjects in that study were asked to place the verbal quantifiers in the order they thought the scale should run, and to number the scale they created. The results indicated that there is a problem with the way the de Boer scale is numbered, and that some of the quantifiers are confusing and can lead to improper scaling of glare.

Because of the problems with evaluating discomfort glare, Weintraub, Gellatly, Sivak, and Flannagan (1991) compared discomfort-glare ratings and brightness ratings for the same stimuli. The results indicated that brightness ratings were highly correlated with discomfort-glare ratings. Based on this finding, Weintraub et al. (1991) concluded that brightness ratings provide essentially the same information as discomfort-glare ratings. Furthermore, Weintraub et al. (1991) argued that, to the extent that brightness is easier to communicate to subjects than is discomfort, researchers interested in discomfort might consider using a brightness scale.

Weintraub et al. (1991) used a tungsten-filament light source for generating the stimuli. The wavelength output of a tungsten-filament light source is continuous, spans the entire range of the visible spectrum, and is greatest in the long-wavelength end of the spectrum. However, several new light technologies (such as high-intensity discharge headlamps and neon brake lights) use light sources that have discontinuous, narrow wavelength-band outputs. Consequently, it is not clear whether the findings obtained by Weintraub et al. (1991) would apply to these light sources. The present study was designed to investigate the relationship between discomfort-glare ratings and brightness ratings for relatively narrow-band stimuli.

METHOD

Subjects

Sixteen paid subjects participated in this study. There were four subjects in each of the following groups: younger males, younger females, older males, and older females. The ages of the younger subjects ranged from 17 to 26, with a mean age of 22.4, while those in the older group ranged in age from 60 to 71, with a mean age of 65.5. All sixteen subjects performed normally on a simple test of color vision (the Dvorine Pseudo-Isochromatic Plates, Second Edition).

Apparatus

Schematic diagrams of the experimental setup are shown in Figures 1 and 2. The subject was seated in a chair behind a chin rest that controlled the subjects' head position throughout the study. In front of the subject at a distance of 2 m was a large white panel, 3.65 m wide and 2.25 m high. A projector equipped with an electronic shutter that provided the glare source was positioned behind the panel. The shutter aperture was round, with a diameter of 2.5 cm. A black plus sign (+) was placed on the wall 35.5 cm to the right of the glare source, corresponding to 10.0 degrees of visual angle. The white panel was illuminated indirectly (and approximately uniformly) by incandescent lamps directed at small diffusing screens to the right and left of the subject (see Figure 1). The diffusing screens prevented the subjects from having direct views of the lamps. No other sources of light were present. A large black hood covered a table illuminated by a small flashlight on which the experimenter recorded subject responses. 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 out of the projector's slide bracket. Neutral density filters were attached to these carriers so that there would be approximately the same photopic lux value at the eyepoint of each subject for each wavelength. Additional carriers, containing neutral density filters with nominal densities of 0.8 and 1.6, were inserted into the projector along with the interference-filter carriers.

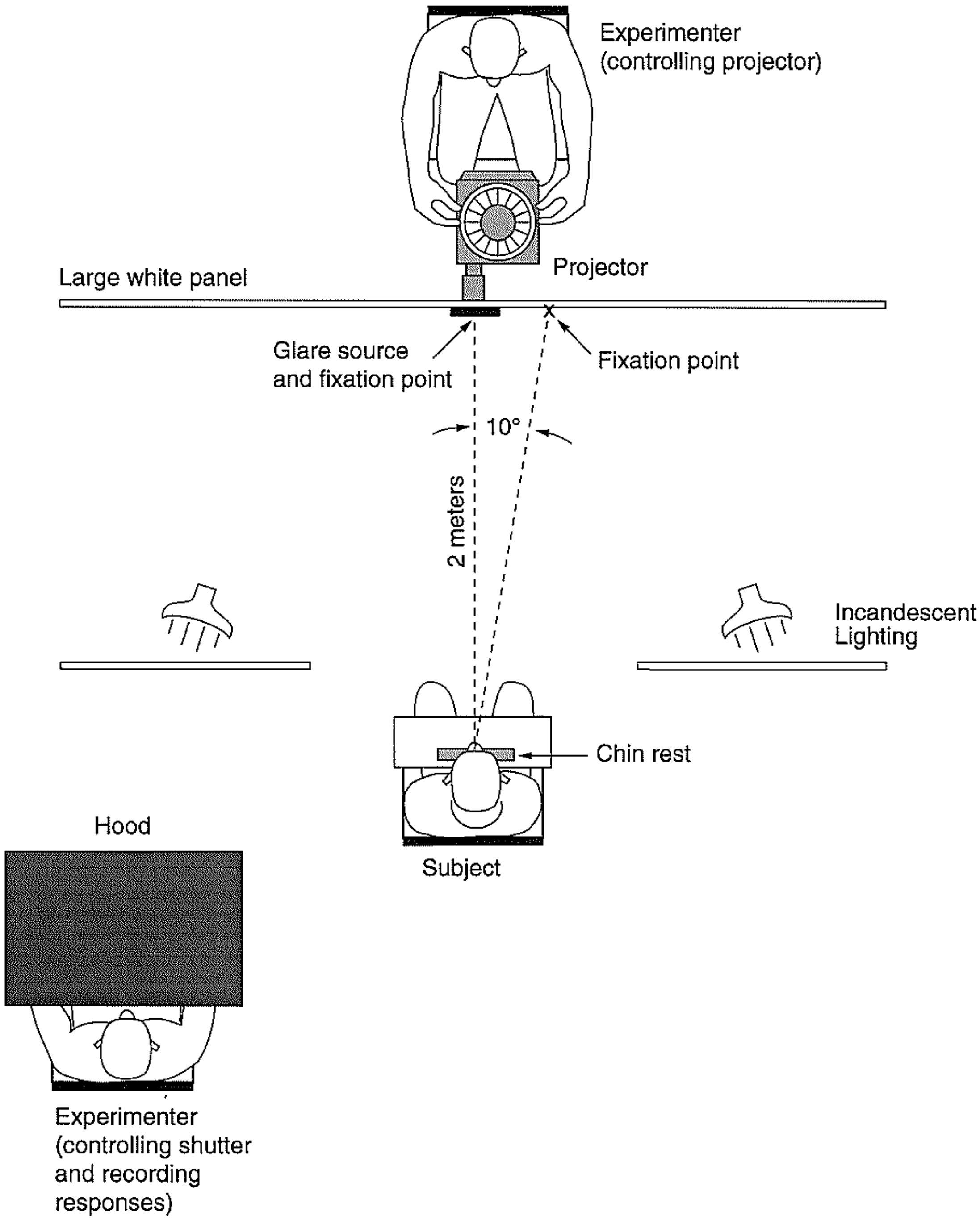

Figure 1. A schematic design of the experimental setup.

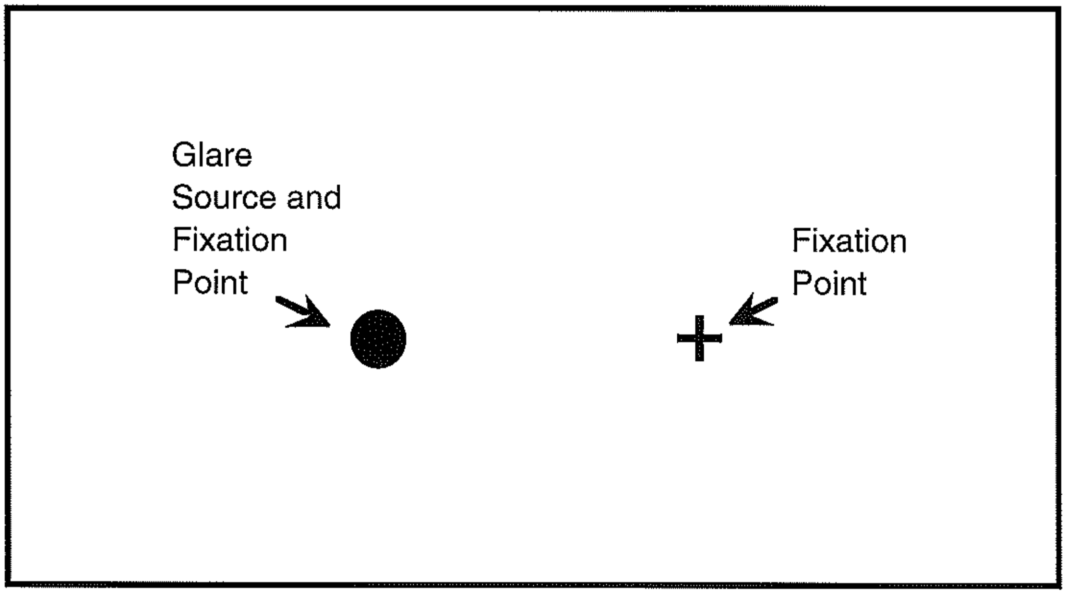

Figure 2. The subject's view.

Stimuli

Eighteen different stimuli were presented to each subject: six wavelengths each presented at three illuminances. These stimuli were produced by using neutral density filters (no filter, or nominal densities of 0.8 and 1.6) with each of six interference filters (480, 505, 550, 577, 600, and 650 nm). The highest intensities of each wavelength were adjusted to about 4.0 lx by adding neutral density filters to the carriers that held the interference filters. Each of the eighteen conditions was presented twice during each block of trials: once for each eye fixation point (one fixation point was directly on the glare stimulus and the other fixation point was on a black plus sign (+) 10 degrees of visual angle to the right).

Photometry

The illuminance values produced at the subject's eyepoint by each combination of the six interference filters (with accompanying compensatory neutral density filters) and the two additional neutral density filters, as well as the combinations with 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.

The luminance of the background was measured at seven locations (see Figure 3). Mean luminance values for each of the seven points taken for 15 subjects (readings were not taken for one subject) are given in Table 3. The mean background luminance (an average taken over all 105 measured values) was 0.10 cd/m^2. This mean background luminance was stable over the course of data collection.

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

Wavelength (nm)	Nominal illuminance level		
	High (filter density 0.0)	Medium (filter density 0.8)	Low (filter density 1.6)
480	4.21	0.55	0.09
505	4.06	0.54	0.09
550	4.18	0.60	0.10
577	4.46	0.66	0.12
600	4.13	0.63	0.11
650	4.28	0.60	0.10
Mean	4.22	0.60	0.10

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

Wavelength (nm)	Nominal irradiance level		
	High (filter density 0.0)	Medium (filter density 0.8)	Low (filter density 1.6)
480	44.38	5.80	0.93
505	14.60	1.96	0.32
550	6.15	0.89	0.15
577	7.26	1.07	0.19
600	9.58	1.45	0.25
650	58.54	8.26	1.34

Table 3
Background luminance levels tested at the 7 points shown in Figure 3.

Location	Luminance (cd/m^2)
A	0.09
B	0.09
C	0.11
D	0.10
E	0.10
F	0.11
G	0.11
Mean	0.10

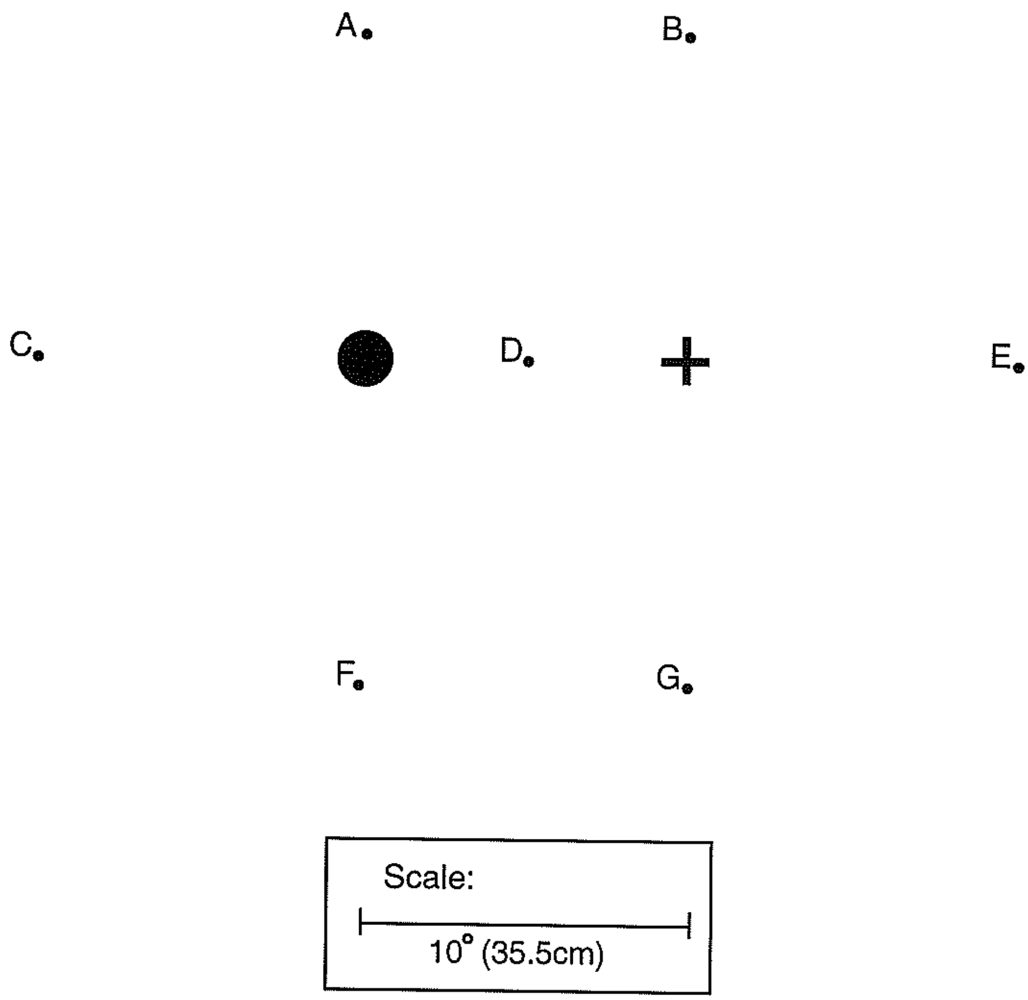

Figure 3. Seven points photometered to measure background luminance. The figure is to scale. The separations between the glare source and the second fixation point; between the glare source and points A, C, and F; and between the second fixation point and points B, E, and G are 10 degrees of visual angle, corresponding to 35.5 cm distances on the screen. The center photometry point, D, was halfway between the glare source and the second fixation point (5 degrees from each of them).

Psychophysical tasks

The psychophysical method was magnitude estimation without an anchor (e.g., Marks, 1974). Subjects were told to assign for each glare stimulus a number that stood for the degree of apparent discomfort (or brightness, depending on the instruction). The exact wording, as read to each subject, depending on which instruction group he or she was in, follows:

> *Brightness instructions:*
> I am going to present a number of light stimuli to you. Your task is to judge how bright each stimulus looks to you by assigning numbers to stand for the degree of brightness. To the first stimulus, assign whatever number seems most appropriate to represent the degree of brightness. Then, for succeeding stimuli, assign other numbers in proportion to brightness. If one stimulus seems three times as bright as another, assign a number three times as great; if it feels one-fifth as bright, assign a number one-fifth as great. Any type of number—whole number, decimal, or fraction, may be used.
>
> *Discomfort instructions:*
> I am going to present a number of light stimuli to you. Your task is to judge how much discomfort you feel because of the glare from each stimulus by assigning numbers to stand for the degree of apparent discomfort caused by the stimulus. To the first stimulus, assign whatever number seems most appropriate to represent the degree of discomfort. Then, for succeeding stimuli, assign other numbers in proportion to discomfort. If one stimulus causes three times as much discomfort as another, assign a number three times as great; if it causes one-fifth as much discomfort, assign a number one-fifth as great. Any type of number—whole number, decimal, or fraction, may be used.

These instructions were repeated twice, once near the beginning of the instruction period, and again near the beginning of the first trial.

Procedure

Subjects were tested individually. Each subject was assigned to one of two experimental groups, distinguished by the object of the rating task. In one of the two groups, each subject was instructed to judge how much discomfort he or she felt due to the glare from each stimulus by assigning numbers to stand for the degree of apparent discomfort caused by the stimulus. The other group was instructed to judge how bright each stimulus looked them by assigning numbers to stand for the degree of brightness produced by the stimulus. Each group was balanced in age and sex. Subjects were not told that there was a second experimental group that would be given slightly different instructions, and the experimenter took special care not to mention anything that would reveal any information related to the other set of instructions.

Because the height of the chin rest was fixed, chair height was adjusted as necessary so that the chin rest would allow the subject to be in a comfortable position throughout the experiment. After the subject was comfortably seated, the overhead fluorescent lights that normally illuminated the laboratory were turned off. The subject was then allowed to adapt to the new lighting conditions for ten minutes. The only lighting that was present in the laboratory at this time was provided by the two incandescent lamps directed at diffusing screens on each side of the subject (see Figure 1). During the adaptation period, the instructions for the ratings task were read to the subjects.

Subjects were told that they would hear a beep to indicate when each trial was beginning, and that at that beep the experimenter would call out "on" or "off," signifying whether they were to look directly on the glare source, or at a point 10 degrees to the right of the glare source, marked with a black plus sign (+). They were also instructed to maintain fixation while the shutter was open, as well as not to move their heads. Each subject was also asked to make a special effort not to allow their gaze to be attracted towards the glare source when they were fixating on the second fixation point, even though the glare source might attract their attention.

Two experimenters ran the study (see Figure 1). One experimenter was behind the large white panel and inserted the proper combination of neutral density and interference filters into the projector before each trial. The other experimenter, sitting behind the subject, controlled the shutter on the projector, indicated to the subject the appropriate fixation point, and recorded the subject's responses.

Trials were run in blocks of 36. Each block consisted of all combinations of eye fixation point, glare wavelength, and glare intensity (2 eye fixation points by 6 wavelengths by 3 intensities), and those combinations were individually randomized within each block. Each subject was given 4 blocks, for a total of 144 trials.

The first trial began approximately 10 minutes after lights were turned off in the laboratory. The intertrial interval was 20 seconds; each block thus lasted about 12 minutes. With the addition of the adaptation period and the color-vision test, the entire session took about 75 minutes.

RESULTS

An analysis of variance was performed on log-transformed ratings, using the following independent variables: instruction (discomfort glare or brightness), illuminance (4.2, 0.6, or 0.1 lx average levels), age of the subject (younger or older), wavelength (480, 505, 550, 577, 600, or 650 nm), and visual eccentricity (0 or 10°).

Effect of instruction

While there was a tendency for the discomfort-glare ratings to be higher than the brightness ratings (1.48 vs. 1.28), the effect was not statistically significant, $F\ (1, 12) < 1$. No two-way interaction involving instruction was significant.

Effect of illuminance

The effect of illuminance was significant, $F(2, 24) = 140.27$, $p < .001$. The stimuli at average levels 4.2, 0.6, and 0.1 lx, respectively, yielded log ratings of 1.66, 1.37, and 1.10, respectively. The interaction of illuminance with subject age was significant (see below).

Effect of age

Although there was a tendency for older subjects to give higher ratings than younger subjects (1.56 vs. 1.20), the main effect of age was not significant. However, the interaction of age with illuminance was significant, $F(2, 24) = 4.16$, $p < .05$. As is evident in Table 4, as the illuminance decreased, the differences between the older and younger subjects tended to increase.

Table 4
Log ratings by subject age and illuminance.

Average illuminance	Subject age	
	Younger (17 - 26)	Older (60 - 71)
4.2	1.52	1.80
0.6	1.20	1.54
0.1	0.87	1.34

Effects of wavelength

The effect of wavelength was significant, $F(5, 60) = 46.33$, $p < .001$. Log ratings of discomfort and brightness by wavelength are shown in Table 5 and Figure 4. No two-way interaction involving wavelength was significant.

Table 5
Log ratings of discomfort glare and brightness by wavelength.

Wavelength (nm)	Log discomfort glare	Log brightness
480	1.68	1.44
505	1.51	1.32
550	1.39	1.22
577	1.35	1.16
600	1.39	1.20
650	1.54	1.33
Mean	1.48	1.28

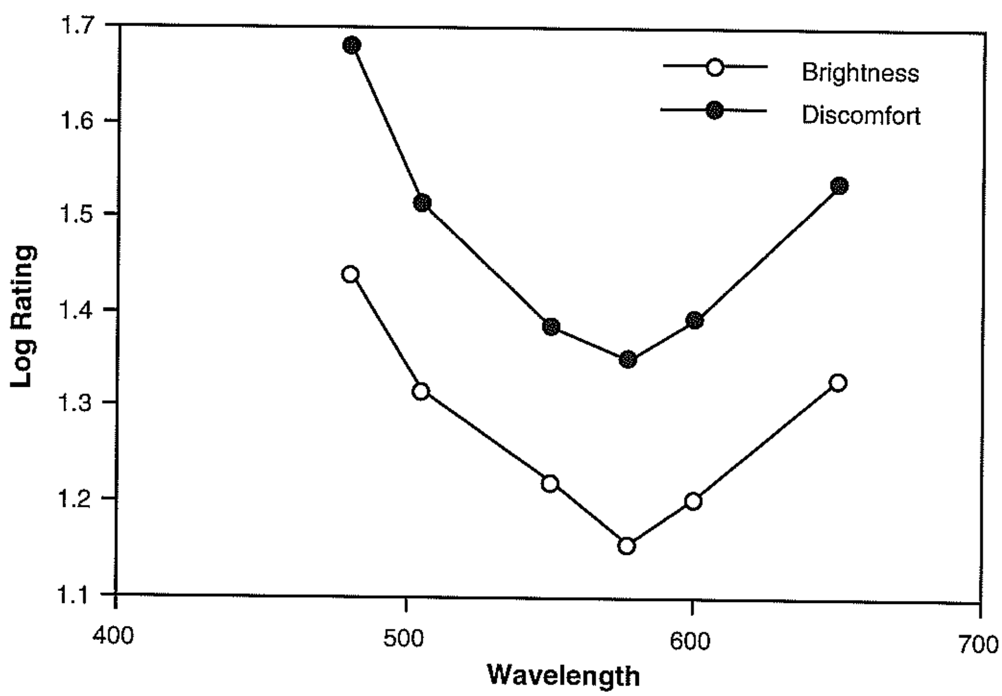

Figure 4. Log ratings of discomfort glare and brightness by wavelength.

Effects of visual eccentricity

The effect of visual eccentricity was not significant, $F(1, 12) < 1$. No Two-way interaction involving visual eccentricity was significant. The mean log ratings are shown in Table 6 by visual eccentricity and wavelength, and in Table 7 by visual eccentricity and instruction.

Table 6.
Log ratings by visual eccentricity and wavelength.

Wavelength (nm)	Visual eccentricity 0°	Visual eccentricity 10°
480	1.55	1.58
505	1.42	1.42
550	1.31	1.29
577	1.26	1.24
600	1.29	1.30
650	1.44	1.43
Mean	1.38	1.38

Table 7
Log ratings by visual eccentricity and instruction.

Instruction	Visual eccentricity 0°	Visual eccentricity 10°
Discomfort glare	1.48	1.48
Brightness	1.28	1.28
Mean	1.38	1.38

Relationship of discomfort glare to brightness

There were 36 unique experimental conditions (6 wavelengths x 3 illuminances x 2 visual eccentricities) for both the discomfort-glare and brightness instructions. Over all those conditions, the correlation between the two sets of 36 mean ratings was very high, $r = .983$, $p < .001$.

DISCUSSION

Wavelength

The results indicate that, when keeping the photopic illumination constant, both discomfort glare and brightness are U-shaped functions of wavelength. The least discomfort glare and brightness were experienced at a middle wavelength (yellow, 577 nm). The shortest wavelength tested (blue, 480 nm) resulted in the greatest discomfort glare and brightness, followed by the longest wavelength tested (red, 650 nm).

The results concerning discomfort glare essentially replicate our previous findings (Flannagan, Sivak, Ensing, and Simmons, 1989). That study (using the same six wavelengths and a 9-point response scale) found the minimum discomfort glare to be at 577 nm, and the maximum at 650 nm.

Visual eccentricity

Schmidt-Clausen and Bindels (1974) found discomfort glare to decrease with an increase in visual eccentricity. Consequently, the widely used discomfort-glare model that Schmidt-Clausen and Bindels derived contains a parameter for the visual angle between the glare source and the observer's fixation point. Based on those results, we also expected to find (1) a decrease in discomfort glare with an increase in visual eccentricity, and (2) no effect of visual eccentricity on brightness. However, the present study found no differences between visual eccentricity of 0° and 10° for either discomfort-glare ratings or brightness ratings. The reason for the discrepancy between the present findings and those of Schmidt-Clausen and Bindels (1974) is not known.

Discomfort glare versus brightness

The present results indicate that across wavelengths and visual eccentricity, discomfort glare is highly correlated with the sensation of brightness, replicating and extending the findings of Weintraub et al. (1991). The correlation coefficient between brightness ratings and discomfort-glare ratings was $r = .983$ in the present study using monochromatic stimuli, and $r = .991$ in Weintraub et al. (1991) using a broad-band stimulus. These results indicate that, under these conditions, the sensation of brightness is not differentiated from the sensation of discomfort glare. Consequently, as pointed out by Weintraub et al. (1991), "to the extent that brightness is a concept that is easier to communicate to subjects than is discomfort, researchers interested in discomfort might consider using brightness scales" (p. 17).

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