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Final Report

# The Relation Between Discomfort Glare and Driving Behavior

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16. Abstract

The present study investigated the effects of discomfort glare on actual driving behavior. Subjects (old and young; US and European) were exposed to glare of a light source mounted on the hood of an instrumented vehicle simulating headlamps of an oncoming car. The luminous intensity of the light source was similar to the maximum glare intensities of European and US headlamp standards. Subjects drove at night the instrumented vehicle in actual traffic along a particular track consisting of urban, rural and highway stretches. Driving behavior and the detection of critical objects as well as various subjective measures of discomfort glare were determined.

The results indicate that due to the glare source subjects adapted their behavior in a safe direction: on dark and winding roads subjects drove significantly slower and invested more effort when the glare source was on than when it was off. The two higher glare intensities caused a significant drop in detecting objects erected along the road. Older subjects showed the largest behavior adaptation and the largest drop in object detection performance. Furthermore, the results indicated that the widely used De Boer ratings on discomfort glare were not related to the actual changes in driving behavior.

The finding that subjects adapted their behavior into a safe direction by reducing speed and/or investing more effort independent of the actual glare illuminance suggests that a glare illuminance equivalent to the US headlamp standard is acceptable as a maximum upper limit.

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## EXECUTIVE SUMMARY

The present study investigated the effects of discomfort glare on actual driving behavior. The study's goal was to provide a validation in terms of driving behavior of the widely used De Boer rating scale for measuring discomfort glare. Subjects (old and young; US and European) were exposed to glare of a light source mounted on the hood of an instrumented vehicle simulating headlamps of an oncoming car. The luminous intensity of the light source was either 350, 690 or 1380 cd. The two higher intensities were similar to the maximum glare intensities of European and US headlamp standards. Subjects drove at night the instrumented vehicle in actual traffic along a particular track consisting of urban, rural and highway stretches. Driving behavior and the detection of critical objects as well as various subjective measures of discomfort glare were determined.

The results indicate that due to the glare source, subjects adapted their behavior in a safe direction: on dark and winding roads subjects drove significantly slower and invested more effort when the glare source was on (690 and 1380 cd per headlamp) than when it was off. The two higher glare intensities (690 and 1380 cd) caused a significant drop in detecting objects erected along the road, both in terms of missed targets and detection distance. Older subjects showed the largest behavior adaptation and the largest drop in object detection performance. Furthermore, the results indicated that De Boer ratings on discomfort glare were not related to changes in driving behavior caused by the glare source: high levels of discomfort were not associated with a large reduction in driving speed nor with poor object detection performance.

The finding that subjects adapted their behavior into a safe direction by reducing speed and/or investing more effort independent of the actual glare illuminance (i.e., within the ranges measured both US and European glare sources caused the same speed reduction) indicates that a glare illuminance of at least 1.1 lx (the maximum US level comparable to 1380 cd per headlamp) is acceptable as a maximum upper limit. It should be realized however that on a dark road, basically any glare illumination will cause a drop in object detection performance.

# 1 INTRODUCTION

Automobile headlamps provide illumination for driving that enables efficient lane-keeping, detection of potential obstacles such as other vehicles and pedestrians and the perception of traffic signs. There is an inherent conflict between the visibility that headlamps may provide for the user and the impairment due to glare it may cause for oncoming traffic. Traditionally, two types of glare have been recognized. The first type is disability glare and causes a reduced contrast sensitivity. Although there are large individual differences in the sensitivity to disability glare, the average reduction in contrast sensitivity can be calculated objectively. However, the subjective sensation of discomfort referred to as discomfort glare is determined subjectively, primarily using the De Boer rating scale (De Boer, 1967; Vos, 1985).

Although it has generally been accepted that discomfort caused by automobile headlamps can be determined by the De Boer scale, there has never been any investigation to what extent headlamps *that are supposed to only cause discomfort and annoyance* affect actual driving behavior. The present study, commissioned by the US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), was designed to establish the relationship between discomfort glare caused by automobile headlamps and the effects it has on actual driving behavior. The study provides a validation in terms of driving behavior of the widely used De Boer rating scale for measuring discomfort glare. In addition, two new subjective measures for discomfort glare were evaluated.

In the present study, subjects were exposed to a simulated light source mounted on the hood of an instrumented vehicle. The light source was equivalent to either US (an intensity of 1380 cd per headlamp equivalent to 1.1 lx glare illuminance) or European (an intensity of 690 cd per headlamp equivalent to 0.55 lx) standards for low-beam headlamps. Subjects drove at night the instrumented vehicle in actual traffic along a particular track consisting of urban, rural and highway stretches. Driving behavior and the detection of critical objects as well as various subjective measures of discomfort glare were determined. Since the amount of discomfort glare experienced might depend on age as well as on previous exposure to glare sources, three groups of subjects were tested: young drivers from the USA who only had driving experience with US headlamps, and young and old drivers from the Netherlands who had experience with European headlamps.

The goal of the present study was to determine whether headlamps that supposedly only cause discomfort have an effect of driving behavior. More specifically, it investigated whether an annoying light source can cause a change in driving behavior, specifically whether it changed behavior into an unsafe direction. Since the present study used glare sources equivalent to US and European low-beam headlamps, the present data provides input to a possible future international harmonization of low-beam patterns (see e.g. Sivak & Flannagan, 1993, 1994). It indicates which upper limits in terms of glare illuminance on the eye of the driver are acceptable from a traffic safety point of view; that is, at what headlamp intensities do drivers change their behavior into an unsafe direction.

## 2 GLARE AND ITS EFFECTS ON DRIVING PERFORMANCE

### 2.1 Glare

Glare is the blinding experience that results from a bright light source in the visual field of view, such as the headlights of an oncoming car at night. In general, the effect of glare will increase when the source luminance increases, the background luminance decreases, and the angle between the line of sight and the direction of the light source decreases. Generally, two types of glare are recognized: disability glare and discomfort glare.

### 2.2 Disability glare

In case of disability glare, the visibility is reduced by the straylight in the eye. The light source(s) cause light scatter in the eye which is perceived as a luminous veil over the scene. This veil reduces the contrast of the objects and hence their visibility.

The amount of disability glare, expressed in terms of veiling luminance, can be measured objectively by comparing the visibility of an object seen in the presence of the glare source in question with the visibility of that same object as seen through an artificial luminous veil (also referred to as equivalent veil). When the visibility in these two cases are equal, the luminance ($L_v$ in cd/m$^2$) of the veil is a measure for the disability glare. A lot of studies have been performed to determine $L_v$ as a function of various parameters. The veiling luminance is strongly dependent on the glare angle $\theta$ (in degrees), which is the angle between the viewing direction and the direction of the glare source. The veiling luminance decreases with an increasing glare angle. The veiling luminance is proportional to the glare illuminance at the eye of the observer ($E_{gl}$ in lx). One of the most famous equations to describe the veiling luminance is the Stiles-Holladay equation (see e.g., Vos, 1985):

$$L_v = \frac{k\ E_{gl}}{\theta^2} \tag{1}$$

The straylight parameter k depends on the age of the observer. It is normally set to a value of 10. Due to its simplicity, this equation has widely been used in the field of lighting engineering. Since then, a lot of other authors proposed alternative equations for various glare angle ranges. Vos (1985) summarized these studies in a state-of-the-art paper and proposed an equation in which also age-dependency is included.

$$L_v = E_{gl}\left[\frac{10+5.10^{-7}A^4}{(\theta+0.02)^2}+\frac{10}{(\theta+0.02)^3}+\frac{10^6(1-1.8\ 10^{-8}A^4)}{e^{(\theta/0.02)^2}}\right] \tag{2}$$

A is the age of the observer in years. In practical situations in which the glare angle is usually larger than 0.1°, the first two terms of the equation are sufficient to calculate the disability glare. In Figure 1 the ratio $L_v/E_{gl}$ (the glare function) is plotted for glare angles between 0.1 and 100° for 20 to 80 year old observers.

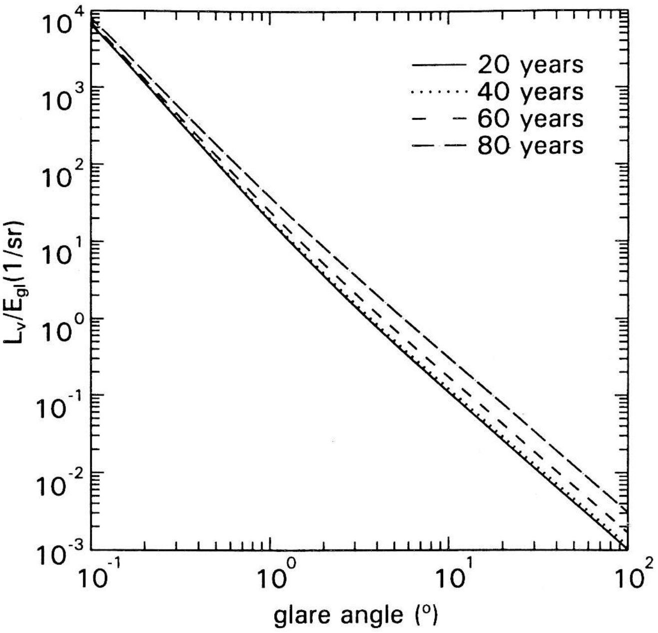


Figure 1 The glare function $L_v/E_{gl}$ as a function of the glare angle for various ages.

As Figure 1 shows, the glare effect rapidly increases with decreasing glare angle, and also increases with age. Typical glare angles in traffic range from 1.5 to 7°, representative for oncoming cars approaching at distances between 25 and 100 m on a two-lane road with lanes of 3 m width. For these glare angles it can be calculated with equation (2) that the glare increases with almost a factor 3 between 20 and 80 years.

It should be noted that in the case of an extended glare source, such as a bright sky above a tunnel entrance, the glare function should be integrated over the whole area of the glare source. However, since car headlamps can be considered as point sources the disability glare can be calculated using equation (2).

The contrast reduction due to the veiling can be expressed in different ways, depending on the definitions for contrast. The one generally used in visibility studies is

$$C = \frac{L_a - L_b}{L_b} \quad \textbf{(3)}$$

in which $L_a$ is the object luminance and $L_b$ de background luminance. To perceive a target object, the contrast C should exceed a certain threshold level, which is generally in the order of 0.05. For small objects and low light levels this threshold increases (Blackwell, 1946). In case of reading text a contrast of about 10 is recommended (Alferdinck, 1992).

Since the veiling luminance affects the luminance of both the object and the background, $L_v$ should be added to both $L_a$ and $L_b$, so eq. (3) becomes

$$C = \frac{L_a - L_b}{L_b + L_v} \quad \textbf{(4)}$$

Note that $L_v$ only affects the denominator and thus causes contrast to decrease with increasing veiling luminance. When the contrast is lower than the threshold contrast, the object is not visible.

## 2.3 Calculation and measurement of disability glare

In a practical situation the illuminance of the (two) headlamps ($E_{gl}$) can be measured with an illuminance measurement device. For a given lane width, the glare angle can be determined from the distance between the observer and the headlamps and the viewing direction of the observer. With equation (2) the veiling luminance can be calculated.

> Example:
> At 50 m distance the glare angle is about 3.4°. Let the luminous intensity of the headlamps be 350 cd each, which is the median value as found by Alferdinck and Padmos (1988) in a field study. The illuminance at the observers eye of one headlamp can be calculated by the inverse square law: $E_{gl}=350/50^2=0.14$ lx. For a 20 years old observer the veiling luminance $L_v=0.14\times3.08=0.43$ cd/m². For two headlamps: $L_v=0.86$ cd/m².
> Assume a grey object (luminance factor=0.3) on the road at 50 m from the observer. The object luminance can be calculated using the headlamp data of the field study of Alferdinck and Padmos (1988). The median illumination intensity on the road at 50 m is 2500 cd, and the corresponding illuminance at $2500/50^2=1.00$ lx. The object luminance is about $1\times0.3/3.14=0.095$ cd/m². When we assume that the luminance of the pavement is black the pavement luminance is a factor 10 lower : 0.0095 cd/m². According to equation (3) the contrast without glare is $(0.095-0.0095)/0.0095=9$. In the glare situation equation (4) should be used and the contrast becomes $(0.095-0.0095)/(0.0095+0.86)=0.1$, which is a low visibility in practice. The threshold contrast for an object with a size of 15 cm at 50 m distance in these light circumstances is 0.06. For a 5 cm object this value is 0.26. Hence, in the glare situation only the largest object is visible. Without glare both objects are visible.

When the scenes are very complex or consists of extended light sources the veiling luminance can be measured with a special objective lens on a luminance meter. The lens actually acts as an artificial eye and integrates the veiling luminance over a wide range of glare angles. However, in case of headlamps the calculating method is more appropriate.

The variation in sensitivity to disability glare among individuals is rather large (Vos, 1985). Van den Berg and IJspeert (1992) developed a straylight meter to measure for individual observers the straylight parameter of the glare function as described by equation (1).

## 2.4 Discomfort glare

Discomfort glare is the subjective sensation of discomfort of the observer when he is exposed to bright light sources. Discomfort glare is measured by means of a subjective rating scale. Although, there is no complete consensus which rating scale should be used (Gellatly & Weintraub, 1990; Weintraub *et al.*, 1991; Olson & Sivak, 1984), the nine-point De Boer scale is most widely used in the field of automotive and public lighting (De Boer, 1967). In Table 1 this scale is shown. A low rating means high discomfort glare.

Table 1 De Boer rating scale for discomfort glare.

| rating | identifier |
|---|---|
| 1 | unbearable |
| 2 | – |
| 3 | disturbing |
| 4 | – |
| 5 | just admissible |
| 6 | – |
| 7 | satisfactory |
| 8 | – |
| 9 | unnoticeable |

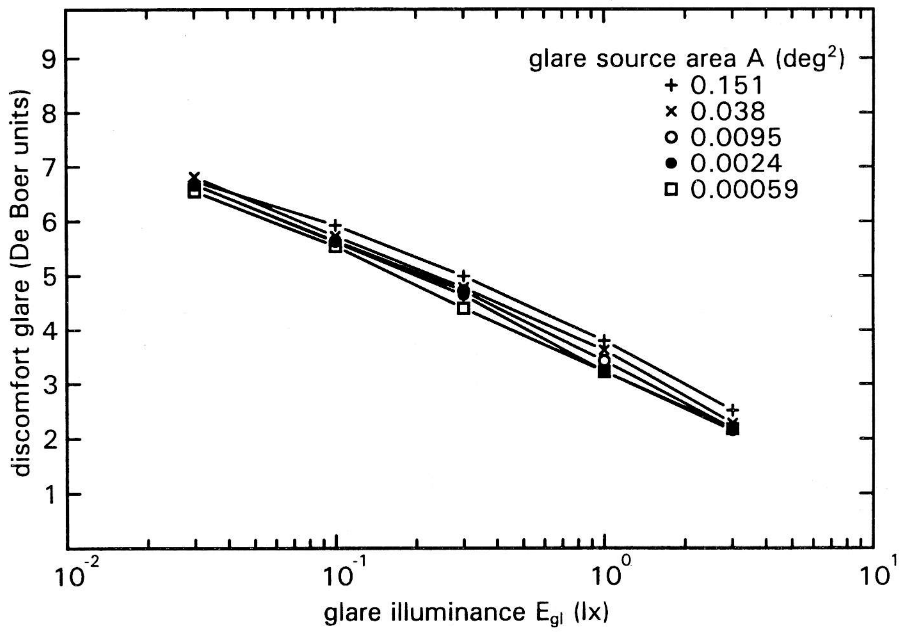


Figure 2 Discomfort glare rating as a function of glare illuminance, with the glare source area as parameter (Alferdinck, 1994). A high rating implies low discomfort glare.

Schmidt-Clausen and Bindels (1974) performed laboratory experiments and published an equation which describes the discomfort glare as a function of glare illuminance ($E_{gl}$ in lx), glare angle ($\theta$ in ~~degrees~~), and background adaptation luminance ($L_a$ in cd/m²):

arcmin

$$D = 5 - 2 \log \left[ \frac{E_{gl}}{0.003 \left(1+5\sqrt{L_a}\right) \theta^{0.46}} \right] \qquad \textbf{(5)}$$

In addition, Sivak *et al.* (1990) and Alferdinck (1994) found also a small effect of the glare source area. When the area of the glare source decreases by a factor four, the discomfort increases with a 0.1 points on the De Boer rating scale. In Figure 2 the main results of Alferdinck (1993) are shown.

Alferdinck derived an equation which describes the discomfort glare D (in De Boer scale units) as a function of the glare source area A ($deg^2$), the glare illuminance $E_{gl}$ (lx) and the glare angle $\theta$ (deg).

$$D = 2.89 - 2.19 \log \left[ \sum_{i=1}^{n} \left( E_{gl,i} . \theta_i^{-0.74} . A_i^{-0.0772} \right) \right] \tag{6}$$

The symbol $\Sigma$ indicates that the equation can describe the discomfort glare of more than one glare source, each with its own illuminance, angle and area (see also Schmidt-Clausen & Bindels, 1974). Note that the effect on the glare source area is very small in comparison to the effect of glare illuminance and glare angle. In fact, Alferdinck and Varkevisser (1991) found a small interaction between glare angle and glare source area, which is neglected in this equation.

Combining the influence of the glare illuminance, glare angle and glare source area of the equation of Alferdinck and Varkevisser with the effect of the adaptation luminance in the equation of Schmidt-Clausen and results in the equation:

$$D = 1.87 - 2.19 \log \left[ \sum_{i=1}^{n} \left( E_{gl,i} . \theta_i^{-0.74} . A_i^{-0.0772} \right) \right] + 2 \log\left(1 + 5\sqrt{L_a}\right) \tag{7}$$

There is some evidence that the discomfort glare ratings are also dependent on the prior experience with the glare sources. For example, in a field study carried out by Sivak, Olsen and Zeltner (1989) showed that European subjects rated the same levels of glare as being much more uncomfortable than did the American subjects. It has been claimed that the differences in the type of headlights in Europe and the US may have made Americans more tolerant to glare than Europeans because Americans are exposed to higher levels of glare.

## 2.5 Glare and driving behavior

In case of disability glare there is a direct relation between the amount of glare and the contrast detection performance (see the calculation example). With increasing glare there is a reduction in the ability to perceive small contrasts. This decrease may affect a number of visual tasks required in traffic such as the detection of critical objects, headway control, reading of signs, and evaluation of critical encounters.

Discomfort glare causes discomfort without necessarily impairing the vision of objects. This means that there may be aspects of lighting that do not affect the disability glare but increase discomfort glare. A good example is the headlamp size, which influence discomfort glare and not affect the disability glare (Alferdinck, 1994; Sivak, Simmonds & Flannagan, 1990). However, it is possible that an increase of the discomfort glare, with a constant disability glare, results in a changes in driving behavior (e.g., risky behavior) and feelings of uncertainty. It has been shown that discomfort glare ratings depend to some extent on the task difficulty (Sivak *et al.*, 1991). Thus the same glare is judged more uncomfortable on a road with poor delineation (a more difficult task) than on one with good delineation. The relationship between discomfort glare and task difficulty suggests that driving behavior is affected by discomfort glare. For example, if the discomfort glare is too high, drivers may slow down in order to make their task easier and thereby reduce the effects of discomfort glare.

Although glare may affect visual performance such as detection thresholds, the effects of both disability and discomfort glare on actual driving behavior have never been assessed. The present project aims at determining the relationship between disability glare and discomfort glare and its effects on driving behavior and performance.

## 3 ISSUES ON STANDARDIZED HEADLAMPS

Car headlamps should illuminate the road in front of the car in order to visualize the road course, traffic signs, other road users and possible obstacles. On the other hand, oncoming traffic should not be dazzled. These are reasons to emit the most of the light to the right (for right-hand traffic) and down on the road and as little as possible in the direction of the approaching cars, although sufficient light should be left make retroreflecting gantry signs and traffic signs visible. The border between the upper and lower part of the beam pattern is called the cut-off.

In the low beam patterns for car headlamps two main types can be recognized, the European beam with a rather sharp cut-off and the US with a more diffuse pattern. The intensities in the upper-left quadrant of the beam are important with respect to glare. The intensities have upper limits to avoid glare. On the other hand there lower limits are necessary to ensure enough light on retroreflecting signs. In Table 2 the requirements for the European (ECE, 1986), US (FMVSS) and Japanese standard (JIS, 1985; Sivak *et al.*, 1992; Taniguchi *et al.*, 1989) in the upper left quadrant are listed.

Table 2 Requirements for the upper left quadrant of the headlamp beam pattern of three different standards. The figures between brackets refer to practical values at a lamp voltage of 13.5 V.

| Standard | Test location (horizontal, vertical in degrees) | Luminous intensity (cd) | |
|---|---|---|---|
| | | Minimum | Maximum |
| Europe (ECE, 1986) | (0.5, −3.5) (B50L) | – | 250 (535) |
| | Zone III with corners: (0,0), (−8,0),(−8,4),(0,4) | – | 438 (937) |
| US (FMVSS) | line from (−1.5,1) to left | – | 700 (840) |
| | line from (−1.5,0.5) to left | – | 1000 (1200) |
| | Zone with corners: (0,0), (−8,0),(−8,4),(0,4) | 64 (77) | – |
| | Zone with corners: (0,0), (−4,0),(−4,2),(0,2) | 135 (162) | – |
| Japan (JIS, 1984) | line from (−1, 1) to left<br>line from (−1, 0.5) to left | –<br>– | 1300 (1560)<br>1700 (2040) |

Note that the luminous intensities of the ECE standard should be measured at a lamp voltage of 12 V. Assuming a lamp voltage of 13.5 V in practice, the intensities increase with a factor $(13.5/12)^{3.4}=1.49$ (IES, 1966). Moreover, when the headlamp is produced an increase of 50% is allowed. This results in practical intensities which are a factor $1.49\times1.5=2.14$ higher. The US and Japanese standard are based on a voltage of 12.8 V. For the practical voltage of 13.5 V, the intensity values increase with a factor $(13.5/12.8)^{3.4}=1.2$. These practical luminous intensity values are printed between bracket in Table 2.

The maximum intensity limits in practice for an oncoming car at a distance of 50 m (location 0.5, −3.5) according the European, US and Japanese standard are respectively 535, 1200 and 2040 cd. Hence, the intensity range between countries varies in practice almost a factor four.

From a economic point of view it is desirable to strive for an international harmonization of the low-beam light distribution. To start the process of harmonization the Groupe de Travail "Bruxelles 1952" (GTB) proposed four directions in the European and USA light beam with corresponding light intensities, three below and one above the cut-off (GTB, 1995). The proposed common location above the cut-off is $(-1.5,0.5)$ with a lower and upper limit of respectively 100 and 531 cd at 12 V. This corresponds to practical values of 214 and 1136 cd. Note that this latter value corresponds to the "high" intensity condition as used in the present experiment.

4 EXPERIMENT

## 4.1 Rationale

The main goal of the present experiment was to determine the relationship between driving behavior and discomfort glare, i.e., the luminous output of headlamps that only cause *discomfort*. Subjects drove an instrumented vehicle with a simulated light source mounted on the hood along an experimental stretch consisting of urban, rural and highway roads. The light source on the hood either had one of four intensities: the light source was off (control condition); an intensity of 350 cd per headlamp representing a glare illuminance of 0.28 lx; an intensity of 690 cd representing a glare illuminance of 0.55 lx, an illuminance comparable to the maximum of European low-beam headlights (in the glaring direction); or an intensity of 1380 cd representing a glare illuminance of 1.1 lx, an illuminance comparable to the maximum of US low-beam headlights (in the glaring direction). Driving behavior in terms of speed, gas reversal, steering wheel reversal and the detection distance of particular objects was determined. These measures constitute a representative sample of relevant variables defining road user behavior (Van der Horst & Godthelp, 1989). Speed (i.e., changes in speed) may change when drivers feel less sure about the driving task. For example when the driving task becomes harder and/or when workload gets increased. High levels of steering wheel reversal rates are indicative of high driving task demands (MacDonald & Hoffman, 1980). High rates of gas pedal reversals may indicate that drivers become unsure about the driving task, i.e., unsure what is ahead of the vehicle.

Three measures of discomfort glare were applied: the widely used De Boer rating consisting of a 9-point rating scale, a rating on a 5-point rating scale at which subjects had to indicate their willingness to look into the light source, and a measure referred to as BCD (Border between Comfort and Discomfort) at which subjects had to adjust manually the light source to a level they considered between comfortable and discomfortable. The 5-point scale on the willingness to look into the light source ("the willingness to look for example for a turn signal", see instructions § 4.2.4) was used to determine whether a subjective measure on discomfort glare related in some way to search behavior during driving, would give favorable results. The BCD was applied as a subjective measure for discomfort glare because it was thought that such a continuous scale where subjects can adjust the light source to their maximum acceptable level would provide reliable results.

Since the amount of discomfort glare experienced depends on age as well as on previous exposure to glare sources, three groups of subjects were tested: young drivers from the USA who had experience with US headlamps, young drivers from the Netherlands who had experience with European headlamps, and old drivers from the Netherlands.

Main overall purposes of the present study were: (1) to determine the viability of subjective measures of discomfort glare and the relation of these measures to actual driving behavior; (2) to determine the maximum light source intensity that does not change driving behavior in a unsafe direction.

Figure 3 present a hypothetical model showing the relationships among the various variables. The extent to which a driver experiences glare depends on the headlamp intensity and the size headlamp area (e.g., Sivak *et al.*, 1990; Alferdinck, 1994). The driving situation and the difficulty of the driving task does also have an effect on the discomfort experienced by the driver (Sivak *et al.*, 1991). If a task is more difficult the discomfort experienced is larger. Aspects of the driver that play a role in glare are: age in relation to straylight sensitivity (Vos, 1995) and previous experience with the glare source (Sivak *et al.*, 1989). The ambient luminance level also has an effect: when a higher ambient luminance level the glare experienced is somewhat less (Schmidt-Clausen & Bindels, 1974). Dependent on the glare intensity this may result in an impairment of visual performance (e.g., reduction in contrast sensitivity) usually referred to as disability glare or when the light intensity is less in experiences of discomfort usually referred to discomfort glare. Both types of glare may have an effect on actual driving behavior. For example, under the influence of glare drivers may choose a lower speed to compensate for the adverse effects of glare, drivers may have to invest more effort to keep the vehicle on the road as represented by an increased Steering wheel activity rate.

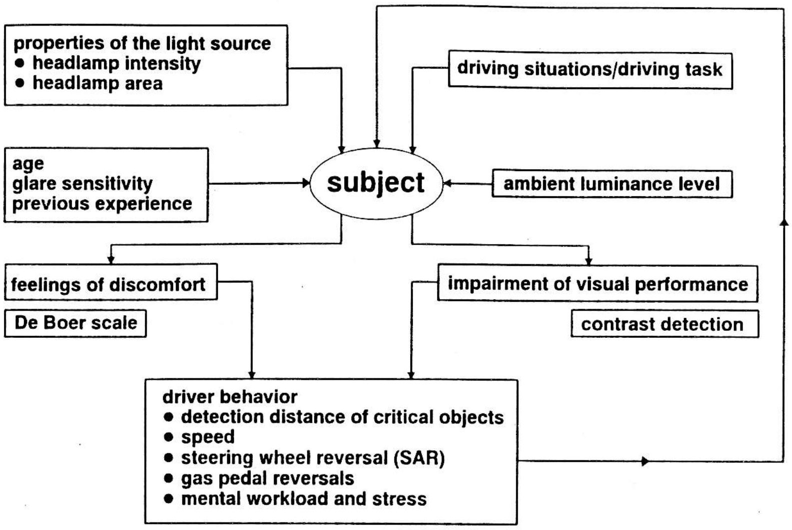


Figure 3 Hypothetical model depicting the relationship among various variables.

## 4.2 Method

### *4.2.1 Driving route*

The experimental track, located along the outskirts of Soesterberg, was 23,555 km long. The track was divided into different experimental sections, each representing a different type of road.

Appendix A gives pictures of each experimental section. Although the actual experiment was conducted at night, these picture were taken during daylight to give a general impression of the type of road. Each picture is representative of the particular section. In addition, Appendix A gives the important characteristics of the sections.

| section | distance (m) | description |
|---|---|---|
| 1 | 2,915 | residential like urban area (speed limit 50 km/h) |
| 2 | 2,060 | wide road outside built-up area with street lighting (speed limit 80 km/h) |
| 3 | 1,770 | wide road outside built-up area with street lighting and intersections (speed limit 50 km/h) |
| 4 | 2,090 | wide road outside built-up area without street lighting (section where plate detection took place) (speed limit 80 km/h) |
| 5 | 3,900 | wide road outside built-up area partly with and without street lighting (speed limit 80 km/h) |
| 6 | 1,730 | dark rural and winding road without road markings (speed limit 50 km/h) |
| 7 | 1,230 | wide somewhat winding road outside built-up area without street lighting (speed limit 80 km/h) |
| 8 | 3,250 | wide winding road partly with and without street lights (speed limit 80 km/h) |
| 9 | 4,610 | a 2×2 interstate highway without street lights (speed limit 120 km/h) |
| total | 23,555 | |

Table 3 Lighting characteristics of the sections of the test route. The ambient luminance was measured with a luminance meter at the experimental car. Types of public lighting: F=fluorescent, LS=low pressure sodium, HS=high pressure sodium.

| section | ambient luminance ($cd/m^2$) | | | public lighting | | |
|---|---|---|---|---|---|---|
| | at start of section | mean over whole section | mean over analyzed part of section | type | mean pavement luminance ($cd/m^2$) | remarks |
| 1 | 0.2230 | 0.2525 | 0.2346 | LS<br>F<br>LS | 0.22<br>0.1<br>0.25 | |
| 2 | 0.1699 | 0.5597 | 0.3377 | HS<br>LS | 0.8<br>0.9 | first part<br>second part |
| 3 | 0.1166 | 0.1417 | 0.1524 | LS | 0.21 | |
| 4 | 0.1342 | 0.1324 | 0.0903 | – | – | plate detection section |
| 5 | 0.2245 | 0.3760 | 0.1457 | LS<br>F<br>– | 0.27<br>0.026<br>– | light at parallel road (about 25 m left of road) |
| 6 | 0.0688 | 0.0860 | 0.0825 | – | – | |
| 7 | 0.1106 | 0.2850 | 0.1287 | – | – | |
| 8 | 0.0891 | 0.4456 | 0.2173 | –<br>LS | –<br>0.85 | |
| 9 | 0.1927 | 0.1548 | 0.1438 | – | – | |

The ambient background luminance and the type of lighting along these stretches is shown in Table 3. Three ambient luminance levels are provided: at the start of the experimental stretch at the location where the subjective rating scale willingness to look into the light source was given and the BCD rating; the average luminance over the whole stretch and the luminance on those parts of the sections for which the behavioral measures were analyzed.

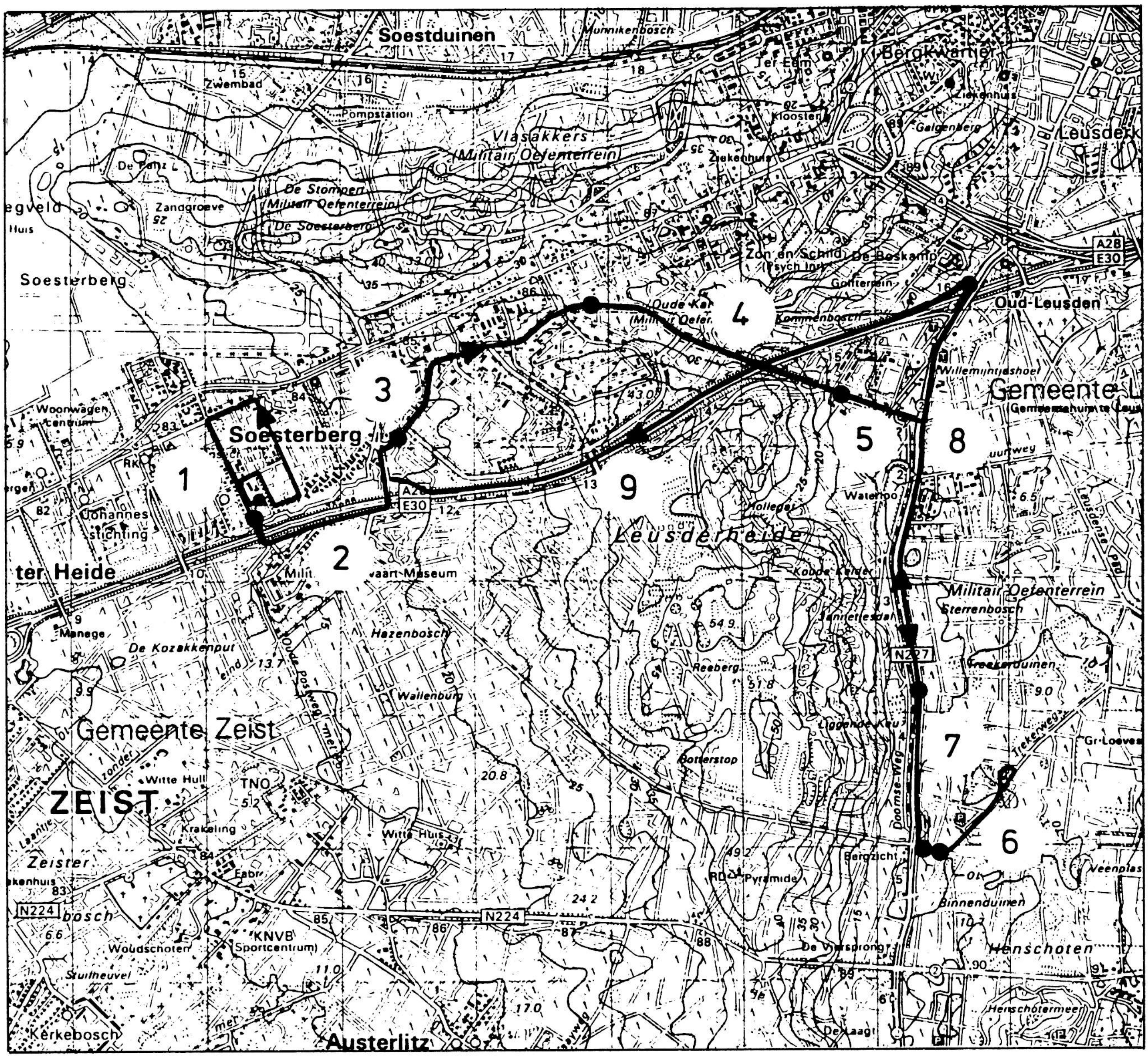


Figure 4 Map of the experimental track. The dots indicate the end of a section and the beginning of a new section.

Figure 4 gives a map of the experimental track. It took about 35 minutes to drive the entire experimental track. Subjects stopped at specially marked locations (see dots in Figure 4) at the beginning and end of each experimental section to allow computer re-calibration and to perform subjective tests (De Boer rating scale, adjustment of light source, rating scale regarding "willingness to look into the light source").

*4.2.2 Subjects*

In total 24 subjects took part in the experiment. Eight subjects were American students who had just arrived in Holland and had not yet driven in Europe. The US subjects consisted of 5 females and 3 males with an average age of 24.4 years (between 18 and 28 years). The young Dutch subjects were 4 males and 4 female with an average age of 28.3 (between 23 and 34 years). The older Dutch subject were 4 males and 4 females with a average age of 62.3 years (between 57 and 69 years). All subjects had their driving license for at least 2 years and had driven at least more than 10,000 km a year.

*4.2.3 Apparatus*

**1 Instrumented vehicle**

The TNO instrumented car ICARUS (Instrumented Car for Road User Studies) was used in the experiment. ICARUS is a Volvo 240 stationwagon with dual controls and an on-board IBM AT computer. The equipment in the car registered linear speed, distances travelled (e.g., detection distances), steering wheel and gas reversals (for a detailed description see Van der Horst & Godthelp, 1989).

Figure 5 Side view of the instrumented vehicle; there is a luminance measurement device is mounted on the roof of the car.

For the present experiment a luminance measurement device was mounted on the roof of the car allowing the on-line measurement of the ambient luminance levels in the viewing direction of the driver. Figure 5 gives a side view of the instrumented vehicle. The device measured the luminance (in cd/m$^2$) in a circular measuring area with a diameter of 20°.

**2 Lighting Rig**

On the hood of the car a lighting rig was mounted simulating the low-beam headlights of an oncoming car at a distance of 50 m at a fixed glare angle. It should be realized that the lighting rig *simulates* the glare illuminance on the driver's eye of a continuous stream of oncoming cars. It is a simulation and does not capture dynamic aspects of glare caused by an oncoming car such as an increase in glare angle, an increase in glare surface area and an increase in glare illuminance while approaching. The advantage of using the lighting rig is that it is possible to present a constant and well-defined glare illuminance level on the eye of the driver for a period of time long enough to allow the determination of the effect of glare illuminance on driving behavior. It should be noted that an oncoming stream of vehicles will cause a glare illuminance on the eye of the driver which is comparable to the illuminance presented in the present study.

In Table 4 all dimensions of the simulated headlamps, the lighting rig and the experimental car are listed. Note that the dimensions of the rig are the dimensions of the oncoming car scaled down by a factor 2.2/50=0.044.

Table 4 Dimensions of the parameters of the headlamps of the simulated oncoming car, the lighting rig and the experimental car.

| parameter | dimensions | |
|---|---|---|
| lane width | 3 m | |
| lateral distance between observer's eyes and car center | 0.34 m | |
| height of observer's eyes above the road-surface | 1.15 m | |
| | *simulated oncoming car* | *lighting rig* |
| distance headlamps and observer's eye (measured parallel to driving direction) | 50 m | 2.2 m |
| headlamp height | 12 cm | 5.3 mm |
| headlamp width | 24 cm | 10.6 mm |
| distance between headlamp centers | 1.09 m | 48.0 mm |
| height of headlamp center above the road-surface | 0.64 m | – |
| vertical glare angle headlamps | 0.58° | |
| horizontal glare angle headlamps | left headlamp: 3.67°<br>right headlamp: 2.42° | |
| area of one headlamp | 0.038 $deg^2$ | |

Figure 6 gives a picture of the lighting rig as it was mounted on the hood of the car. As shown in Figure 7 the pattern of light produced by the lighting rig corresponds to a car at a distance of about 50 m. This point was chosen because it corresponds to the point B50L of the European beam pattern (see § 3), the "glaring" point in the beam pattern that causes the largest glare illuminance. For the US beam pattern a "glaring" point similar to B50L is recognized (see § 3).

Figure 6 Lighting rig as mounted on the hood.

Figure 7 The view from the position of the driver. To the left is an actual car, to the right is the lighting rig.

In the experiment the four light levels were tested (lighting condition). Table 5 gives the values.

Table 5 Lighting conditions.

| condition | glare illuminance at the observer's eyes (lx) | luminous intensity per headlamp (cd) | rationale |
|---|---|---|---|
| 1 (no lights) | – | – | control condition |
| 2 (low) | 0.28 | 350 | close to just admissible discomfort glare (0.3 lx or 375 cd) |
| 3 (medium) | 0.55 | 690 | close to European beam at 13.5 V (0.45 lx or 560 cd) |
| 4 (high) | 1.10 | 1380 | close to US beam at 13.5 V (0.96 lx or 1198 cd) |

The goal was to choose luminous intensities which represent the glare intensities of European and US headlamps.

*The high light level* of 1380 cd per headlamp corresponds an intensity of an US headlamp operating at a practical voltage of 13.5 V. The US requirements in the glare directions are 1000 cd at a voltage of 12.8 V (FMVSS, 1991). In practice the voltage on the lamp is about 13.5 V, which corresponds to an intensity of $1000\times(13.5/12.8)^{3.4}=1198$ cd (IES, 1966).

*The medium light level* corresponds to the light level of an European headlamp operating at a practical voltage of 13.5 V. The European requirements are 250 cd in the glare direction (B50L) with a voltage of 12 V for headlamp type approval (ECE, 1986). However when the headlamp is produced an increase of 50% is allowed and in practice the lamp voltage is 13.5 V. This results in an in intensity of $250\times1.5\times(13.5/12)^{3.4}=560$ cd.

*The low light level* is 50% of the medium level and corresponds to the just acceptable level in terms of discomfort as measured by Alferdinck and Varkevisser (1991).

Due to the limited set of neutral and color shift filters and the photometric characteristics of the lighting rig, the experimental light levels differ a little from the initial goal. The final experimental luminous intensities are 350, 690 and 1380 cd per headlamp, corresponding to glare illuminance of respectively 0.28, 0.55 and 1.1 lx at the observer's eye (see Table 5). The color temperature of the lighting rig was about 3100 K, which matched very closely to the headlamp colors on the road.

The luminous intensity of the rig was controlled by a dial of a ten-turn-potentiometer or by putting neutral density filters in front of the rig. The three different luminous levels were obtained by setting the lamp voltage to 31% of the nominal voltage and by placing a neutral density filters with a density of 0.3, 0.6 and 0.9 (LEE, 209, 210, 211) in front of the rig.

Because the halogen lamp operated at a lower than the normal voltage the color temperature was to low. To compensate this color shift a blue filter was added (LEE, 201). The light source of the rig was a halogen reflector lamp (Philips, type: 6° 6424 GBA, 6 V/15 W).

For the stationary assessment discomfort glare (De Boer scale at parking lot) the halogen lamps of the rig were operated at normal voltage (6 V) and the 9 different light levels were obtained by using neutral filters with densities from 0 to 2.4 in steps of 0.3. No blue filter was used for this measurement. Since the maximum illuminance was 40 lx the illuminance levels at the observer's eye were 40.0, 20.0, 10.1, 5.0, 2.5, 1.26, 0.63, 0.32, and 0.16 lx (two rig lamps).

For the BCD score the blue filter and a neutral filter with a density of 0.6 was used. The subjects were asked to adjust the light level by controlling the lamp voltage. When the lamp voltage changes also the color temperature varies a little. Flannagan *et al.* (1989, 1991, 1994) found that color affects the discomfort rating. However, in the operating range of the lighting rig, from 20% to 100% lamp voltage (color temperature from 2000 to 5000 K or a dominant wavelength between 586 and 560 nm), this effect can be neglected.

### 3 Detection of wooden plates

Pedestrians were simulated by grey plywood boards, which is common in pedestrian visibility studies (Olson *et al.*, 1990; Helmers & Rumar, 1975; Taniguchi *et al.*, 1989). Plywood board with the same dimensions as used in the study of Olson *et al.* were used, with a height of 76.2 cm (30 inches) and a width of 30.6 cm (12 inches). The reflection was 12.5% (RAL color number 7031, blue-grey) which corresponds to dark clothing. Note that it is not necessary to use larger boards to simulate pedestrians because in practice pedestrians are detected when the headlamps illuminate the lower part of the body (e.g., legs).

Six locations on the left and 6 locations on the right side of the road were marked. The distance between the locations was 80 m. According to a fixed schedule either 4 or 6 plates were visible during a trial, half on the left and half on the right side. Plates were positioned about 1 meter from the right and left edge of the road. Before each trials subjects were unaware of the number and the locations of the plates.

### *4.2.4 Procedure*

The experiment took place between April 19 and May 12, 1995 during 18 nights between 8.30 pm and 3 am. Each night 2 subjects were tested. The complete experiment took place in dry and clear weather conditions.

### 1 Pretesting

Upon arrival subjects first read and signed the informed consent and read a form stating the purpose of the experiment (see Appendix B). The straylight sensitivity of each subject was determined by means of the Van den Berg and IJspeert (1992) straylight measurement device. Subjects looked into the device with both eyes and fixate the center of the visual field. While looking, a ring of lights was presented at 10 degrees in the periphery flickers. By adjusting the luminance, subjects were required to minimize the perceived flicker.

Visual acuity was determined by means of the Landolt-C acuity test. The visual acuity in this test refers to the ability to perceive a small gap in a broken ring (Landolt-C). The visual acuity is equals the reciprocal value of the visual angle subtending the gap in arcminutes (1 arcminute = 1/60 degrees). Therefore, a gap with a visual angle of x arcminutes corresponds to a visual acuity of 1/x. At a distance of 5 meters, subjects were required to indicate the orientation (bottom, top, left, right) of the gap of the Landolt-C.

Subjects were seated in the experimental car which was parked at the TNO parking lot. The immediate background was relatively dark (background luminance of 0.41 cd/m$^2$). Various tests were performed.

*The De Boer rating*: While seated in the instrumented vehicle subjects were asked to fixate a dot which was positioned straight ahead in the forward viewing direction. This corresponded to a position 3.05° to the right and 0.58° above the glare source mounted on the rig. In a random order different filters were positioned in front of the glare source creating 9 different light levels (40, 20, 10, 5.0, 2.5, 1.26, 0.63, 0.32, and 0.16 lx at the observer's eye). Each time a filter was placed in front of the glare source, it was switched on for a few seconds and subjects were asked to indicate verbally on the 9-point De Boer rating scale how they judge the glare illuminance. While making this judgement subjects could look at a sheet of paper showing the De Boer rating scale (see Table 6a for the English and Table 6b for the Dutch version). The experimenter registered the response. During the procedure the subjects were requested to fixate the fixation dot at all times. After the De Boer measurements the fixation dot was removed.

Table 6a  De Boer rating used in the experiment (based on De Boer, 1967).

| rating | qualification |
|---|---|
| 1 | unbearable |
| 2 | – |
| 3 | disturbing |
| 4 | – |
| 5 | just admissible |
| 6 | – |
| 7 | satisfactory |
| 8 | – |
| 9 | unnoticeable |

Table 6b  The Dutch translation of De Boer rating used in the experiment (Alferdinck & Varkevisser, 1991).

| waarderings-cijfer | kwalificatie |
|---|---|
| 1 | ondraaglijk |
| 2 | – |
| 3 | storend |
| 4 | – |
| 5 | net toelaatbaar |
| 6 | – |
| 7 | acceptabel |
| 8 | – |
| 9 | niet noemenswaardig |

*The BCD procedure*: Subjects were instructed to manually adjust the potentiometer mounted on the dashboard, allowing the adjustment of the intensity of the light source on the hood. Subjects were asked to adjust the light source to a level they thought was the border between comfort and discomfort (BCD score). While adjusting the light source, subjects had to image that they would encounter this light in actual traffic. The level to which the potentiometer was adjusted was registered by the experimenter.

## 2 Experiment

Before the start of the experiment subjects were familiarized with the experimental car. Subjects were told to drive as they normally would do without endangering other traffic or themselves. They were told to obey traffic laws. It was indicated that the driving instructor would give directions and would indicate when to stop and start. Each subject took a test drive with the driving instructor until the instructor thought that the subject controlled the car adequately.

At the beginning of the experiment the instructor again explained the purpose of the experiment and stressed that at all times the subject should behave in a safe manner. The instructor explained that there was a stretch during which the subject had to detect plywood objects erected along the section. An example of such a plywood object was placed at the beginning of the experimental track so that subjects knew what they were looking for. Subjects were told that they should keep their heads in the normal driving position (e.g., subjects were not allowed to lower their heads); at all times the driving instructor checked whether subjects did follow this requirement.

Each subject drove the experimental track (divided into 9 sections) 4 times. Each time a different filter was placed in front of the light source of the lighting rig creating 4 different light intensity conditions [control: no lights, 350 cd (0.28 lx), 690 cd (0.55 lx) or 1380 cd (1.1 lx)]. The order of presentation was randomized by means of a Digram Latin Square.

At the beginning of each experimental section the experimental car was stopped at an exact position so that the subject had a "representative" view on the experimental section that was coming up. Subjects were asked "*would you given the current circumstances be willing to look into the light source (for example to see a direction light?) Please indicate on a scale 1 to 5*". While being asked a rating scale from 1 to 5 was shown to the subject. Table 7 presents this rating scale. This procedure was done 9 times during a drive (at the beginning of each section) and only when the glare source was lit (i.e., not during the control condition).

Table 7 Rating scale for "Do you want to look in the glare source?".

| rating | qualification |
|---|---|
| 1 | absolutely not |
| 2 | – |
| 3 | neutral |
| 4 | – |
| 5 | no problem |

At the end of each experimental section, the car was stopped and subjects were asked to indicate on the De Boer rating scale how they judged the light source. While pointing at the De Boer rating scale (see Table 6 the driving instructor asked: "*can you indicate on a scale from 1 to 9 (see sheet at dashboard) what you thought about the light source on the road you just have been driving*". This procedure was done 9 times during a drive (at the end of each section) and only when the glare source was lit (i.e., not during the control condition).

Only during the control condition in which the lighting rig was switched off, at the beginning of each section, subjects were asked to adjust the potentiometer mounted at the dashboard to a level between discomfort and discomfort. They were asked "*please indicate by turning this knob what would be a just acceptable light level to you given the current circumstances*".

During section 4 (dark rural road) subjects were required to detect plywood plates erected both on the left and right side of the road. Before section 4 subjects were told: "*during the next part of the route there are several wooden plates positioned on the left and right side of the road; try to detect these plates as soon as possible and hit the horn as soon as you have seen one*". Between 4 to 6 objects were present at 12 possible locations (6 left 6 right side of the road). The subject pressed to horn upon detection of a plate which started the time measurement on the on-board computer. The experimenter pressed a button as soon as the experimental car passed the object which stopped the time measurement. In this way the detection distance could be determined. After each drive the order and location of the wooden plates was changed according to a fixed schedule.

After each experimental drive, the subject that just drove took a rest, while the other subject performed the experiment. While resting subjects were allowed to watch television, eat and drink non-alcoholic beverages.

### *4.2.5 Data analyses and design*

The experiment involved a two within and a two between subjects design. Within subjects factors were glare source intensity (control, 350, 690, 1380 cd) and section (section 1 to 9). Between subjects factors were age (young versus old) and nationality (US versus Dutch). The latter two factors were not completely factorial because old US subjects were not tested in the present experiment.

Table 8 gives an overview of the dependent variables measured before and during the experiment.

Table 8 Dependent variables used in the experiment.

| | | |
|---|---|---|
| *Subjective measures* | | |
| De Boer rating scale | before the experiment | scale 9 to 1 |
| Subjective adjustment, BCD | before the experiment | in lx |
| Willingness to look in source | during the experiment | scale 1 to 5 |
| De Boer rating scale | during the experiment | scale 9 to 1 |
| Subjective adjustment, BCD | during the experiment | in lx |
| *Behavioral measures* | | |
| driving speed | during the experiment | km/h |
| steering wheel reversal | during the experiment | #/s |
| gas pedal reversal | during the experiment | #/s |
| detection of wooden plates | | |
| distance | during the experiment | meters |
| missed targets | during the experiment | % |

The subjective measures were determined at the start of the experiment at the TNO parking lot and at the beginning and end of each experimental section. The detection of the wooden plates took place at section 4 which consisted of a wide dark road. Driving speed, gas and steering wheel reversals were determined during "free driving behavior" (behavior not determined by other traffic, traffic lights, characteristics of the car, etc.) on parts of the section where the background light level was relatively low and fairly constant (for details regarding this analysis see § 4.3.2).

## 4.3 Results

The data of one US subject had to be discarded because the subject did not follow the instructions (e.g., the subject gave discomfort ratings without looking at the light source). In addition, the subject turned out to be unable to handle the vehicle adequately.

### *4.3.1 Visual functions*

#### 1 Acuity

Figure 8 presents the results of the Landolt-C acuity test. T-tests showed that there were no differences in acuity between the US and Dutch subjects. Older subjects had a significant worse acuity than young subjects [$t(14)=2.31$; $p<0.05$].

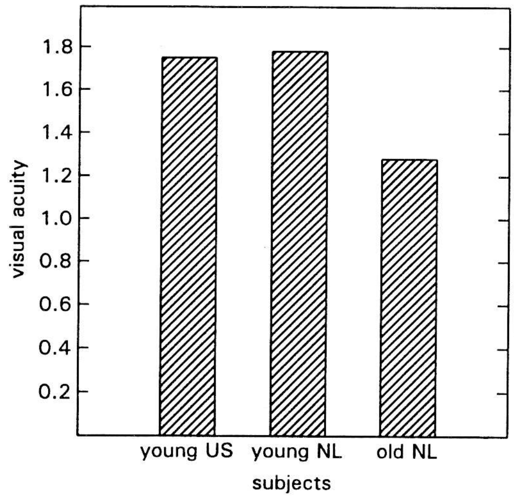


Figure 8 Acuity measures for the three subjects groups.

Walraven and Blokland (1982) derived from data of McDowell (1964) that the visual acuity of the population of 18 years and older is normally distributed with a mean of 1.61 and a standard deviation of 0.54. For elderly people with ages above 65 years the mean is 1.02 and the standard deviation is 0.44.

The younger subjects in the present study had an acuity of about 1.78. In comparison to the acuity of 1.61 of the whole population (including the old) this reasonable since the subset of younger subject should have a higher acuity than that of the whole population. The older subjects in the present study (which were 57 years and older) had an acuity slightly better than that of older people in the population over 65 years.

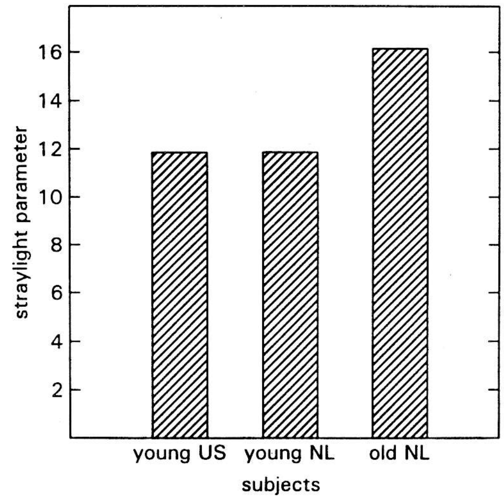


Figure 9 Straylight measures for the three subjects groups.

## 2 Straylight

Figure 9 gives the sensitivity to straylight as measured by the IJspeert and Van de Berg straylight measurement device. The difference between US and Dutch subjects was not reliable.

There was a trend that the older subjects were more sensitive to straylight than the young subjects [$t(14)=1.64$; $p=0.065$)].

The straylight parameter K (eq. 1) depends on the age of the observer. Vos (1985) gives a equation for this dependency.

$$K = 10\left[1+\left(\frac{A}{70}\right)^4\right] \qquad \textbf{(8)}$$

At ages from 0 to 40 years K is about 10. Above an age of 40 the parameter increases strongly as a function of the age. At an age of 70 K is doubled.

The straylight parameter determined in the present study is somewhat more for the young subjects (about 12) than what Vos (1985) would have predicted. The straylight for the older subjects is higher (about 16) and is in line with what Vos predicted.

*4.3.2 Subjective measures*

**1 The De Boer rating before the experiment**

The De Boer rating at the TNO parking lot before the start of the experiment indicated no differences between young Dutch and Us subjects nor between young and old subjects. As expected, the De Boer rating depended on the glare illuminance on the eye of the observer [$F(8,168)=109.9$; $p<0.001$]. Figure 10 presents the results. The expected ratings based on the model of equation (5) and Schmidt-Clausen & Bindels, 1974; Sivak, 1990) are also given in this figure. The model of equation (5) was calculated with $\theta=3.01°$, $A=2*0.38°$ and $L_a=0.4$. As is clear from Figure 10, subjects rated a glare illuminance of about 3 lx as just admissible (rating 5). This value corresponds to a luminous intensity per lamp of about 3000 cd, which is 10 times more than the existing models predict.

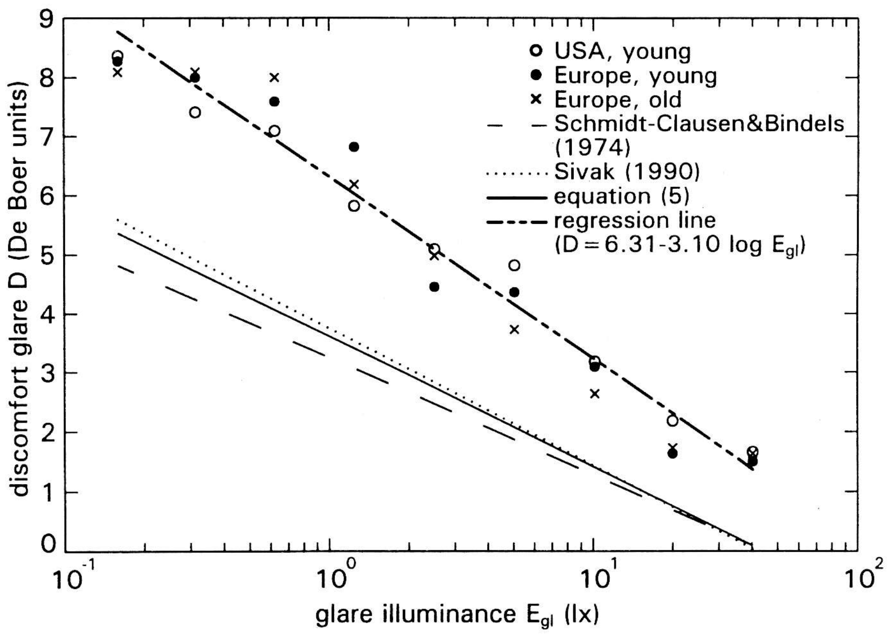


Figure 10 The De Boer rating as a function of the glare illuminance on the eye of the observer. Also plotted are the predictions from the model of Schmidt-Clausen and Bindels (1974) and Sivak *et al.* (1990) and the model of equation (5).

## 2 The BCD before the experiment

The adjustment of the light source between comfort and discomfort (BCD rating) at the TNO parking before the start of the experiment showed no differences between the US and Dutch subjects [$t(13)=1.77$; $p>0.05$]. There was a difference between the young and old subjects [$t(14)=2.82$; $p<0.05$]. As shown by Figure 11, the older subjects accepted a significant higher glare illuminance (2.35 lx) than the younger drivers (0.896 lx). Although US subjects accepted a higher level illuminance level (1.841 lx) than NL subjects (0.896 lx) this difference was not reliable because there were large individual differences between the ratings. These glare illuminance values correspond to De Boer ratings between 5 and 7 (see Figure 10), which according to De Boer rating is equivalent to just admissible (De Boer rating 5) and satisfactory (De Boer rating 7).

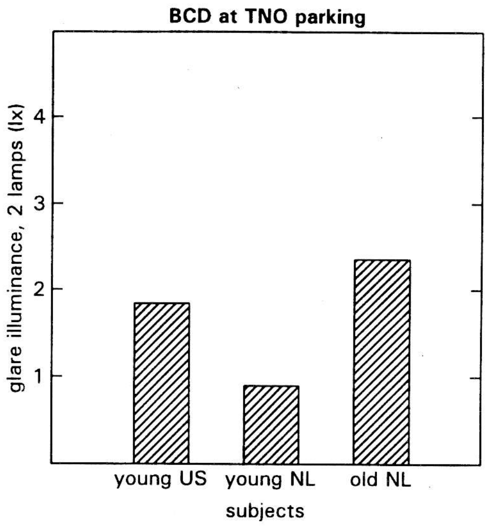


Figure 11 BCD score at TNO parking for the different subjects groups.

## 3 Willingness to look in the light source

The willingness to look in the light source (1=absolutely not; 5=no problem) depended on the intensity of the light source: subjects were less willing to look in the source when the intensity was higher [$F(2,42)=25.5$; $p<0.01$]. At an intensity of 350 cd the willingness was 3.9 (on a 5-point rating scale), at 690 cd the willingness was reduced to 3.7; and at 1380 cd the willingness was 3.2. Older drivers were more willing to look in the light source than younger subjects [$F(1,14)=7.2$; $p<0.05$]. There was no difference between the willingness to look in the light source between American and Dutch subjects. Figure 12 gives the willingness to look into the light source dependent on the glare source intensity for each of the different subjects groups.

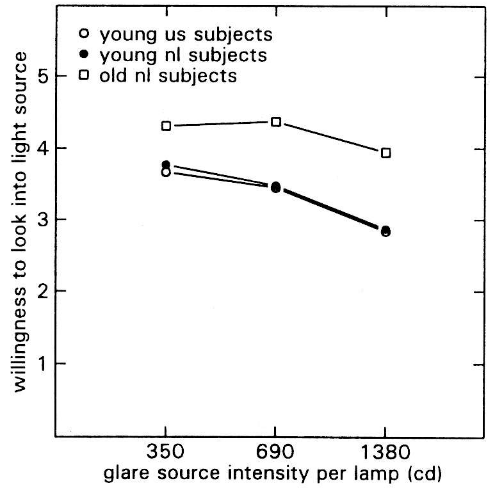


Figure 12 The willingness to look into the light source (rating scale 1 to 5) as a function of the glare source intensity.

The willingness to look in the light source depended also on the section driven [$F(8,168) = 16.9$; $p < 0.01$]. During section 6 (narrow, dark and small winding road) subjects were least likely to look in the source. During section 1 (city road with lighting) they had least problems looking in the source. Figure 13 presents the willingness to look in the light source for US young and NL young and old subjects for each experimental section.

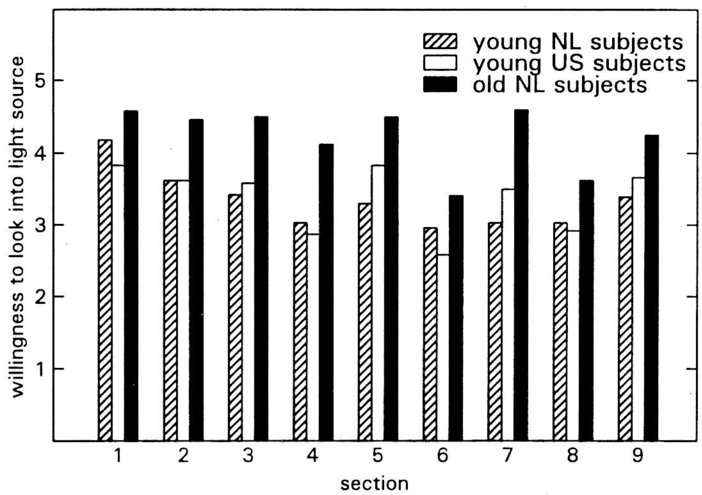


Figure 13 The willingness to look into the light source (rating scale 1 to 5) for each of the experimental sections for the different subject groups.

As can be expected the willingness to look into the light source should depend on the ambient light level of the immediate background while giving this rating. Since ratings were giving at the beginning of each experimental section, the background luminances at the start of each experimental section were determined. Figure 14 gives the relation between the willingness to look into the light source dependent on the immediate background luminance. The correlation between background luminance and willingness to look into the light source was $r(7)=0.89$, which is significantly different from zero ($p<0.01$).

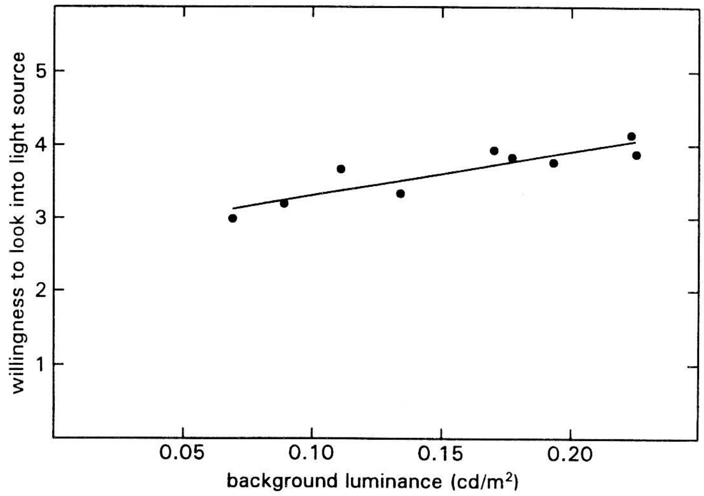


Figure 14 The willingness to look into the light source as a function of the background luminance.

As is clear from Figure 14 there is a linear relationship between the willingness to look into the light source and the immediate background luminance. This analysis suggest that 80 percent of the variance in the rating "willingness to look into the light source" can be accounted for by the immediate background luminance.

The finding that the rating "willingness to look into the light source" depended on the intensity of the light source presented to the subject and on the immediate background luminance suggests that this measure is adequate for determining the discomfort caused by the light source.

## 4 The De Boer rating during the experimental drive

Overall there was a main effect on the De Boer rating of intensity of the light source [$F(2,42)=26.5$; $p<0.01$], and of section [$F(8,168)=30.0$; $p<0.01$]. The results indicate that the highest light level of 1380 cd was rated as just acceptable (mean=5.4); the level of 690 cd was rated between just acceptable and satisfactory (mean=6.7); the level of 350 cd was rated as satisfactory (mean=7.0). Additional planned comparisons showed that all De Boer ratings for the different glare source intensities differed significantly from each other (all $p<0.05$).

Overall, there were no differences between the De Boer ratings for US (5.7) vs Dutch (6.2) and young (6.2) vs old (7.2) drivers. Figure 15 gives the De Boer rating as a function of glare source intensity for the different subjects groups. Note from Figure 15 that there is a trend that older subjects complain less than younger subjects although in this case it did not reach significance ($p=0.2$).

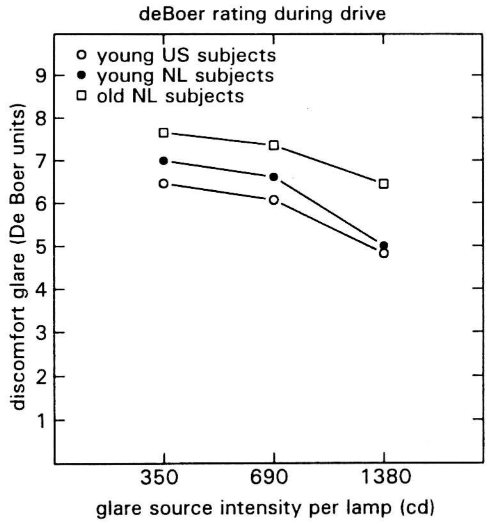


Figure 15 The De Boer rating as a function of glare source intensity for the different subject groups.

Section 6 (narrow, dark and winding road) was rated as least acceptable of all sections (mean of 4.2, between disturbing and just acceptable). Section 2 which had the highest public lighting level (a wide clearly lit road outside the built-up area) was rated as least problematic (mean=7.2). Figure 16 presents the De Boer rating during the drive for the different glare sources dependent on the experimental section driven.

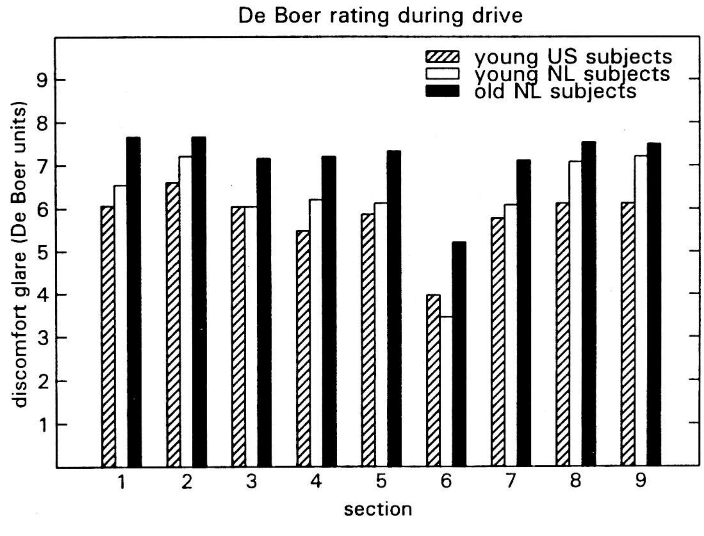


Figure 16 The De Boer rating for each of the experimental sections for the different subjects groups.

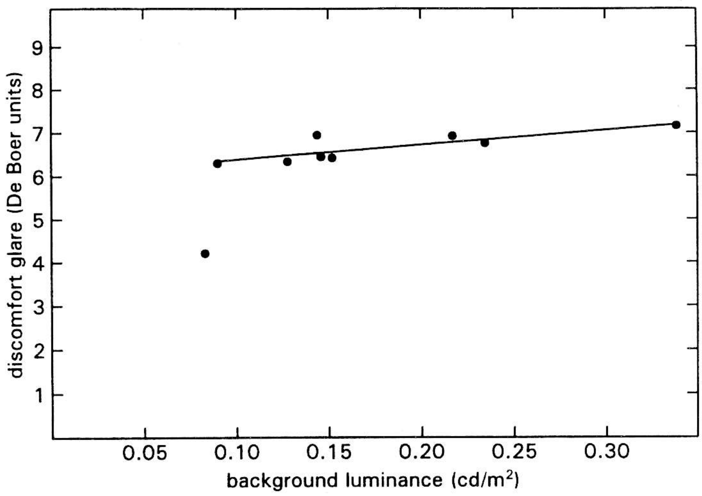


Figure 17 The De Boer rating as a function of the background luminance.

De Boer ratings were given each time subjects finished an experimental section. Subjects were asked to base their the De Boer rating on the section they just drove. In order to determine the relation between the De Boer rating and the background luminance, the average light level during a section was determined. Figure 17 presents the De Boer rating as a function of the background luminance. When calculating the linear regression, the lower left point was not included since this appeared to be an outlier. The correlation between background luminance and the De Boer rating scale was $r(6)=0.81$ when the lower left point was not included ($p<0.01$). The correlation was $r(7)=0.64$ when the lower left point was included ($p>0.05$).

The lower left point refers to the De Boer rating on section 6 which was the dark small winding road without roads markings. Obviously, subjects rated this section least acceptable in terms of the De Boer rating scale (see also Figure 16). A direct comparison of this section with the section with a comparable background luminances (section 6: average luminance of 0.083 cd/m$^2$ and a De Boer rating of 4.2; section 4: average luminance of 0.0903 and a De Boer rating of 6.3) indicates that the De Boer rating was significantly lower for section 6 than for section 4 [$F(1,21)=51.3$; $p<0.001$]. This result indicates that after driving a small winding rural road subjects gave significantly lower De Boer ratings (i.e., less acceptable) than after they drove a wide rural road even though the background luminances were about equal. In line with an earlier laboratory study (Sivak *et al.*, 1991) this result suggests the extent to which the glare source is rated as uncomfortable depends on the difficulty of the task.

Figure 18 presents the De Boer rating dependent on the background luminance for the three different glare source intensities. Again the data points of section 6 were taken out when calculating the regression line. As indicated above, the mean De Boer scale ratings for the three glare source intensities differed significantly from each other.

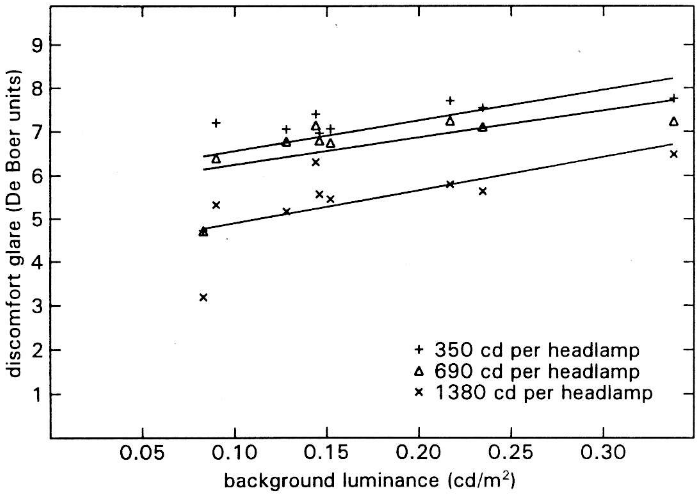


Figure 18 The De Boer rating as a function of the background luminance for the three glare source intensities (in cd per lamp).

The relationship between discomfort glare and background luminance has also been described by Schmidt-Clausen and Bindels (1974) for a laboratory task. Alferdinck and Varkevisser (1991) incorporated the relationship between discomfort glare and ambient luminance in their equation (see equation 7). Figure 19 gives these results. Figure 19 indicates that the effect of background illuminance on the discomfort rating according to the model of Alferdinck and Schmidt-Clausen and Bindels is very similar to the relationship as found in the present study (see Figure 18). Both for the model and for the observed data, over the whole range of background luminance the De Boer rating changes with about one step on the rating scale. Note however that there is a large discrepancy between the absolute values on the De Boer scale for the model prediction and the observed data. In the current experiment the De Boer ratings are about twice as high as those derived from Schmidt-Clausen and Bindels (1974). The only explanation for these large absolute differences in De Boer ratings can be that the task used by Schmidt-Clausen and Bindels was much more difficult than the actual driving task that was applied in the present experiment. In Schmidt-Clausen and Bindels (1974) subjects were required to detect a centrally presented test object with a luminance of about twice the threshold luminance. Obviously, while performing a detection task like this, a glare source causes much more discomfort than when performing an actual driving task as in the present experiment.

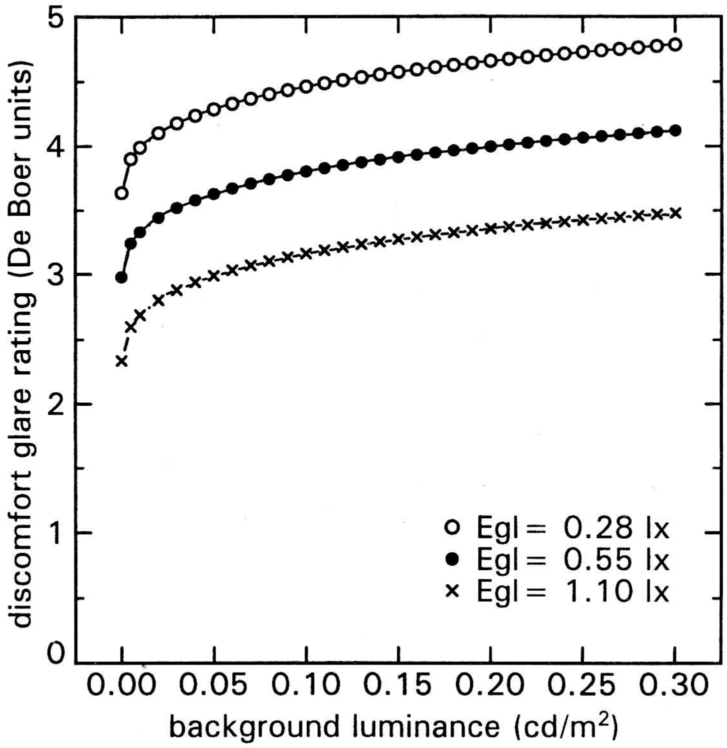


Figure 19 De Boer rating as a function of background luminance according to model predictions based on equation (7).

## 5 The BCD during the experiment

There was a main effect of section on the subjective adjustment (BCD) rating [$F(8,168)=2.76$; $p<0.01$]. As clear from Figure 20, during section 4 and 6 subjects considered a glare illuminance of about 0.43 lx as just between comfort and discomfort (BCD). Both sections do not have public lighting. Section 9 where subjects accept a glare illuminance of 1.16 lx is highway driving without public lighting.

US subjects accepted a higher illuminance level than Dutch subjects on some of the sections [interaction group × section: $F(8,112)=1.97$; $p=0.056$]. An additional Tukey-test indicated as clear from Figure 20 that US subjects tended to choose significant higher illuminance levels for highway driving than Dutch subjects. There were no reliable differences between the old and young subjects.

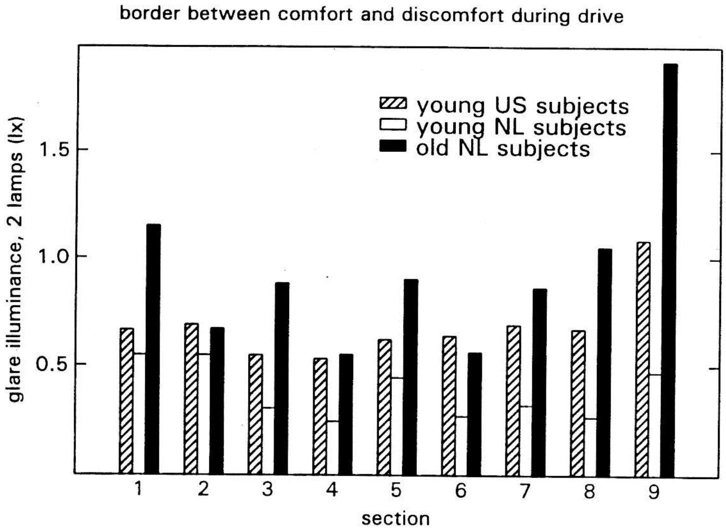


Figure 20 The border between comfort and discomfort in glare illuminance on the eye of the driver (in lx) for the different experimental sections.

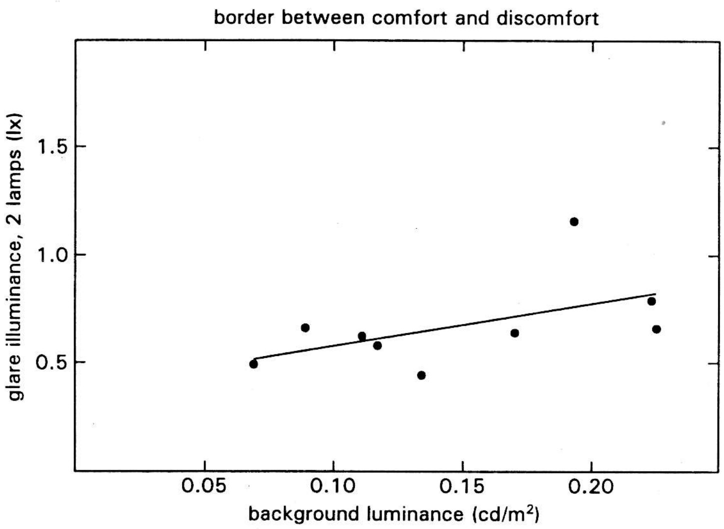


Figure 21 The border between comfort and discomfort in terms of glare illuminance (in lx) as a function of the background luminance.

The BCD adjusted light level was given at the beginning of each experimental session. Figure 21 gives the BCD score as a function of the background luminance as measured at the beginning of the various sections. As clear from Figure 21 there is not a strong relationship between background luminance and BCD score [$r(7)=0.54$; $p>0.05$]. The background luminance can only account for 29 percent of the variance in the BCD score. Since it is to be expected that there is a relationship between how much light a driver can accept and the background luminance (compare the De Boer rating and the willingness rating), the present analysis suggest that the procedure of adjusting the light source to a level just between comfort and discomfort is less adequate in determining the maximum acceptable the glare source illuminance.

*4.3.3 Behavioral measures*

For each experimental section the driving speed in the control condition and the background luminance level was plotted (see Figure 22). To ensure that the analyses on driving behavior (driving speed, steering wheel reversal and gas reversal) were concerned with free driving behavior (not determined by characteristics of the vehicle, curves, traffic lights, other traffic, standing still at intersections, etc), based on these plots, portions of each of the sections were selected for further analyses. Only those portions without acceleration and decelerations (e.g., constant speed) were selected. In addition, only portions within a section which had approximately the same low background luminance level were used in the analyses (see e.g., sections 4 and 5).

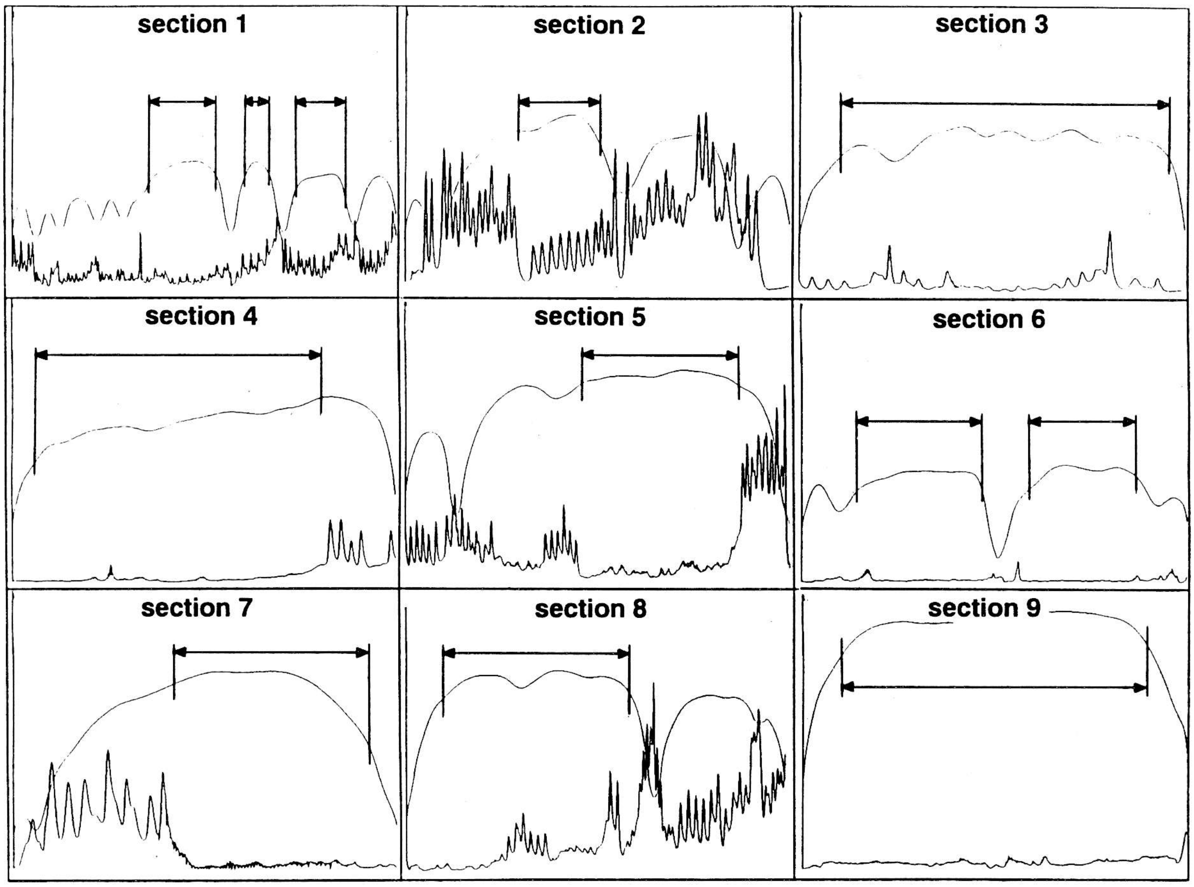


Figure 22 The mean driving speed (top line) in the control condition and the background luminance (bottom line) for each section. Those portions that are marked were selected for further analyses.

* This ensured that conclusions drawn from the analysis refer to sections with approximately the same background luminance. The approximate areas of the sections used in the analysis are marked in Figure 22. The top line represents the speed driven in the control condition, the lower

line represents the luminance level within a section. Note that the spikes in the lower line correspond to the individual light fixtures of the public lighting.

## 1 Driving speed

For each of the selected sections the mean driving speed per subject was determined. An ANOVA on mean driving speed with subject group, section, glare source intensity as factors showed main effects of subject group [$F(2,21)=3.96$; $p<0.05$], section [$F(8,168)=436$; $p<0.01$] and of glare source intensity [$F(3,63)=30.5$; $p<0.05$].

Figure 23 gives the driving speed for the different subject groups. Planned comparisons showed that US drivers drove significantly slower than Dutch drivers ($p<0.01$). There was a trend that also older Dutch drivers drove significantly slower than young Dutch drivers ($p=0.096$). An interaction of old/young with section ($p<0.05$) indicated that the older driver drove especially slow on some sections, i.e., on section 4 (dark wide road with target detection) and section 9 (highway driving).

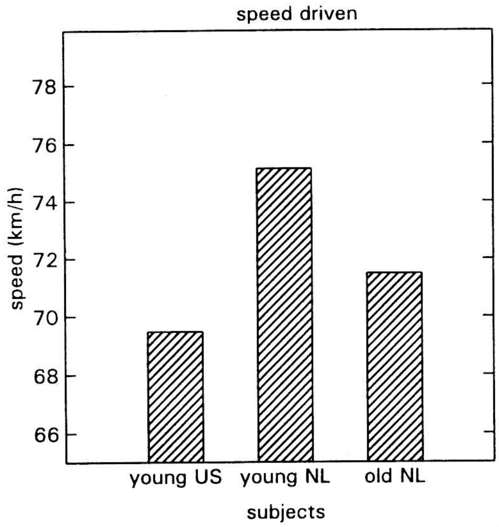


Figure 23 The driving speed for the different subject groups.

Figure 24 gives the effect of glare source intensity on driving speed. As clear from this figure, relatively to the control the glare source does reduce speed with about 2 km/h; yet there is no effect of the difference glare source intensities on the speed driven. This analysis suggests that, due to the light source, subjects adapt their behavior in a safe direction; yet, the actual glare illuminance does not modulate this behavior.

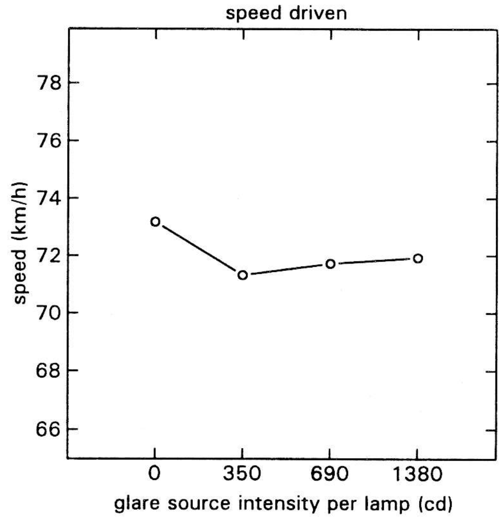


Figure 24 The driving speed as a function of glare source intensity.

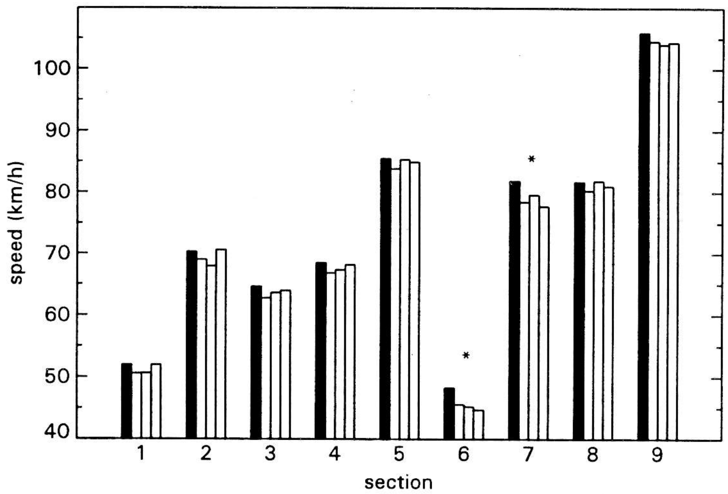


Figure 25 The driving speed for each of the different sections for each glare source intensity. The marked section represents the control condition; the other bars represent 350, 690, and 1380 cd from left to right.

Figure 25 gives the speed for each section for each of the glare source intensities. As clear from this figure in all cases the speed is slower when the glare source is on than when it is off (control condition). Planned comparisons showed that when analyzed separately, this effect reached statistical significance for sections 6 and 7 ($p<0.05$). Section 6 is a dark narrow winding road without road markings (mean driving speed of about 46 km/h); section 7 is a wide, somewhat winding road with clear road markings (mean driving speed of about 80 km/h). Note that the slowing down was not statistically significant for section 4, the section on which subjects performed the object detection task.

In an additional analysis, the mean speed collapsed over the three glare source intensities (350, 690 and 1380 cd) was calculated and compared to the control condition in which there was no light. The speed reduction relatively to the control was calculated. This measure was plotted against the average background luminance for the different portions for each of the sections (see Figure 26). The corresponding section numbers are indicated. The correlation between speed reduction and background luminance was $r(7) = -0.48$. Notice that sections 6 and 7 give relatively large speed reductions while sections 4 and 5 with the same luminance background give relatively small speed reductions. The speed reduction induced by the glare source obviously does not only dependent on the background luminance. If the driving task is relatively difficult (as driving the small winding road of sections 6 and 7) the glare source gives relatively large speed changes.

Figure 26 gives the relation between background luminance and speed reduction when sections 6 and 7 are excluded from the analysis. As clear from Figure 26, when the driving task difficulty is about the same (sections 1, 2, 3, 4, 5, 8, 9), independent of the background luminance, drivers choose a speed which is about 1 km/h slower than the control. When the driving task is relatively difficult drivers subjects choose speeds of about 3 km/h slower.

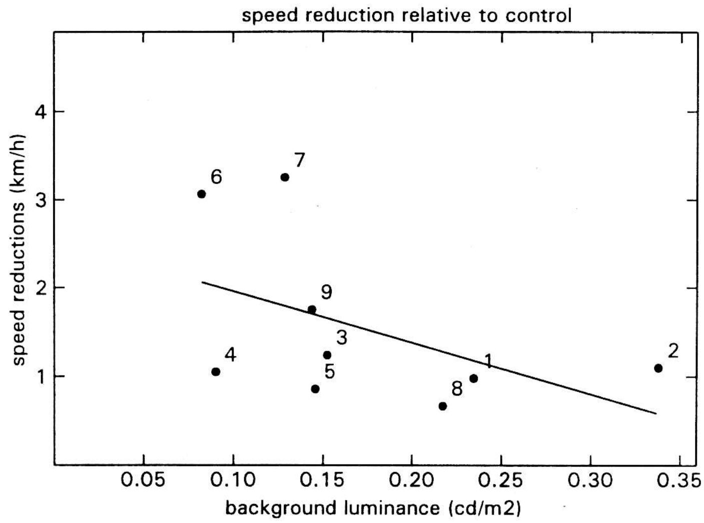


Figure 26 Speed reduction induced by glare source as a function of background luminance.

## 2 Steering wheel Rate Reversal

For each of the selected sections the mean Steering wheel Rate Reversal (SRR) per subject were determined. This measure was derived from steering wheel movements analyzed in terms of number of reversals per second (e.g., Verwey, 1993; Verwey & Veltman, 1995). A movement was defined as a change from a negative (clockwise movement) to a positive (counterclockwise) rotational velocity given that the positive rotational velocity exceeded 3.0 °/s.

There was only a main effect of section [$F(8,168) = 80.2$; $p < 0.01$]. As clear from Figure 27, the highest effort of steering was found during section 6 the narrow dark winding road.

Additional analysis showed that during section 7 the steering reversal rate became significant larger when a glare source was present then when it was absent (see Figure 27). This result indicates due to the glare source subjects made more steering wheel reversals. High values of SRR are indicative of high driving task demands (MacDonald & Hoffman, 1980; Verwey & Veltman, 1995). The glare source may have made the driving task more difficult (i.e., it is harder to see where the road is going) causing subjects to devote more attention to the steering subtask.

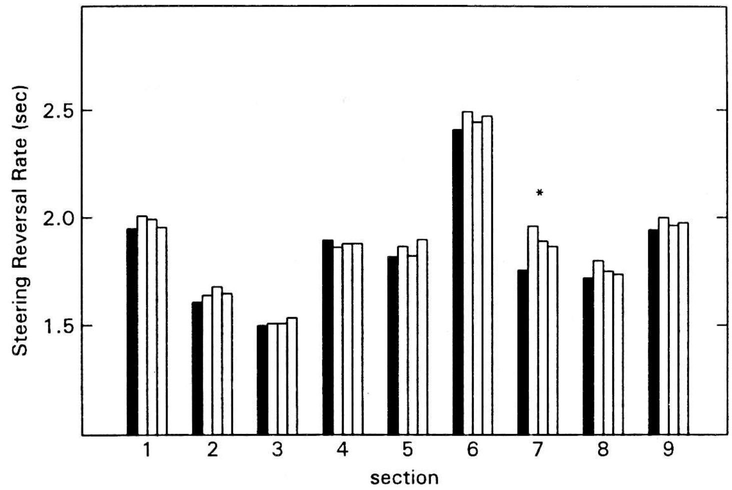


Figure 27 Steering wheel Rate Reversal Rate for the different sections for each of the glare conditions. The marked section represents the control condition; the other bars represent 350, 690, and 1380 cd from left to right.

## 3 Gas Pedal Reversals

For each of the selected sections the mean Gas Pedal Reversal per subject was determined. This measure is derived from gas pedal reversals exceeding a speed at a reversal of 5%/s. The percentage refers to the amplitude of the gas pedal (i.e., 100% is the total amplitude of the gas pedal).

There was only a main effect of section [$F(8,168)=43.2$; $p<0.01$]. As clear from Figure 28, most gas pedal reversals were made during section 6, the small and winding road. Least gas pedal reversal were made during the highway drive (section 9). Additional analysis showed no relation between this measure and the presence or absence of the glare source.

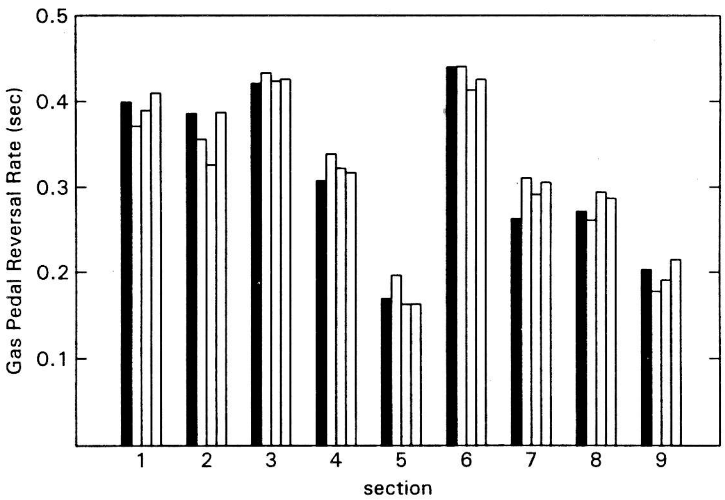


Figure 28 Gas Pedal Reversal for the different sections. The marked section represents the control condition; the other bars represent 350, 690, and 1380 cd from left to right.

## 4 Detection of wooden plates

### *1 Distance*

For those trials in which the driver detected the wooden plates, the detection distances (distance between the plate and car upon detection of the plate) were determined for plates erected along the right and left side of the road. There was a main effect of target erected left vs right side of the road on detection distance [$F(1,21)=109$; $p<0.001$]. Wooden plates erected along the right side were detected at 41.4 m. When presented on the left side, in the direction of the glare source, they were detected on average at a distance of 20.5 m. There was also a main effect of glare source [$F(3,63)=9.4$; $p<0.01$]. When no glare source was present on average subjects detected the wooden plate at 35.4 m. With a light source of 350 cd, 690, and 1380 cd these distance were 33.3, 27.7 and 27.5 m, respectively. Planned comparisons showed that there were no differences between the control condition and the 350 cd condition. Glare source intensities of 690 and 1380 cd gave significantly shorter detection distances than the control condition (all $p<0.05$). There is no significant difference between these latter two light sources. The results are given by Figure 29.

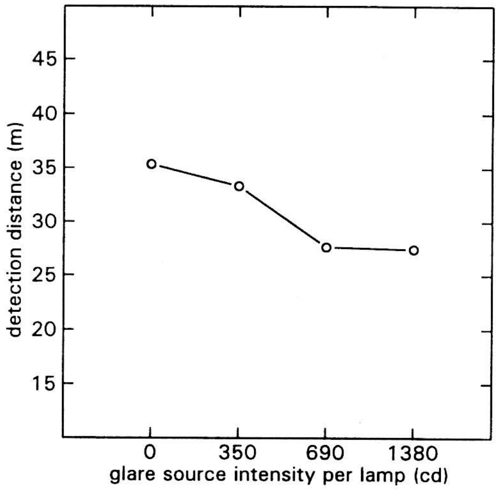


Figure 29 Detection distance as a function of glare source intensity.

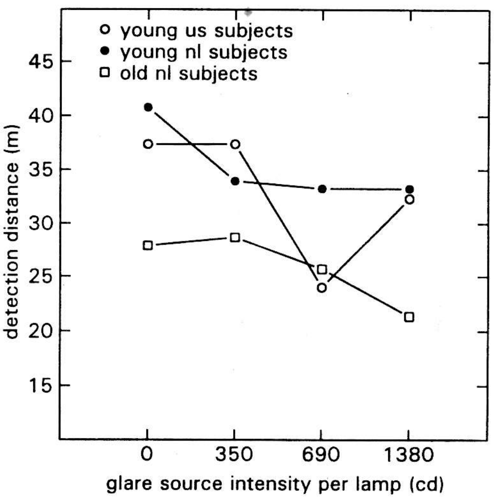


Figure 30 Detection distance as a function of glare source intensity for the different subject groups.

There was no difference in detection distance between the US and Dutch subjects. However, the detection distance for older drivers was significantly shorter than for young drivers [old drivers at 25.8 m vs young drivers at 34.2 m; $F(1,14)=4.00$; $p=0.063$]. Figure 30 presents the results.

The difference between the old and the young drivers was more pronounced when the target was located on the right than on the left side of the street [interaction left vs right × young vs old $F(1,14)=3.9$; $p=0.065$]. Figure 31 gives these results.

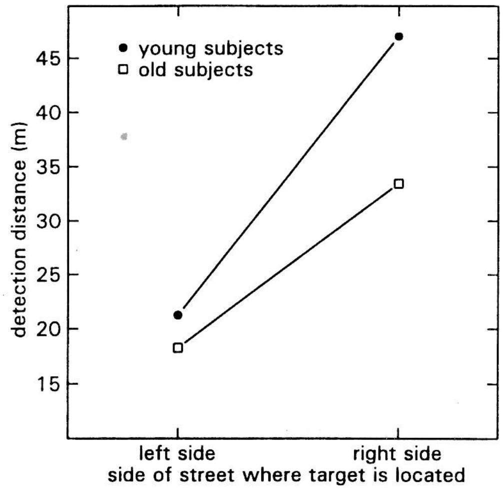


Figure 31 Detection distance for targets located on the left and right side of the road for old and young drivers.

## 2 *Missed targets*

Trials in which subjects did not detect a wooden plate were counted as misses. There was a main effect of target erected left/right on missed targets [$F(1,21)=202$; $p<0.001$]. When presented on the right side 3.5% of the targets were missed, when presented on the left side 22.5% were missed. There was also a main effect of glare source [$F(3,63)=2.8$; $p<0.05$]. With an increasing light source, the number of missed target increased. Additional planned comparisons showed that there were no differences in missed targets between the control condition and glare source intensity of 350 cd. At glare source intensities of 690 and 1380 cd there were significantly more targets missed than at control condition (all $p<0.05$). There were no differences between the 690 and 1380 cd in missed targets. Figure 32 gives the results.

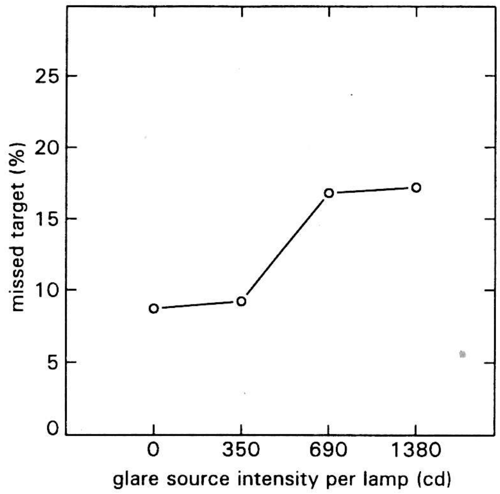


Figure 32 Percentage of missed target as a function of glare source intensity.

There was no effect of missed target between US and Dutch subjects. Older subjects suffered significantly more from the higher glare illuminance levels than did younger subjects [interaction old/young × glare source intensity: $F(3,42)=3.4$; $p<0.05$]. As shown by Figure 33 old subjects missed many targets at the higher glare levels (690 and 1380 cd).

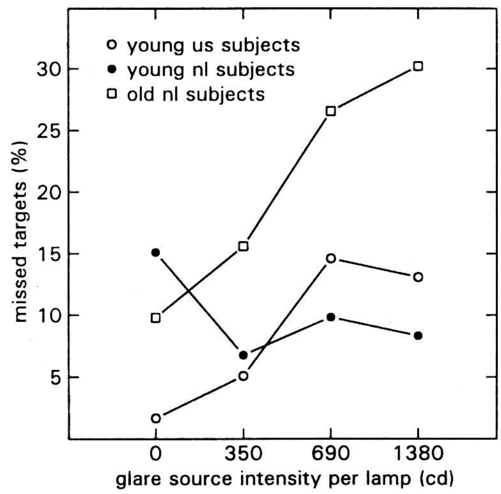


Figure 33 Percentage of targets missed as a function of glare source intensity for the different subject groups.

The difference in targets missed between old and young drivers was large when the targets were presented on the left side of the street (in the direction of the glare source) and basically absent when presented on the right side [interaction left/right × young/old $F(1,14)=2.1$; $p=0.073$]. As is clear from Figure 34, when located on the right side, both old and young drivers hardly ever missed a target.

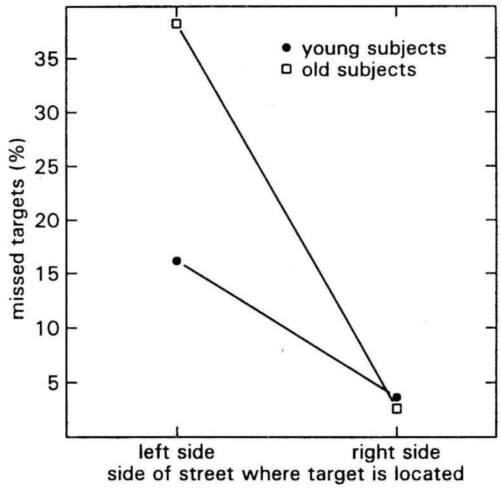


Figure 34 Percentage of targets missed for targets on the left and right side for old and young drivers.

## 4.4 Discussion

### *4.4.1 Subjective measures*

*De Boer rating before the experiment*: The De Boer rating before the experiment at the parking lot is unlike the predictions based on the models (see Figure 10). Overall, subjects rated the light sources as less annoying than what is predicted according by any of the models.

There is, however, an important difference between the way the De Boer ratings was assessed in the present experiment and the way it was assessed in previous laboratory studies on which the model predictions are based. In all lab studies subjects had to perform a task (e.g., a target detection task as in Schmidt-Clausen & Bindels or a tracking task as in Alferdinck & Varkevisser, 1991) while giving the De Boer rating while in the present study subjects gave their De Boer rating while fixating a dot straight ahead. As discussed earlier (see § 4.3.2.4) the difficulty of the task while giving the discomfort rating does play a crucial role and affects the absolute level of the De Boer rating (e.g., Sivak *et al.*, 1991). In the present study before the actual start of the experiment subjects gave their rating *without* an additional task. Obviously, in the absence of an additional task, subjects rate the glare illuminance as much less annoying than when performing a relatively difficult lab detection task.

There were no differences between the different subject groups. The finding that there is no difference between US and Dutch subjects indicates that previous findings of Sivak *et al.* (1989) which showed that Europeans judged the same level of glare as being more uncomfortable than US subjects, cannot be confirmed by the present study. In addition, although the older subjects had a higher straylight sensitivity than younger subjects they did not judge the light source as being more uncomfortable. This finding is in line with an early study of Alferdinck (1991, in press) who showed that older subjects did not complain more than younger subjects about the glare source although their straylight sensitivity was significantly higher than that for the young subjects. This finding suggest that aspects such as the extent that subjects feel they should complain about something does play a crucial role in the De Boer ratings. From a physiological point of view, due to the higher sensitivity to straylight, older subjects do experience more glare than younger subjects; yet, they do not rate the glare source as more annoying than younger subjects.

Although the current ratings are different from the model ratings based lab studies, the current rating for the glare illuminance of 1.1 lx, equivalent to US headlamps (rating of about 5.1) does compare to a rating as reported by Sivak *et al.* (1989). In this study, on a closed track subjects had to judge the glare source illuminance of a car with US headlamps while approaching this vehicle slowly. For a vehicle separation of 150 to 50 m subjects gave a rating of 5.6 which is slightly higher (less discomfort) than our rating.

*De Boer rating during the experiment:* Again, as the De Boer ratings before the experiment there were no differences in ratings between the different subjects groups. Note that there was a trend that older subjects rated the glare source as less annoying than younger subjects.

The De Boer ratings were lowest (4.2, between disturbing and just acceptable) after subjects drove the narrow, dark and winding road. The glare source was rated least problematic during section 2 which had the highest public lighting.

As expected, overall the De Boer rating depended on the glare illuminance; ratings were 7.0, 6.7, and 5.4 for glare illuminance of 0.28, 0.55 and 1.1 lx. When comparing these ratings to the model predictions (see Figure 10), again, even when subjects perform an actual driving task, the glare illuminance is rated as less annoying than what the models predict. Thus, according to the model 0.28 lx should give a rating of about 4.9 while in the present study the rating was 7.0. For 0.55 lx the model predicts a rating of 4.4 while an average rating of 6.7 was given. For 1.1 lx the model predicts 3.6 while an average rating of 5.4 was given. The mean de Boer rating per glare source illuminance averaged over subjects and sections is about 2 steps on the rating scale higher (e.g., less annoying) than what would be predicted by the models. Again, the difference in the absolute value on De Boer scale can be attribute to the difficulty of the driving task: the data suggest that the *overall* driving task as used in the present experiment is in fact easier than the tasks applied in the lab on which the model predictions are based.

There is evidence that task difficulty is the reason for the discrepancy between model predictions and ratings measured in this study. When comparing the De Boer ratings after driving section 6 (the most difficult section in the current experiment) with the model predictions, there are basically no differences between the model predictions and those measured in this study. For glare illuminance of 0.28, 0.55 and 1.1 lx subjects gave ratings of 4.8, 4.8 and 3.2, which is comparable to the model predictions.

The high correlation of 0.81 between the De Boer rating and the average background luminance (see Figure 17, the lower left point is left out) indicates that given a particular glare source the background light modulates the De Boer rating with about one step unit on the rating scale. From absolute darkness (luminance zero) to 0.35 cd/m$^2$ (high ambient light level) the De Boer rating scale would vary from 6.04 in darkness to 7.21 for the high background light level.

The finding that given a particular background light level and glare source the De Boer rating was significantly lower after driving a difficult stretch (De Boer rating scale: 4.2) than after driving an easy stretch (De Boer rating scale: 6.3) signifies again that task difficulty has an effect on the De Boer rating.

Overall, these findings indicate that the difficulty of performing an actual driving task plays a crucial role in the discomfort glare ratings. This result is comparable to that of Sivak *et al.* (1989) who showed for a laboratory gap detection task, that an increase in task difficulty also resulted in an increase in discomfort glare as measured by the De Boer rating scale.

*BCD rating before the experiment*: The adjustment of the light source at the TNO-parking indicated no difference between US and Dutch subjects. As for the De Boer ratings these data do not confirm Sivak *et al.* (1989) claims that European drivers judge the same level of glare as more uncomfortable than US drivers. Even though older drivers were more sensitive to straylight, they accepted a higher glare illuminance than the younger drivers. The glare illuminance the older drivers accepted was high (2.35 lx). Based on an earlier study (Alferdinck, 1991) such a glare illuminance corresponds to a De Boer rating of about 2.5 (i.e., a little more than disturbing). This result indicates that the BCD procedure of adjusting the light to an acceptable level may not be adequate: it is unlikely that the older driver does feel safe to drive around with a glare illuminance of 2.35 lx.

*BCD ratings during the experiment*: The BCD rating during the experiment ranged from 0.43 lx for section 4 and 6 which were both relatively dark to 1.16 lx for section 9 which was highway driving. The lower end of 0.43 lx corresponds to the maximum glare illuminance (0.550 lx) of the European standard. The 1.16 lx is somewhat more than the maximum glare illuminance according to the US standard (1.10 lx). US subjects did accept a significantly higher glare illuminance for highway driving than did Dutch subjects. The relative ease of highway driving may have led to the acceptance of a higher glare illuminance.

Similar to the De Boer rating one expects a relationship between how much glare illuminance a driver can accept and the immediate background light level. Since the correlation between the BCD rating and the background light level is statistically not reliable, it may be suggested that the BCD procedure is a less accurate measure to determine discomfort glare. Subjects may have had trouble in judging the output of the light source and make the inference of what is acceptable and what not.

*Willingness to look into the light source*: Again, as with all other subjective measures there was no difference in willingness to look into the light source between US and Dutch subjects. Older subjects were more willing to look into the light source than young subjects. Similar findings were found for the BCD score at the parking lot and a trend in this direction was found for the De Boer rating scale during the experiment.

The significant correlation between the willingness to look into the light source and the background light level indicates that this may be an adequate measure for discomfort glare. Since this measure was taken before driving a particular section it is likely that subjects gave their rating based on the immediate background light level and not—as with the De Boer rating—on the difficulty of the driving task. This might be the reason that section 4 (dark and winding road) does not show up as an outlier.

### *4.4.2 Behavioral measures*

*Driving speed*: The finding that US subjects drove significantly slower (about 5 km/h) than Dutch subjects suggests that US subjects who, as a requirement did not drive at all in Europe, might have felt somewhat insecure about driving. The finding that this effect was independent of the intensity of the glare source on the hood indicates that this feeling of insecurity had to do with driving in general and not with the conditions applied. The older drivers tended to be somewhat slower (about 3 km/h) than the young drivers especially on some of the sections.

Overall, the presence of a lit lighting rig on the hood reduced speed significantly with about 2 km/h. Important is the finding that there was no effect of the glare source intensity on the speed driven: drivers obviously slow down as soon as they experience some glare. Note that the lowest glare source illuminance of 0.28 lx is clearly within a range generally considered to cause only discomfort. Even such a relatively moderate glare source illuminance causes behavioral adaptation. It is important to realize that the glare source does cause a behavioral adaptation yet, this adaptation is into a safe direction. Drivers obviously slow down to counteract the effect of the glare source.

Although overall on all sections the presence of a lit lighting rig slowed down speed, separate analyses showed that for sections 6 and 7 alone this effect was most significant. Section 6 is characterized as a dark and winding road without road markings. Obviously, when the lighting rig was lit, subjects had more trouble in maneuvering the vehicle along this road. To compensate for these effects, subjects slowed down from about 48 km/h to 45 km/h. Section 7 is a somewhat curvy dark wide road with markings. Again, the glare source may have increased the uncertainty about the path giving rise to problems in lane keeping, causing a reduction in speed from about 82 km/h to 78 km/h.

It is important to note that subjects did not slow down on section 4 where they had to detect the wooden plates. This finding indicates that subjects did not slow down in order to compensate for their poor object detection performance. The result suggests that, unlike the lane keeping problems subjects encountered due to the glare source, subjects may not have realized that the glare source caused problems in detecting objects. Subjects were unable to realize how poor their performance was because the number and the location of the wooden plates varied from trial to trial.

Figure 26 which shows the relationship between speed reduction relative to the control as a function of background luminance indicates that the speed reduction does not depend on the background luminance. The difficulty of the driving task plays a crucial role: sections 6 and 7 give much larger speed reductions than sections 4 and 5 although the background light level is about the same for these sections. It may be assumed that for a driving task in which drivers are uncertain about the path of the vehicle (lane keeping), the presence of a glare source forces the driver to choose slower driving speeds.

*Steering wheel Reversal Rate*: During section 7 the SRR was larger when a glare source was present, indicating that the steering effort went up. According to MacDonald and Hoffman (1980) high value of SRR are indicative of high driving task demand associated with increased difficulty of the driving subtask. Usually this is mediated by a high level of effort. Although subjects reduced speed during section 7, the steering task still required a lot of attention. The finding that the SRR went up instead of down indicates that subjects coped with the more difficult task by increased the total effort (MacDonald & Hoffman, 1980). Overall, this analysis suggest that the presence of the glare source increased task demands, yet without exceeding it. Subjects may have devoted more attention to the steering subtask; yet without reducing attention to other subtasks. Overall, the results suggest that under the influence of the glare source drivers adapt their behavior to a level they feel safe either by decreasing speed and increasing effort. This latter results in an increased SRR.

*Gas Pedal Reversal*: As expected this measure was related to the section driven: highway driving gave a reversal about every 5 s while driving on a dark winding rural road gave a reversal about every 2 s. Gas pedal reversals proved not to be related to the presence or absence of the glare source.

*Detection of wooden plates:* With a glare illuminance of 0.55 lx (690 cd) and 1.1 lx (1380 cd) drivers detected the wooden plates at significantly shorter distances than when the glare source was off or when the illuminance was 0.28 lx (350 cd). Similar results were found for the number of missed targets: at glare illuminance of 0.55 and 1.1 lx subjects missed more targets than when the glare source was off or had an illuminance of 0.28 lx.

Together these results suggest that a glare illuminance of 0.28 lx or less on the eye of the driver has no harmful effects on the detection of objects along the road side. A glare illuminance of 0.55 lx (the maximum according to the European standard) or 1.1 lx (the maximum according to the US standard) however does reduce the ability to detect object along the road side. Note that both had a decremental effect, yet there was no reliable difference between a glare illuminance of 0.55 and 1.1 lx.

There were no differences between US and Dutch subjects both in terms of detection distance and number of missed targets. Older subjects however had both shorter detection distances and missed more targets than young drivers. The performance of the older driver was especially poor for objects on the left side of the road (in the direction of the glare source): about one out of three objects was not detected; if they were detected it was at a distance of about 17 meters.

### *4.4.3 Comparisons among the different measures*

#### *1 Subjective measures*

The correlation between the De Boer rating and the rating willingness to look into the light source was relatively high [$r(621)=0.54$]. This implies that 29.7% of the variance of the De Boer rating can be explained by the "willingness" score. It can be concluded that both measures basically assess the same underlying phenomenon, that is, the extent to which subjects rate the glare source as annoying. Figure 35 presents this correlation.

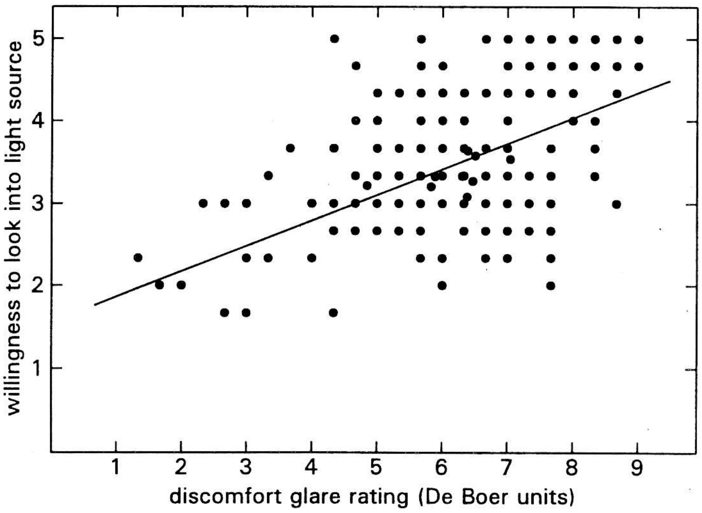


Figure 35 Relation between De Boer rating and the rating "willingness to look into the light source".

If the willingness to look into the light source can be considered as a behavioral measure representing looking and search strategies during driving (see § 4.1 for rationale) then one could claim this "behavioral" measure is related to the De Boer scale. A particular willingness rating would for example indicate the relative likelihood that drivers would not detect front turn signals because of the discomfort associated with looking at the glaring headlights. In this sense, the willingness rating may provide a "behavioral benchmark" for comparing the significance of the general categories of discomfort glare on the De Boer scale. Note however that the "willingness" is not a real objective behavioral measure (as for example speed or SAR) but is determined by means of a subjective rating scale.

The correlation between De Boer and BCD score and the correlation between the BCD and willingness score were both relatively low [$r(214)=0.34$, $r(214)=0.36$, respectively]. As the previous analysis on the BCD score and the background light level indicated, the present low correlations suggests that the BCD is a less reliable measure to determine the discomfort caused by a glare source.

## 2 *De Boer rating and behavioral measures*

*Driving speed*: The change in driving speed relative to the control condition was correlated with the De Boer ratings during the experiment. The correlation was relatively low [$r(617)=0.16$]. Only 2.7% of the variance in speed reduction could be explained by the score on the De Boer rating scale. When taking only those sections into account that did show a significant decrease in speed, the score on the De Boer rating scale explained 4.1% of the variance in speed change. Figure 36 gives the results of the latter analysis.

As clear from Figure 36, there is no relationship between the De Boer rating and the actual speed change. Although the De Boer ratings are well spread within the scale of 1 to 9, a lower De Boer rating (i.e., more discomfort) is certainly not associated with a larger speed change. One could argue that since the De Boer rating was given after driving a particular stretch, subjects did not consider the glare source as annoying *because* they adapted their behavior.

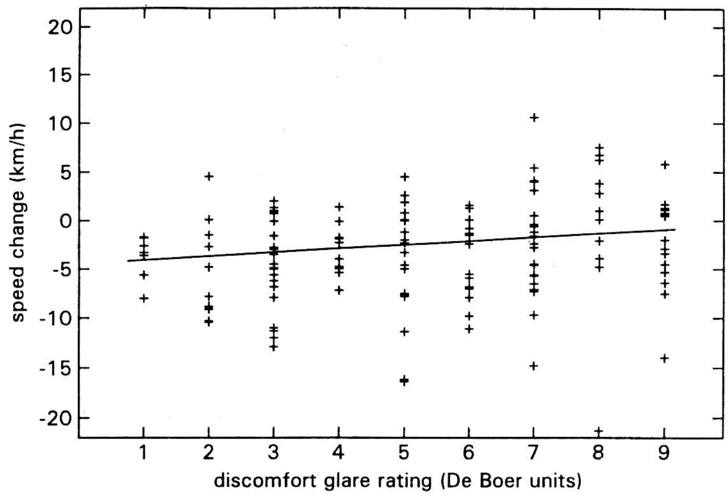


Figure 36 Correlation between the De Boer rating and the reduction in driving speed for sections 6 and 7.

In other words, subjects all gave a more a less constant De Boer rating because they were allowed to adapt their behavior in such a way (i.e., reduce speed) that they experienced the glare source as being more or less at a fixed level of annoyance. The feedback loop as displayed in the hypothetical model (see Figure 3) illustrates the relation between what drivers experience during driving (e.g., how difficult the task is) and how this may affect their rating of discomfort. If drivers adapt their behavior to counteract the negative effects of the glare source, the rating of discomfort may stay the same.

*Detection distance*: The reduction in detection distance relative to the control collapsed over objects located at the left and right side was correlated with the De Boer rating on section 4 where object detection took place. Again the relation was rather weak [$r(67)=0.28$], suggesting that 8% of the reduction in detection distance could be accounted for by the De Boer rating (see Figure 37).

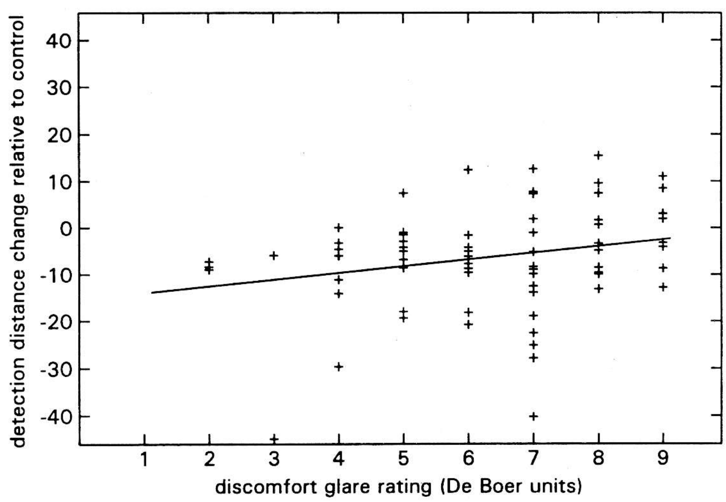


Figure 37 Correlation between the De Boer rating and the reduction in detection distance.

One would expect that a strong reduction in detection distance would result in a low De Boer rating, i.e., drivers who do see the objects rather late would claim that the glare source is annoying. As clear from Figure 37 the best fitting line indicates that to some extent subjects complain more (De Boer become lower) when the detection distance becomes smaller. Yet, this relation is not very strong.

The correlation between De Boer rating and percentage of missed targets was low [$r(67)=0.09$], possibly because there were some young subjects who did not miss any targets. For the older subjects however there was a relation between the De Boer and the percentage of missed targets [$r(22)=-0.48$; $p<0.05$]: the more targets missed the lower the De Boer rating.

Figure 38 gives the De Boer rating averaged over each of the different subject groups for the three levels of glare illuminance. Even though the previous correlation indicated some consistency between the number of missed targets and the De Boer rating *within* a group of subjects, Figure 38 indicates that between groups of subjects there is no consistency.

The older subjects missed very many targets, yet their De Boer rating is always higher (indicating less annoyance) than that of young subjects. This indicates that absolute levels of the De Boer rating are hard to compare: even though one group of subjects report having less annoying than another group of subjects the actual performance may be dramatically worse.

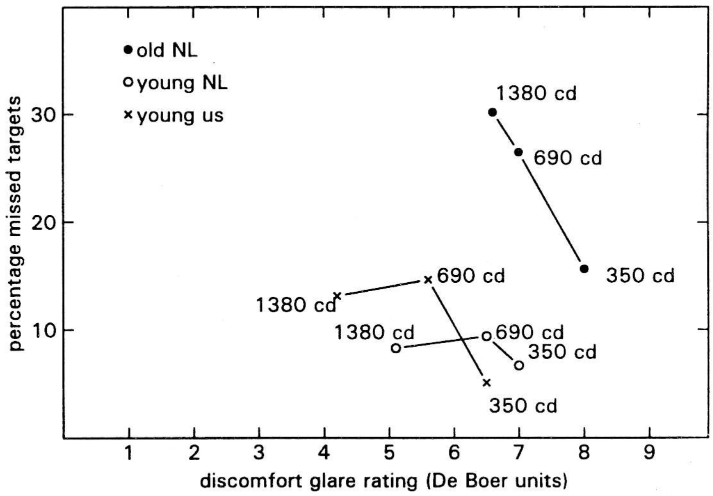


Figure 38 Relation between the De Boer rating and number of missed targets for the different subject groups.

# 5 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

## 5.1 General discussion

The present study shows that there is hardly a relationship between the feeling of discomfort as given by De Boer ratings and the actual driving behavior. Within a group of subjects the rating given on the De Boer scale does not predict how much a subject will adapt his behavior when exposed to a glare source. In addition, the absolute value of the De Boer rating between groups of subjects does not say anything about behavioral changes either. Also De Boer ratings have no predictive value with respect to object detection performance. If one considers the observed changes in driving performance (e.g. speed and object detection) as the true estimate of how much discomfort is experienced by the driver, then a person could claim that the De Boer scale does measure something other than discomfort. This claim is supported by the finding that a group of subjects like the elderly who on the basis of their glare sensitivity should experience more discomfort than any other subject group do not report so. In fact, there is a trend that the elderly report having less discomfort than the young drivers. However, an objective measure such as the performance on object detection task clearly showed that the older drivers did suffer from glare the most. It seems fair to claim that the De Boer rating scale only measures what it can measure, that is, how much annoyance the light source causes. It apparently has nothing to do with how drivers actually respond when they encounter such a light source during driving.

De Boer ratings as measured in the present study do however show the same relationship among the various variables influencing discomfort glare as reported in various laboratory studies. Besides the to be expected dependency on glare illuminance, the present study shows a large effect of task difficulty on the De Boer rating. As reported by Sivak *et al.* (1991) drivers experience more discomfort when performing a difficult driving task than when performing an easy one. In line with Schmidt-Clausen and Bindels (1974) the present study shows that the ambient luminance only has a small effect on the De Boer rating. In line with Alferdinck (in press), older subjects with a higher straylight sensitivity, do not report having more discomfort than young subjects. Contrary to Sivak *et al.* (1989) the present study did not show that Americans who have experience with higher level of glare illuminance report less discomfort glare than Dutch subjects who are used to lower levels of glare. A possible reason might be that for Americans driving for the first time on the public road in Europe, the task is relatively difficult. In the current study, the experience of being exposed to higher glare levels might be counteracted by the feelings of discomfort induced by the more difficult task. The finding that, overall, Americans drove significantly slower than European suggest that they experienced the task as more difficult. Note that Sivak *et al.* who showed the difference between European and American subjects performed his study on a closed track.

The difference in absolute values of the De Boer ratings of the present study and those predicted by the models stresses the role of task difficulty on discomfort glare ratings. The model predictions were comparable however to driving on section 6, a narrow and winding road without marking. This suggests that laboratory tasks as presently used to assess discomfort glare ratings are comparable to a relatively difficult driving task that involves a great deal of lane keeping and heading control.

It is fair to assume that the overall driving route as used in the present study (city, rural, highway driving) is a representative sample of the typical environment in which the driving task normally is performed. This suggests that discomfort glare studies in the laboratory usually use a task which is more difficulty than a representative driving task. The relatively high level of discomfort on the De Boer scale as predicted by the models based on laboratory data may therefore be too high (1.5 to 2 steps) and not valid for the actual practice of driving.

It is important to note the differences in the results of the rating scales between de Boer and "willingness to look into the light source" scales. The De Boer ratings were given after driving a particular section and showed a clear effect of task difficulty. The willingness ratings were given before driving the particular section and, as expected, did not show any effect of task difficulty.

This result highlights that the outcome of ratings scales depends very much of how and when the data are collected.

The observation that the ambient light level does not have much effect on the De Boer rating (about one step on the rating scale) is in line with the model predictions. Yet, it should be realized that even when the ambient light level does not have a direct effect on the de Boer rating, it may have an indirect one: because a high ambient light level makes the driving task easier (especially with respect to lane keeping), a high ambient light level may generate less discomfort *because* the driving task becomes easier. Therefore, given a particular task difficulty, the ambient light level does not have much effect. Yet, if the ambient light level makes the driving task easier then the discomfort experienced may go down. Note, however that other measures that makes lane keeping easier, such as retroreflective markings, may reduce discomfort glare experienced in a similar way.

With respect to driving, the low-beam headlamps fulfill two important functions: first, low-beam headlamps provide illumination for lane keeping; second, low-beam headlamp provide illumination to detect targets (e.g., pedestrians) and signs on both the sides of the road. These functions provided by the headlamps are also the functions that deteriorate under the influence of glare. The present study indicates that only when roads are winding and dark, and lane keeping becomes a problem, drivers slow down to compensate for the negative effects of the glare source. In case the road is wide and fairly predictable there is no behavioral adaptation since lane keeping is easy even when glare is present. This observation implies that in practice, drivers may or may not adapt their behavior under the influence of glare dependent on whether they expect that there are problems with respect to lane keeping. Thus, a road that is wide without many curves may suggest that slowing down under the influence of glare is not necessary. If such a road does, however, have a sharp curve, glare may cause the driver to leave the lane and possibly cause an accident.

The effect of glare on target detection performance on dark road stretches is large and even relatively low intensities of 690 cd per headlamp cause a severe performance decrement. It seems that this is a problem which cannot be solved by designing different beam patterns. Alferdinck and Padmos (1988) stated that "without permanent road lighting a pedestrian on the road is not sufficiently visible to a motorist, unless a pedestrian wears retroreflectors of sufficient quality" (p.16).

## 5.2 Conclusions

- The De Boer rating is determined by glare illuminance, task difficulty (at the maneuvering level) and to a lesser extent by the background luminance level.
- The De Boer rating is not sensitive to age differences: older drivers who were more sensitive to straylight did not report having more discomfort than young drivers.
- US drivers who were used to higher levels of glare than Europeans did not report less discomfort than European drivers.
- The De Boer rating is not related to changes in driving behavior caused by the glare source: high levels of discomfort are not associated with a large reduction in driving speed.
- The De Boer rating is not related to actual object detection performance during driving: the group of subjects that reported the least glare discomfort according to the De Boer rating scale showed the worst performance in terms of detection distance and missed targets.
- Another subjective rating scale measure such as a 5-point scale indicating "the willingness to look into the light source" correlates well with the De Boer ratings.

- The adjustment of the light source to a level that is between comfort and discomfort does not correlate well with the De Boer rating.

- Due to the glare source there is behavior adaptation into a safe direction: due to the glare source drivers choose a slower driving speed. The intensity of the glare source does modulate the change in speed, that is, the mere presence of a light source causes a reduction in speed.

- When the driving task is difficult in terms of maneuvering (i.e., dark winding roads) drivers choose a larger speed reduction than when driving is relatively easy. This is not related to the intensity of the glare source illuminance.

- Due to the glare source, on specific sections (e.g., highway driving, section with target detection) older drivers show larger speed reductions than young drivers.

- Due to the glare source, on dark road sections, drivers may invest more effort in the steering subtask as shown by an increase in steering wheel reversals.

- A glare illuminance of 0.55 and 1.1 lx (690 and 1380 cd per headlamp) causes a significant drop in object detection performance both in terms of distance and missed objects. There is no difference in performance between these glare levels.

- Older drivers show the worst object detection performance. At a glare source illuminance of 0.55 and 1.1 lx (690 and 1380 cd per headlamp) older subjects tend to miss about 28% of the objects.

## 5.3 Recommendations

- There is no relationship between the De Boer ratings and actual observed driving behavior (speed, SAR and detection distance) both within and between groups of subjects. When drivers report hardly any discomfort, their actual driving behavior might be affected dramatically. The De Boer rating may say something about the subjective annoyance a glare source may cause; yet, it cannot be used to predict the effects of discomfort glare on actual driving behavior. How drivers rate a particular glare illuminance level apparently has nothing to do with the way they respond to such a glare source during actual driving.

- The finding that subjects adapt their behavior into a safe direction by reducing speed and/or investing more effort independent of the actual glare illuminance (i.e., within the ranges measured, both US and European glare sources caused the same speed reduction) indicates that a glare illuminance of at least 1.1 lx (the maximum US level comparable to 1380 cd per headlamp) is acceptable as a maximum upper limit. Drivers do adapt their behavior although they are not capable of reporting this by subjective measures such as the De Boer ratings.

- Glare also has an effect on driving behavior for which drivers cannot or do not compensate. Both European and US glare illuminance levels (0.55 and 1.1 lx) cause dramatic drops in object detection performance (e.g. pedestrian detection) on dark roads especially among the older drivers. Thus, glare illuminance levels within the range that is generally agreed to only cause discomfort, in practice also cause a drop in object detection performance.

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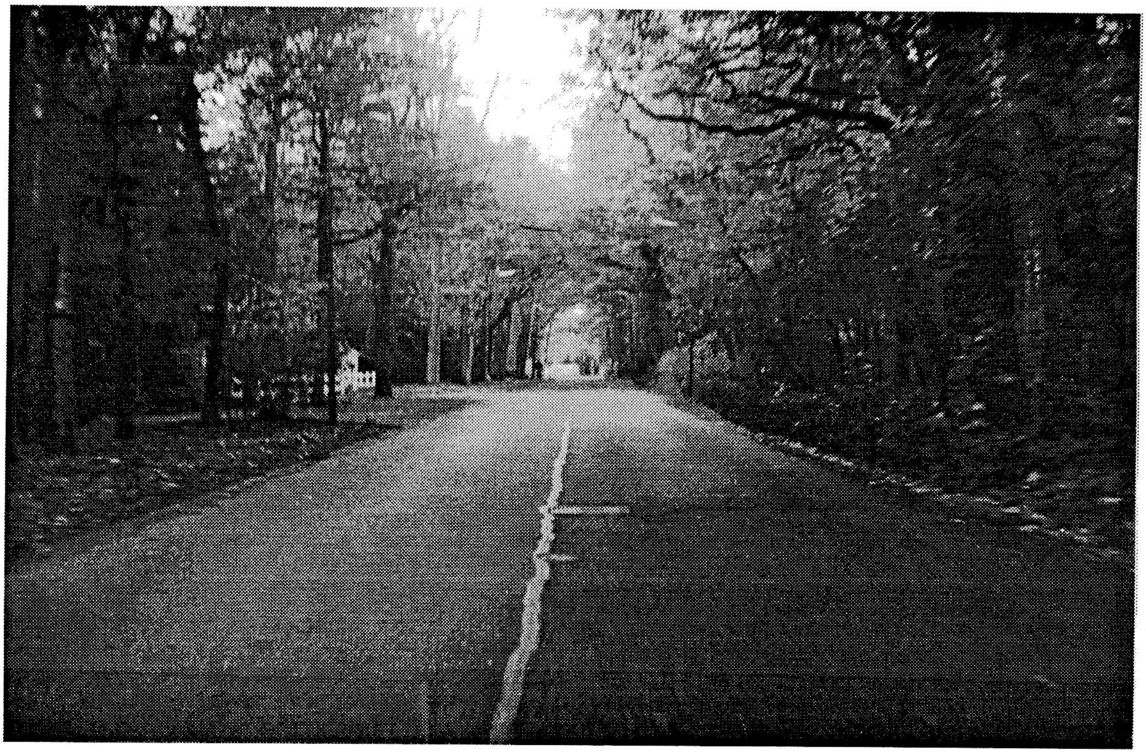
APPENDIX A: Description of experimental sections

Section 1:

| | |
|---|---|
| type: | residential, straight roads with 90-degree corners |
| environment: | houses |
| speed limit: | 50 km |
| number of lanes: | 2 |
| road width: | 6.10 m |
| lane width: | 3.05 m |
| road markings: | no |
| side of road: | pavement or rough shoulder |
| separate bike path: | no |
| intersections: | priority and non-priority |
| public lighting: | both sides |



Section 2:

| | |
|---|---|
| type: | outside built-up area, straight road |
| environment: | industrial area |
| speed limit: | 80 km |
| number of lanes: | 2 |
| road width: | 5.80 m |
| lane width: | 2.40 m |
| road markings: | center & side road markings |
| side of road: | rough shoulder |
| separate bike path: | on right side, two-way |
| intersections: | no |
| public lighting: | right side |

| | |
|---|---|
| Section 3: | |
| type: | outside built-up area, somewhat curvy |
| environment: | woody |
| speed limit: | 50 km |
| number of lanes: | 2 |
| road width: | 7.80 m |
| lane width: | 3.90 m |
| road markings: | center (straight) line & side road markings |
| side of road: | rough shoulder and some parking spaces |
| separate bike path: | no |
| intersections: | no |
| public lighting: | left side |

Section 4:

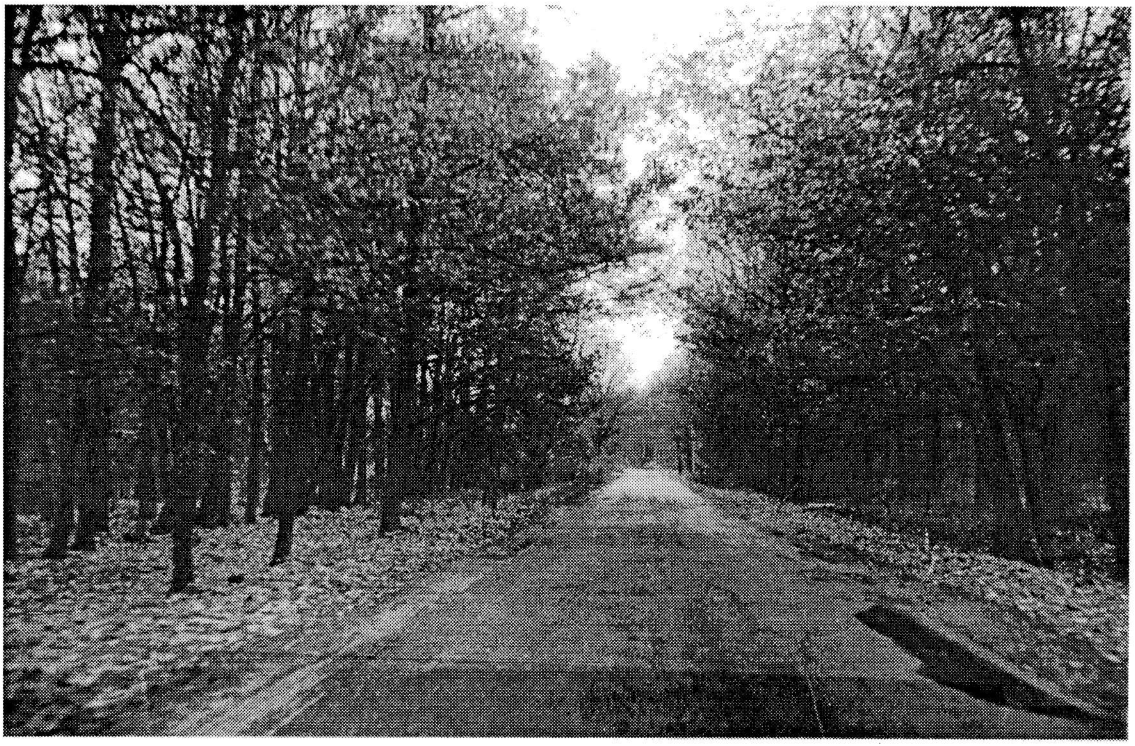
| | |
|---|---|
| type: | outside built-up area, straight road |
| environment: | woody |
| speed limit: | 80 km |
| number of lanes: | 2 |
| road width: | 7.80 m |
| lane width: | 3.90 m |
| road markings: | center & side road markings |
| side of road: | rough shoulder with reflector posts about 1 m from road side |
| separate bike path: | no |
| intersections: | no |
| public lighting: | no |

Section 5:

| | |
|---|---|
| type: | outside built-up area, somewhat curvy |
| environment: | woody, bushes |
| speed limit: | 80 km |
| number of lanes: | 2 |
| road width: | 7.00 m |
| lane width: | 3.50 m |
| road markings: | center & side road markings |
| side of road: | rough shoulder |
| separate bike path: | left side, two-way |
| intersections: | no |
| public lighting: | left side |

Section 6:

| | |
|---|---|
| type: | outside built-up area, very curvy road |
| environment: | woody |
| speed limit: | 50 km |
| number of lanes: | 1 |
| road width: | 4.10 m |
| lane width: | – |
| road markings: | no markings |
| side of road: | rough shoulder, trees close to road |
| separate bike path: | no |
| intersections: | no |
| public lighting: | no |

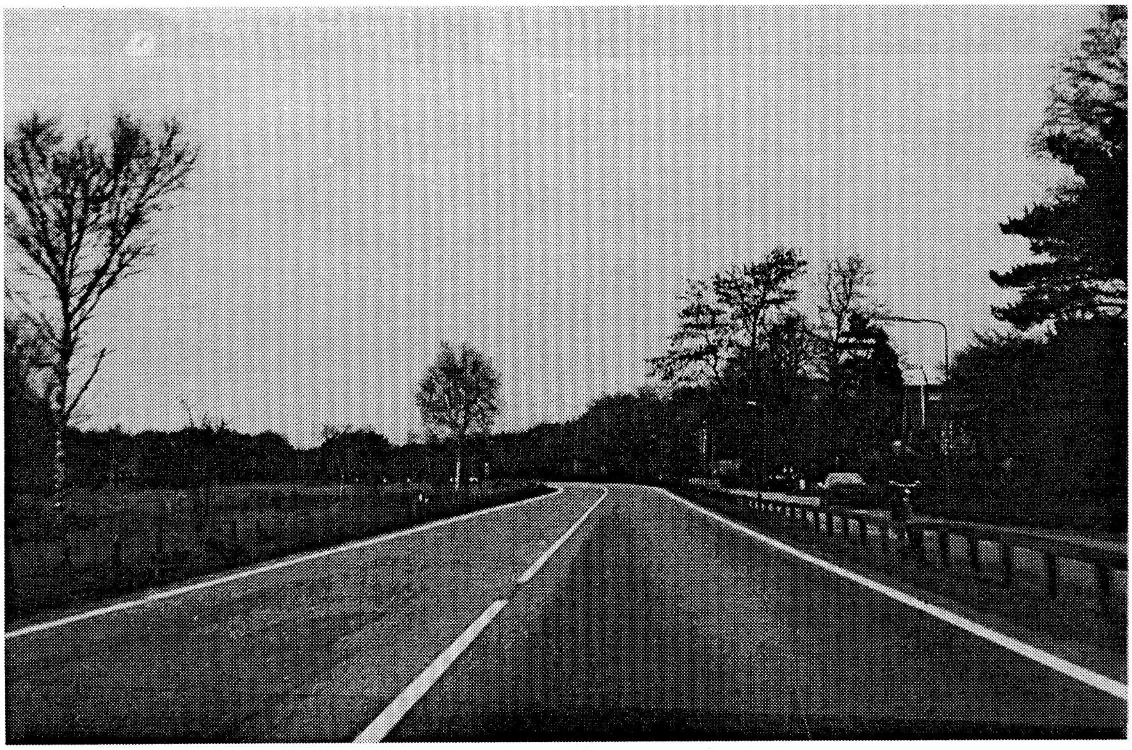


Section 7:

| | |
|---|---|
| type: | outside built-up area, somewhat curvy |
| environment: | woody, bushes |
| speed limit: | 80 km |
| number of lanes: | 2 |
| road width: | 7.00 m |
| lane width: | 3.50 m |
| road markings: | center & side road markings |
| side of road: | rough shoulder |
| separate bike path: | right side two-way |
| intersections: | no |
| public lighting: | no |

Section 8:

| | |
|---|---|
| type: | outside built-up area, somewhat curvy |
| environment: | woody, bushes |
| speed limit: | 80 km |
| number of lanes: | 2 |
| road width: | 7.00 m |
| lane width: | 3.50 m |
| road markings: | center & side road markings |
| side of road: | rough shoulder |
| separate bike path: | right side, two-way |
| intersections: | yes, with traffic lights |
| public lighting: | some lit and some unlit parts |



Section 9:

| | |
|---|---|
| type: | interstate |
| environment: | bushes |
| speed limit: | 120 km |
| number of lanes: | 4 |
| road width: | 7.00 m |
| lane width: | 3.50 m |
| road markings: | center & side road markings |
| side of road: | 3 m emergency lane on right side |
| separate bike path: | – |
| intersections: | no |
| public lighting: | no |

APPENDIX B: Instruction and informed consent

## EXPERIMENT DESCRIPTION

The experiment involves a field study in which you have to drive along a particular route in actual traffic at night in an instrumented car (Volvo 240 with stick shift). A lighting rig mounted on the hood of the car simulates headlamps of an oncoming car. This situation may be compared to a continuous exposure to glare that occurs during actual driving in heavy traffic. The route to be driven in actual traffic will incorporate some highway, rural and city roads.

We ask that you drive as you normally drive, without endangering yourself or any other traffic. At all times there is an certified driving instructor with you in the car. The instructor will sit in the front passenger seat where she can operate extra clutch and brake controls which are build into the experimental car. The instructor will monitor the driving of the subject. The instructor will tell you which route to take and occasionally may ask you to stop. Along the test track there is one specific area (the instructor will tell you) where you are asked to detect as accurately as possible the presence of gray plywood placards erected along the road, both on the left and right side. As soon as you detect a plywood placard, hit the horn, and your response is registered. *Do this as soon as you see the wooden placard.*

Before the experiment begins we will do some testing in the lab and in the car; basically determining the sensitivity of your eyes to light. Before each drive, subjects are asked whether they feel safe driving with the lighting rig on. At all times you as a driver have access to an emergency switch (red button on right side on the dashboard) to shut off the lighting rig.

After each ride you will have a break of about 30 minutes before your next ride will begin. Please use this time to relax.

If you have any questions ask them now.

Please read carefully the informed consent and sign it.

INFORMED CONSENT FORM
GLARE STUDY

I ........................ agree to participate in the TNO Human Factors Research Institute study on discomfort glare.

I understand that:

1. The purpose of this experiment is to investigate the effects of discomfort glare on driving behavior.

2. As a test driver, I will drive an instrumented car which is equipped with a lighting rig on major streets and expressways around Soesterberg at night.
   a. There will be four runs of the same route, each time using a different light output of the lighting rig.
   b. During each run there will be a short stretch where I will be asked to detect plywood placards standing along the test track.

3. A driving instructor and experimenter will be present with me at all times. The driving instructor will familiarize me with the test vehicle and lighting rig. At all times the driving instructor is officially the driver of the car. She will solely monitor the safety of my driving.

4. The driving instructor will provide me with specific instructions as to where I will be driving, operate measurement equipment in the test vehicle, and ensure that no inadvertent safety risks are taken.

5. At no time in this study I will be asked to perform any unsafe driving actions.

6. I agree to obey all traffic laws while driving the test vehicle.

7. I must possess a valid, unrestricted driver's license.

8. I must have a minimum of two years driving experience.

9. I must not be under the influence of alcohol or drugs, or any other substances which may impair my ability to drive, and I have refrained from the use of such items for a period of at least 12 hours.

10. While driving in this study, I will be subject to all risks that are normally present while driving a passenger car. The lighting rig placed on the front bumper of the test vehicle simulates glare as experienced during normal driving. I realize that driving with a glare source may make driving more difficult as sometimes experienced during night time driving.

11. In the unlikely event that an accident occurred; myself, the driving instructor, the experimenter, the test vehicle as well as any other persons or property involved are covered under an insurance policy held by TNO.

12. The result of this study will help in the development for safety standards for low-beam headlamp intensities.

13. I will be paid DFL 150,–. I understand that participation will take approximately six hours.

14. TNO is gathering information on discomfort glare, and not testing me. My name will not be released to anyone who is not working on the project. My name will not appear in any report or papers.

15. The experimenter, an employee of TNO Human Factors Research Institute will answer any questions that I may have about this study. The experimenter in charge of testing is:

Jan Theeuwes, Ph.D.
TNO Human Factors Research Institute
Kampweg 5
3769 ZG Soesterberg
Phone: 03463-56449

16. Participation in this study is voluntary. I understand I may withdraw from this study at any time, and for any reason, without penalty. Should I withdraw, I will be paid DFL 150,– regardless of reason.

I...................., HAVE READ AND I UNDERSTAND THE TERMS OF THIS AGREEMENT. I VOLUNTARILY CONSENT TO PARTICIPATE IN THIS STUDY.

| | |
|---|---|
| Name (print) | Signature |
| Street | Date |
| City | |
| Phone number | |