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# An Investigation of Headlamp Glare:

## Intensity, Spectrum and Size

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16. Abstract
Headlamp glare is an issue that has grown in terms of public awareness over the past decade. Developments in light source technologies and optical design have resulted in headlamp systems with higher efficiency (and thus the ability to produce higher illuminances), as well as differing spectral power distributions and smaller sizes than conventional halogen headlamps. This report describes research to investigate and quantify the impact of glare illuminance, glare spectral power distribution, and glare source size on peripheral detection of small targets in the field. Peripheral visibility is an area that heretofore has not been extensively studied in the context of headlamp glare, although peripheral vision is important for driving. The impact of glare can be segregated into two areas: the reduction of visibility caused by scattered light in the eye (disability glare), and the sensations of discomfort caused by a glare source in the field of view (discomfort glare). These phenomena often, but do not necessarily always, occur simultaneously.

With respect to disability glare, detection of peripheral targets worsened as the glare illuminance increased from 0.2 to 5 lx, as expected. Detection of high-reflectance targets (located 60 m ahead) was relatively unaffected by glare, however, except for targets very close to the glare source and targets furthest from the line of sight. Neither the spectral power distribution (halogen, high intensity discharge or blue-filtered halogen) nor glare source size (from 9 to 77 cm2 in area) affected peripheral detection, once the glare illuminance was held constant.

With respect to discomfort glare, higher glare illuminances elicited subjective ratings of greater discomfort and was the most important determinant of discomfort. Spectral power distribution also affected discomfort (even though it did not affect visual performance) with the high intensity discharge headlamps eliciting ratings of greater discomfort than the halogen and blue-filtered halogen headlamps, when the glare illuminance was held constant. Glare source size had no impact on ratings of discomfort.

For the range of conditions used in the present study, conventional far-field photometry based on the photopic luminous efficiency function, $V(\lambda)$, is appropriate in characterizing a glare source in terms of visual performance, but $V(\lambda)$ does not accurately characterize discomfort glare.


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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# EXECUTIVE SUMMARY

Headlamp glare is an issue that has grown in terms of public awareness over the past decade. Developments in light source technologies and optical design have resulted in headlamp systems with higher efficiency (and thus the ability to produce higher illuminances), as well as differing spectral power distributions and smaller sizes than conventional halogen headlamps. This report describes research to investigate and quantify the impact of glare illuminance, glare spectral power distribution, and glare source size on peripheral detection of small targets in the field. Peripheral visibility is an area that heretofore has not been extensively studied in the context of headlamp glare, although peripheral vision is important for driving. The impact of glare can be segregated into two areas: the reduction of visibility caused by scattered light in the eye (disability glare), and the sensations of discomfort caused by a glare source in the field of view (discomfort glare). These phenomena often, but do not necessarily always, occur simultaneously.

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# I. LITERATURE REVIEW

## Introduction

This section reviews literature on the topic of headlamp glare. The results of previously conducted studies as they pertain to the intensity, spectrum and spatial distribution of light sources used for forward lighting on vehicles, and to the visual characteristics of drivers who experience headlamp glare, are presented. The literature was used to guide the experimental design and conditions for subsequent field studies on headlamp glare.

## Significance of Headlamp Glare

Hemion (1969) estimated in the late 1960s that approximately 1% of accidents could be attributed, at least in part, to headlamp glare (i.e. "blinded by headlamps"). This review outlines the important characteristics of headlamp systems as they relate to glare while driving at night, focusing on *intensity*, *spectrum*, *size* and *temporal properties* (frequency, duration) of headlamps.

## Intensity

As would be expected, the published literature on headlamp intensity indicate that increasing the luminous intensity of headlamps also increases the glare they provide (Powers and Solomon, 1965; Hare and Hemion, 1968; Mortimer, 1969).

### *Disability Glare*

Of interest, a number of studies of seeing distance have demonstrated that from a purely visibility-based point of view, forward visibility increases as overall headlamp intensity increases (Flannagan *et al.*, 2000). Even when two opposing drivers have their high beams switched on, for example, visibility distances in the presence of the increased glare were found to be greater than in a situation when two drivers with their low beams switch on approach each other (Bergström, 1963; Johansson *et al.*, 1963; Schwab, 1965; Hemion, 1969). Of course such studies have generally occurred in clear ambient conditions. In perturbed atmospheres such as fog, use of high beams could severely limit forward visibility. These studies measured the effects of short-term exposure to glare on forward visibility; the annoyance from oncoming high beams could have indirect impacts on driving performance that were not considered.

It is almost always the case that headlamp glare reduces visual performance under driving conditions relative to the level of performance achievable without glare (Mortimer, 1969; Ranney *et al.*, 1999, 2000; Akashi and Rea, 2001). This effect has been shown to be consistent with predictions of contrast reduction caused by a uniform veil of brightness in the field of view (Stiles and Crawford, 1937; Fry, 1954), given by the following equation for a single glare source:

$$L_v = \frac{9.2E}{\theta(\theta + 1.5)} \qquad \textit{(Equation 1)}$$

In Equation 1, $L_v$ is the resulting equivalent veiling luminance (in cd/m$^2$), $E$ is the glare illuminance at the observer's eye (in lx), and $\theta$ is the distance (in degrees) between the observer's line of sight and the glare source. When multiple glare sources are present (e.g., a pair of oncoming headlamps) the individual equivalent veiling luminances from each source are added together.

There are few data describing the impact of headlamp glare on peripheral visibility. Data collected in a field study with oncoming low-beam headlamps showed that glare from oncoming headlamps have a greater effect on visibility for objects located furthest from the line of sight in the periphery (Akashi and Rea, 2001).

### *Discomfort Glare*

Typical glare illuminances from oncoming headlamps were found during the early 1990s (when conventional halogen headlamps were the primary sources of forward lighting) to range from 0 to 10 lx in normal driving conditions (Alferdinck and Varkevisser, 1991). Bhise *et al.* (1977) cite research (Mortimer and Becker, 1965) stating that 0.1 lx at the eye is the threshold from nonglaring to glaring conditions, when the illuminance from a glare source begins to become uncomfortable. An illuminance of 1 to 3 lx appears to be sufficient to cause drivers to flash their own headlamps to signal to oncoming drivers that the glare is unacceptable (Bhise *et al.*, 1977; Rumar, 2001). A value of 3 to 10 lx is close to the illuminance at which discomfort becomes unbearable (Schmidt-Clausen and Bindels, 1974; Olson and Sivak, 1984; Flannagan *et al.*, 1989, 1992, 1993; Sivak *et al.*, 1990, 1999; Alferdinck and Varkevisser, 1991; Flannagan, 1999; Lehnert, 2001; Bullough *et al.*, 2002). Illuminances higher than 10 lx are almost certain to be found unbearable.

The De Boer scale (De Boer, 1967) is the one most commonly used to quantify discomfort from nighttime lighting installations including streetlights and vehicular headlamps. On this 9-point scale, a value of 9 corresponds to just noticeable discomfort and a value of 1 corresponds to discomfort that is unbearable (Table 1). Various models have been developed to predict De Boer ratings from headlamps providing a given illuminance at an oncoming driver's eyes. One such model was developed by Schmidt-Clausen and Bindels (1974), using the following equation:

$$W = 5 - 2\log \frac{E}{0.02\left(1 + \sqrt{L/0.04}\right)\theta^{0.46}} \qquad \textit{(Equation 2)}$$

In Equation 2, $W$ is the De Boer rating, $E$ is the illuminance from the glare source (in lx), $L$ is the adaptation luminance (in cd/m$^2$), and $\theta$ is the angular distance (in degrees) between the glare source and the observer's line of sight.

***Table I-1.*** *The De Boer rating scale for discomfort glare.*

| **Visual response** | **Rating** |
|---|---|
| unnoticeable | 9 |
| | 8 |
| satisfactory | 7 |
| | 6 |
| just admissible | 5 |
| | 4 |
| disturbing | 3 |
| | 2 |
| unbearable | 1 |

Using such models, typical U.S. low beam headlamps during the 1970s result in De Boer ratings of between 4 and 6; U.S. high beams resulted in ratings of between 1 and 4. Typical European low beams from the same time period resulted in De Boer ratings of between 6 and 8 (Bhise *et al.*, 1977).

Based on observations of drivers meeting various configurations of headlamps, Bhise *et al.* estimated that a De Boer rating of 4 elicited headlamp "flashing" from oncoming drivers requesting the other driver to dim the headlamps. As noted above, a similar observation is noted by Rumar (2001). A De Boer rating of 4 appears to be elicited when the illuminance at the eye is on the order of 1 lx (Bullough *et al.*, 2002).

### *Links Between Disability and Discomfort*

Very few studies have probed the interactions between discomfort and disability glare, or indeed any driving-performance related factors. A comprehensive field study was conducted (Theeuwes and Alferdinck, 1996) during which drivers were exposed to illuminances from 0.3 to 1 lx. The results showed that ratings of discomfort were correlated with illuminance, but that above 0.55 lx, driving performance did not deteriorate. Such results are consistent with the hypothesized distinction between disability and discomfort glare (Wright, 1937). Still, these two phenomena tend to be correlated with one another (Schwab and Hemion, 1971).

### *Other Factors Affecting Headlamp Intensity*

The level of ambient illumination along the roadway plays an important role in the perception of glare, as might be expected. Higher ambient levels provided by fixed pole lighting will result in higher thresholds for discomfort glare (Schreuder, 1969; Schmidt-Clausen and Bindels, 1974; Bhise *et al.*, 1977)

Dirty headlamps reduce one's own forward illumination while increasing the illuminance to oncoming drivers (Alferdinck and Padmos, 1988). Misaimed headlamps were yet another factor found to strongly affect the intensity of headlamps in the direction of oncoming drivers, and thus the degree to which they can cause visual discomfort or disability glare (Alferdinck and Padmos, 1988).

## Spectrum

### *Disability Glare*

The impact of spectral power distribution (SPD) on disability glare has generally been understood to be small, at least for the conditions under which it has been studied in previous research (Schreuder, 1976). Formulae for the prediction of disability glare in terms of reduced contrast caused by scattered light in the eye (Stiles and Crawford, 1937; Wright, 1937; Fry, 1954) have been quite successful at predicting threshold detection contrast for vision along the central line of sight. Jehu (1954) reported no differences between unfiltered and yellow-filtered incandescent headlamps in terms of disability glare. Flannagan (1999) and Bullough *et al.* (2002) reported that halogen and HID headlamps providing the same glare illuminance resulted in the same threshold contrast increase.

One factor that has been largely overlooked in studies of disability glare is the potential effect of spectrum on *peripheral* visual performance. During many conditions of nighttime driving, the visual system is adapted to mesopic light levels (He *et al.*, 1997), where both cones and rods contribute to detection of peripheral objects and where the spectral sensitivity of the peripheral retina can be represented by a weighted combination of photopic (cone) and scotopic (rod) spectral sensitivity. Since, as shown in Figure I-1, rods have peak sensitivity at shorter wavelengths (around 500 nm, corresponding to "blue-green" light) than the combined sensitivity of the cones (around 555 nm, corresponding to "yellow-green" light), spectrum plays an important role in peripheral detection at these low light levels (He *et al.*, 1997, 1998; Bullough *et al.*, 2000; Lingard and Rea, 2002; Akashi and Rea, 2002). Light sources with more energy in the "blue-green" portion of the visible spectrum are more effective for these types of tasks.

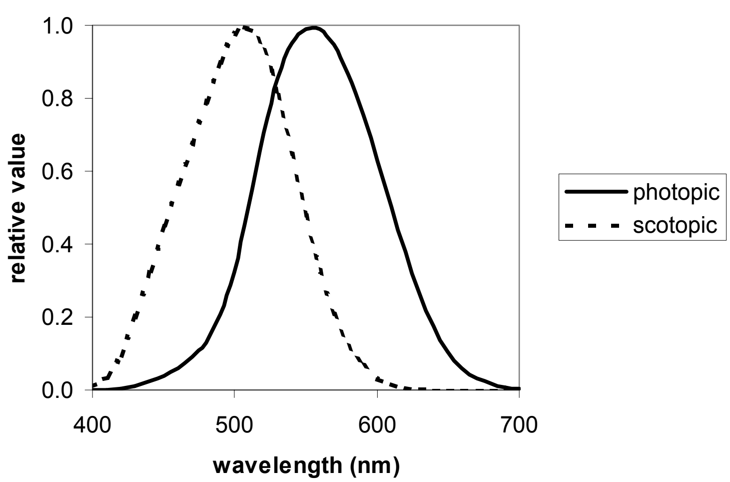


***Figure I-1.*** *Photopic and scotopic luminous efficiency functions. The values at each wavelength are the sensitivity of the photopic and scotopic mechanisms, relative to the peak sensitivity for each mechanism.*

Continuing this logic, it stands to reason that the spectrum of scattered light in the eye could therefore impact peripheral detection, with glare sources having more light in the "blue-green" region of the spectrum possibly having a greater impact on peripheral vision. To date, no studies have been identified that have tested this hypothesis directly. As for the studies of foveal, on-axis, visibility where no effect of spectrum was found (Jehu, 1954; Flannagan, 1999; Bullough *et al.*, 2002), these results are consistent with this hypothesis too, because for foveal visual tasks, like reading or identification of detail, only photopic sensitivity applies because there are no rods in the central part of the retina.

### *Discomfort Glare*

Spectrum does appear to play an important role in the perceptions of visual discomfort that are experienced when presented with a glare source during nighttime driving conditions. This is a phenomenon that has been appreciated since at least the 1930s, when it was reported that discomfort glare was caused more by "blue" than by "yellow" light (Bouma, 1936). The effect of spectrum on discomfort glare for nearly monochromatic, highly saturated colors has shown that yellow sources are perceived as less glaring (from a visual comfort perspective) than green or blue sources (Flannagan *et al.*, 1989, 1993; Bullough *et al.*, 2001). For nominally white light sources, such as halogen and HID headlamps, a series of studies conducted in laboratory and simulated field settings has confirmed that typical HID headlamps, viewed in an oncoming situation, result in greater discomfort than typical halogen headlamps (Flannagan, 1999; Flannagan *et al.*, 1992, 1993; Bullough *et al.*, 2002).

Qualitatively, these results are consistent with early studies of street lighting spectrum and discomfort glare. Ferguson *et al.* (1953) and De Boer and Van Heemskerck Veeckens (1955) asked subjects to compare the discomfort from street lighting luminaires containing low pressure sodium (saturated yellow in color) and mercury lamps (Ferguson *et al.*) and unfiltered and yellow-filtered incandescent lamps (De Boer and Van Heemskerck Veeckens). In order to be perceived as equally glaring, the light output from the "yellower" lamps needed to be higher than the "whiter" lamps. An analysis of the likely spectral content of these lamps (Bullough and Rea, 2001) indicated that the spectral sensitivity of the rod photoreceptors could be a large determinant of the discomfort response. Since HID headlamps typically have 5%-10% more rod-stimulating output than halogen headlamps for an equal light level, their somewhat higher scotopic (rod-stimulating) output might explain the greater degree of glare.

However, the differences in discomfort glare between HID and halogen headlamps is much greater than would be explained by the differences in their scotopic light output. Halogen headlamps need to provide an illuminance at the eye that is 25%-50% higher than that from typical HID headlamps in order to be rated equally glaring (Flannagan *et al.*, 1992, 1993; Bullough *et al.*, 2002, 2003), but as mentioned above they differ only by 5%-10% in terms of scotopic output. Furthermore, Bullough *et al.* (2002) tested a blue-filtered halogen lamp with much higher scotopic light output than either conventional halogen and HID lamps, but the rated discomfort was still greater from HID headlamps. This evidence implies that the rod photoreceptors, having scotopic spectral sensitivity, are not primarily responsible for discomfort glare.

Evidence that brightness might be related not to rods but to short-wavelength ("blue") cones has emerged (Fotios and Levermore, 1998). If discomfort glare were a response caused by excess brightness, as might be possible, then perhaps the spectral sensitivity of short-wavelength cones (with a maximal response near 450 nm) would be suitable to explain the increased discomfort glare that has been found with HID lamps. Indeed, Bullough *et al.* (2002) plotted De Boer ratings from halogen, blue-filtered halogen and HID headlamps providing different illuminances at the eye, as a function of relative short-wavelength cone stimulation, and found that the resulting De Boer ratings were highly correlated with this quantity. While this does not prove that short-wavelength cones are the mechanism for discomfort glare under these conditions, it does provide compelling evidence that some type of short-wavelength mechanism can play an important role in the discomfort response.

Recently a headlamp with an absorptive neodymium coating has been described (Karpen, 2002). The neodymium absorbs light near 580 nm, with the result that color saturation of objects increases slightly with the result that observers prefer the appearance of typical highway sign colors under these lamps (McColgan *et al.*, 2002), although McColgan *et al.* (2002) found this lamp to provide equal color identification performance as unfiltered halogen, blue-filtered halogen and HID headlamps. The resulting SPD is also about 10% higher than unfiltered halogen headlamps in terms of scotopic output when (photopic) light output is equal (Karpen, 2002), and comparable short-wavelength cone stimulation to blue-filtered halogen headlamps.

### *Other Spectral Effects*

In the context of driving, other effects of SPD have been studied. One study of light source color in the context of nighttime driving in poor ambient weather conditions (Bullough and Rea, 2001) measured individuals' visual tracking performance conducted over a 45-minute period of time in the presence of visual "noise" simulating heavy snowfall. As might be expected from studies of spectrum and discomfort glare, subjective ratings of discomfort worsened for blue and white light relative to yellow and red light. Tracking performance also worsened for the blue and white light sources. Since the visual noise stimulus in the experiment covered a large portion of the field of view, this stimulus might have played a role in enhancing or exacerbating any fatigue-related effects of the demanding visual task. Results such as this demonstrate that the traditional dichotomy between disability glare and discomfort glare is, at least sometimes, artificial.

Another effect of SPD that has been investigated is its impact on pupil size. The pupil mechanism is dominated by rod photoreceptors (Alpern and Ohba, 1972), which outnumber cones in the retina by a factor of about 15 to 1 (Rea, 2000). Thus, the pupil has largely a scotopic response. Smaller pupils in some daytime light level conditions with briefly flashed, near-threshold targets resulted in slightly better visual performance (Berman *et al.*, 1993) since smaller pupils in general should increase the depth of field and image sharpness, although Marcos *et al.* (1999) demonstrated that pupil size and SPD have only very small effects on depth of field. Furthermore, pupil sizes at typical nighttime driving light levels are generally large, with little variation that would be caused by spectrum, since these light levels fall below the pupil's dynamic range. It can thus be concluded that pupil size as determined by SPD is at most a minor effect.

## Size

### *Disability Glare*

The size of headlamps with respect to disability glare has not been studied in great detail. Miles (1954) reported that performance in the presence of glare is worse for smaller sized headlamps, and proposed that headlamps be made larger in size to reduce the effects of glare. Flannagan (1999) compared glare sources subtending either 0.3 or 0.6 degrees and found no difference between them in terms of disability glare, as measured by threshold contrast.

### *Discomfort Glare*

Somewhat more research has been conducted to probe the effects of source size on discomfort glare, mainly to test the reasonable hypothesis that in order to provide equivalent luminous intensity, smaller headlamps must have higher luminance and would therefore cause greater discomfort (Manz, 2001). What appears to be the case is that this effect is small, when compared to that of the illuminance produced at the eye (Völker, 1999). Schmidt-Clausen and Bindels (1974) compared single- and multiple-source arrays in terms of the De Boer ratings they elicited and found that once the glare illuminance was equivalent, so were the glare ratings. Alferdinck and Varkevisser (1991) investigated a large range of source sizes (from 0.0006 to 0.15 degrees$^2$) and showed that the maximum difference in discomfort attributable to size was equal to about 1 De Boer unit. Flannagan (1999) found no effect of size when going from 0.3 to 0.6 degrees, while another study using the same sizes (Sivak *et al.*, 1990) showed a very small effect of size.

However, these results should be compared to those of Bhise *et al.* (1977) who field-tested two- and four-headlamp systems producing the same glare illuminance. Of interest, dimming requests from other drivers were greater with the four-lamp systems, even though their luminance was reduced because the overall glare illuminance was the same. This phenomenon implies that other psychological factors could play into driving behaviors associated with discomfort. Drivers might have interpreted the four-lamp array as a vehicle with its high-beam headlamps switched on and responded to that. Such decisions will be important to consider in the design of intelligent forward lighting, which themselves may incorporate arrays of headlamp sources to provide various portions of the forward beam.

## Temporal Properties

### *Disability Glare*

The temporal properties of headlamps with respect to glare are important because these are generally seen briefly and intermittently rather than continuously for long periods of time. Bichão (1995a, 1995) found that intermittent glare sources did not have a large impact on foveal (on-axis) detection but that it did have a larger negative impact on peripheral detection. This appears to contradict the results of Harris (1953) who found that a source that moved across the field impaired visibility no more or less than a continuous, stationary glare source. The issue is complex; Mortimer (1965) compared duration of glare (7 versus 15 seconds) and found that the longer duration sometimes, but not always, negatively impacted simulated driving performance. Frequency of glare exposure (from 1 to 4 times per minute) did not differentially impair performance.

Of interest, two studies (Schwab and Hemion, 1971; Ranney *et al.*, 1999) found that while intermittent glare affected visual performance in a driving context, as would be expected, the effect did not worsen throughout an extended period of time. In particular, Ranney *et al.* (1999) showed no greater difference even after 8 hours of intermittent glare exposure.

### *Discomfort Glare*

What appears to be the case regarding the temporal properties of headlamp illumination and discomfort glare is that it is a smaller effect than glare illuminance. Both Sivak *et al.* (1999) and Lehnert (2001) showed that a glare source shown for a greater period of time will be rated as more uncomfortable, but that this duration was not as important as illuminance.

## Age, Visual Condition and Expectation

### *Disability Glare*

It should not be surprising that older drivers experience greater disability in the presence of a glare source than younger drivers. The eye contains more light-scattering debris and other materials as we age (Rea, 2000) and minor opacities of the lens (Anderson and Holliday, 1995) exacerbate threshold contrast reductions and visual acuity reductions caused by glare sources. However, Schmitz *et al.* (2000) compared older drivers with and without different types of lens implants in terms of threshold contrast in the presence of halogen headlamp glare; there were no differences between people with and without these implants.

A growing proportion of the driving population of all age groups has undergone one of several types of refractive surgery such as laser in situ keratomileusis (LASIK) or photorefractive keratectomy (PRK). Such procedures are generally regarded as quite successful by people who have undergone them (Ben-Sira *et al.*, 1997; Gimbel *et al.*, 1993; Kahle *et al.*, 1992; Freitas *et al.*, 1995; McGhee *et al.*, 2000; Holladay *et al.*, 1999; Sugar *et al.*, 2002; Hadden *et al.*, 1999). Some complications have been reported by patients that relate to nighttime driving and glare sensitivity, but these have diminished over a period of 6 to 12 months and it is thought that cortical adaptation might be a reason for such a long adjustment period.

### *Discomfort Glare*

In terms of discomfort glare, the literature shows mixed results. In some studies comparing younger and older drivers (Flannagan *et al.*, 1993; Olson and Sivak, 1984) and comparing drivers with no vision correction with those wearing eyeglasses or contact lenses (Sivak *et al.*, 1999), the older and corrected-vision subjects reported slightly greater levels of discomfort. This is in contrast with similar studies where the opposite effect was found, and where older drivers actually reported less discomfort (Tsongos and Schwab, 1970; Theeuwes and Alferdinck, 1996) than younger drivers. Factors such as glare experience, expectations and other psychological effects could certainly play a role in explaining these differences. For example, Sivak *et al.* (1989) compared American and German drivers in terms of their discomfort responses to the same glare conditions, and German drivers reported greater discomfort than the American drivers, presumably because European headlamp beams tend to be designed to produce less glare because of sharper cutoffs.

## Summary

In terms of glare, the most significant factors appear to be the glare illuminance, and, for discomfort glare, the SPD. Factors such as light source size, driver age, visual condition (within reasonable limits) and expectations seem to be much smaller effects, and more open to influence by other factors of the environment. Whether spectrum influences peripheral threshold contrast or detection performance has not been studied in detail, and such research would be of value in determining what, if any, role spectrum should play in determining appropriate characteristics of headlamp beams.

# II. METHODS

In order to probe the impact of intensity, spectrum and the size/luminance characteristics of headlamps on visual performance and discomfort under driving conditions, a field study was conducted on an unused runway at Schenectady County Airport in Scotia, NY. This runway afforded a long, straight stretch of unlighted roadway with asphalt surface and little surrounding ambient light.

## Experimental Design

The experimental field study approach has three primary components:

- for a constant glare source SPD, visual performance and discomfort glare was measured for different illuminances at the eye
- for a constant glare illuminance at the eye, visual performance and discomfort glare was measured with three different glare source SPDs: HID, halogen, and blue-filtered halogen
- for a constant illuminance at the eye and a constant SPD, visual performance and discomfort glare was measured for different light source size/luminance combinations

The experimental design was executed in several three-condition blocks, similar to the fashion in which previous field studies have been conducted by the LRC (Van Derlofske *et al.*, 2001a, 2001b). Each study used halogen headlamps as the forward light source. Previously published studies have quite clearly elucidated the impact and benefits of HID headlamps relative to halogen headlamps on forward visibility in the absence of glare (Hamm and Steinhart, 1999; Van Derlofske *et al.*, 2001a). Unlike those previous studies, the present study used a pair of headlamps in the field of view that changed in terms of light level, SPD or spatial extent as shown in the experimental design in Figure II-1.

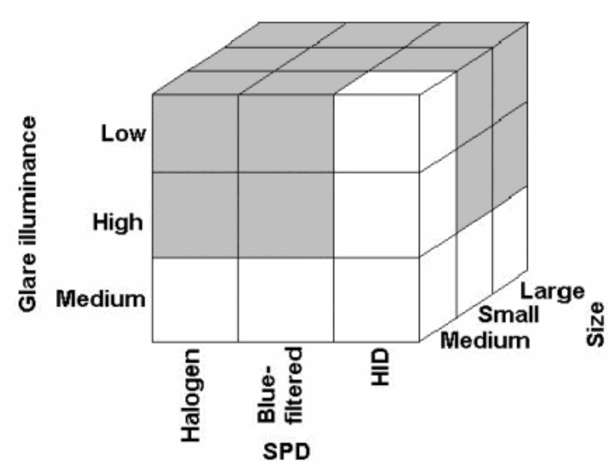


***Figure II-1.*** *Experimental design incorporating three-condition blocks (unshaded).*

In the first study block, HID headlamps were used and were adjusted to provide three levels of illuminance at the eye (the rightmost column in Figure II-1). The illuminances were selected as follows:

- one corresponding to a typical glare illuminance
- one close to the maximum possible illuminance that could be achieved with low-beam headlamps misaimed to a large extent
- one corresponding to a low value of luminous intensity from low-beam headlamps toward the direction of the observer

In the second study block (the bottom row across Figure II-1), the glare source headlamps were HID, halogen or blue-filtered halogen of the "typical" illuminance from the first study block. This level was designed to provide a high, but not necessarily intolerable, level of glare. The offset of the glare headlamps from the observer's line of sight corresponded to that typically found in driving on rural two-lane roads.

In the third study block, the SPD and illuminance at the eye were constant, but the size (and luminance) of the glare source changed according to the range of sizes found on headlamps having differing optical systems.

This experimental design therefore obviated the need for a 3 × 3 × 3 condition matrix of 27 total conditions, but covered a meaningful range of conditions along each parameter, and also contained an experimental condition common to each block in order to analyze whether small differences in subject populations in each study block were significant.

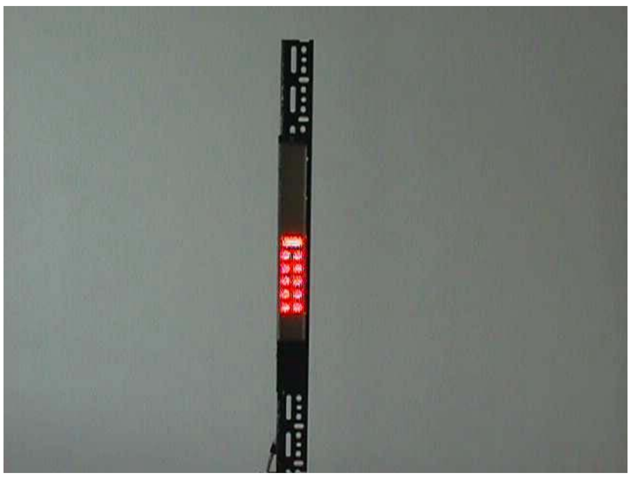

***Figure II-2.*** *LED tracking task.*

## Experimental Apparatus and Setup

The experimental apparatus and layout are shown in Figures II-2 through II-5. Subjects were seated in a black 1995 Mercury Tracer and performed a tracking task cognitively similar to driving. The tracking task consisted of an array of red light emitting diodes (LEDs) with yellow LEDs in the center (Figure II-2). The tracking task was set to display a randomly determined length of red LEDs and subjects were instructed to turn a knob to reduce the length of the red array. After each successful completion, the tracking task reset itself to a new length of the red array. The tracking task was positioned 10 m in front of the subject, along his or her line of sight.

The purpose of the tracking task was to ensure that the subjects' line of sight, and therefore, the angular distance between the line of sight and the targets' locations, remained constant. In order to ensure that the fixed gaze position did not have an effect on subjects' ratings of discomfort, a laboratory pilot study was conducted (Bullough *et al.*, 2003) whereby subjects' ratings of discomfort were gathered under different light sources and illuminances. It was found in that study, which controlled the gaze position of one group of subjects (as done in the present study) and allowed the other group of subjects to gaze freely anywhere in the visual scene, that discomfort ratings were highly ($r^2$=0.99) correlated between the groups.

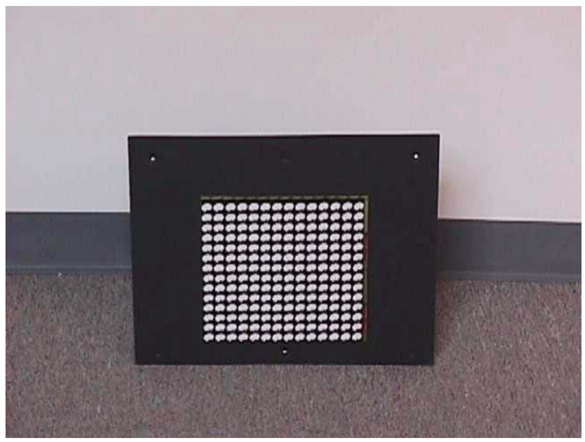

***Figure II-3.*** *Flip dot target.*

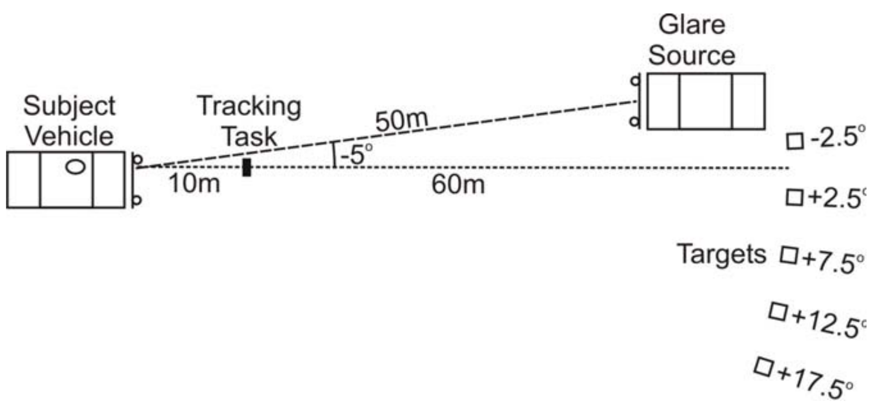


***Figure II-4.*** *Plan view of experimental layout. Targets were slightly rotated so that they faced the subject vehicle; rotation is not indicated in this figure.*

At the same time, five small targets (Figure II-3) consisting of square-shaped arrays of flip dots (approximately 20 × 20 cm) were positioned on the roadway 60 m in front of the subject, separated by 5° intervals (Figures II-4, II-5 and II-6). The leftmost target was 2.5° to the left of the line of sight and the rightmost target was 17.5° to the right of the line of sight. The flip dots on the targets were painted black on one side and white on the other; they normally appeared black but when activated, flipped (within 20 ms) to the white side. The average reflectance of the square target was 40%; a neutral density filter placed in front of the target reduced this reflectance to 20%.

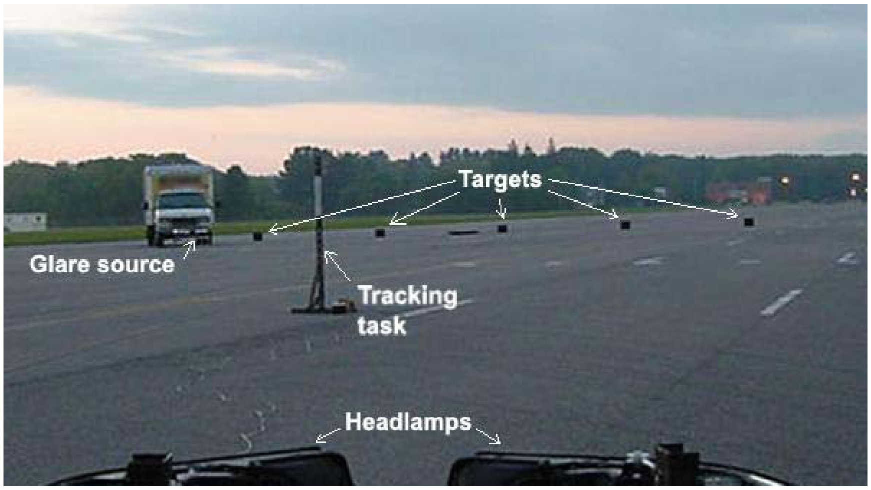


***Figure II-5.*** *Daytime view of the glare headlamps, small targets and tracking task, approximately from the subjects' viewing location.*

A set of halogen, low-beam, optically aimable headlamps was positioned directly on the roadway surface in front of the subjects' vehicle, mounted on a rack. During each session the headlamps were aimed according to Society of Automotive Engineers (SAE) standards to ensure proper aim. The vertical illuminances on the small targets were measured for each session and are shown in Figure II-7. The headlamps were powered from the subject vehicle.

***Figure II-6.*** *View of glare headlamps, the three centermost targets and the tracking task as they appeared during experimental nighttime sessions.*

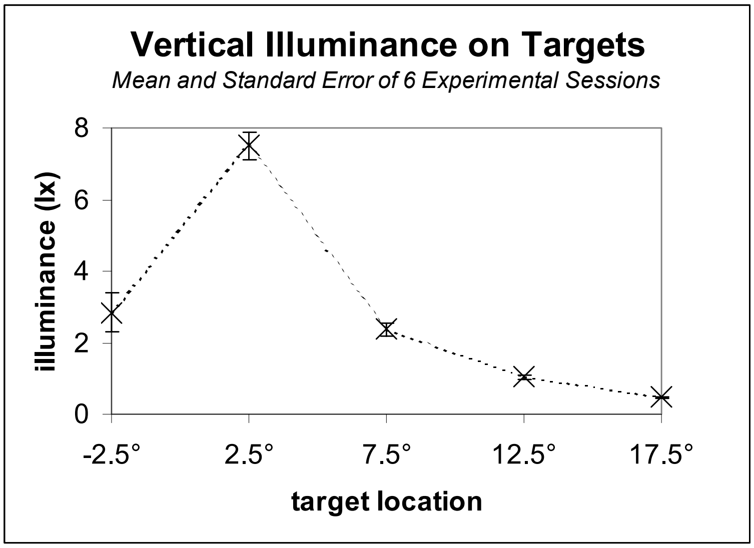


***Figure II-7.*** *Illuminances measured on the vertical surfaces of peripheral targets from subject vehicle headlamps.*

The glare headlamps were positioned 50 m in front of the subject, centered 5$^o$ to the left of the line of sight, and 2.5$^o$ from the closest small target. They were powered by a van located directly behind the glare headlamps from the subjects' point of view. Black cloth covered the headlamps and turn signals of the van to eliminate extraneous reflections toward the subjects. This position simulated oncoming traffic from a distance of 50 m with a lateral separation of 4.4 m, as might be found on a rural, two lane road. To measure the illuminance from the glare headlamps, an illuminance meter (Gigahertz-Optik) was clipped to the driver side sun visor, which was flipped down to a vertical position. The glare headlamps were then tilted slightly using wooden shims to achieve the desired conditions (see below) and to ensure that the apparent brightness of the headlamps was the same. The glare headlamps were never tilted more than 1$^o$ in order to modulate the luminous intensity.

The photometric characteristics of the glare sources were as follows:

- glare illuminance study block: 0.2, 1 and 5 lx (from 50 m, this corresponds to luminous intensities of 500, 2500 and 12,500 cd, respectively) from HID headlamps having a luminous area of 26 cm$^2$
- spectrum study block: 1 lx (2500 cd from 50 m) from halogen, HID and blue-filtered halogen headlamps, all having a luminous area of 26 cm$^2$
- size study block: 1 lx (2500 from 50 m) from HID headlamps having luminous areas of 9, 26 and 77 cm$^2$

The small glare headlamp size was achieved by placing masks with circular holes (9 cm$^2$ area) in them over the headlamp lens, blocking the remaining headlamp lens and providing the appearance of very small points of light. The large size was achieved by placing masks containing larger holes (77 cm$^2$ area) and containing diffusing glass, several cm in front of the headlamps. The diffusing glass made the resulting spots of light appear to be uniform, bright disks of larger size than the conventional headlamps.

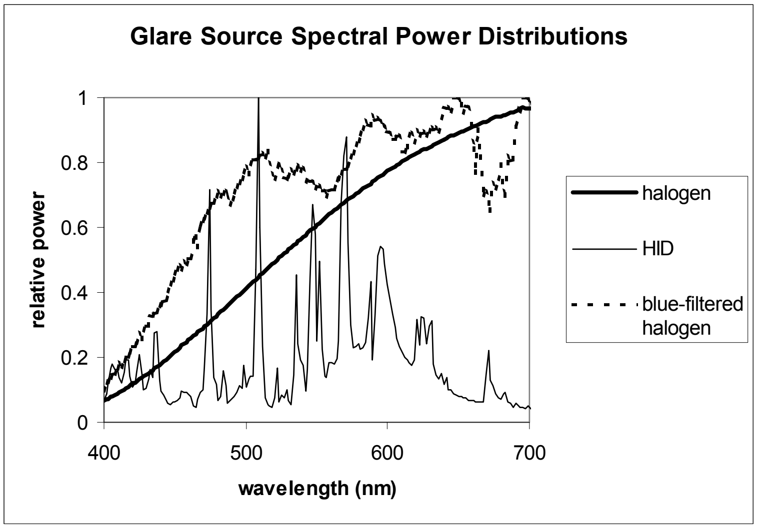


***Figure II-8.*** *Spectral power distributions of the glare sources used in the spectrum study block (scaled arbitrarily).*

Figure II-8 shows the SPDs of the three sets of headlamps used in the spectrum study block (the HID spectrum was used in the other study blocks). The blue-filtered halogen conditions were created by filtering the halogen headlamps with theatrical gels (Roscolux 003 and 061). This reduced their output but as described above, the lamps were tilted slightly with shims to provide the desired glare illuminance. The relative scotopic content of each of these sources can be quantified using the ratio of their scotopic to photopic light output (see Appendix). The resulting scotopic/photopic ratios of the sources are:

- halogen: 1.62
- HID: 1.67
- blue-filtered halogen: 1.95

It is important to note that the absolute values of these ratios are unimportant from any physiological point of view. All photometry according to the Commission Internationale de l'Éclairage (CIE) requires the values of *luminous efficacy* to be normalized at a wavelength of 555 nm, corresponding to the peak of the photopic response. Since the scotopic *luminous efficiency function* has its peak at 507 nm, shorter than the 555 nm peak of the photopic *luminous efficiency function* shown in Figure I-1, the values of the scotopic *luminous efficacy function* at shorter wavelengths take on larger absolute values, but this is a mathematical artifact. However, the relative values of the scotopic/photopic ratios can be directly compared to one another. Therefore, the blue-filtered halogen source has greater rod-stimulating potential than the halogen and HID sources.

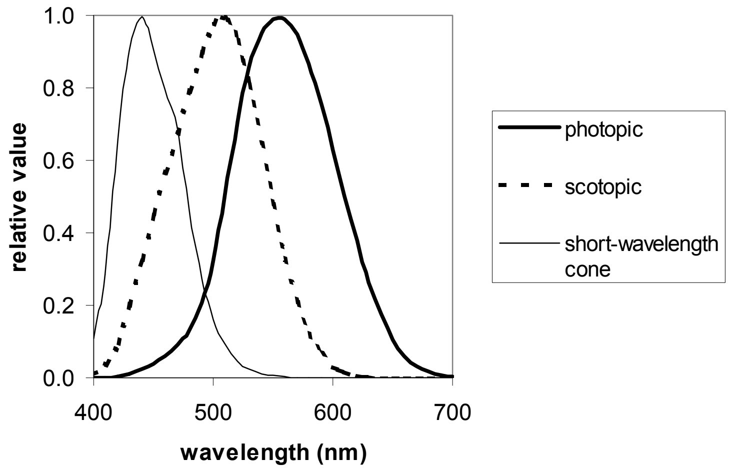


***Figure II-9.*** *Photopic and scotopic luminous efficiency functions, and a luminous efficiency function based on the spectral sensitivity of the short-wavelength cone.*

Similarly, it is possible to estimate the potential of these sources to stimulate the short-wavelength cones, using a luminous efficiency function based on the spectral sensitivity of this photoreceptor, shown in Figure II-9. Using the same type of calculation, the resulting short-wavelength-cone-response to photopic ratios are:

- halogen: 67
- HID: 102
- blue-filtered halogen: 86

## Procedure

The apparatus was set up on the runway surface prior to the experimental sessions. The locations of the headlamps, glare source, and targets were marked on the pavement surface with dark green spray paint to ensure consistent and easy placement. The headlamps in front of the subject vehicle were visually aimed. Upon arriving at the airport, subjects read and completed an informed consent form (approved by the Institutional Review Board at Rensselaer Polytechnic Institute) and reported their age. Between four and six subjects participated during each evening session; sessions lasted approximately two to three hours and started after sunset when ambient light levels on the pavement were between 0.1 and 0.2 lx.

Each subject was given the opportunity to practice the tracking task and target detection task to ensure familiarity with the apparatus and procedure and to reduce learning effects during the study. During each session, each subject performed a total of six sets of trials, one for each combination of target reflectance and either glare illuminance, glare spectrum or glare source size. The order of lighting conditions was randomized during the evening session in order to further reduce learning effects. For each set of trials, subjects performed the visual tracking task and were exposed 20 target onsets, four for each of the five targets, in random order, and asked to release a button on the subject's control box as soon as a target was detected. They were instructed to look directly at the tracking task throughout each set of trials.

After completing the 20 trials, an experimenter asked the subject to rate the level of discomfort experienced by the subjects, using the nine-point De Boer scale (Table I-1). Each of the target presentations was separated by a random interval between 2 and 4 s; thus, each set of 20 trials took about 1 min. The reaction times were collected by a microprocessor unit (Basic Stamp) and relayed to a laptop computer (Dell) for data storage. This computer was located behind the targets and was operated by a second experimenter who maintained radio contact with the first experimenter. Reaction times longer than 1 s were considered missed targets.

Each subject performed each lighting condition in turn, and the conditions were changed after all subjects completed the previous condition. Switching between lighting conditions typically took between 5 and 10 min.

A total of 31 subjects participated in the study. Ten subjects ranging in age from 17 to 32 years (mean 24 years, median 24 years, standard deviation 6 years) participated in the glare illuminance study block. Eleven subjects ranging in age from 24 to 62 years (mean 38 years, median 33 years, standard deviation 12 years) participated in the spectrum study block. Ten subjects ranging in age from 22 to 34 years (mean 28 years, median 30 years, standard deviation 5 years) participated in the glare source size/luminance study block. All subjects had drivers' licenses or permits and wore corrective lenses if needed. One subject in the glare illuminance study block had undergone LASIK surgery within the past year.

# III. RESULTS: TARGET DETECTION

## Glare Illuminance

The reaction time and missed target data for the glare illuminance study block are shown in Figure III-1. (In this and subsequent blocks, response times and missed targets for subjects with corrective lenses or for the subject with LASIK correction were not observably different than for the subjects with uncorrected refraction.) All reaction time data were treated in several different ways for subsequent analysis. As described above, if subjects did not see a target within one s, the reaction time was recorded by the computer as 1000 ms, and that target was considered missed. These raw values are shown in the upper left panel of Figure III-1. When there were a large proportion of missed targets, therefore, the reaction times in this panel converge near 1000 ms. The upper right panel of Figure III-1 shows the reaction times only for those trials which were not missed signals (all 1000 ms times are discarded). When all trials were missed, the graph shows points scaled to an arbitrarily high value on the ordinate of the graph. The lower left panel shows of Figure III-1 shows the data with the reaction times for missed targets arbitrarily set to 1200 ms rather than 1000 ms. Finally, the lower right panel of Figure III-1 shows the overall percentages of missed targets for each condition.

Also shown in the top right panel of this figure are two thick, smooth curves. These curves are predictions for reaction times using an empirical model of peripheral detection performance under conditions without glare (Bullough, 2002) for different target positions, reflectances and illuminances on the targets. This model is based on field research (Van Derlofske et al., 2001, 2002) that used experimental geometries and target characteristics similar to those in the present study. The model for reaction times excluded missed targets, so it is comparable only to the data with the misses excluded. Similarly, the thick, smooth curves in the bottom right panel are the predictions of missed targets using the same empirical model.

In this and subsequent graphs showing the overall data for each study block, error bars are not shown, in order to increase clarity of the graphs. Table III-1 lists the average standard errors for the reaction times in each of the six lighting conditions in the illuminance study block.

***Table III-1.*** *Average standard errors for the reaction times in the illuminance block.*

| Glare illuminance (lx) | Target reflectance | Average standard error (ms) |
|---|---|---|
| 0.2 lx | 0.2 | 50 |
| 0.2 lx | 0.4 | 51 |
| 1 lx | 0.2 | 31 |
| 1 lx | 0.4 | 39 |
| 5 lx | 0.2 | 32 |
| 5 lx | 0.4 | 41 |

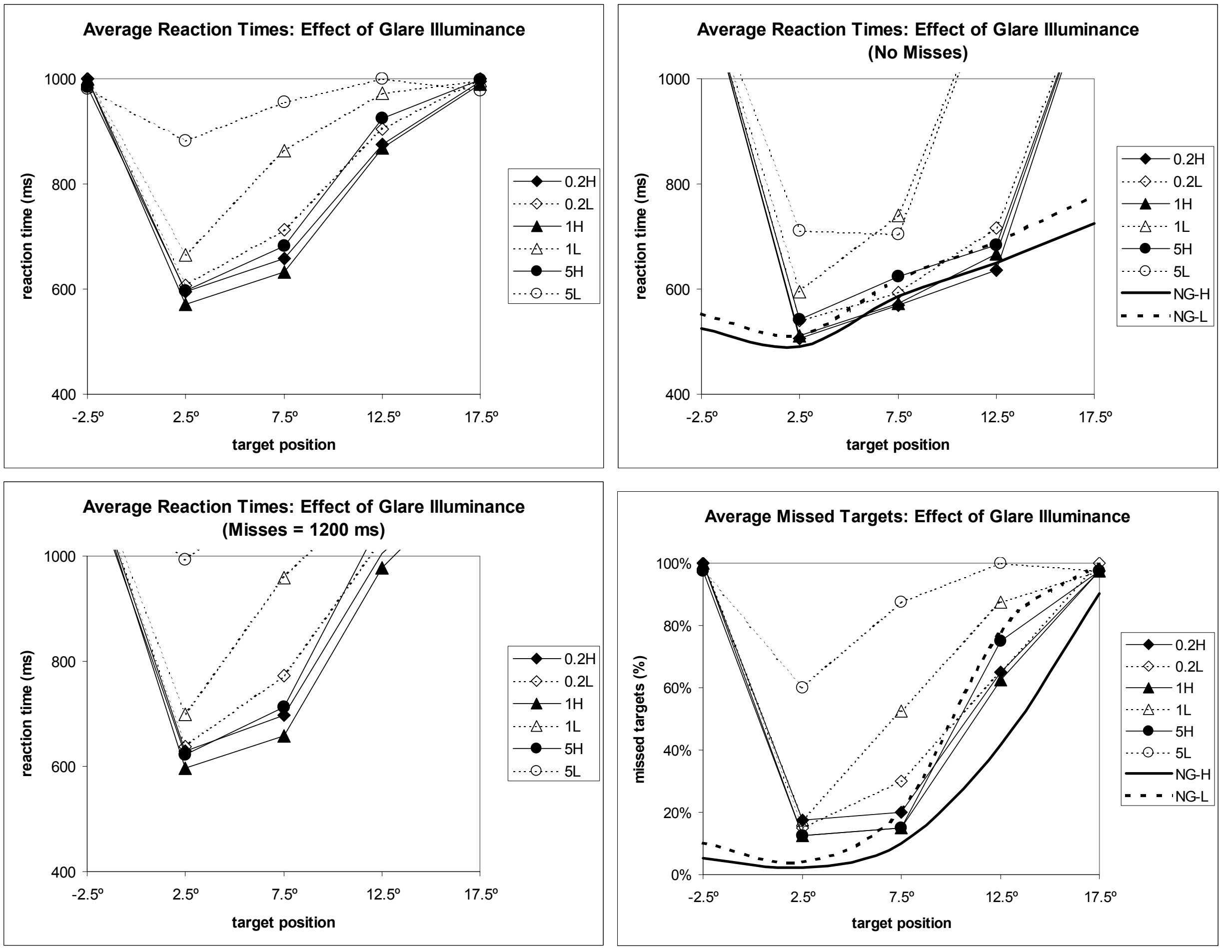


***Figure III-1.*** *Reaction times and missed targets for each target position and reflectance under each lighting condition. Top left: Average reaction times with missed target trials assigned a value of 1000 ms. Top right: Average reaction times with missed targets excluded, as well as predicted reaction times without glare from Bullough (2002). Bottom left: Average reaction times with missed target trials assigned a value of 1200 ms. Bottom right: Overall missed target percentages, as well as predicted missed target percentages without glare from Bullough (2002). Figure legends: 0.2, 1 and 5 refer to glare illuminances (in lx); NG refers to predicted responses without glare; H and L refer to high (40%) and low (20%) target reflectances.*

The data shown in Figure III-1 demonstrate several clear trends:

- they show the effect of target location on detection performance, with the far-peripheral targets (12.5$^{o}$ and 17.5$^{o}$) and the target closest to the glare source (-2.5$^{o}$) being very difficult to detect
- they show the impact of target reflectance on performance, with the low reflectance targets resulting in poorer visual performance
- for the low reflectance targets (open symbols in Figure III-1), they show a clear effect of increasing glare illuminance on both reaction times and missed targets

Using a repeated-measures analysis of variance on the raw reaction time data, there were statistically significant ($p<0.01$) effects of target position, target reflectance, glare illuminance, as well as statistically significant ($p<0.01$) two- and three-way interactions among all of these variables. Figure III-2 shows the main effects of each of these three factors on reaction time, with all other factors collapsed across all conditions in each panel of the figure. This figure more clearly shows the impact of glare illuminance and target reflectance.

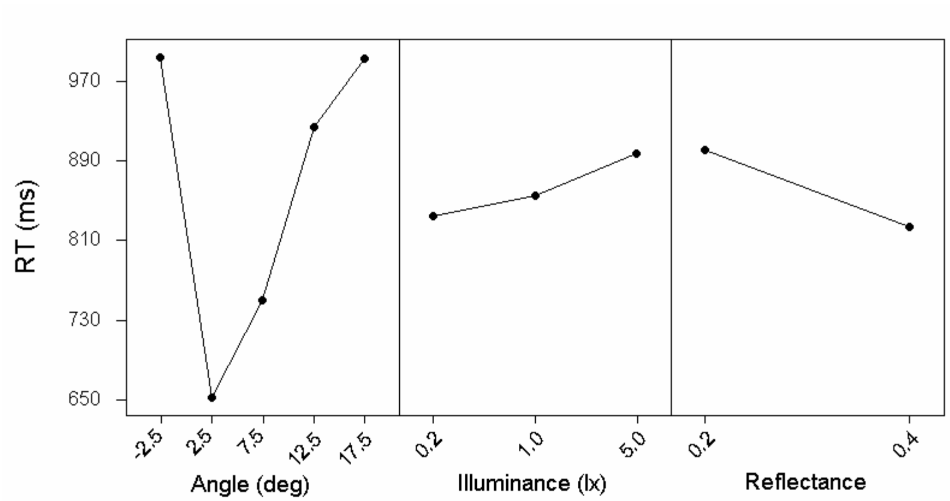


***Figure III-2.*** *Overall effects of target position angle, glare illuminance and target reflectance on reaction time.*

A similar analysis of variance on the missed target data found all of the same statistically significant main effects and interactions. Figure III-3 shows the main effects on missed targets.

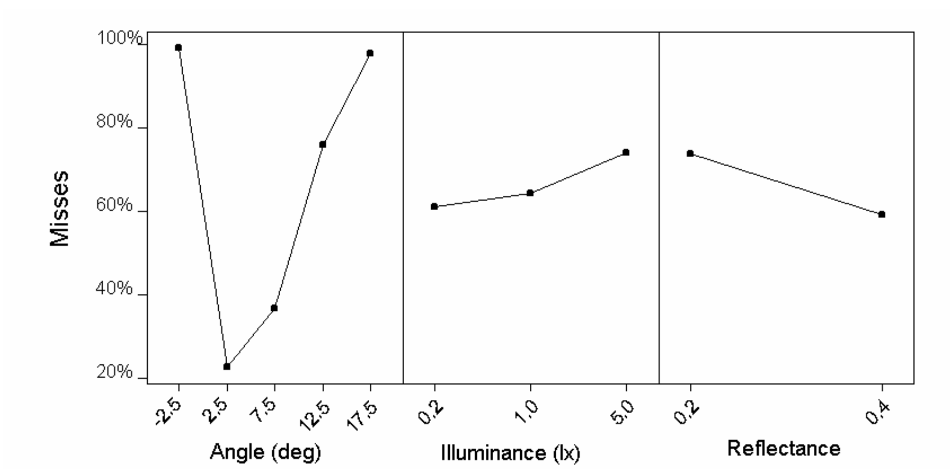


***Figure III-3.*** *Overall effects of target position angle, glare illuminance and target reflectance on missed targets.*

## Glare Spectrum

The reaction time and missed target data for the glare spectrum study block are shown in Figure III-4. Table III-2 lists the average subject standard error for each of the six lighting conditions in this study block.

***Table III-2.*** *Average standard errors for the reaction times in the spectrum block.*

| **Glare spectrum** | **Target reflectance** | **Average standard error (ms)** |
|---|---|---|
| halogen | 0.2 | 49 |
| halogen | 0.4 | 59 |
| blue-filtered halogen | 0.2 | 50 |
| blue-filtered halogen | 0.4 | 57 |
| HID | 0.2 | 58 |
| HID | 0.4 | 61 |

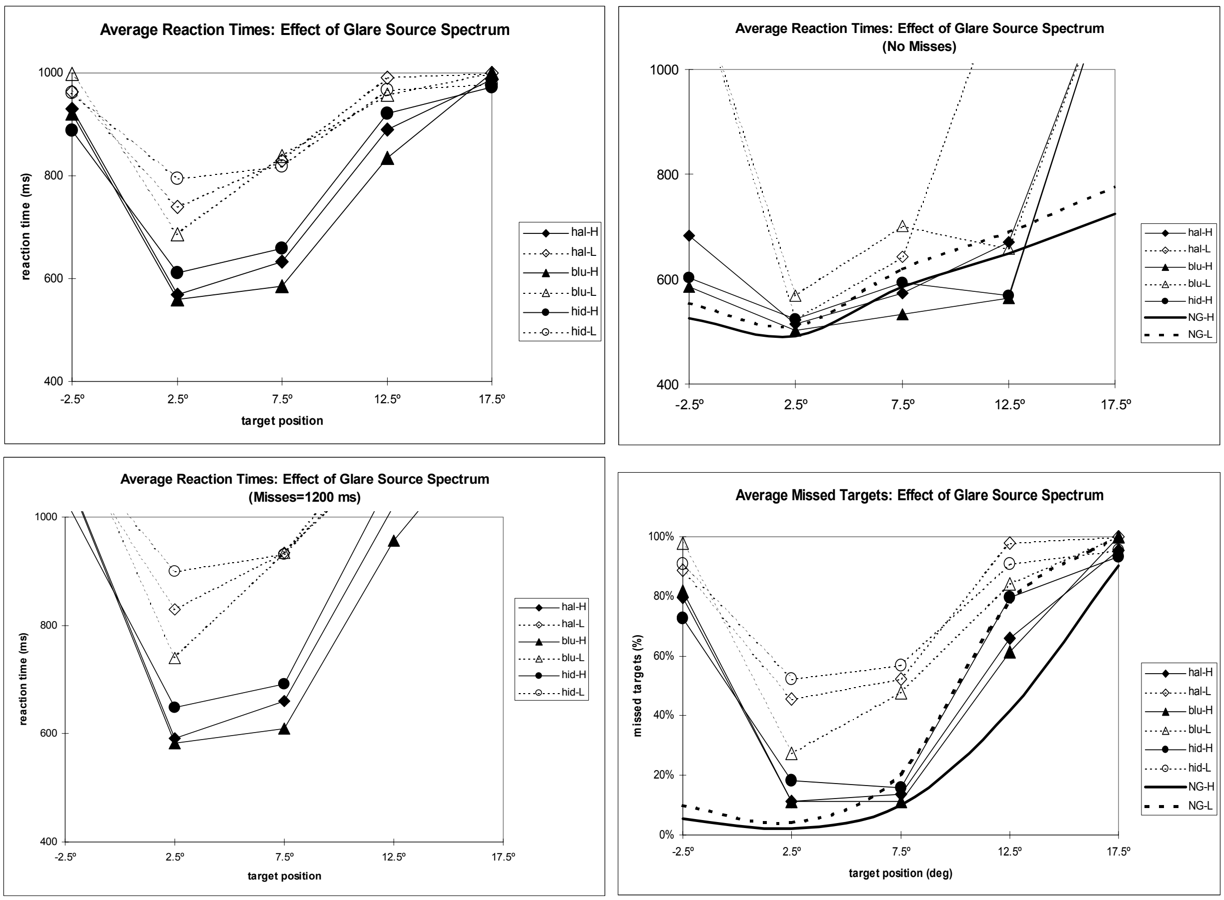


***Figure III-4.*** *Reaction times and missed targets for each target position and reflectance under each lighting condition in the spectrum study block. Top left: Average reaction times with missed target trials assigned a value of 1000 ms. Top right: Average reaction times with missed targets excluded, as well as predicted reaction times without glare from Bullough (2002). Bottom left: Average reaction times with missed target trials assigned a value of 1200 ms. Bottom right: Overall missed target percentages, as well as predicted missed target percentages without glare from Bullough (2002). Figure legends: Glare spectra denoted by hal (halogen), blu (blue-filtered halogen) and hid (HID); NG refers to predicted responses without glare; H and L refer to high (40%) and low (20%) target reflectances.*

The data shown in Figure III-4 demonstrate several clear trends:

- as in the glare illuminance block, they show effects of target location and reflectance
- they show no strong effect of glare spectrum on either reaction times or missed targets

A repeated-measures analysis of variance on the raw reaction time data showed that there were statistically significant ($p<0.01$) effects of target position and target reflectance, as well as a statistically significant ($p<0.01$) two-way interaction between target position and reflectance. Figure III-5 shows the main effects of position, spectrum and reflectance on reaction time, with all other factors collapsed across all conditions in each panel of the figure.

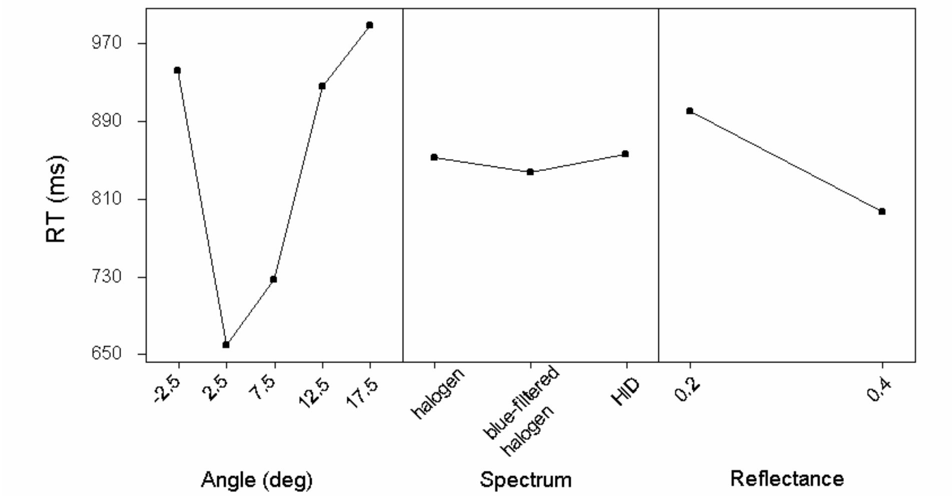


***Figure III-5.*** *Overall effects of target position angle, glare spectrum and target reflectance on reaction time.*

A similar analysis on the missed target data revealed the same trends and significant main effects as shown in Figure III-6.

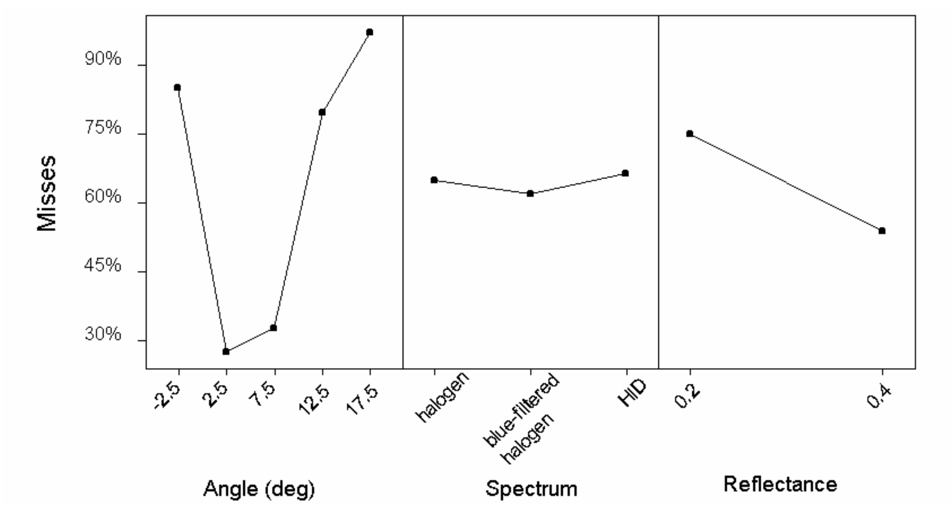


***Figure III-6.*** *Overall effects of target position angle, glare spectrum and target reflectance on missed targets.*

## Glare Source Size

The reaction time and missed target data for the glare source size study block are shown in Figure III-7. Table III-3 lists the average subject standard error for each of the six lighting conditions in this study block.

*Table III-3.* *Average standard errors for the reaction times in the size block.*

| Glare source size ($cm^2$) | Target reflectance | Average standard error (ms) |
|---|---|---|
| 9 | 0.2 | 47 |
| 9 | 0.4 | 44 |
| 26 | 0.2 | 35 |
| 26 | 0.4 | 56 |
| 77 | 0.2 | 48 |
| 77 | 0.4 | 93 |

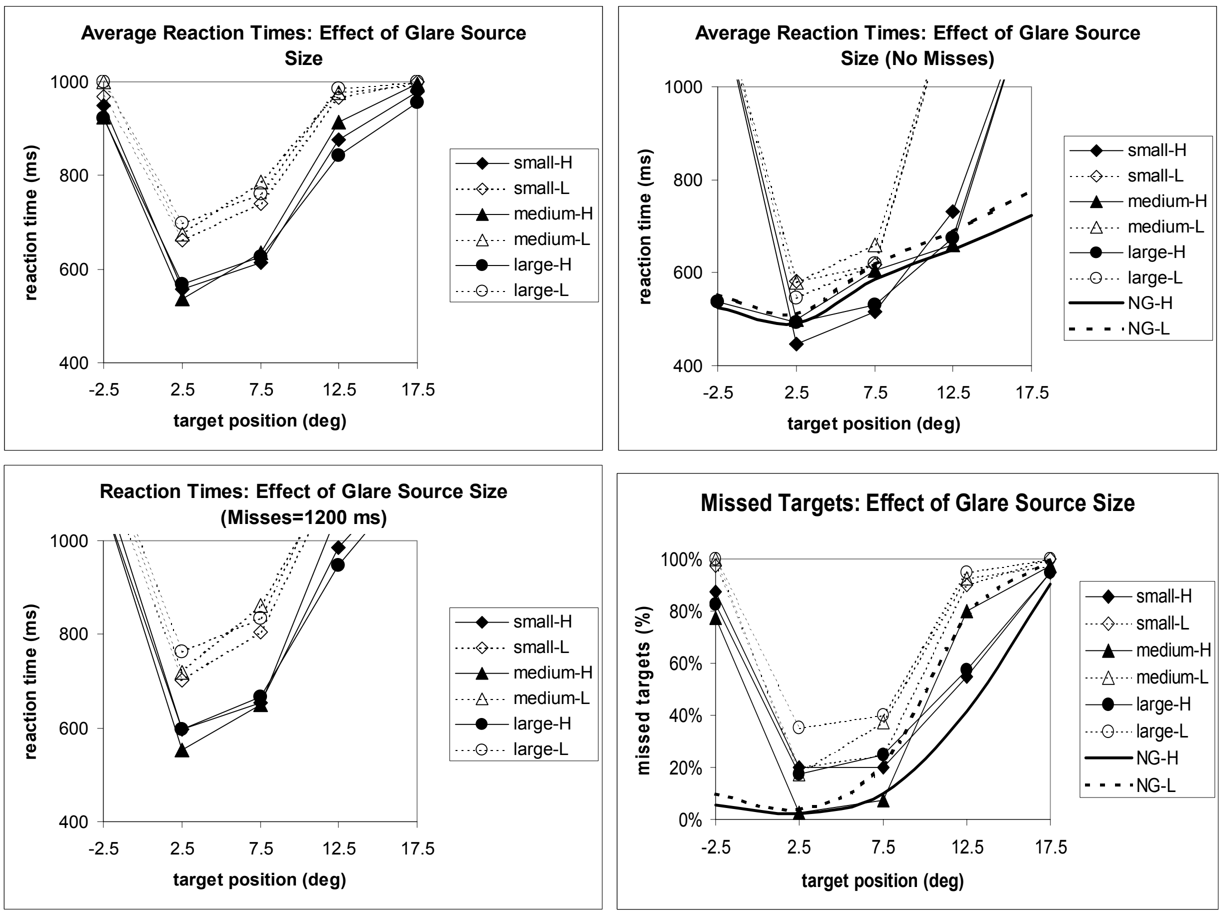


***Figure III-7.*** *Reaction times and missed targets for each target position and reflectance under each lighting condition in the size study block. Top left: Average reaction times with missed target trials assigned a value of 1000 ms. Top right: Average reaction times with missed targets excluded, as well as predicted reaction times without glare from Bullough (2002). Bottom left: Average reaction times with missed target trials assigned a value of 1200 ms. Bottom right: Overall missed target percentages, as well as predicted missed target percentages without glare from Bullough (2002). Figure legends: Glare spectra denoted by hal (halogen), blu (blue-filtered halogen) and hid (HID); NG refers to predicted responses without glare; H and L refer to high (40%) and low (20%) target reflectances.*

The data shown in Figure III-7 demonstrate several clear trends:

- as in the glare illuminance and glare spectrum blocks, they show large effects of target location and reflectance
- they show no apparent effect of glare source size on either reaction times or missed targets

Using a repeated-measures analysis of variance on the raw reaction time data, there were statistically significant ($p<0.01$) effects of target position and target reflectance, as well as a statistically significant ($p<0.05$) two-way interaction between target position and reflectance. Figure III-8 shows the main effects of position, size and reflectance on reaction time, with all other factors collapsed across all conditions in each panel of the figure.

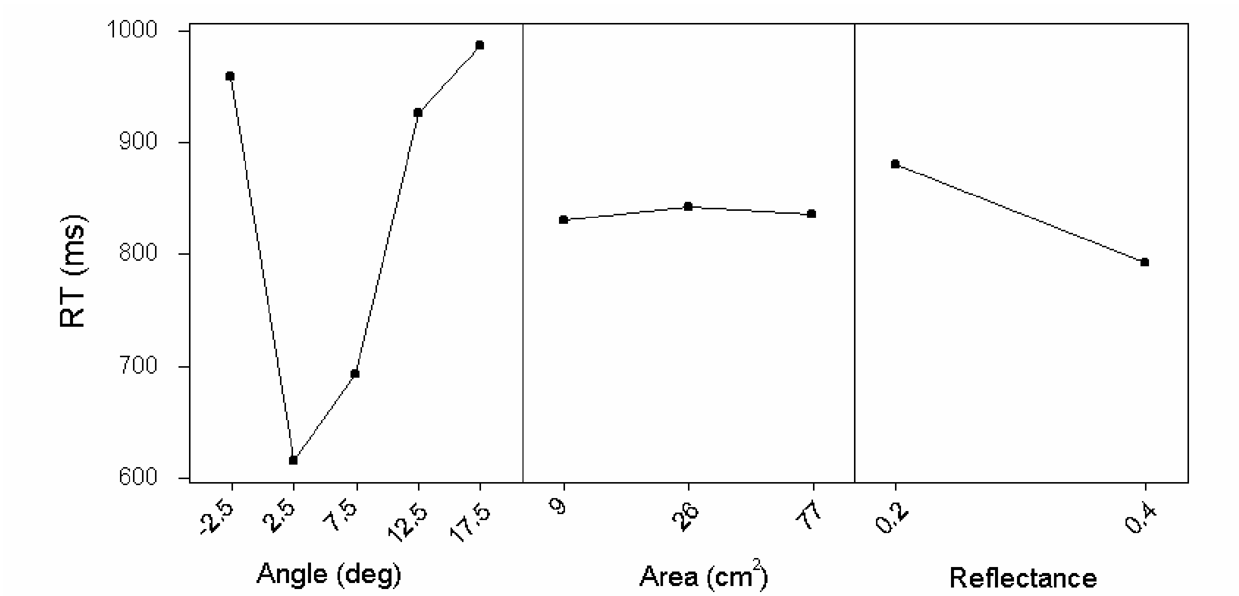


***Figure III-8.*** *Overall effects of target position angle, glare source size and target reflectance on reaction time.*

The same type of analysis on the missed target data revealed the same main effects and interaction as for the reaction time data as indicated in Figure III-9.

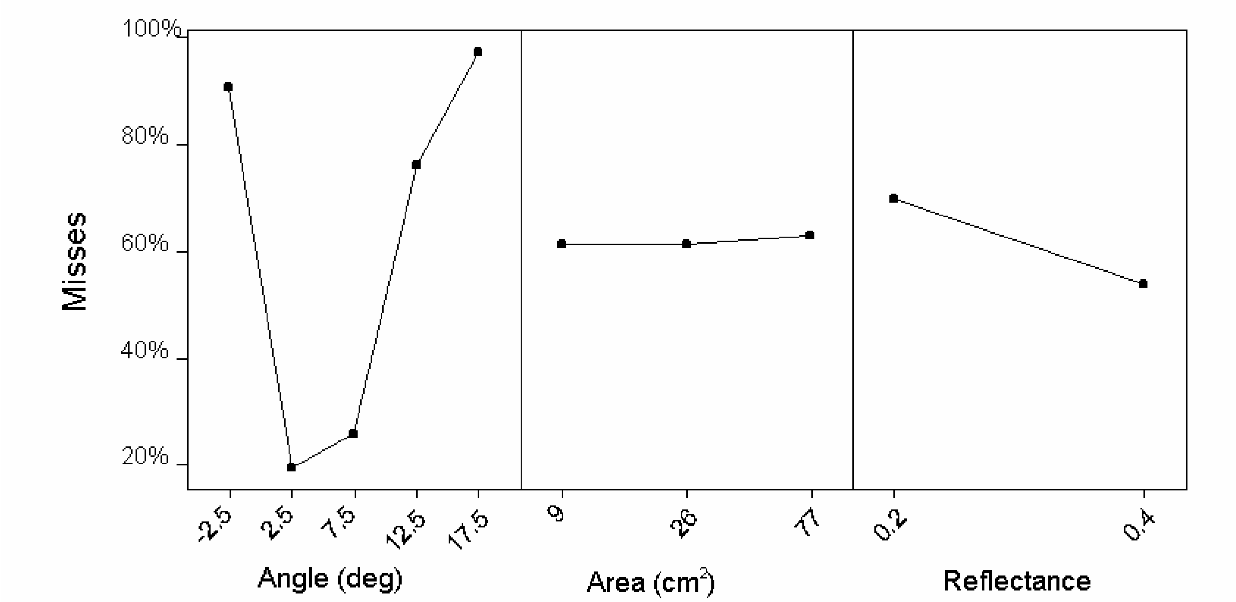


***Figure III-9.*** *Overall effects of target position angle, glare source size and target reflectance on missed targets.*

## Interblock Comparison

As described above, each of the three study blocks contained a condition that was common to all three blocks. Since there were different participants in each block with somewhat differing age characteristics (e.g., the participants in the second block contained several subjects over the age of 50 years), it is possible to compare the results obtained in each block under these common conditions:

- glare illuminance: 1 lx
- glare source spectrum: HID headlamps
- glare source size: medium headlamp area (26 $cm^2$)

Figure III-10 shows the reaction time data and the missed target data from each of the blocks for the conditions matching the criteria above. The graphs in Figure III-10 indicate the strong relationship between target position and target reflectance on performance. Although these graphs do indicate that perhaps the older subjects in the second study block had somewhat longer reaction times and greater missed targets than the subjects in the other blocks (particularly for the target located 2.5$^o$ to the right of the line of sight), analyses of variance showed that there was a statistically significant effect of study block on neither reaction time nor on missed targets ($p>0.05$ for both responses).

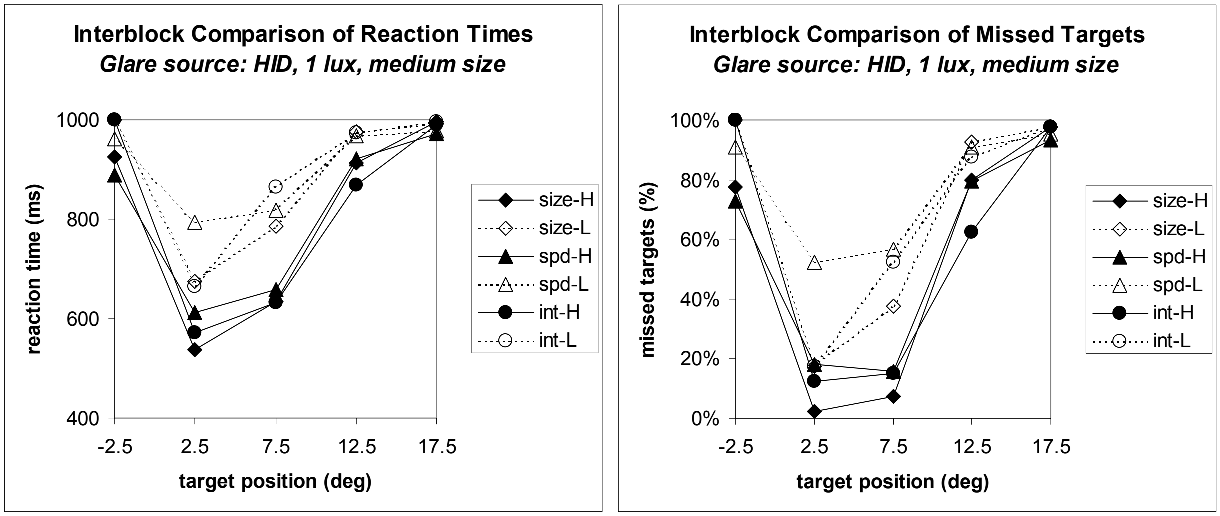


***Figure III-10.*** *Left panel: Reaction times for the lighting conditions common to all three study blocks. Right panel: Missed targets for the lighting conditions common to all study blocks.*

# IV. RESULTS: DISCOMFORT RATINGS

## Glare Illuminance

Figure IV-1 shows the average De Boer ratings for each lighting condition in the glare illuminance study block. (In this and subsequent blocks, ratings for subjects with corrective lenses or for the subject with LASIK correction were not observably different than for the subjects with uncorrected refraction.) The graph shows clearly the trend of decreased ratings (increased discomfort) with increasing illuminance. Figure IV-1 also shows a separation between the high and low reflectance targets, with the low reflectance targets resulting in greater discomfort. An analysis of variance of these ratings showed statistically significant ($p<0.01$) effects of glare illuminance and of target reflectance, as well as a significant ($p<0.05$) two-way interaction between these factors.

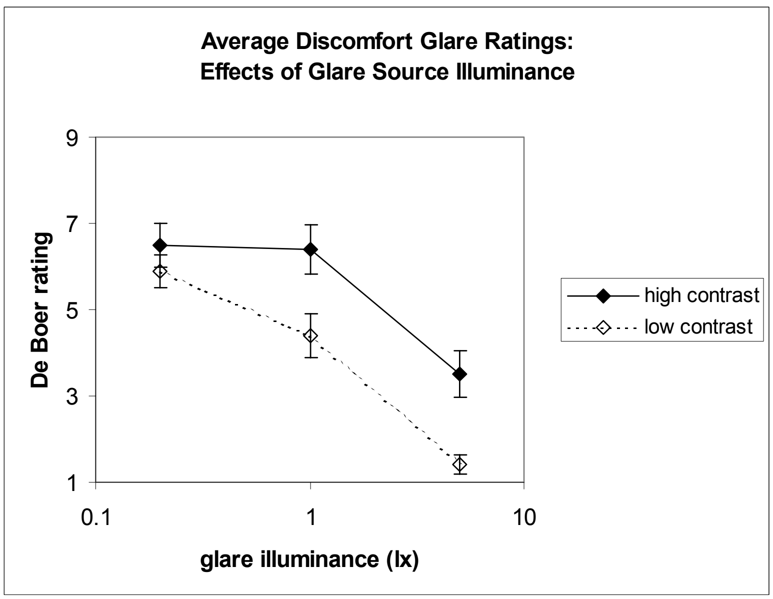


***Figure IV-1.*** *Average De Boer ratings (and standard errors) in the glare illuminance study block.*

## Glare Spectrum

Figure IV-2 shows the average De Boer ratings for the glare spectrum study block. An analysis of variance on these ratings shows a statistically significant ($p<0.05$) main effect of glare spectrum but no significant effect of target reflectance; nor was there an interaction between these factors.

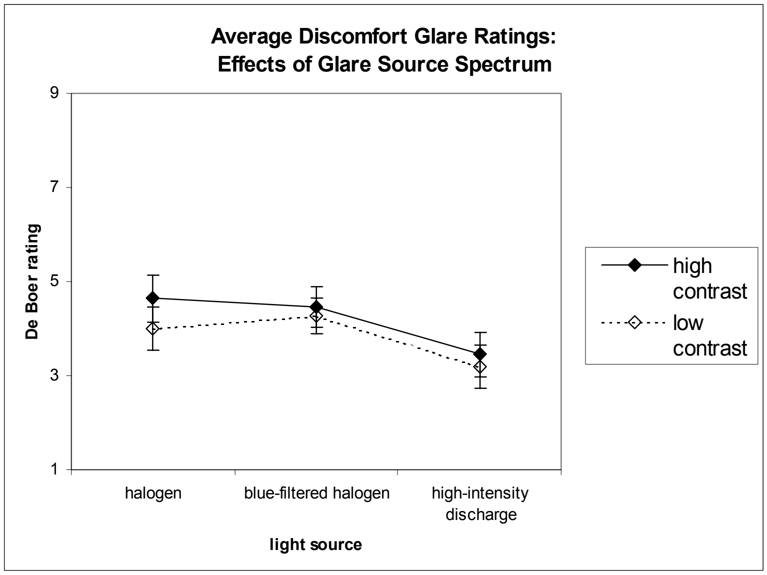


***Figure IV-2.*** *Average De Boer ratings (and standard errors) in the glare spectrum study block.*

## Glare Source Size

Figure IV-3 shows the average De Boer ratings for the glare source size study block. An analysis of variance on these ratings shows no statistically significant main effects: neither size nor target reflectance.

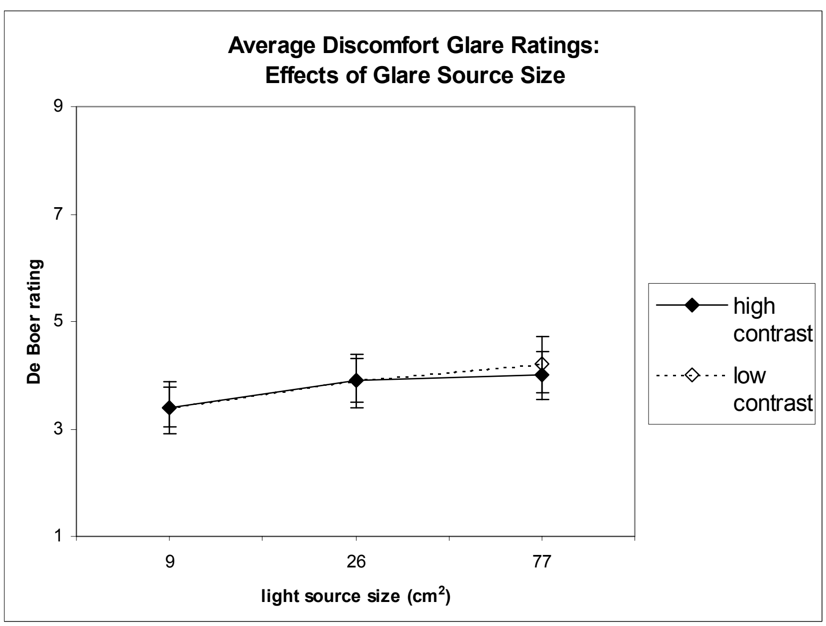


***Figure IV-3.*** *Average De Boer ratings (and standard errors) in the glare source size study block.*

# V. DISCUSSION

## Disability Glare

### *Glare Illuminance*

The results of the target detection study clearly show an effect of glare illuminance on target detection, but the practical significance of this effect is dependent upon the characteristics of the objects in and along the roadway that must be detected. Figure V-1 shows the interaction on reaction time between target reflectance and glare illuminance for this study block. It is a striking demonstration of both how much and how little headlamp glare can impact visual detection. The higher reflectance (40%) targets are not differentially affected by headlamp glare even up to 5 lx at the eye, while even 1 lx greatly impairs detection of the low reflectance (20%) targets compared to 0.2 lx.

What is also interesting is that even the relatively low amount of headlamp glare providing 0.2 lx at the eye significantly impacted detection of the target located closest to the glare source, regardless of its reflectance. The oncoming glare headlamps were positioned $5^{o}$ to the left of the subjects' line of sight with the nearest target $2.5^{o}$ to the right of the headlamps. As seen in the lower right panel of Figure III-1, the percentage of missed targets was very high regardless of target reflectance, a large difference over the predicted percentage of missed targets for the $-2.5^{o}$ location, using the model developed by Bullough (2002).

This calls into question the range of conditions for which disability glare formulae such as Equation 1 apply. This formula is used to calculate the luminance of a uniform veil over the entire field of view that would result in equivalent visual performance as the presence of a glare source. Using Equation 1 and the glare illuminances of 0.2, 1 and 5 lx, the resulting veiling luminances are:

- 0.2 lx: equivalent veiling luminance of 0.06 $cd/m^2$
- 1 lx: equivalent veiling luminance of 0.3 $cd/m^2$
- 5 lx: equivalent veiling luminance of 1.4 $cd/m^2$

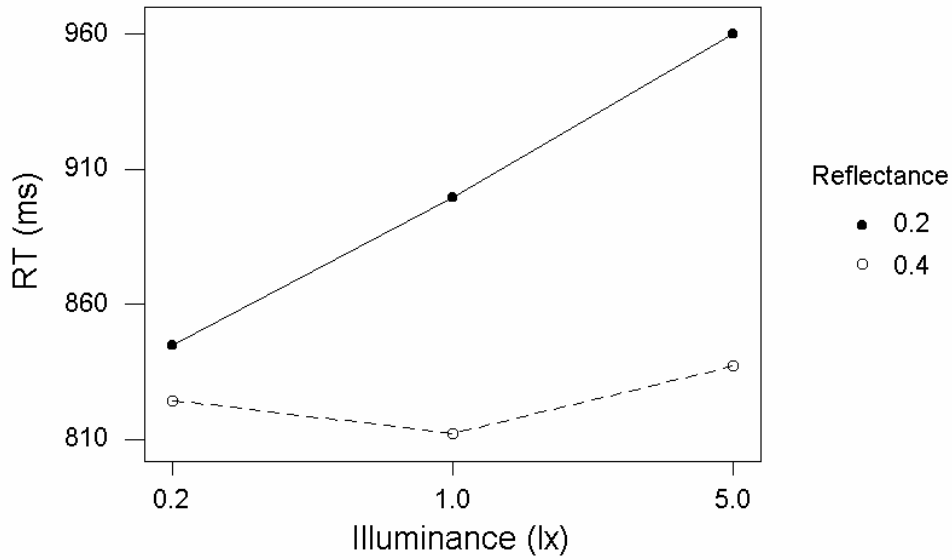


***Figure V-1.*** *Interaction between glare illuminance and the reflectance of the targets on reaction time, collapsed across all target locations.*

Clearly the glare formula in Equation 1 is not sufficient to explain the detection performance to the leftmost target. The results in Figure III-1 demonstrate that using such formulae to predict peripheral detection can be problematic. A revision to the equation of Fry (1954) was suggested by Hills (1976) in order to capture the larger-than-expected impact of a glare source near the line of sight (within 1.5$^{o}$):

$$L_v = \frac{9.2E}{\theta^{3.44}} \qquad \textit{(Equation 3)}$$

In Equation 3, $L_v$ is the resulting equivalent veiling luminance (in cd/m$^2$), $E$ is the glare illuminance at the observer's eye (in lx), and $\theta$ is the distance (in degrees) between the observer's line of sight and the glare source. As with Equation 1, when multiple glare sources are present (e.g., a pair of oncoming headlamps) the individual equivalent veiling luminances from each source are added together.

Nonetheless, both Equation 1 and Equation 3 predict the impact of disability glare on foveal (on-axis) visibility, but not on peripheral visibility, which was an important outcome measure used in the present study. The results in Figure III-1 demonstrate that using such formulae to predict peripheral detection can be problematic, because some the visbility of some targets (e.g., those closest to the glare source as well as those furthest from the line of sight) are greatly affected by glare while others (e.g., the targets about 7.5$^{o}$ from the line of sight) were not.

### *Glare Spectrum*

The lack of effect of spectrum on the detection of peripheral targets (Figures III-5 and III-6) was perhaps surprising. Based on studies of peripheral spectral sensitivity at mesopic light levels (He *et al.*, 1997, 1998) it was found that sources with greater scotopic content resulted in improved peripheral visual performance. Using the scattering theory of disability glare, and considering that the equivalent veiling luminances for the glare illuminances ranged from 0.06 to 1.4 $cd/m^2$. Even taking into account the increase in adaptation brought on by the subject vehicle headlamps (Olson *et al.*, 1990), which is estimated to be about 1 $cd/m^2$, the resulting equivalent veiling luminances would still keep observers in the mesopic region of adaptation (approximately 0.001 to 3 $cd/m^2$). Thus, as argued in the literature review section of this report, glare sources with higher scotopic content might have been expected to result in worse visual performance than glare sources with lower scotopic content.

However, this expectation was not born out by the present results, shown in Figures III-5 and III-6. Indeed the source with the highest scotopic/photopic ratio is the blue-filtered halogen; if anything, this source results in slightly better performance than the other two (but note that any differences are not statistically significant). Thus, these data provide no basis to challenge the currently-accepted use of photometry based on photopic response to quantify the impact of headlamp glare on disability glare, both in the central field of view (as demonstrated by Flannagan, 1999 and by Bullough *et al.*, 2002) and in the peripheral field of view.

### *Glare Source Size*

Despite a nearly log-unit variation in the sizes of the glare sources, there was essentially no difference in performance among them. The data in Figures III-8 and III-9 again, demonstrate that at least down to a headlamp size of 9 $cm^2$ (the smallest size used in the present study), conventional far-field photometry, based on luminous intensity, is sufficient to characterize the impact of headlamp glare on visual performance, at least under the range of conditions corresponding to those used in the present study.

## Discomfort Glare

### *Glare Illuminance*

Both the dependence of glare ratings on the illuminance from the glare source and the differences in terms of target reflectance were predicted by the literature (e.g., Theeuwes and Alferdinck, 1996). In particular the 5 lx condition elicited very low De Boer ratings with the low-reflectance target resulting in an average rating of just over 1. Of interest, the equation by Schmidt-Clausen and Bindels (1974) for predicting ratings of discomfort glare on the De Boer scale (Equation 2) gives the resulting predictions:

- 0.2 lx: De Boer rating of 5.2
- 1 lx: De Boer rating of 3.8
- 5 lx: De Boer rating of 2.4

Olson and Sivak (1984) reported that discomfort ratings in field studies tended to be more tolerating of glare (or, for the De Boer scale, higher) than discomfort ratings in controlled laboratory studies. For the high reflectance targets in the present study this also appears to be the case; all of the ratings with those targets are higher than would be predicted by Schmidt-Clausen and Bindels (1974). However, for the low-reflectance targets, the ratings were more closely in line with the predictions of Schmidt-Clausen and Bindels (1974). Thus, the original assertion of Olson and Sivak (1984) might not apply when the objects in the scene are near the visual threshold.

### *Glare Spectrum*

As found in previous laboratory studies (e.g., Flannagan, 1999 and Bullough *et al.*, 2002), the HID glare source was found somewhat more glaring than the other two glare sources. While this is consistent with the greater short-wavelength-cone-stimulating properties of the HID SPD, the fact that the halogen and blue-filtered halogen glare sources elicited about equal responses (despite the blue-filtered halogen source having greater short-wavelength energy than the unfiltered halogen) means caution must be applied before using the short-wavelength-cone mechanism as the appropriate spectral sensitivity for discomfort glare. Indeed, Bullough *et al.* (2001) and Flannagan *et al.* (1989) showed that a saturated red light source could be more glaring than a shorter-wavelength yellow source under certain conditions, which could imply a mechanism more complex than short-wavelength cones.

In addition, the ambient light level does not seem to change the spectral response for discomfort glare. A pilot study conducted for the present project (Bullough *et al.*, 2003) found no interactions between glare source spectrum, glare illuminance and background luminance (0.1 $cd/m^2$ or 3 $cd/m^2$) in terms of visual discomfort. HID headlamps were rated consistently as providing greater discomfort for a low (0.1 $cd/m^2$) background luminance as well as a high (3 $cd/m^2$) background luminance.

Regardless, inspection of Figures IV-1 and IV-2 demonstrates that the magnitude of the spectral effect on discomfort glare appears to be much smaller than that of glare illuminance.

### *Glare Source Size*

Some previous research (Alferdinck and Varkevisser, 1991; Manz, 2001) predicted a small dependence of glare source size on visual discomfort; while a very slight trend can be found in agreement with this prediction in Figure IV-3, this effect is not statistically significant, and is probably of no significance for real driving conditions.

### *Target Reflectance*

It is noted above in the subsection on Discomfort Glare and Glare Illuminance that the low reflectance targets elicited lower ratings (more glaring) than the high reflectance target conditions, in the glare illuminance study block. This effect was not, however, significant for the spectrum study block, although the average ratings are consistently more glaring for the low reflectance target; for the size study block there was essentially no effect of target reflectance at all. Certainly, the range of conditions experienced by subjects in the illuminance study block was much wider than in the other two blocks. Looking broadly at the overall results for the spectrum and size blocks, it is arguable that the spectrum block had the next largest range of conditions. While no disability glare difference was found, at least a significant discomfort glare effect of spectrum was found; there was no effect of headlamp size on any measure of glare.

The impact of target reflectance on discomfort glare ratings might therefore be a function of the range of conditions experienced while driving. This opens up the intriguing possibility, for example, that higher levels of discomfort glare might be tolerable in an interstate highway driving scenario (a relatively more monotonous condition) than driving on a road through various types of countryside and with more curves or hills. This idea is consistent with the findings of Sivak *et al.* (1991) and of Theeuwes *et al.* (2002), who found discomfort (as measured through the De Boer rating scale) to be increased when the task being performed was more complex and difficult.

# VI. CONCLUSIONS, SPECULATION AND CAVEATS

## Conclusions

The present study reinforces the idea that disability glare and discomfort glare are discrete phenomena, and that from the perspective of disability glare, the different technologies presently employed in automobiles seem to be equivalent to one another at reducing peripheral visual performance when equated for the glare illuminance they provide at oncoming drivers' eyes. Nor is the size of the headlamp's illuminated area (within the range employed in this study) a factor impacting disability glare in this study. Thus, conventional photometry based on luminous intensity using the photopic luminous efficiency function appears to be appropriate for characterizing disabilty glare from headlamps.

The same is not true for discomfort glare. Two sources having the same luminous intensity using the photopic luminous efficiency function will not necessarily produce the same amount of discomfort. In the present study as well as in previous studies, HID headlamps were consistently found more glaring in terms of discomfort than halogen headlamps. Interestingly, the blue-filtered halogen headlamps used in this study were rated about equally in terms of discomfort as conventional halogen lamps, despite their higher scotopic light output and "bluer" appearance. Based on the SPDs of the glare sources used in this study, short-wavelength light output appears to be one determinant of discomfort glare, although this result has not yet been validated for other sources with different SPDs. Nonetheless, glare illuminance, moreso than spectrum, appears to be the primary factor relating the characteristics of a light source and its resulting discomfort.

## Speculation and Caveats

Blue-filtered halogen lamps are sometimes cited as one of the culprits in complaints about increased discomfort from headlamps. Since blue-filtered lamps were not found to increase discomfort in the present study, complaints about these lamps possibly help to demonstrate that the response to new headlamp technologies are in part psychological (based on their "whiter" or "bluer" appearance) rather than physiological. There could also be other factors not evaluated in the present study that might account for such complaints, such as increased glare illuminances from some blue-filtered headlamps relative to conventional halogen headlamps. Nonetheless, complaints about discomfort from HID headlamps do appear to have some basis in physiological response, albeit at present a poorly understood one.

It must be recognized that the present study utilized relatively short periods of time in order to assess the impact of headlamp glare. Driving under extended periods might exacerbate the discomfort glare response and have interactions that could lead to reduced visual performance. Indeed, when Bullough and Rea (2001) measured visual tracking performance in the presence of visual noise simulating heavy snowfall, they found that performance of the tracking task was worsened over a duration of 30 minutes, consistent with ratings of visual discomfort but not with photometric measurements nor with disability glare formulae.

The present study did not explore the impact of these headlamp technologies when used in a driver's own vehicle. Van Derlofske *et al.* (2001, 2002) found that HID headlamps result in much improved peripheral detection, as might be expected based on their much higher light output at peripheral angles. As pointed out by those authors, this greater light output might well lead to increase glare. Since glare illuminance is the most important factor in predicting both disability and discomfort glare, it might be important to revisit luminous intensity limitations for lamps with greater ability to cause glare. Approaches such as leveling systems might be important components to limitations of glare from these lamps.

## Recommendations for Future Research

Because of the caveats discussed above, future research in the area of headlamp glare should focus on several questions pertaining to the temporal aspects of glare. The present study utilized static lighting conditions to explore disability and discomfort glare, but the effects of dynamic exposures are not well known and should be explored. The present study also used a relatively short period of time for measuring visibility and discomfort (a few minutes). If longer-term exposure to discomfort glare causes drivers to look away from the glare source or engage in other behaviors, such as using sun visors or tinted eyeglasses, these behaviors might possibly impact driving performance above and beyond that predicted by discomfort glare alone, which accounts for scattered light in the eye. Determining whether these behaviors occur, and if so, what they are, is also recommended in order to more fully understanding the consequences of headlamp glare.

# VII. REFERENCES AND ANNOTATIONS


Akashi Y, Rea MS. 2001. The effect of oncoming headlight glare on peripheral detection under a mesopic light level. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 9-22).

- oncoming low beam headlamp glare degraded detection performance of a target 23$^{o}$ off-axis but not 15$^{o}$ off-axis

Akashi Y, Rea MS. 2002. Peripheral detection while driving under a mesopic light level. *Journal of the Illuminating Engineering Society* 31(1): 85-94.

- the spectral power distribution of fixed-pole lighting impacted peripheral detection more than one's own headlamps

Alferdinck JWAM, Padmos P. 1988. Car headlamps: Influence of dirt, age and poor aim on glare and illumination intensities. *Lighting Research and Technology* 20(4): 195-198.

- headlamps on many vehicles were found to be misaimed and dirty, increasing glare illuminance to other drivers and reducing one's own forward illuminance

Alferdinck JWAM, Varkevisser J. 1991. *Discomfort Glare From D1 Headlamps of Different Size*, Report IZF 1991 C-21. Soesterberg, Netherlands: TNO Institute for Perception.

- De Boer ratings were highly correlated with glare illuminance
- size (from 0.0006 to 0.15 deg$^2$) had a small influence on rated discomfort (less than 1 De Boer unit total) using the De Boer scale

Alpern M, Ohba N. 1972. The effects of bleaching and backgrounds on pupil size. *Vision Research* 12: 943-951.

- the pupil mechanism is dominated by rods and thus has a spectral sensitivity similar to rods

Anderson SJ, Holliday IE. 1995. Night driving: Effects of glare from vehicle headlights on motion perception. *Ophthalmic and Physiological Optics* 15(6): 545-551.

- glare from oncoming high beam headlamps greatly reduces visual acuity and threshold contrast especially when minor lens opacities are present

Ben-Sira A, Loewenstein A, Lipshitz I, Levanon D, Lazar M. 1997. Patient satisfaction after 5.0-mm photorefractive keratectomy for myopia. *Journal of Refractive Surgery* 13: 129-134.

- patients having refractive surgery reported high levels of satisfaction one year after the procedure

Bergström S. 1963. Visible distances during night driving. In *Lighting Problems in Highway Traffic, Vol. 2*. New York, NY: Pergamon Press.

- seeing distance increased with high beams against high beams over that obtained with low against low beams

Berman SM, Fein G, Jewett DL, Ashford F. 1993. Luminance-controlled pupil size affects Landolt C task performance. *Journal of the Illuminating Engineering Society* 22: 150-165.

- identifying the orientation of briefly-flashed (200 ms), low-contrast letter-c-shaped targets improved slightly under blue illumination relative to red-pink illumination

Bhise VD, Farber EI, Saunby CS, Troell GM, Walunas JB, Bernstein A. 1977. Modeling vision with headlights in a systems context. *Society of Automotive Engineers Congress and Exposition*, Detroit, MI: Society of Automotive Engineers (Paper 770238).

- regions of acceptable and unacceptable discomfort glare from headlamps are bounded by situations giving a De Boer rating of 4 and the conditions created by 110% of the illuminance caused by properly aimed low beam headlamps
- previous research is cited that 0.1 lx is an upper limit for the border from nonglaring to glaring conditions (from a comfort perspective)
- four-headlamp systems resulted in more dimming requests than two-headlamp systems having the same glare illuminance
- it was found in field studies that dimming requests from oncoming drivers began to occur when the calculated De Boer rating reached a value of 4 or lower
- depending upon adaptation level, U.S. low beams at the time of the report had corresponding calculated De Boer ratings from 4 to 6, U.S. high beams from 1 to 4, and European ("H4") low beams from 6 to 8; all were calculated for oncoming distances from 400 to 1800 feet
- a model for dimming request prediction is developed that shows the probability of a request as a function of De Boer rating and the exposure time to glare

Bichão IC, Yager D, Meng J. 1995. Disability glare: Effects of temporal characteristics of the glare source and of the visual-field location of the test stimulus. *Journal of the Optical Society of America A* 12(10): 2252-2258.

- transient (temporary) disability glare sources could have a larger negative impact on threshold contrast than steady glare sources

Bichão IC. 1995. Existing glare testers and the evaluation of night driving glare problems. *Vision Research* 35: S79.

- transient glare affected peripheral detection more than foveal detection
- the difference between transient and steady glare was greater in the periphery

Bouma PJ. 1936. The problem of glare in highway lighting. *Philips Technical Review* 1: 225-229.

- discomfort glare was stated to be caused more by blue than by yellow light

Bullough JD. 2002. Modeling peripheral visibility under headlamp illumination. *Transportation Research Board 16th Biennial Symposium on Visibility and Simulation*, Iowa City, IA, June 2-4.

- a predictive model of peripheral target detection under headlamps is developed

Bullough JD, Boyce PR, Bierman A, Hunter CM, Conway KM, Nakata A, Figueiro MG. 2001. Traffic signal luminance and visual discomfort at night. *Transportation Research Record* (1754): 42-47.

- red and green saturated-color glare sources were rated more uncomfortable to view than yellow sources of equal luminous intensity

Bullough JD, Fu Z, Van Derlofske J. 2002. Discomfort and disability glare from halogen and HID headlamp systems. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0010).

- De Boer ratings were strongly correlated with glare illuminance (0.04 to 2.6 lx)
- threshold contrast was strongly correlated with glare illuminance
- HID glare sources were consistently rated as more glaring than halogen sources, but less so than blue-filtered halogen sources, although the blue source had higher scotopic content than both the HID and unfiltered halogen sources
- different sources did not result in different threshold contrast once glare illuminance was constant
- De Boer ratings were more highly correlated with glare illuminance calculated using a short-wavelength cone luminous efficiency function

Bullough JD, Rea MS. 2000. Simulated driving performance and peripheral detection at mesopic and low photopic light levels. *Lighting Research and Technology* 32(4): 194-198.

- driving performance in terms of speed and on-axis obstacle detection did not depend upon spectrum
- detection of peripheral objects improved for "cooler" or "bluer" light sources relative to "warmer" or "yellower" sources

Bullough JD, Rea MS. 2001. Driving in snow: Effect of headlamp color at mesopic and photopic light levels. In *Lighting Technology Developments for Automobiles*, SP-1595. Warrendale, PA: Society of Automotive Engineers.

- an analysis of discomfort glare studies relating to street lighting provided initial evidence that rod photoreceptors might play a role in discomfort glare under some conditions

Bullough JD, Van Derlofske J, Fay CR, Dee P. 2003. Discomfort glare from headlamps: Interactions among spectrum, control of gaze and background light level. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2003-01-0296).

- a background light level ranging from 0.1 to 3 cd/m2 did not affect the spectral discomfort response to headlamp glare
- a fixed gaze resulted in similar trends for ratings of discomfort as a free gaze

De Boer JB. 1967. Visual perception in road traffic and the field of vision of the motorist. In *Public Lighting*. Eindhoven, Netherlands: Philips Technical Library.

- the nine-point De Boer scale for measurement of discomfort in a driving context is described

De Boer JB, van Heemskerck Veeckens JFT. 1955. Observations on discomfort glare in street lighting. *Proceedings of the CIE*, Zurich.

- illumination from yellow-filtered incandescent street lighting needed to be about 25% higher than from unfiltered incandescent lighting in order to be considered equally uncomfortable by observers

Dickinson HC. 1931. Report on vehicle and highway mechanics as related to traffic: Headlighting. *Highway Research Board Proceedings* (11): 388-409.

- concludes that visibility with low versus low beams and high versus high beams is equivalent, with small benefits for right shoulder viewing obtained in the low beam case

Ferguson HM, Reeves J, Stevens WR. 1953. A note on the relative discomfort from mercury, sodium and tungsten light sources. *GEC Journal* (July).

- low pressure sodium illumination required a luminance approximately three times that of mercury vapor illumination to appear equally "uncomfortable"

Flannagan M, Sivak M, Ensing M, Simmons CJ. 1989. *Effect of Wavelength on Discomfort Glare from Monochromatic Sources*, Report UMTRI-89-30. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- six wavelengths (480, 505, 550, 577, 600 and 650 nm) were presented at four light levels
- De Boer ratings were highly correlated with glare illuminance (0.03 to 3 lx)
- older subjects gave lower De Boer ratings
- 577 and 600 nm sources were least glaring; 480 and 505 nm sources were most glaring

Flannagan MJ, Sivak M, Battle DS, Sato T, Traube EC. 1993. *Discomfort Glare from High-Intensity Discharge Headlamps: Effects of Context and Experience*, UMTRI-93-10. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- HID headlamps were rated on the De Boer scale as more glaring than halogen headlamps (approximately 50% difference in illuminance to achieve equivalent ratings)
- older drivers gave lower De Boer ratings
- having HID headlamps on one's own vehicle increased De Boer ratings
- for sources with more saturated colors, the order in increasing 'glariness' is: red, yellow, green, blue

Flannagan MJ, Sivak M, Gellatly AW, Luoma J. 1992. *A Field Study of Discomfort Glare from High-Intensity Discharge Headlamps*, Report UMTRI-92-16. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- glare illuminance from 0.02 to 4.6 lx was strongly correlated with De Boer ratings
- SPD (HID or halogen) significantly impacted De Boer ratings with HID lamps having lower ratings
- for equal De Boer ratings, halogen lamps needed to be more than 50% higher in intensity than HID lamps

Flannagan MJ, Sivak M, Traube EC, Kojima S. 2000. Effects of overall low-beam intensity on seeing distance in the presence of glare. *Transportation Human Factors* 2(4): 313-330.

- based on visibility alone, there is no obvious upper limit for glare
- however, based on discomfort, subjects find glare objectionable long before it will negatively impact visual performance

Flannagan MJ. 1999. *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution*, Report UMTRI-99-36. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- glare illuminance from about 1 to 4 lx had a strong relationship with De Boer ratings and with threshold contrast of a visual target
- SPD (halogen versus HID) did not impact disability glare but did impact De Boer ratings, with lower ratings for the HID glare sources
- size (0.3 or 0.6 deg) did not impact either disability or discomfort glare

Fotios SA, Levermore GJ. 1998. Chromatic effect on apparent brightness in interior spaces, II: SWS lumens model. *Lighting Research and Technology* 30(3): 103-106.

- a model of brightness incorporating the response of short-wavelength cones is developed and found to provide a good match to brightness matching data

Freitas C, Oliveiros BM, Marques E, Leite EB. 1995. Effect of photorefractive keratectomy on visual functioning and quality of life. *Journal of Refractive Surgery* 11: S327-S334.

- patients having refractive surgery reported improvements in visual functioning such as nighttime driving, six months after surgery

Fry GA. 1954. Evaluating disability effects of approaching automobile headlights. *Highway Research Bulletin* (89): 38-42.

- concludes that the effect of disability glare can be predicted by using a veiling luminance concept to capture the impact of scattered light in the eye

Gimbel HV, Van Westenbrugge JA, Johnson WH, Willerscheidt AB, Sun R, Ferensowicz M. 1993. Visual, refractive, and patient satisfaction results following bilateral photorefractive keratectomy for myopia. *Refractive and Corneal Surgery* 9; S5-S10.

- most patients having refractive surgery reported little or no problems with nighttime driving

Hadden OB, Ring CP, Morris AT, Elder MJ. 1999. Visual, refractive, and subjective outcomes after photorefractive keratectomy for myopia of 6 to 10 diopters using the Nidek laser. *Journal of Cataract and Refractive Surgery* 25: 936-942.

- most patients receiving refractive surgery reported no significant night vision problems, some patients reported improvements in night visibility and reduced glare at night

Hare CT, Hemion RH. 1968. *Headlamp Beam Usage on U.S. Highways*, Report AR-666. San Antonio, TX: Southwest Research Institute.
- most drivers tended to overdrive their own headlamps, even without glare, and more so with glare
- dimming from high to low beams seems to be a function of discomfort, or more likely, the anticipation of discomfort

Harris AJ. 1953. The meeting beams of headlights: Effects of deterioration and misaim. *Illuminating Engineering Society Transactions* 18(8): 207-220.
- visibility in the presence of a stationary glare source is found to be the same as that in the presence of a moving glare source

He Y, Bierman A, Rea MS. 1998. A system of mesopic photometry. *Lighting Research and Technology* 30(4): 175.
- peripheral detection response speeds improve for rod-dominated spectra increasingly as light level is reduced
- a model of photometry at mesopic (low, nighttime) light levels is presented to predict peripheral visibility as a function of spectrum

He Y, Rea MS, Bierman A, Bullough J. 1997. Evaluating light source efficacy under mesopic conditions using reaction times. *Journal of the Illuminating Engineering Society* 26(1): 125-138.
- off-axis detection (at $15^{o}$) improved with a "bluer" spectrum (metal halide) relative to a "yellower" one (high pressure sodium) as light level decreased below 1 cd/$m^2$
- on-axis detection did not depend on spectrum at any light level

Hemion RH. 1969. *A Preliminary Cost-Benefit Study of Headlight Glare Reduction*, Report AR-683. San Antonio, TX: Southwest Research Institute.
- accidents in which headlamp glare (or "blinding by headlamps") could be stated as a cause numbered around 1% (or slightly less), based on results from several U.S. states

Hemion RH. 1969. *Night Visibility Improvement Through Headlight Glare Reduction*, Report AR-696. San Antonio, TX: Southwest Research Institute.
- "safe" driving speeds were computed to be higher when using high beams with opposing high beams than when using low beams against low beams

Hills BL. 1976. Visibility under night driving conditions: Derivation of (□L, A) characteristics and factors in their application. *Lighting Research and Technology* 8: 11.
- a revised glare formula to that commonly used and promulgated by Fry (1954) is proposed when the glare source is close to the line of sight

Holladay JT, Dudeja DR, Chang J. 1999. Functional vision and corneal changes after laser in situ keratomileusis determined by contrast sensitivity, glare testing, and corneal topography. *Journal of Cataract and Refractive Surgery* 25: 663-669.
- short-term impacts on vision after LASIK surgery depend largely upon the resulting shape of the cornea

Jehu VJ. 1954. A comparison of yellow and white headlamp beams. *Light and Lighting* 4(10): 287-291.

- no disability glare differences were found between white and yellow headlamps
- subjects preferred to drive with white headlamps, but some preferred to see yellow headlamps in an oncoming situation

Johansson G, Bergstrom S, Jannson G, Ottander C, Rumar K, Ornberg G. 1963. Visible distances in simulated night driving conditions with full and dipped headlights. *Ergonomics* 6(2): 171-179.

- visibility distances were better for high beams seen against high beams than with low versus low beams
- high versus high beams did result in greater reported discomfort

Kahle G, Seiler T, Wollensak J. 1992. Report on psychosocial findings and satisfaction among patients 1 year after excimer laser photorefractive keratectomy. *Refractive and Corneal Surgery* 8: 286-289.

- one year after refractive surgery, patients were generally satisfied with the procedure and reported improvement of their lifestyle

Karpen D. 2002. Reducing headlight glare. *Lighting Design and Application* 32(2): 52-53.

- headlamps with neodymium coatings are proposed as countermeasures for headlamp glare
- the lamps have about 10% higher scotopic output than conventional halogen headlamps

Lehnert P. 2001. Disability and discomfort glare under dynamic conditions: The effect of glare stimuli on human vision. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 582-592).

- halogen lamps were used as glare stimuli
- De Boer ratings were highly correlated with glare illuminance (0.1 to 10 lx)
- De Boer ratings were highly correlated with glare duration (0.2 to 10 sec)
- glare illuminance had a greater impact on De Boer ratings than duration

Lingard R, Rea MS. 2002. Off-axis detection at mesopic light levels in a driving context. *Journal of the Illuminating Engineering Society* 31(1): 33-39.

- detection of peripheral objects from $12^o$ to $29^o$ off axis and with varying contrasts was improved with metal halide illumination relative to high pressure sodium illumination at mesopic light levels

Manz K. 2001. The influence by size of headlamp on discomfort glare. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 618-634).

- previous investigations on discomfort glare and stimulus size are discussed
- some proposed requirements for limiting the smallest size of headlamps or the luminance of the source are discussed

Marcos S, Moreno E, Navarro R. 1999. The depth-of-field of the human eye from objective and subjective measurements. *Vision Research* 39: 2039-2049.

- depth of field is only slightly affected by spectrum and by pupil size

McColgan MJ, Van Derlofske J, Bullough JD, Shakir I. 2002. Subjective color preferences of common road sign materials under headlamp bulb illumination. *Society of Automotive Engineers 2002 World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0261).

- color naming performance for common sign colors was equivalent under conventional halogen, blue-filtered halogen, neodymium-coated halogen and HID headlamps

McGhee CNJ, Craig JP, Sachdev N, Weed KH, Brown AD. 2000. Functional, psychological, and satisfaction outcomes of laser in situ keratomileusis for high myopia. *Journal of Cataract and Refractive Surgery* 26: 497-509.

- most patients with relatively severe levels of myopia reported little difficulty driving at night and 98% were satisfied with the outcome of their LASIK surgery

Miles PW. 1954. Visual effects of pink glasses, green windshields and glare under night driving conditions. *American Medical Association Archives - Ophthalmology* 51: 15-23.

- glare is stated to be inversely proportional to the size of the glare source (for the same intensity), and it is proposed that headlamps be designed larger in area

Mortimer RG, Becker JM. 1974. Some operational considerations affecting the performance of current and proposed head-lamp beams. *Transportation Research Record* (502): 34-40.

- a glare illuminance of 0.1 lx from headlamps is proposed as the point at which discomfort begins

Mortimer RG. 1965. The effect of glare in simulated night driving. *Highway Research Record* (70): 57-62.

- glare illuminance (3 or 9 lx) negatively impacted simulated driving performance but 9 lx was not statistically significantly worse than 3 lx
- duration of glare (7 or 15 sec) did affect performance under some conditions
- frequency of glare (once, twice or four times per min.) did not significantly affect performance
- forward light level affected performance, and it is concluded that headlamp illumination might be increased to improve forward visibility without making glare problems worse

Mortimer RG. 1969. Requirements for automobile exterior lighting. In *Visual Factors in Transportation Systems*. Washington, DC: National Academy of Sciences.

- research showing that reductions in visibility distance are correlated with the logarithm of glare illuminance at the eye is discussed
- use of a spot lamp to increase forward illumination did not seem to increase glare to oncoming drivers as evidenced by headlamp dimming requests

Olson PL, Aoki T, Battle DS, Flannagan MJ. 1990. *Development of a Headlight System Performance Evaluation Tool*, Report UMTRI-09-41. Ann Arbor, MI: University of Michigan.
- an average adaptation luminance of 1 cd/m$^2$ while driving at night is derived

Olson PL, Sivak M. 1984. Discomfort glare from automobile headlights. *Journal of the Illuminating Engineering Society* 13(3): 296-303.
- glare illuminance (0.0004 to 6.5 lx in a laboratory study and 0.003 to 11 lx in a field study) was highly correlated with De Boer ratings
- De Boer ratings were higher in the field study than in the laboratory study
- older subjects reported lower De Boer ratings
- authors conclude that estimates of acceptable discomfort glare based on laboratory results might be too conservative

Powers LD, Solomon D. 1965. Headlight glare and median width: Three exploratory studies. *Highway Research Record* (70): 1-28.
- as expected, threshold contrast increased as the amount of glare light increased

Ranney TA, Simmons LA, Masalonis AJ. 1999. Prolonged exposure to glare and driving time: Effects on performance in a driving simulator. *Accident Analysis and Prevention* 31: 601-610.
- intermittent glare presented over two 8-hour sessions reduced performance, but glare did not increasingly impair performance more after 8 hours than it did after shorter periods

Ranney TA, Simmons LA, Masalonis AJ. 2000. The immediate effects of glare and electrochromic glare-reducing mirrors in simulated truck driving. *Human Factors* 42(2): 337-347.
- the presence of glare negatively impacted simulated driving performance in terms of target detection and lane control
- reduction of glare with electrochromic mirrors did not significantly improve performance although subjects preferred the mirrors

Rea MS (editor). 2000. *IESNA Lighting Handbook: Reference and Application*, 9th edition. New York, NY: Illuminating Engineering Society of North America.
- rods outnumber cones in the retina by about fifteen to one

Rumar K. 2001. Intensity of high-beam headlights. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 829-848).
- reference is made to previous research that dimming of one's own high beams occurs when the discomfort from oncoming vehicles is between 4 and 5 on the De Boer scale
- reference is made to previous research that a glare illuminance just higher than 1 lx is the maximum acceptable by drivers

Schmidt-Clausen HJ, Bindels JTH. 1974. Assessment of discomfort glare in motor vehicle lighting. *Lighting Research and Technology* 6(2): 79-88.
- discomfort as measured by the De Boer rating was highly correlated with the logarithm of the glare illuminance (from 0.003 to 20 lx)
- discomfort was reduced at higher background adaptation levels (from 0.015 to 15 cd/m$^2$)
- discomfort was reduced at larger angles from the field of view (from 1 to 20 degrees)
- discomfort from multiple sources was the same as from a single source within the range 1 to 5 degrees and 0.003 to 9.6 lx
- a formula for the predicted De Boer rating is provided for the range of conditions used in the experiments reported

Schmitz S, Dick HB, Krummenauer F, Schwenn O, Krist R. 2000. Contrast sensitivity and glare disability by halogen light after monofocal and multifocal lens implantation. *British Journal of Ophthalmology* 84(10): 1109-1112.
- older subjects with different types of lens implants did not experience glare to different degrees; contrast threshold in the presence of glare was the same in both groups

Schreuder DA. 1969. *Side Lights and Low-Beam Headlights in Built-Up Areas.* Voorburg, Netherlands: Institute for Road Safety Research.
- it is stated that without high ambient light levels along roadways provided by fixed lighting, glare from low beams is unacceptably high because the resulting veiling luminance reduces contrast of important objects along the road

Schreuder DA. 1976. *White or Yellow Lights for Vehicle Head-Lamps?* Voorburg, Netherlands: Institute for Road Safety Research.
- literature on SPD of headlamps is reviewed supporting small benefits of yellower sources for discomfort glare but no appreciable differences for forward visibility or disability glare

Schwab R. 1965. Night visibility for opposing drivers with high and low headlight beams. *Highway Research Record* (70): 87-88.
- it is concluded that the amount of forward light from headlamps, which determines adaptation level, is the primary determinant of visibility and that glare is less important; higher intensities would increase glare but also adaptation and still result in net visibility gains

Schwab RN, Hemion RH. 1971. Improvement of visibility for night driving. *Highway Research Record* (377): 1-23.
- a correlation between disability glare and subjective ratings of discomfort was found
- no strong relationship between glare and fatigue (performance reduction over longer periods of time) was identified

Sivak M, Flannagan MJ, Ensing M, Simmons CJ. 1991. Discomfort glare is task dependent. *International Journal of Vehicle Design* 12: 152-159.
- performance of a complex associated task increased the perception of discomfort glare

Sivak M, Flannagan MJ, Miyokawa T. 2000. *A First Look at Visually Aimable and Harmonized Low-Beam Headlamps*, Report UMTRI-2000-1. Ann Arbor, MI: University of Michigan Transportation Research Institute.

- visually aimable and harmonized beam lamps tend to result in reduced glare to oncoming drivers, compared with conventional headlamps in the U.S.

Sivak M, Flannagan MJ, Traube EC, Kojima S. 1999. The influence of stimulus duration on discomfort glare for persons with and without visual correction. *Transportation Human Factors* 1(2): 147-158.

- glare illuminance from 0.5 to 8 lx had a strong relationship with De Boer ratings
- glare duration (from 0.125 to 2 sec) also had a correlation with De Boer ratings but less so than illuminance
- subjects with glasses or contact lenses had slightly lower De Boer ratings but the difference was not statistically significant

Sivak M, Flannagan MJ. 1993. Human factors considerations in the design of vehicle headlamps and signal lamps. In *Automotive Ergonomics* (Peacock B, Karwowski W, eds.). London, UK: Taylor and Francis.

- the authors challenge the conventional notion that disability glare and discomfort glare are separate phenomena
- nonetheless, experimental results described tended to focus on one or the other aspect

Sivak M, Olson PL, Zeltner KA. 1989. Effect of prior headlighting experience on ratings of discomfort glare. *Human Factors* 31(4): 391-395.

- German subjects reported lower De Boer ratings to headlamps than American subjects, presumably because of reduced experience with headlamp glare in Europe

Sivak M, Simmons CJ, Flannagan MJ. 1990. Effect of headlamp area on discomfort glare. *Lighting Research and Technology* 22(1): 49-52.

- glare illuminance (0.03 to 3 lx) was strongly correlated with De Boer ratings
- glare source size (0.3 or 0.6 deg) had a small impact on De Boer ratings with the smaller size resulting in lower ratings

Stiles WS, Crawford BH. 1937. The effect of a glaring light source on extrafoveal vision. *Proceedings of the Royal Society of London, Series B, Biological Sciences* 122(827): 255-280.

- the impact of glare on peripheral vision is well predicted by treating the source of glare as a uniform field of brightness that reduces contrast

Sugar A, Rapuano CJ, Culbertson WW, Huang D, Varley GA, Agapitos PJ, de Luise VP, Koch DD. 2002. Laser in situ keratomileusis for myopia and astigmatism: Safety and efficiency. *Ophthalmology* 109: 175-187.

- LASIK surgery is most successful for low to moderate levels of myopia but rarely leads to permanent negative effects
- appearance of potential glare sources might change in some patients (star burst patterns)

Theeuwes J, Alferdinck JWAW. 1996. *The Relation Between Discomfort Glare and Driving Behavior*, Report DOT HS 808 452. Soesterberg, Netherlands: TNO Human Factors Research Institute.

- actual driving in the field was performed
- glare illuminance from 0.28 to 1.1 lx from rig mounted sources (halogen SPD)
- De Boer ratings less 'glaring' than predicted by Schmidt-Clausen and Bindels (1974) but depended on task difficulty
- De Boer ratings correlated with willingness to look into glare source (e.g., to see a turn signal)
- older drivers gave higher De Boer ratings
- European and American drivers gave equivalent De Boer ratings
- 0.55 and 1.1 lx impaired driving performance about equally (detection of targets and distance at which they were detected), and older drivers performed worse, despite higher De Boer ratings

Theeuwes J, Alferdinck JWAW, Perel M. 2002. Relation between glare and driving performance. *Human Factors* 44(1): 95-107.

- De Boer ratings of discomfort depended upon difficulty of the driving conditions.
- De Boer ratings alone are not predictive of the conditions experienced while driving, nor of driving performance.

Tsongos NG, Schwab RN. 1970. Driver judgments as influenced by vehicular lighting at intersections. *Highway Research Record* (336): 21-32.

- older drivers reported lower discomfort from oncoming headlamps than younger drivers

Van Derlofske J, Bullough JD, Hunter CM. 2001. Evaluation of high-intensity discharge automotive forward lighting. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2001-01-0298).

- HID headlamps produce similar amounts of light as halogen headlamps in the center of the beam pattern, but much more light in the beam periphery
- the light distribution leads to shorter response times to peripheral targets

Van Derlofske J, Bullough JD, Hunter CM. 2002. Visual benefits of high-intensity discharge forward lighting. *Society of Automotive Engineers World Congress*, Detroit, MI: Society of Automotive Engineers (Paper 2002-01-0259).

- detection of peripheral targets under typical HID headlamps is improved relative to typical halogen headlamps because of increased peripheral light from HID lamps

Völker S. 1999. The effect of discomfort glare on the development of headlamps. *Progress in Automobile Lighting Symposium*, Darmstadt, Germany: Darmstadt University of Technology (pp. 765-773).

- several investigations into discomfort glare from automotive headlamps are described and tabulated
- size was concluded to be a relatively unimportant factor

Wright WD. 1937. The foveal light adaptation process. *Proceedings of the Royal Society of London, Series B, Biological Processes* 122(827): 220-245.

- the perception of brightness or glare and the performance of some visual tasks do not necessarily use the same visual channels
- it might be possible to design a stimulus to provide good visibility while reducing glare, for example

# APPENDIX: LUMINOUS EFFICIENCY FUNCTIONS

The photopic luminous *efficiency* function (shown in Figures I-1 and II-9 of this report) is used to determine the relative weighting for radiant power from a light source (e.g., in W) at each wavelength in order to calculate photometric quantities (e.g., luminous flux in lm, illuminance in lx, or luminous intensity in cd). This function characterizes the spectral sensitivity of the cone photoreceptors in the central retina. Similarly, the scotopic luminous *efficiency* function characterizes the spectral sensitivity of the rod photoreceptors in the eye.

In order to calculate the scotopic/photopic ratio of a given spectral power distribution such as the ones shown in Figure II-8, the relative values of the photopic and scotopic luminous *efficacy* functions must first be calculated. These functions give the luminous efficacy (in lm/W) of radiant power at each wavelength. By convention of the Commission Internationale de l'Éclairage (CIE), the international organization associated with defining photometric quantities, radiant power at 555 nm is, by definition, associated with a luminous efficacy of 683 lm/W. Thus, the photopic luminous efficacy function has a peak value of 683 lm/W at 555, while the scotopic luminous efficacy function has a peak value of 1700 lm/W at 507 nm (and, as defined, a value of 683 lm/W at 555 nm, as shown in Figure A-1.

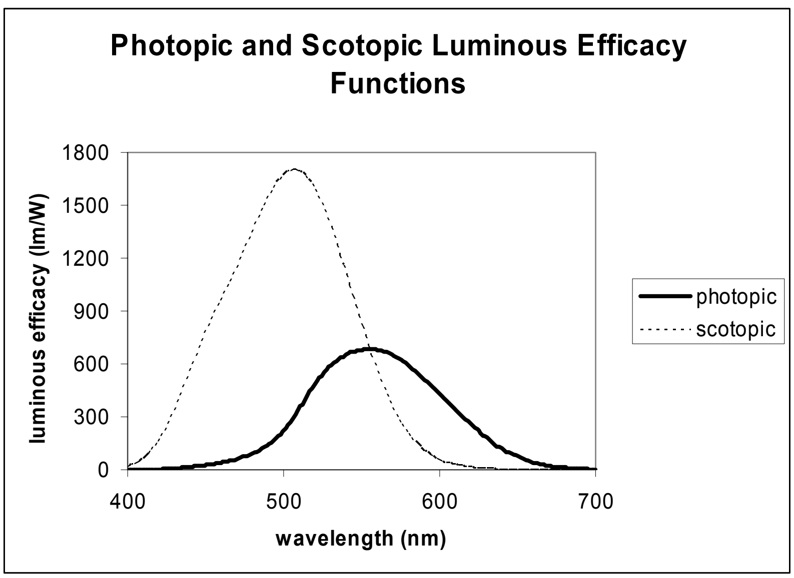


***Figure A-1.*** *Photopic and scotopic luminous efficacy functions. Unlike the luminous efficiency functions shown in Figure I-1, these functions are scaled to a value of 683 lm/W at 555 nm.*

Since the scotopic/photopic ratio is, as described in this report, a unitless ratio, it is possible to use scaled spectral power distributions such as those in Figure II-8. For example, suppose the array $S(\lambda)$ is a given spectral power distribution, defined for wavelengths ($\lambda$) from 400 to 700 nm. Suppose $V(\lambda)$ is the photopic luminous efficacy function and $V'(\lambda)$ is the scotopic luminous efficacy function. The scotopic/photopic ratio is defined as the quantity:

$$scotopic / photopic\ ratio = \frac{\sum_{\lambda=400}^{700} S(\lambda)V'(\lambda)}{\sum_{\lambda=400}^{700} S(\lambda)V(\lambda)} \qquad \textit{(Equation A-1)}$$

Using the same types of formulations it is possible to calculate the short-wavelength-cone/photopic ratio, by scaling the spectral sensitivity of this photoreceptor (shown in Figure II-7) so that it is equal to 683 lm/W at 555 nm. Since the relative sensitivity of this cone is much higher at 440 nm than at 555 nm, this function will have very large values around 440 nm.

For this reason it is important to emphasize that the values of the scotopic/photopic ratios, or the short-wavelength-cone/photopic ratios calculated in this report, by themselves are not meaningful; they only serve as relative indicators of a spectral power distributions ability to stimulate the rods in comparison to the foveal cones.

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