

**UMTRI-2001-9**

**VISUAL EFFECTS OF BLUE-TINTED  
TUNGSTEN-HALOGEN HEADLAMP  
BULBS**

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Report No. UMTRI-2001-9  
April 2001

**Technical Report Documentation Page**

1. Report No. <b>UMTRI-2001-9</b>		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle <b>Visual Effects of Blue-Tinted Tungsten-Halogen Headlamp Bulbs</b>				5. Report Date <b>April 2001</b>	
				6. Performing Organization Code <b>302753</b>	
7. Author(s) <b>John M. Sullivan and Michael J. Flannagan</b>				8. Performing Organization Report No. <b>UMTRI-2001-9</b>	
9. Performing Organization Name and Address <b>The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, MI 48109-2150 U.S.A</b>				10. Work Unit no. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address <b>The University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety</b>				13. Type of Report and Period Covered	
				14. Sponsoring Agency Code	
15. Supplementary Notes <p>The Affiliation Program currently includes Adac Plastics, AGC America, Automotive Lighting, Avery Dennison, BMW, Corning, DaimlerChrysler, Denso, Donnelly, Federal-Mogul Lighting Products, Fiat, Ford, GE, Gentex, GM NAO Safety Center, Guardian Industries, Guide Corporation, Hella, Ichikoh Industries, Koito Manufacturing, LumiLeds, Magna International, Meridian Automotive Systems, North American Lighting, OSRAM Sylvania, Pennzoil-Quaker State, Philips Lighting, PPG Industries, Reflexite, Renault, Schefenacker International, Stanley Electric, TEXTRON Automotive, Valeo, Vidrio Plano, Visteon, Yoroka, 3M Personal Safety Products, and 3M Traffic Control Materials.</p> <p>Information about the Affiliation Program is available at: <a href="http://www.umich.edu/~industry/">http://www.umich.edu/~industry/</a></p>					
16. Abstract <p>Manufacturers have recently introduced several types of tungsten-halogen headlamp bulbs that have been filtered to produce bluish tints. Some informal reports suggest that the differences in spectral power distribution due to the tinting enhance visual performance and reduce fatigue; others suggest that they simply provide esthetic benefits. In this study, we investigate the effect of three headlamp types (a standard tungsten-halogen lamp, a broadly filtered blue-tinted lamp, and a neodymium-filtered blue-tinted lamp) on two aspects of vision (discomfort glare judgments and the luminance threshold for target detection).</p> <p>Consistent with prior studies, the results show that discomfort glare ratings increase as chromaticity moves toward the blue range. No evidence was observed that target detection is enhanced with blue headlamps for either peripherally viewed or centrally viewed targets. However, when deeply colored light sources (beyond the range of nominal white that headlamps are required to meet) were introduced into the detection task, differences in spectral sensitivity were observed in the near-periphery.</p>					
17. Key Words <b>spectral power distribution, color vision, discomfort glare, detection, blue bulbs</b>				18. Distribution Statement <b>Unlimited</b>	
19. Security Classification (of this report) <b>None</b>		20. Security Classification (of this page) <b>None</b>		21. No. of Pages <b>27</b>	22. Price

## Acknowledgements

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

Adac Plastics  
AGC America  
Automotive Lighting  
Avery Dennison  
BMW  
Corning  
DaimlerChrysler  
Denso  
Donnelly  
Federal-Mogul Lighting Products  
Fiat  
Ford  
GE  
Gentex  
GM NAO Safety Center  
Guardian Industries  
Guide Corporation  
Hella  
Ichikoh Industries  
Koito Manufacturing  
LumiLeds  
Magna International  
Meridian Automotive Systems  
North American Lighting  
OSRAM Sylvania  
Pennzoil-Quaker State  
Philips Lighting  
PPG Industries  
Reflexite  
Renault  
Schefenacker International  
Stanley Electric  
TEXTRON Automotive  
Valeo  
Vidrio Plano  
Visteon  
Yorka  
3M Personal Safety Products  
3M Traffic Control Materials

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## Introduction

The idea that the spectral characteristics of light can affect visual or mental performance has long been used to promote a variety of products that either filter light (eyeglass lenses, tinted windows) or produce light. Reported effects are quite varied. For example, some have promoted the use of colored filters to correct “scotopic sensitivity,” an affliction speculated to affect individuals with a variety of nonspecific learning deficits (Irlen, 1983); others have reported relief from seasonal affective disorder, lessened fatigue, heightened productivity, reduced eyestrain, better contrast sensitivity, and lessened dental caries with full-spectrum lighting (see Veitch & McColl, 1994 for a comprehensive review).

The reasons cited for these effects are nearly as varied as the effects themselves. Some effects can be attributed to specific physical mechanisms in the eye. For example, if the spectral content of light is biased to match the responsiveness of rod receptors, improved visual clarity is reported even when the photopic luminance of the object is the same or less (Berman, 1992). This effect has been explained as a consequence of selective pupil response to ambient scotopic luminance levels. Not all research, however, makes a precise statement about either the nature of the effect, or the mechanism responsible for it. Indeed, some evidence that has been offered on this issue appears to lack scientific rigor (see, for example, a review by Gifford, 1994). Many anecdotal reports about “the healing power of light” and the use of colored lenses have also appeared in the popular press (e.g., Brister, 1996; Greenman, 2000; Malamanig, 2000; McKenna, 1992; Williams, 1999), often without substantive critical scrutiny. In any case, it is clear that people find something compelling about the idea that the spectral characteristics of light may influence behavior and performance.

With respect to the motor vehicle consumer, interest in altering the spectral output of tungsten-halogen headlamps has probably developed as a consequence of the growing use of high-intensity discharge (HID) sources, particularly on expensive vehicles. Conventional tungsten-halogen headlamps appear relatively yellow next to HID lamps, which appear relatively blue. Both lamps, however, produce light within the definition of white set forth in SAE Standard J578. And indeed, perhaps partly because of color

constancy, if each bulb were the sole source of illumination for a scene, it would usually be seen as white. The color difference is most noticeable when the two lamp types are seen at the same time.

Although HID lamps provide more light than TH lamps, it is their distinctive color that has most caught consumer attention. Many car owners find this difference appealing, and manufacturers have responded to this interest by marketing replacement tungsten-halogen bulbs that resemble the color (if not the light output) of the HID lamps. Accompanying this growing interest in headlamp spectra are popular beliefs about the ways in which blue-tinted bulbs are superior to conventional tungsten-halogen lamps. Some beliefs are confined to subjective, aesthetic judgment—the bulbs are said to look *cool*. Other beliefs are that roadway visibility is improved or that glare or driver fatigue is reduced by the difference in bulb color. These latter ideas have clear safety implications and bear closer scrutiny.

The investigations described in this report use two tasks to help evaluate possible visual effects of blue-tinted bulbs. In the first task, observers were asked to rate the subjective discomfort they experienced when viewing various bluish-tinted oncoming headlamps. We did this to see if discomfort glare, which seems to be affected by the chromaticity differences between tungsten-halogen and HID lamps (Flannagan, Sivak, & Traube, 1994), would be similarly affected by blue-tinted halogen lamps. In the second task, observers indicated when a target, illuminated by differently tinted headlamps, first became visible as the amount of reflected light from the target was increased. Observers were also asked when the target became invisible as the amount of reflected light was decreased.

### *Blue-tinted bulb characteristics*

In the experiments discussed in this report, we compared a conventional 9004 tungsten-halogen replacement bulb installed in a conventional headlamp to: (a) a widely available, blue-tinted 9004 bulb produced by a major manufacturer, installed in the same lamp; and (b) a tungsten-halogen lamp filtered through a glass neodymium filter. It should be noted that the replacement bulb marketplace offers a wide variety of blue replacement bulbs. Some of these bulbs are of markedly inferior quality. To ensure that

observed differences between bulbs would be related to bulb *color*, and not characteristics related to inferior bulb design (e.g., uneven coatings, poor filaments), we limited our bulb selection to established manufacturers. As can be seen in Figure 1, the spectral power distribution of the blue-tinted tungsten-halogen bulb used in these studies is quite similar to that of a tungsten-halogen bulb. There appears to be only a small reduction in the blue-tinted bulb's output, mostly between 580 and 680 nm. In contrast, the neodymium filtered tungsten-halogen bulb shows a characteristic absorption notch at about 580 nm. We also note that the color similarity observed here should not be assumed to exist for all blue-tinted tungsten-halogen bulbs. Some blue-tinted bulbs on the market are more deeply tinted than the type we investigated.

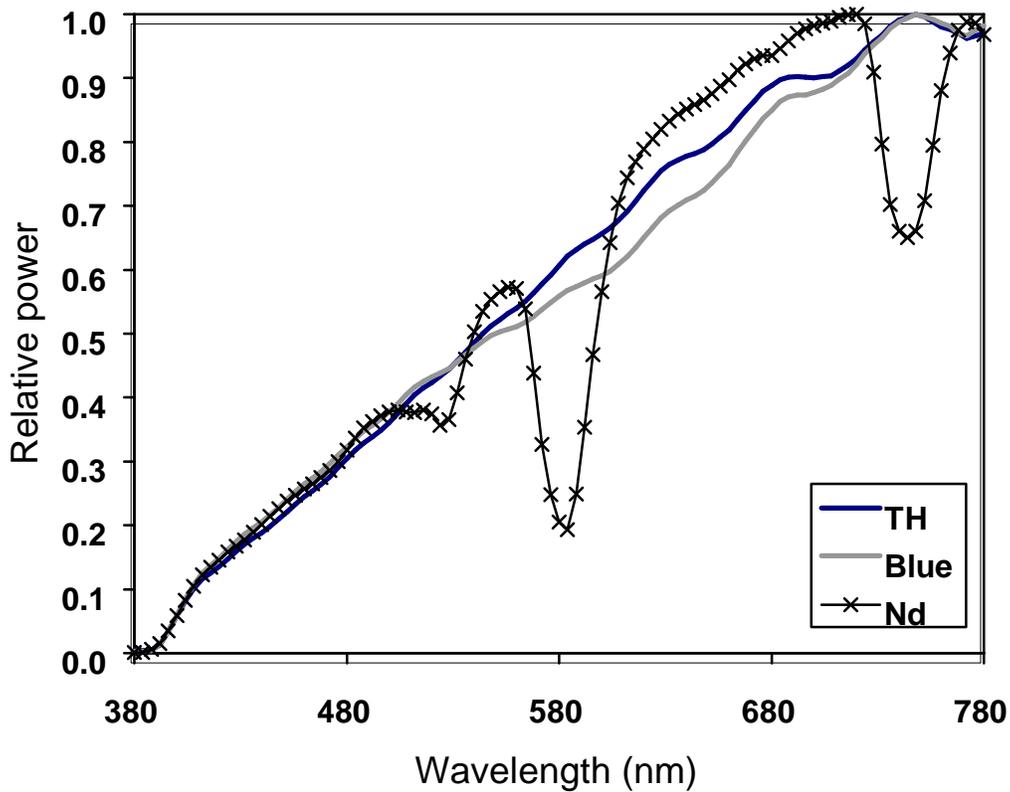


Figure 1. Relative power of tungsten-halogen (TH), blue-tinted tungsten-halogen (Blue), and neodymium filtered (Nd) sources.

All the headlamps in this study fall within the chromaticity limits for white lamps as defined in SAE Standard J578 (Society of Automotive Engineers, 1988) and are, as Figure 2 shows, relatively near to each other, when compared to a sample HID lamp chromaticity. This similarity is also consistent with our informal subjective impressions. When a vehicle was fitted with a conventional TH bulb in one headlamp, and one of the blue-tinted bulbs in the other, it was not readily obvious which bulb was installed in which lamp. Figure 3 depicts the chromaticity in  $u'$  and  $v'$  coordinates (in which distances are more representative of perceived color differences than in  $x$   $y$  coordinates), rescaled to better resolve the differences among the three bulbs.

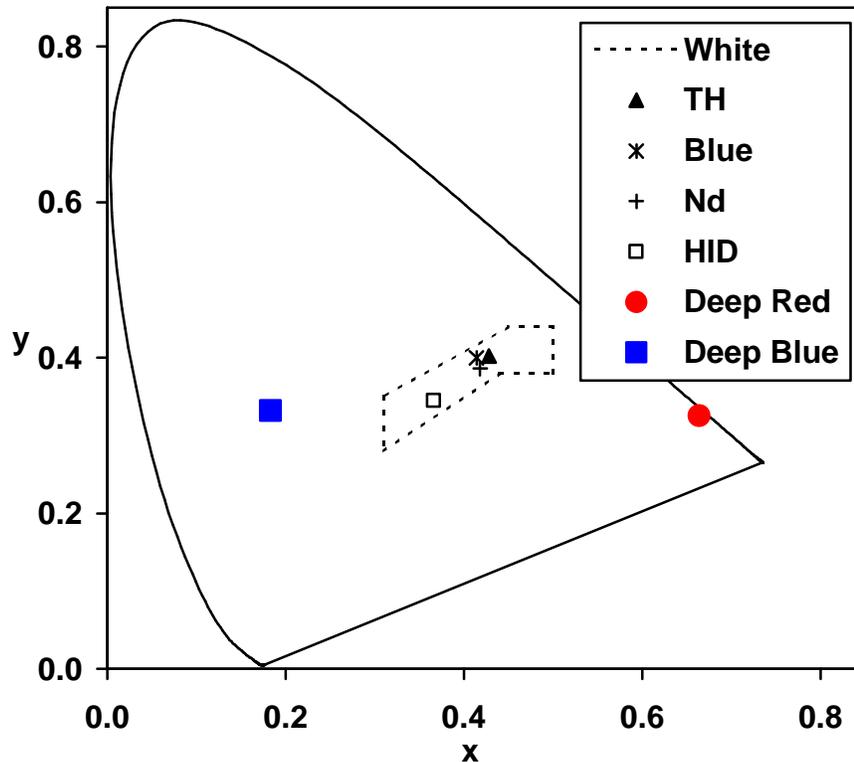


Figure 2. Chromaticity coordinates of tungsten-halogen (TH), blue-tinted replacement (Blue), neodymium filtered tungsten-halogen (Nd), and high-intensity discharge lamp (HID) with reference to the spectrum locus and the SAE J587 standard boundary for white (dashed lines). Also depicted are the two deeply colored lamps used in Experiment 2.

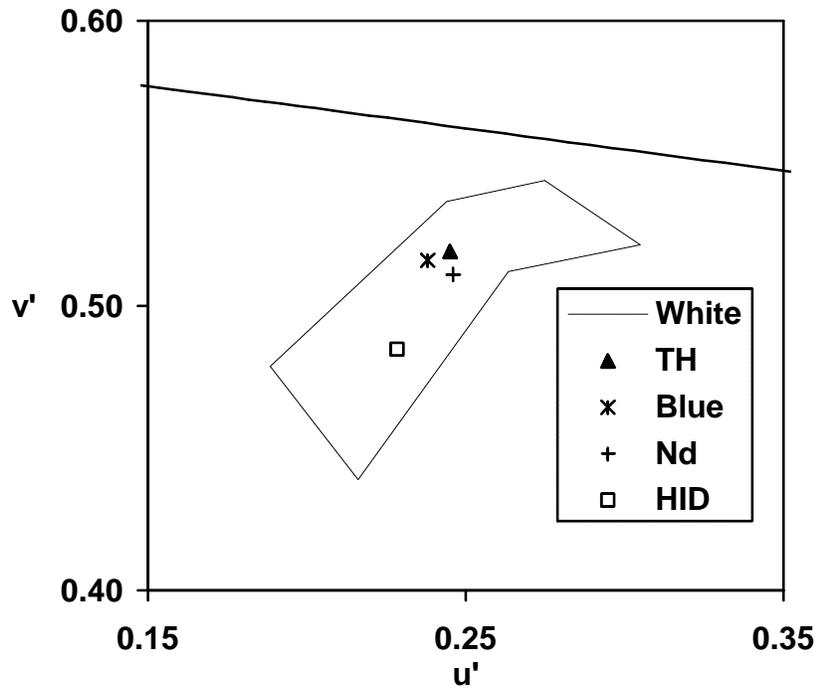


Figure 3. Chromaticity of sample tungsten-halogen (TH), blue-tinted tungsten-halogen (Blue), neodymium filtered tungsten-halogen (Nd), and HID headlamps. Note that the apparent differences in color are greater between any of the tungsten-halogen lamps and the HID sample, than they are among the various tinted tungsten-halogen lamps.

## Experiment 1: Ratings of Discomfort Glare

In this study, we investigated whether an observer's subjective judgment of discomfort glare is different for each type of light source at comparable levels of photopic illuminance. In previous research examining the influence of wavelength on glare ratings, middle wavelengths (yellow, 577 nm) produced the least discomfort, while short wavelengths (blue, 480 nm) produced the greatest discomfort (Flannagan et al., 1994). Insofar as glare judgment may be influenced by spectral power distribution, we might expect that light with more pronounced energy at the shorter wavelengths (bluish light) would be judged as more glaring.

### **Method**

#### *Subjects*

Sixteen paid subjects participated in the study. Eight of the subjects were young (ranging from 20 to 29 years old, with a mean of 22) and eight were older (ranging from 65 to 75 years old, mean 67). All subjects were licensed drivers with normal or corrected to normal vision (20/20 minimum), and were color normal based on testing with an Optec 2000 Vision Tester, Stereo Optical Company, and Standard Pseudoisochromatic Plates, Igaku-Shoin.

#### *Stimuli*

Subjects viewed a pair of headlamps mounted in a rack located 50 m in front of them. The headlamps were mounted 62 cm above the pavement and were separated horizontally by 112 cm, measured between the optical axes of the lamps. These dimensions were based on the average lamp height and separation for passenger cars in the U.S. (Sivak, Flannagan, Budnick, Flannagan, & Kojima, 1996). The rack was offset 3.66 m to the left of straight ahead to mimic the headlamps from an oncoming vehicle one lane to the left. Each lamp was partially masked around the edges to accommodate a rigid 110 by 150 mm filter. Lamps were aimed in the rack to produce a standard low-beam distribution pattern. Each lamp was fitted with a 9004 bulb. Only the low-beam filament was energized.

Three different spectral distributions were investigated: one produced by standard tungsten-halogen bulbs (TH), one produced with blue-tinted replacement bulbs (Blue), and a third produced by the tungsten-halogen bulb filtered through neodymium-doped glass (Nd). A neutral density filter (Lee Filters .15ND 298) was applied to balance the luminous intensity of the Blue and TH bulbs so that approximately the same photopic illuminance level was obtained for all three light sources at the observer's eye. The actual illuminances were then measured to enable the interpolation discussed later in this report.

Three illuminance conditions were investigated for each color condition, by applying to the lamps either no additional filter, or one of two neutral density filters: 0.3 and 0.6 optical densities (Lee Filters .3ND 209, and .6ND 210), producing approximately 100%, 50%, and 25% transmittance. Thus, nine glare stimuli were produced by combining three illuminance levels with the three colors.

*Procedure*

Observers were seated in a stationary vehicle 50 m from the headlamp rack, parked in a dry, darkened (0.02 lx), otherwise vacant, asphalt-paved parking lot. The vehicle's low-beam headlamps were turned on, producing pavement luminances along a line directly ahead of the observer as described in Table 1. The maximum pavement luminance was 1.3 cd/m<sup>2</sup>, and was found at 15 m, slightly to the right of the observer's eyepoint.

Table 1. Pavement luminance measured from the driver's eyepoint at selected straight ahead distances from the observation vehicle.

Distance (m)	Luminance (cd/m <sup>2</sup> )
10	0.89
15	1.00
20	0.82
25	0.24
30	0.07

Observers were instructed to rate the discomfort from the lamps in the rack using the de Boer scale rating system for glare (de Boer, 1967) as shown in Table 2.

Table 2. The de Boer rating scale.

Rating	Meaning
1	Unbearable
2	
3	Disturbing
4	
5	Just Acceptable
6	
7	Satisfactory
8	
9	Just Noticeable

Observers were run in groups of three, each seated in a different position in the vehicle: two were seated in the driver and passenger front seats, and a third was seated in the middle of the rear seat. All observers had unobstructed views through the vehicle's windshield. They were first instructed about the use of the de Boer scale and advised about the experimental procedures as follows.

At the start of a trial, Experimenter 1, seated with the observers, requested them to direct their gaze toward a target located on the pavement 40 m straight ahead, to approximate the center of a driver's normal eye fixations during night driving (Graf & Krebs, 1976). Experimenter 2, located at the lamp rack, then switched on the glare stimulus lamps for about three seconds, and then switched them off. Following this, each observer recorded his or her numeric rating on a data sheet. Experimenter 2 then prepared the next glare stimulus. Experimenter 1 alerted the observers when the next trial was about to start, and signaled Experimenter 2 (via radio) to present the glare stimulus.

Experimental trials were initiated only after observers had a minimum of ten minutes of visual adaptation to the lighting condition produced by the low-beam lamps of the observation vehicle. Trials were organized in four blocks, with each block consisting of a complete set of the 9 color and filter conditions. Presentation orders of trials within

blocks were randomized with the restriction that no more than two identical color or filter conditions occurred in a row.

To summarize, the experimental design included three between-subjects factors: age group, sex, and seating position (driver, passenger, rear), and two within-subjects factors: source color (TH, Blue, Nd) and filter (0.0, 0.3, and 0.6 optical density).

## Results

Summary results of the observers' average de Boer ratings by color and filter condition are shown in Table 3. As filter density increased, glare ratings increased (which on the de Boer scale indicates less discomfort). Also, observers rated the TH source as less discomforting than the other sources. These results, however, do not account for the actual photometry across the nine experimental conditions. The next analysis will take this into account.

Table 3. Average de Boer rating by color and filter condition.

Filter	Color		
	Blue	Nd	TH
0.0	3.8	4.1	4.7
0.3	5.5	5.9	6.3
0.6	6.9	7.3	7.3

For each observer and color, a linear regression was performed across the three filter conditions, relating the observer's de Boer rating to the log of the measured illuminance of the light source at the observer's viewing position. This enabled us to correct for the actual photopic levels of the different light sources. For each color, we then computed the illuminance level at which an observer would have given a de Boer rating of 6.

For example, Observer 4 produced the ratings given in Table 4. The illuminance levels given in the table were measured at the eye point of the observer during the experimental session. For each observer, equal-slope regression lines were computed for each color, regressing de Boer ratings on log of illuminance (Figure 4). The validity of the assumption of equal slopes was directly tested in a separate regression analysis that compared the slopes of separately computed regressions of de Boer ratings on

illuminance for each observer and color. No differences in slope among colors were observed in this analysis,  $F(2,22) = 1.52, p > .2$ . Using each observer's regression lines, we determined what the log lux value for each color would be for a de Boer rating of 6. (We chose 6 because it is the median score across all observers. However, because of the requirement for equal slopes, any de Boer value would have produced exactly the same differences among the light sources.) In the case of Observer 4, we found where the respective lines crossed the de Boer rating of 6, yielding a log lux value of -0.41 for blue, -0.34 for Nd, and -0.24 for TH light sources (also depicted in Figure 4).

Table 4. Average discomfort glare ratings of Observer 4, using the de Boer scale.

Source	Filter Level (Density)	Illuminance (Lux)	Average Rating
Blue	0.0	0.72	4.50
Blue	0.3	0.36	6.25
Blue	0.6	0.18	7.75
Nd	0.0	0.71	5.25
Nd	0.3	0.35	6.50
Nd	0.6	0.17	8.00
TH	0.0	0.69	5.75
TH	0.3	0.34	6.75
TH	0.6	0.17	8.75

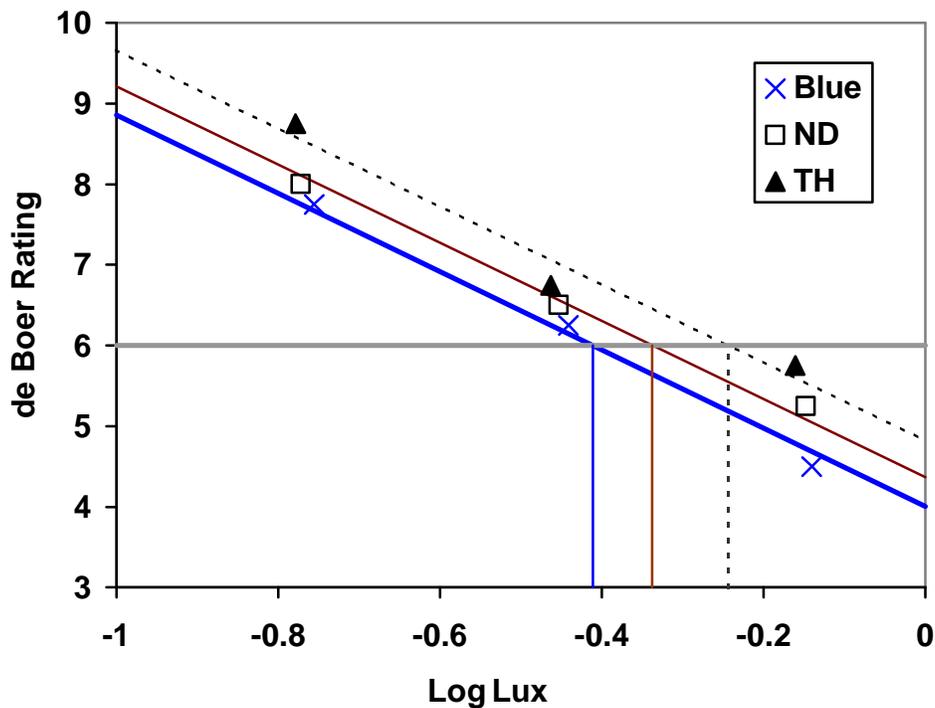


Figure 4. Linear regressions of de Boer ratings on illuminance for each lamp color. This plot shows the log lux value at which the median de Boer glare rating (6) intersects the fit lines for each light source for Observer 4. Note that for this observer, for equal glare ratings, the lux levels of the Blue and Nd sources were lower than the level of the TH source, indicating that the Blue and Nd sources are judged as relatively more glaring.

An analysis of variance was performed on log lux values derived from each observer's regression lines for each color. A significant main effect of light source was found,  $F(2,12) = 30.85$ ,  $p < .001$ , and is illustrated in Figure 5. The influence of color on de Boer ratings can be compared to the influence found in a previous study comparing HID and TH lamps (Flannagan, Sivak, Battle, Sato, & Traube, 1993). In that study, the same glare rating was associated with lamps that differed in log lux values by 0.165 (a factor of 1.46). The present study found log lux differences between the blue bulb and the TH of 0.135 (a factor of 1.36), between the neodymium and the TH source of 0.066 (a factor of 1.16), and between the blue and neodymium source of 0.068 (a factor of 1.17). The observed differences in the present study are perhaps larger than would be expected from differences in each source's  $u'-v'$  chromaticity coordinates (see Figure 3). That is, the color difference between an HID and a tungsten-halogen source is much larger than

the difference between either of the blue-tinted tungsten-halogen sources used here and a normal tungsten-halogen source; however, the differences in equal-glare levels found in the present study are more than proportional to the size of the color differences.

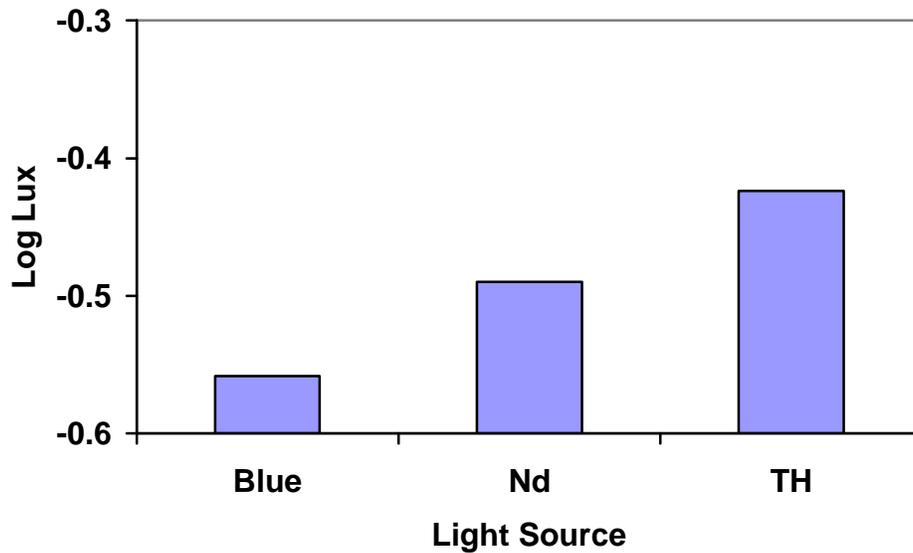


Figure 5. Average log lux value of each light source corresponding to levels of discomfort glare across observers. The TH lamp is seen as least glaring in this analysis because it has the highest photometric value when glare is subjectively equal.

An interaction effect was also observed between age and light source,  $F(2,12) = 4.58, p < .05$ , as illustrated in Figure 6. It shows that younger and older observers appear to differ in the degree to which they found the blue light source to be glaring relative to the other light sources,  $F(2,12) = 4.5, p < .05$ . The interaction is small, however, and it seems clear from the figure that the effects of color for both younger and older observers are at least in the same direction. There also appears to be a difference in the older observer's application of the de Boer rating of 6 (the median), possibly reflecting differing interpretations of the verbal anchors used in the scale, but the effect did not reach statistical significance.

There were no other main effects (e.g., age and seat position) or interactions that approached statistical significance.

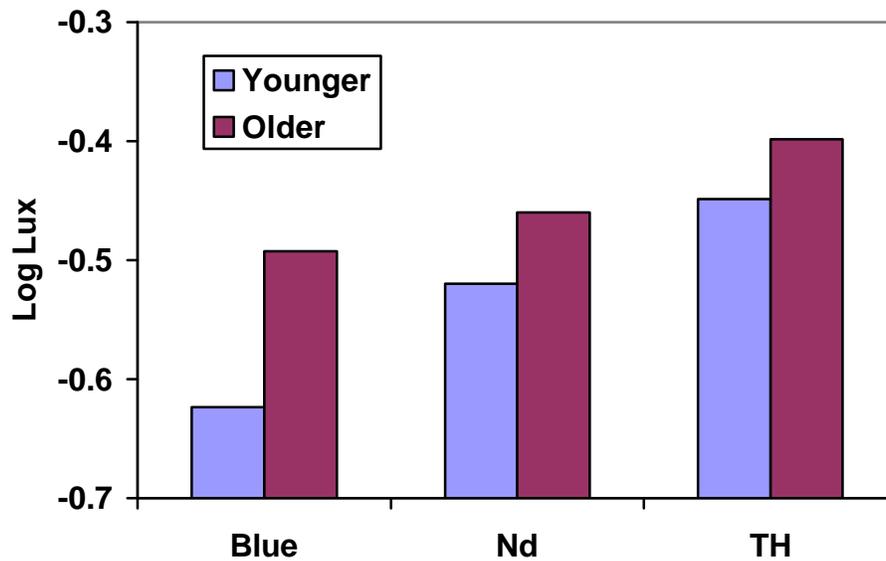


Figure 6. Average log lux value of each light source corresponding to equal levels of discomfort glare (de Boer rating 6) across observers by age. Note that for older observers the rating of 6 seems to be assigned to slightly higher light levels.

## Discussion

These results are consistent with other results (Flannagan et al., 1993) that indicate observers regard light with a bluer appearance to be more glaring. It is also consistent with previous studies that report yellowish lamps to be less glaring to observers (Schreuder, 1976), although evidence of objective advantages is not typically observed.

## Experiment 2: Target Detection with Tinted Sources

In this study, we measured an observer's ability to detect a retroreflective disk illuminated by each of the three headlamp colors (Blue, Nd, and TH) investigated in Experiment 1 during nighttime viewing conditions. In addition, two more color conditions were added in order to investigate the effects of very large differences in color. That is, we attempted to push the color values in extreme directions to see if we could find any influence of color on detection in a task that was similar, at least in some characteristics, to what drivers typically encounter on the road. These additional colors were deep red and deep blue. Their chromaticities are shown in Figure 2. Our strategy in using these somewhat unrealistic sources was based on our expectation that any visibility differences among the relatively conventional colors would likely be extremely small, and that being able to measure effects of the extreme colors might allow us, by interpolation, to make at least preliminary estimates of the magnitude of any differences that one might expect among the relatively conventional colors.

This experiment also looked at differences between foveal and parafoveal detection by presenting the detection stimulus either straight ahead of a fixation point, or offset from the fixation direction by 6 degrees to the left. We did this because there appear to be differences in the spectral sensitivity of the retina, depending on where—between the periphery and the fovea—light happens to fall. Some of these differences can be attributed to differences in the distribution of visual receptors about the retina. In particular, rod receptors, which mediate night vision, are absent in the center of the fovea, but increase in density in the near periphery. Cones, which mediate color vision, are concentrated in the fovea and decline in density toward the periphery (Osterberg, 1935). The two systems of receptors also display different sensitivities to wavelengths of light, as illustrated in Figure 7. That figure shows the luminous efficiency functions for photopic (day/color vision) and scotopic (night/monochromatic vision). Of particular interest for this discussion is that scotopic (rod-mediated) vision is more sensitive to shorter wavelengths of light than photopic (cone-mediated) vision.

Rod and cone density, however, are not the only likely mechanisms influencing spectral sensitivity across the retina. Macular pigment density also changes with retinal

eccentricity, and the cones themselves change in size and shape, altering their spectral sensitivity. One consequence of this is that there are two sets of color matching functions (CMFs) defined by the CIE: one for a 2-degree stimulus, and another for a 10-degree stimulus. The differences among the CMFs involve a greater sensitivity to short (blue) wavelengths with the 10-degree stimulus. From a practical perspective, it seems reasonable to look for differences in an observer's detection capability both for foveal and peripheral stimuli, even if all of the mechanisms that might produce a difference cannot be unambiguously identified.

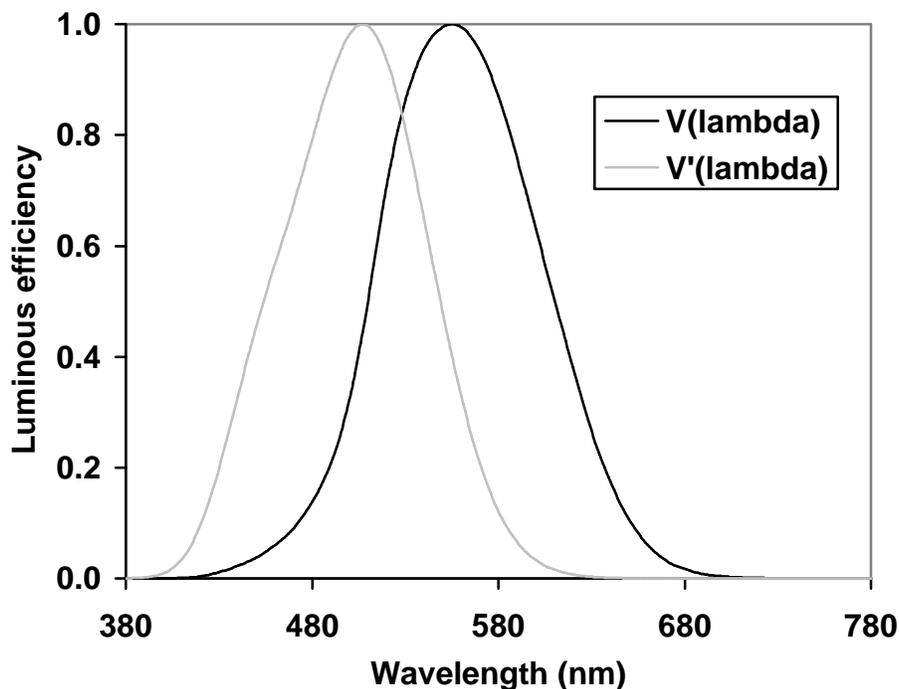


Figure 7. Photopic (daytime),  $V(\lambda)$ , and scotopic (nighttime),  $V'(\lambda)$ , luminous efficiency functions.

## Method

### *Subjects*

Two licensed drivers with normal or corrected to normal visual acuity, and color-normal vision served as subjects in this experiment. Visual screening was conducted as in Experiment 1.

### *Apparatus*

The colored headlamps were positioned in front of a stationary test vehicle with the observer seated in the driver's seat. A fixation point was marked in the roadway at 40 m in the straight-ahead direction as in Experiment 1. The detection stimulus was a white retroreflective disk (30 mm diameter), positioned 75 m from the observer, with its center 0.62 m above the pavement, in one of two locations: center (C, straight ahead) or eccentric (E, 6 degrees left of straight ahead). The target subtended a visual angle of approximately 13 minutes. Because the target was located beyond the fixation point, and was slightly elevated above the pavement, from the subjects' point of view its center was about 1.2 degrees from the fixation point in the center condition, and about 6.1 degrees from the fixation point in the eccentric condition.

The stimulus was illuminated by one of five different colors—the same TH, Blue, and Nd colors used in Experiment 1, plus a tungsten-halogen lamp filtered with a deep blue filter (Lee Filters, No. 118) and a tungsten-halogen lamp filtered by a deep red filter (Lee Filters, No. 164). For each position and light color, the illumination at the target was measured (Table 5).

Table 5. Illuminance levels at the target locations without the variable neutral density filtering described in the text.

Color	Position	Illuminance (Photopic Lux)
Blue	E	0.18
	C	0.44
Nd	E	0.18
	C	0.42
TH	E	0.18
	C	0.42
Deep Red	E	0.11
	C	0.17
Deep Blue	E	0.11
	C	0.17

The luminance of the target stimulus was adjusted using a long band of neutral density filters increasing in effective optical density in increments of 0.1. The band ranged from 0.1 to 3.5 in density (79.4% to 0.03% transmission). An experimenter,

located 75 m away from the observer at the target disk, either increased or decreased the brightness of the target disk by scrolling the filter band until the observer reported that the target was visible (as filter density decreased) or invisible (as filter density increased).

### *Procedure*

Two experimenters participated in this procedure. One accompanied the subject in the observation vehicle, seated in the rear, while the other was situated 75 m down the roadway and controlled the positioning and brightness of the detection disk. The remote experimenter was hidden from view so that the observer was unable to predict the initial position (6 degrees left or straight ahead) of the detection disk.

Observers were allowed 10 minutes to adapt to the ambient roadway light levels while an experimenter read them instructions. An individual trial began at the signal from the remote experimenter, whereupon the subject fixed his or her gaze on a marker located 40 m straight ahead in the roadway. Direction of gaze was verified using an infrared video camera positioned to unobtrusively monitor the observer's eyes. The remote experimenter, starting at a filter density which dimmed the target disk well below the observer's detection threshold, proceeded to lower the filter density, increasing the target brightness until the observer signaled that the target was visible by sounding the observation vehicle's horn. After the horn was sounded, the observer was asked to identify the location of the target to verify the detection. The remote experimenter recorded the filter density at which the detection was made. Following the initial detection, the experimenter reduced the filter density by 0.50 so that the target was clearly visible to the observer and began a descending adjustment series, decreasing the brightness of the target by increasing the filter density. For the descending series, the observer signaled with the horn when the target was no longer visible. The ascending and descending trials were then repeated three more times, yielding four ascending measures of the brightness at which the target was first detected, and four descending measures of the brightness at which the target first disappeared. Notably, the position of the target (center or eccentric) was uncertain only for the first trial of the series.

Trials were blocked by color (Blue, Nd, TH, Deep Red, Deep Blue). Within each block, each of the two target positions was tested twice in a constrained random order—

the order of repeated trials was inverted from their initial presentation. The order of light-source blocks was randomized and then repeated in the reverse of the initial order.

## Results

For each subject, luminance detection thresholds (in  $\log \text{cd/m}^2$ ) were computed by calculating the resulting target luminance based on the measured illuminance of the unfiltered target (Table 5) for each light source and position, the retroreflectivity of the target, and the optical density of the filter in place when the target was either first detected or judged to have first disappeared. An analysis of variance was then performed on this dependent variable.

### *Main Effects*

The ANOVA revealed no main effects of color, positional eccentricity, or ascending versus descending order. There was a main effect of order within the trial, such that the first target detection judgment in the series appeared to occur at a lower threshold than the later judgments (Figure 8). It is unclear what the basis for this difference is, but it may be that observers had a lower criterion for detection when the target position was uncertain.

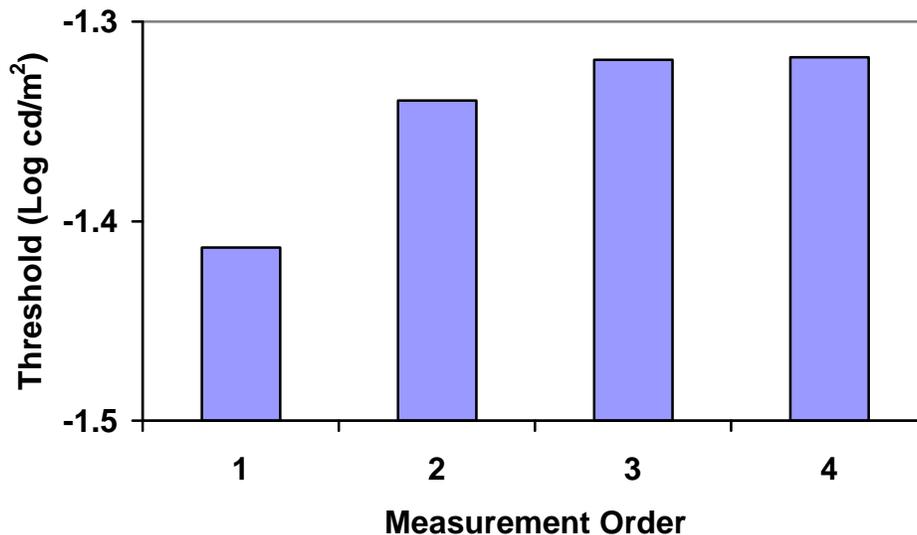


Figure 8. Detection threshold by measurement order within a trial. The location of the target is uncertain in the first ascending measurement taken in a trial.

Although no other main effects were statistically significant, there were some noteworthy trends. For example, detection thresholds tended to be higher by a factor of 1.4 at the 6-degree offset location relative to straight ahead ( $-1.42 \log \text{cd/m}^2$  at center,  $-1.27$  at  $-6$  degrees). This is what might be expected if observers were less sure of what they saw in the periphery and thus raised their detection criteria.

Detection thresholds tended to be higher for ascending (brightening) trials than descending (dimming) trials by a factor of 2.4. This is expected, and likely also reflects criterion differences between the judgment that an object is visible and the judgment that an object has disappeared.

#### *Interaction effects*

The interaction of color and eccentricity, shown in Figure 9, was statistically significant,  $F(4,4) = 24.9, p < .001$ . It appears that the threshold for the red light source is much higher in the periphery (by a factor of 2.72) than it is for the other light sources, demonstrating that, at least with deeply colored sources, differences can be observed in an observer's spectral sensitivity at different eccentricities, under visual conditions similar to those faced by drivers at night.

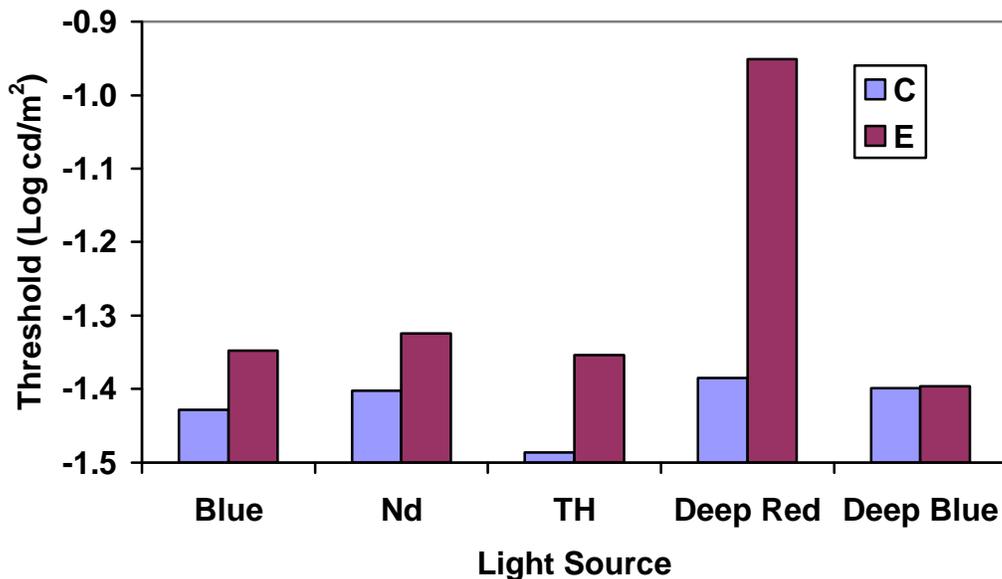


Figure 9. Interaction effect between target eccentricity (C, center; E,  $-6$  degrees) and light source. The figure shows that the threshold for the deep red light source is higher in the eccentric location than it is for the other light sources.

## Discussion

The interaction between color and eccentricity in Figure 9 is qualitatively what one would expect from the idea that detection in the central position depends relatively more on the cone (photopic) system and that detection in the eccentric position depends relatively more on the rod (scotopic) system. Table 6 shows the threshold differences for each color, along with the ratios of scotopic to photopic luminosity for those colors. As might be expected, the deep red source is very low in the scotopic to photopic ratio, and the deep blue source is very high. The relatively conventional colors (Blue, Nd, and TH) are all much more moderate. The differences between center and eccentric thresholds are very closely related to the ratios of the scotopic and photopic measures. The Deep Blue source yields the largest ratio of center to eccentric threshold (0.99) and the Deep Red source yields the smallest (0.37). In fact, the linear relationship between the logs of the values shown in Table 6, as illustrated in Figure 10, is very strong.

As we expected, the present experiment did not have enough power to detect any small differences in visibility that might exist among the relatively conventional colors, but the strategy of including unrealistically extreme colors at least allows us to make a preliminary prediction of how big such differences might be. The two blue-tinted sources (Blue and Nd) are both slightly above and to the right of the TH source in Figure 10, indicating that the observed differences in visibility, as given in Table 6, are consistent with the regression model in terms of their direction. However, the differences in visibility between either of the blue-tinted sources and the TH source (the vertical separations in Figure 10) are larger than would be expected from the differences in relative scotopic and photopic luminosity (the horizontal separations in Figure 10). Thus, to the extent that the empirical relationship in Figure 10 is valid, any differences in visibility among the relatively conventional colors would be very small.

Table 6. Threshold difference factors between centrally viewed (C) and eccentrically viewed (E) light sources, and the calculated scotopic/photopic ratios.

Source	C vs. E Threshold Difference	Scotopic/Photopic Ratio
Blue	0.83	1.63
ND	0.84	1.72
TH	0.74	1.55
Deep Red	0.37	0.19
Deep Blue	0.99	3.90

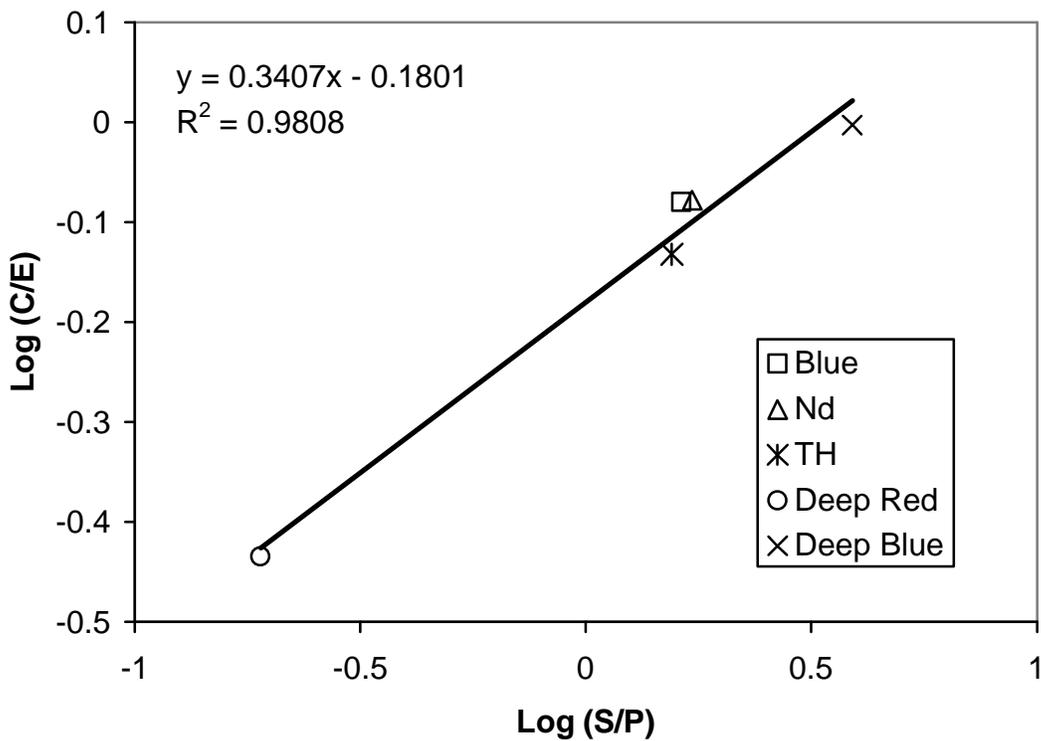


Figure 10. The relationship between log of the threshold ratios (central threshold divided by eccentric threshold) and log of the scotopic/photopic ratios.

## Conclusion

In Experiment 1, blue-tinted light sources were judged to be more glaring than standard tungsten-halogen light sources. The result is consistent with previous reports (Flannagan, Sivak, & Gellaty, 1991). The size of the difference does not appear to be closely related to chromaticity differences characterized by  $u'$  and  $v'$  coordinates, nor to the scotopic/photopic luminance ratio (calculated in Table 6). Thus, although it is true as a rough empirical generalization that relatively blue sources have been found to produce more subjective glare, and relatively yellow sources have been found to produce less subjective glare, the quantitative nature of this relationship remains to be explained. Also, differences in subjective glare are not always accompanied by differences in the tendency of glare sources to reduce objective visual performance (Flannagan, 1999). Although both subjective and objective effects of glare sources may affect safety, objective effects are probably more important. The effects of color on objective glare should therefore be further evaluated.

With regard to possible differences in the visibility provided by the various sources tested here, there were no statistically significant differences among the relatively conventional colors (Blue, Nd, and TH). However, when the more extreme colors are included (Deep Blue and Deep Red) a statistically reliable interaction of color and retinal location emerges, and the pattern of the interaction seems to be well accounted for by the idea that, under conditions similar to night driving, the rod system makes a relatively larger contribution to detection in the near periphery, compared to the center of the visual field. However, interpolation based on the visibility of the extreme colors suggests that any differences in the visibility provided by the relatively conventional headlamp colors are likely to be very small.

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