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DISCOMFORT GLARE FROM SMALL, HIGH LUMINANCE LIGHT SOURCES IN OUTDOOR NIGHTTIME ENVIRONMENTS

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by

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The overarching goal of this research was to examine humans' subjective and physiological responses to small, high luminance light sources in outdoor nighttime environments. Currently, discomfort glare is rarely calculated in lighting practice (Remaking Cities Institute (RCI) 2011), partly, because it is not known which metric predicts glare most accurately in the given application.

This dissertation describes a parametric experiment evaluating the effects of three glare source luminances (20,000; 205,000; 750,000 cd/m^2), two source positions (0°, 10°), two source sizes (10^{-5}, 10^{-4} sr), and three background luminances (0.03; 0.3; 1 cd/m^2) on the subjective measure of perceived glare (a seven-point rating scale) and two objective measures (relative pupil size (RPS) and electromyographic (EMG) recordings of the muscles around the eyes). Subjective responses and predictions by four metrics (the outdoor sports and area lighting metric (CIE 112-1994), the motor vehicle lighting metric (Schmidt-Clausen and Bindels 1974), a combination of two metrics by Bullough et al. (2008, 2011), and the Unified Glare Rating (UGR) small source extension (CIE 146, 147-2002)) were correlated to determine which metric predicts discomfort glare best in the tested ranges. Fifty-six participants were tested at Musco Sports Lighting in an apparatus constructed specifically for this experiment and fully controlled through custom software.

Repeated-measures Analysis of Variance was applied to subjective and RPS data; one of the results showed that when background luminance decreases, the RPS increases ($F = 390.94$, $df = 2$, $p < 0.0001$). The EMG data were not analyzed due to problems with data acquisition that resulted in partial data incompleteness, however, insights gained are discussed. The correlation analysis showed that the UGR small source extension correlated best with subjective responses ($r = 0.879$, $p < 0.0001$).

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CHAPTER 1 - INTRODUCTION

A problem well stated is a problem half solved.
-Charles Kettering

Glare is a condition of vision in which there is a feeling of discomfort and/or a reduction in visual performance. It occurs when the luminance or luminance ratios are too high. Two well-known types of glare have been distinguished in the literature: disability glare and discomfort glare. Disability glare reduces visibility due to scattered light in the eye, whereas discomfort glare causes “a sensation of annoyance or pain caused by high luminances in the field of view” (DiLaura et al. 2011). The latter type of glare causes a feeling of discomfort without necessarily impairing vision. Both types of glare have been extensively studied in the literature. However, while disability glare is well understood, much less is known about discomfort glare (Boyce 2014). Therefore, discomfort glare is the focus of this research.

The subject of glare has concerned researchers since the early years of the twentieth century (Poulton 1991), but even today, the causal mechanism of discomfort glare is not well understood (Boyce 2014). However, the four factors that contribute to the perception of discomfort glare produced by an individual light source are well known (DiLaura et al. 2011): (1) the luminance of the light source; (2) the position of the light source in relation to the point of fixation; (3) the visual size of the light source; and (4) the luminance of the background. Although these are widely accepted as factors affecting discomfort glare, existing metrics differ in parameters (e.g. Bullough’s et al. metric uses only illuminances (2008)).

A reliable method for quantifying discomfort glare is necessary for predicting and minimizing glare, comparing lighting installations, and ensuring comfortable visual environments. Without a metric that accurately predicts discomfort glare for a given application, it is hard to improve lit environments (Eble-Hankins and Waters 2004). It is especially challenging to minimize glare in outdoor nighttime environments, because these environments are characterized by low background luminances, high contrasts between lit and unlit surfaces, and small light sources such as light emitting diodes (LEDs) in the field of view. The challenges that exist when one assesses discomfort glare are the following: (1) LEDs that are only now becoming popular in outdoor installations have high luminance with the potential to cause more glare than conventional systems; (2) the predictive utility of existing discomfort glare formulae for small sources in outdoor nighttime environments is questionable due to metrics' limitations; and (3) most existing formulae are based on subjective measures. Therefore, high variability in subjective discomfort glare judgements may decrease the accuracy of predictions. Each of these issues is discussed in more detail in the following paragraphs.

First, discomfort glare has been an issue in lighting for a long time, but it becomes even more apparent with the popularity of LEDs. Even though LEDs are not new sources, they are only recently finding widespread use in outdoor lighting applications such as sports arenas, roadways, parking lots, etc. These sources allow more design freedom with respect to luminance distributions due to their small size and high luminance. At the same time, this market transformation of using LEDs in outdoor environments introduces challenges for both researchers and designers, because LED luminaires have a sharp intensity cut-off and high-contrast luminance patterns. A single LED chip within a luminaire can produce luminances of approximately $19x10^6$ cd/m^2 (Tyukhova and Waters 2014). These very high luminances increase the probability of causing glare. Yet, according to the LED web report (Remaking Cities Institute (RCI) 2011), the visual quality of LED lighting is rarely taken into account in street lighting projects, where emphasis is placed almost entirely on energy savings. The substantial glare that can be caused by LEDs is not typically included as a measurable criterion in the evaluation process of lighting installations (RCI 2011). As a result, glare persists as an issue in outdoor environments (RCI 2011).

Second, despite decades of glare research, the predictive utility of existing metrics for small, high luminance glare sources in outdoor nighttime environments is questionable due to their limitations. The limitations include the following: infinitely large glare predictions when looking directly at the glare source (CIE 112-1994 and Schmidt-Clausen and Bindels (1974) metrics), calculation of glare through illuminances and glare source luminance only (Bullough et al. (2008, 2011)), lack of validation of metrics through independent studies (the Unified Glare Rating (UGR) metric of the International Commission on Illumination (CIE 146,147-2002)), and limited applicability and anomalous results (CIE 31-1976, CIE 115-2010).

Third, the causal mechanism of discomfort glare is not well understood, and most of the previous research was done with subjective measures only. However, oftentimes responses to discomfort glare include multiple reactions such as blinking, frowning, changes in pupil size, apparent changes in facial muscles, and even lacrimation (Hopkinson 1956, Lin et al. 2015). Recently, a growing number of researchers started including objective measures in their analysis (Berman et al. 1994, Lin et al. 2014, Lin et al. 2015). Researchers found correlations between subjective responses and objective measures such as electromyographic (EMG) readings of the muscles around the eyes (Berman et al. 1994), relative pupil size (RPS) data, and eye movement data (Lin et al. 2014, Lin et al. 2015). Since subjective responses are known to have high variability (Bennet 1977b), it is highly desirable to validate results through an objective measure of discomfort glare that may offer the potential for higher predictive reliability.

Currently, discomfort glare from small, high luminance sources in outdoor nighttime environments is rarely calculated in lighting practice. The first steps in the direction of facilitating discomfort glare calculations is to address the three issues mentioned above. Therefore, the experimenter believes that further research is required to examine the effects of luminance of the glare source, its solid angle, its position, and background luminance on humans' perceptions of discomfort glare from small, high luminance light sources such as LEDs. The ranges of these four variables can be based on previous studies that examined small sources and low luminance backgrounds (e.g. Bennett 1977b, Benz 1966, Putnam and Faucett 1951, Putnam and Gillmore 1957) and on field measurements.

The experimenter is also convinced that to encourage the use of discomfort glare metric, it is essential to determine which existing metric predicts discomfort glare best when compared to human subjects' assessments in the given application. With the availability of multiple metrics, the choice of metric is not obvious for this outdoor application. For this reason, a thorough comparison of subjective responses to glare predictions by existing metrics in the ranges of outdoor nighttime conditions was performed. Suitable metrics that were correlated with human subjects' assessments include the following: the outdoor sports and area lighting metric (CIE 112-1994, in the remainder of this dissertation also referred to as metric 1), the motor vehicle lighting metric by Schmidt-Clausen and Bindels (1974, metric 2), and the combination of two metrics by Bullough and colleagues (2008, 2011, metric 3). Another discomfort glare metric specifically applicable to small sources is the UGR small source extension (CIE 146,147-2002, metric 4). Though the latter is designed for interior lighting applications, it also was included in this work because of its applicability to small sources. The road lighting formula (CIE 31-1976) was not examined in this research, since it was developed for very limited conditions (e.g. number of luminaires has to be in the range of 20 to 100 per km) and according to the CIE (115-

2010) "no fully satisfactory method has yet been devised for quantifying discomfort glare to drivers….the Glare control Mark (CIE 31-1976) was used but resulted in anomalies".

To potentially increase the reliability of the collected data, the experimenter believes it is necessary to include physiological measures in the experiment in addition to subjective ratings of glare. Therefore, pupil diameter measurements and EMG readings that measure electrical activity of muscles around the eyes in response to glare were recorded in this study. Moreover, simultaneously assessing several reactions to discomfort glare might give a deeper understanding of how humans respond to visual stimuli that cause glare.

In summary, the overarching goal of this research was to examine how humans respond to discomfort glare from small, high luminance light sources, particularly from LEDs, in outdoor nighttime environments. Additionally, this study aimed at determining which of the metrics mentioned above predicts discomfort glare most accurately when compared to human subjects' responses, and at validating existing discomfort glare metrics in the ranges of the tested conditions. Finally, RPS and EMG readings were recorded to potentially increase the reliability of the data and to simultaneously study discomfort glare from different perspectives.

To accomplish these goals, a parametric experiment was conducted that evaluated the effects of three glare source luminances (20,000; 205,000; 750,000 cd/m^2), two positions (0°, 10°), two sizes (10^{-5}, 10^{-4} sr), and three background luminances (0.03; 0.3; 1 cd/m^2) on the subjective judgements of perceived glare (a seven-point rating scale). Additionally two physiological measures of visual function (RPS and EMG recordings of the muscles around the eyes) were recorded. A correlation analysis between subjective responses to discomfort glare and predictions by four applicable metrics (metrics 1, 2, 3, and 4) was completed.

Fifty-six subjects participated in this study at Musco Sports Lighting in Oskaloosa, IA using an apparatus constructed specifically for this experiment, which was fully controlled through custom software. Subjects reported their judgements of discomfort glare on a rating scale, which were recorded together with EMG data and eye tracking (pupil) data. Subjects were sitting in a custom-made dark sphere and were exposed to glare sources without any additional task. Data from only forty-seven subjects were included in the analysis, due to the low quality of the excluded subjects' data.

Two analysis techniques were applied to the recorded data: a repeated-measures Analysis of Variance (ANOVA) applied to both subjective and pupil data, and a correlation analysis between subjective data and predictions by each of the four metrics used in this study. The results showed that higher discomfort glare is caused by an increase in the luminance of the glare source as well as an increase in its solid angle. Similarly, a decrease in the angle between the fixation point and the glare source and a decrease of the background luminance cause higher perceived discomfort glare. The correlation analysis showed that the UGR small source extension correlated best with the subjective responses compared to the other three metrics ($r = 0.879$, $p < 0.0001$) in the tested ranges – even though it was not specifically designed for use in outdoor environments. The pupil data analysis in this study suggests that RPS is correlated with discomfort glare to some extent ($r = 0.659$, $p < 0.001$), meaning that, on average, when subjects perceive more discomfort glare, their pupils constrict more compared to the less uncomfortable initial condition. The EMG data were not analyzed due to problems with data acquisition that resulted in partial incompleteness (e.g. there were randomly missing values in the recorded data). The repeated-measures ANOVA on pupil data showed that all four tested variables were significant predictors of RPS. In particular, the analysis showed that the background luminance has a significant effect on the RPS, such that when background luminance decreases, the RPS increases ($F = 390.94$, $df = 2$, $p < 0.0001$). The section below provides an overview of how this dissertation is structured.

1.1 Dissertation Outline

This dissertation consists of four additional chapters.

Chapter 2 reviews the literature on discomfort glare from small, high luminance sources in outdoor nighttime environments, existing metrics, measurement techniques, and provides a detailed discussion of the problems and needs.

Chapter 3 discusses the methodology for the discomfort glare experiment used in this study. It describes the methods, variables and levels selection, the apparatus and the controls software (both created specifically for this research), the measurement equipment, subjects, and a detailed description of the procedure.

Chapter 4 describes the three bodies of data that were collected and how each dataset was analyzed.

Chapter 5 discusses the results of the experiments and how they can be interpreted in a larger framework. It also outlines directions of future research topics.

The appendices include additional information critical to this document.

CHAPTER 2 – LITERATURE REVIEW

If practice and prediction conflict, then prediction has to be modified.
- Paul and Einhorn 1999

This literature review consists of several major parts. First, both types of glare - discomfort and disability - are described. Then, small, high luminance sources in outdoor nighttime environments, such as LEDs, are briefly discussed. Next, existing metrics related to outdoor nighttime environments and/or to small sources are outlined. In addition, subjective and objective (physiological) measures of discomfort glare are described. Finally, research gaps are summarized.

2.1 Glare

Discomfort glare is "a sensation of annoyance or pain caused by high luminances in the field of view" (DiLaura et al. 2011). This type of glare causes a feeling of discomfort without necessarily impairing vision. The causal mechanism of discomfort glare is not well understood. However, the four factors that contribute to the perception of discomfort glare produced by an individual light source are well known: (1) the luminance of the light source; (2) the position of the source in the field of view; (3) the size of the glare source; (4) and the luminance of the background.

The common form of a discomfort glare formula for a single glare source is (Boyce 2014):

$$G = \frac{L_s^a \cdot \omega_S^b}{L_b^c \cdot p^d} \qquad \textbf{(2-1)}$$

Where

G is a quantity that expresses the subjective sensation on a semantic/numerical scale;

L_s is the luminance of the glare source, in cd/m^2;

ω_S is the solid angle subtended at the eye by the glare source, in sr;

L_b is the luminance of the background, in cd/m^2;

p is the deviation of the glare source from the line of sight;

a, b, c, d are weighting exponents that differ between the discomfort glare prediction systems.

Brighter and larger light sources increase the probability of discomfort glare. Brighter background luminance reduces the experience of glare as does locating the light sources farther away from an observer's line of sight.

Besides the four factors mentioned above, additional factors are known to influence the perception of discomfort glare such as the number of light sources in the field of view (Bennett 1979a, 1979b), immediate surround luminance (Hopkinson 1957), and the spectral characteristics of the luminous surround (Sweater-Hickcox et al. 2013). In addition, age and demographics (Bennett 1972, 1977a), mood of the observers, and previous experience of the participants (Boyce 2014) were shown to impact the perception of discomfort glare. Discomfort glare has a cumulative effect; it can build up when people are exposed to high luminance sources for long periods of time (CIE 55-1983). It is more troublesome at the end of the day, or late in a week (Poulton 1991). Also, discomfort glare raises one's level of irritability, and lowers the level of tolerance to distractions.

In the book "Human Factors in Lighting", Boyce discusses the importance of the context in which glare is assessed (2014). Glare is task dependent, meaning that the ratings depend on whether the participant is reading, writing, etc. In a daylighting study, for example, it was shown that discomfort glare is more easily tolerated if the observer finds the view interesting (Shin et al. 2012). What makes this issue more complex is that in some lighting installations, instead of creating adverse feelings, "sparkle" causes visual interest and stimulates the viewer (Akashi et al. 2006).

Disability glare or physiological glare, the second well-known type, reduces visibility due to light scattered in the eyes, which produces a luminous veil across the retinal image of an object and/or changes the local state of adaptation (Boyce 1981). Typically, if there is disability glare there is discomfort glare. However, there might be situations in which disability glare is present without discomfort glare, for example, when photographs are displayed on a wall adjacent to a window (DiLaura et al. 2011).

Disability glare is little affected by the length of time it is experienced (CIE 55-1983) and is typically described by equivalent veiling luminance resulting from stray light in the eyes, which is superimposed on the vertical image, thereby lowering the contrast. The equivalent luminance is defined by the following basic formula (CIE 112-1994):

$$L_{veil} = 10 \sum_{i=1}^{n} \frac{E_{glare,i}}{\theta_i^2} \tag{2-2}$$

Where

L_{veil} is the veiling luminance, in cd/m^2;

E_{glare} is the illuminance at the eyes due to the glare source, in lx, and;

θ is the angle between the direction of the light incidence of the i-th light source on the eye and the direction of the observer's line of sight, in degrees.

Illuminance at the eyes due to the glare light (in lux) is defined by the equation (2-3) (CIE 146,147-2002):

$$E_{glare} = \frac{I_{glare} \cdot cos\theta}{d^2} \tag{2-3}$$

Where

I_{glare} is the luminous intensity of the source in the direction of the eyes, in cd;

d is the distance between the source and the eyes, in m, and;

θ is the angle between the glare source and the line of sight, in degrees.

Further developments of disability glare include taking into account the effect of age and ocular pigmentation, and the extension of the angular domain in the veiling luminance formula (CIE146,147-2002).

Although both types of glare can occur in combination, these two phenomena are quite different. Discomfort glare is determined mainly by the luminance of the source, while disability glare depends on the quantity of light falling on the eye, and is largely independent of the source luminance. Discomfort glare influences people, while disability glare influences task performance (CIE 55-1983). In "Outdoor Lighting", Schreuder mentioned that disability glare is considered the exclusive glare aspect in most recommendations (2008). However, the author pointed out that the lighting community is not fully satisfied with disregarding discomfort glare.

2.2 Small Sources in Outdoor Nighttime Environments

In outdoor nighttime environments it is especially challenging to minimize glare. These environments are characterized by low background luminances, high contrasts between lit and unlit surfaces, and small light sources in the field of view. These characteristics increase the likelihood of perceiving glare.

In the past years, discomfort glare from small sources in dark environments was studied by several authors with vastly varying apparatus and methodological differences (Bennett 1977b, Benz 1966, Putnam and Faucett 1951, etc.). However, discomfort glare becomes even more apparent with the popularity of LEDs. LEDs are not new sources, but only recently they are finding widespread use in outdoor lighting applications such as sports arenas, roadways, parking lots, etc. These sources are of a small size and high luminance, which, on the one hand, allows more design freedom with respect to luminance distributions. On the other hand, the increasing use of LEDs in outdoor environments introduces challenges due to a sharp intensity cut-off and high-contrast luminance patterns. A single LED chip within a luminaire can produce luminances of approximately 19×10^6 cd/m^2 (Tyukhova and Waters 2014). These very high luminances increase the probability of causing glare. Yet, discomfort glare from small, high luminance sources, such as LEDs, in outdoor nighttime environments is rarely calculated in lighting practice, and glare persists as an issue (RCI 2011). Further research is required to examine human subjects' judgements of discomfort glare in this application.

2.3 Discomfort Glare Metrics for Outdoor Nighttime Environments

To encourage the calculation of discomfort glare from small, high luminance sources in outdoor nighttime environments, one needs to know which metric predicts discomfort glare best compared to human subjects' responses. Therefore, one of the aims of this research was to determine which of the applicable metrics predicts glare most accurately in this application. Reliable comparison between degrees of discomfort glare caused by lighting installations is necessary and desirable in the lighting industry. Glare metrics allow for a quantification of discomfort glare, and the comparison between the amount of glare caused by one lighting installation versus another. Without such reliable metrics, it is hard to improve lit environments (Eble-Hankins and Waters 2004). A great amount of research on discomfort glare produced discomfort glare metrics for different applications. However, disagreements on how to evaluate discomfort glare still exist (Clear 2013).

This section covers relevant metrics that were developed specifically for outdoor nighttime environments and/or for small sources and discusses their limitations. Six discomfort glare metrics are covered in the next sections – the outdoor sports and area lighting metric (CIE 112-1994), the motor vehicle lighting metric (Schmidt-Clausen and Bindels 1974), the road lighting installations metric (CIE 31-1976, CIE 115-1995), the outdoor lighting installations metrics (Bullough et al. 2008, 2011); the Unified Glare Rating (UGR) of the International Commission on Illumination (CIE) (CIE 117-1995), and the UGR small source extension.

2.3.1 Discomfort Glare in Outdoor Sports and Area Lighting (CIE 112-1994)

Bommel's et al. study (1983) was one of the studies that formed the basis for the glare evaluation formula for outdoor sports and area lighting (CIE 112-1994). In their research, Bommel et al. investigated the quantitative relationship between 3000 glare assessments made on a nine-point scale (Figure 2-1) and lighting parameters for outdoor sports grounds in 140 different situations. Horizontal illuminances (assumed on the sports grounds) ranged from 50 to 1500 lx.

1 unbearable
2
3 disturbing
4
5 just admissible
6
7 noticeable
8
9 unnoticeable

Figure 2-1. Rating on a nine-point scale (Bommel et al. 1983)

Both veiling luminances, namely - the equivalent veiling luminance produced by luminaires (L_{v1}) and the equivalent veiling luminance produced by the environment (L_{ve}), correlated best with the glare assessments. Equivalent veiling luminance (as defined by Holladay-Stiles, equation (2-2)) produced by luminaires is simply the luminance produced by the light from the luminaires that is directly incident on the eye. The veiling luminance from the environment is the equivalent veiling luminance caused by light reflected towards the eye by the environment such as the field; it can be viewed as an adaptation measure. For a given observer position and a given viewing direction, below the eye level, the degree of glare depends on both equivalent veiling luminances (described above). The glare index obtained by Bommel et al. through a regression analysis of all data collected is called glare control mark for floodlighting (GF):

$$GF = 7.3 - 2.4\log\left(\frac{L_{vl}}{L_{ve}^{0.9}}\right) \qquad \textbf{(2-4)}$$

Where

L_{vl} is the veiling luminance produced by the luminaire, in cd/m^2;

L_{ve} is the veiling luminance produced by the environment, in cd/m^2.

Validity was obtained for the veiling luminance produced by the luminaire in the range of 0.02 to 20 cd/m^2 and for the veiling luminance produced by the environment in the range of 0.02 to 5 cd/m^2 (Bommel et al. 1983, Tekelenburg 1982). The formula is valid for viewing directions below the eye level (CIE 600/89-1989).

In a simplified method for outdoor sports grounds with viewing directions towards the field, the veiling luminance produced by the environment can be approximated as follows:

$$L_{ve} = 0.035 \times L_{f,av} \qquad \textbf{(2-5)}$$

Where

$L_{f,av}$ is the average field luminance from the observer's position, in cd/m^2.

$$L_{f,av} = E_{hor,av} \times \frac{\rho}{\pi} \qquad \textbf{(2-6)}$$

$E_{hor,av}$ is the average horizontal area illuminance, in lx;

ρ is the reflectance of the surface.

The glare control mark formula (2-4) was tested for tennis court floodlighting and showed good agreement with average observers' assessments (Hargroves 1986).

Note that Bommel et al. investigated the effect of discomfort glare and found that veiling luminance correlates best with glare assessments (1983). However, previously, equivalent veiling luminance was used for the description of disability glare (section 2.1). For this reason, Bommel et al. referred to glare in general instead of distinguishing between the two well-known types of glare (CIE600/89 1989).

The glare rating (GR) as defined in the CIE standard (112-1994) is as follows:

$$GR = 27 + 24\log(\frac{L_{vl}}{L_{ve}^{0.9}}) \qquad \textbf{(2-7)}$$

Where

L_{vl} is the veiling luminance produced by the luminaire, in cd/m^2;

L_{ve} is the veiling luminance produced by the environment, in cd/m^2.

Equivalent veiling luminance in equation (2-7) is determined as in equation (2-2) . The CIE standard provides the same simplified approximation of glare parameters as in Bommel's et al. 1983 study (equations (2-5),(2-6)). The angle between the observer's line of sight and the direction of the light incidence is limited to the range of $1.5° < \theta < 60°$. Glare ratings vary from 10 (unnoticeable) to 90 (unbearable). The GR (CIE 112-1994) can be calculated from the previously defined glare control mark (GF) reported by Bommel et al. (1983) as follows:

$$GR = (10 - GF) \cdot 10 \qquad \textbf{(2-8)}$$

Using GR it is possible to compare sports and area lighting installations to each other. Until the publication of the CIE standard of 1994 no generally accepted glare evaluation formula existed for outdoor sports areas. The most recent standard CIE 169-2005 refers to CIE 112-1994 for the glare calculations.

2.3.2 Discomfort Glare Metric for Roadway Lighting (CIE 115-1995)

The next outdoor nighttime metric is concerned with glare in roadway lighting which was investigated in both static and dynamic models (Bommel and De Boer 1980). Based on previous studies an elaborate formula for assessing discomfort glare in road lighting installations was derived by Schreuder (Narisada and Schreuder 2004). It was accepted by the CIE as the Glare Control Mark formula (CIE 31-1976, CIE 115-1995):

$$G = 13.84 - 3.3logI_{80} + 1.3(log\frac{I_{80}}{I_{88}})^{0.5} - 0.08\log\frac{I_{80}}{I_{88}} + 1.29\log F + C + 0.97\log L_{av} + 4.41logh' - 1.46logp \quad \textbf{(2-9)}$$

Where

I_{80} is the luminous intensity of a luminaire emitted in a direction with an angle of 80˚ with respect to the downward vertical, in cd;

I_{88} is the luminous intensity of a luminaire emitted in a direction with an angle of 88˚ with respect to the downward vertical, in cd;

F is the area of the projected light-emitting surface of the luminaire in the direction of 76˚ with respect to the downward vertical in the road axis parallel meridian plane, in m^2;

C is a color factor. C=0.4 for low-pressure sodium lamps, C=0 for other light sources;

L_{av} is the average road surface luminance, cd/m^2;

h' is the reduced mounting height of the luminaires (the actual mounting height minus 1.5 m, which represents the eye height of the observer), in m;

p is the number of luminaires per km.

This formula is applicable for installation longer than 300 m for one or two luminaire rows in the road axis direction. Its validity is guaranteed in the following ranges:

$50 < I_{80} < 7000\ (cd)$;

$1 < \frac{I_{80}}{I_{88}} < 50$;

0.007<F<0.4 (m^2);

0.3<L_{av}<7 (cd/m^2);

5<h'<20 (m);

20<p<100.

According to the latest CIE document (115-2010), "no fully satisfactory method has yet been devised for quantifying discomfort glare to drivers on traffic routes. Formerly G, the Glare control Mark (CIE 31-1976), was used but resulted in anomalies". Therefore, this metric was excluded from this research.

2.3.3 Discomfort Glare in Motor Vehicle Lighting (Schmidt-Clausen and Bindels 1974)

To assess discomfort glare from automotive headlamps, Schmidt-Clausen and Bindels investigated glare illuminance, adaptation luminance, the angle between the light source and the line of sight, and the number of sources. The effects of these variables on the perception of discomfort glare were described mathematically by the following formula:

$$W = 5 - 2log\frac{E_{glare}}{0.003\left[1+\sqrt{\frac{L_{adap}}{0.04}}\right]\cdot\theta^{0.46}} \quad \textbf{(2-10)}$$

Where

W is the discomfort glare rating on a 9-point scale (smaller values mean more discomfort);

E_{glare} is the glare illuminance at the eyes due to the glare source, in lx;

L_{adap} is the adaptation luminance, in cd/m^2;

θ is the angle between the light source and the line of sight, in min. arc.

This formula was investigated for a glare source that subtended an angle of 8' at the observer's eyes (equivalent to the diameter of 24 cm at the distance of 100 m) in the following ranges. The road (adaptation) luminance was in the range of 0.0015 to 2 cd/m^2, the sky was black (luminance was not specified). Illuminance at the eyes was varied from 0.0025 to 6.9 lx. Up to five light sources simultaneously present in the field of view were investigated. The authors concluded that it is possible to replace multiple glare sources by a single source located at the center of all glare sources. The angle between the glare source and the line of sight varied from 10' (which is 1/6º) to 90º in the experiment. The authors indicated that the results are applicable to motor vehicle lighting and to street lighting.

The model by Schmidt-Clausen and Bindels predicts discomfort glare ratings well for situations when subjects attempted to detect the onset of low reflectance off-axis targets (Boyce 2009). However, according to the motor vehicle glare formula (equation (2-10)), looking directly at the light source produces invalid glare ratings that approach infinity. This drawback was addressed in the Bullough's et al metric (2008).

2.3.4 Discomfort Glare Formula in Outdoor Lighting Installations (Bullough et al. 2008, 2011)

Bullough and colleagues at the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI) proposed a discomfort glare model for outdoor lighting installations solely based on illuminances (2008). The authors defined three illuminances - the illuminance from the light source(s), the surround illuminance, and the ambient illuminance - that relate to subjective judgments of discomfort glare in outdoor installations. The illuminance from the glare source includes only the direct component from the glare source. The surround illuminance is the illuminance resulting from the subtraction of the ambient and the direct components from the total illuminance at the eyes, which essentially is the reflected component of the illuminance from the glare source. The ambient illuminance is the illuminance from other sources in the environment, when the light source under consideration is switched off.

The researchers acquired subjective glare appraisals for light sources of various sizes (not specified in their publication), illuminances from the light sources (0.1-113.3 lx), surround illuminances (0.01-0.4 lx), ambient illuminances (0.01-1.6 lx), light source luminances (5,300-196,000 cd/m^2), and viewing distances (3 - 20 m) using the De Boer scale in indoor, outdoor, and indoor/outdoor environments.

The resulting discomfort glare model for outdoor lighting installations is the following:

$$DG = \log(E_l + E_s) + 0.6\log\left(\frac{E_l}{E_s}\right) - 0.5log(E_a) \quad \textbf{(2-11)}$$

Where

E_a is the vertical ambient illuminance at the subject's viewing location (the light source being tested is switched off), in lx;

E_l is the vertical illuminance from the light source at the subject's viewing location (h=1.5m), in lx, (direct illuminance from the light source being tested);

E_s is the surround illuminance, in lx (the total illuminance at the subjects' eyes minus E_l and E_a, i.e. illuminance at the eyes received from a light source after being reflected or scattered).

The relation between the model prediction from equation (2-11) and the De Boer ratings (DB) (smaller values mean more discomfort) is the following:

$$DB = 6.6 - 6.4logDG \quad \textbf{(2-12)}$$

Where

DG is the calculation of discomfort glare through the model for outdoor lighting installations (equation (2-11)).

The authors reported a goodness-of-fit $r^2 = 0.7$ between the model predictions and the overall set of data. The authors pointed out the simplicity of the model and its ability to predict discomfort glare in a wide range of outdoor lighting installations. It can be readily incorporated into conventional application software. Bullough's et al. (2008) metric also overcomes the difficulty of using the Schmidt-Clausen and Bindels formula (1974), in which the background luminance is assumed to be a single, uniform value, which is rarely the case.

Later, Bullough and colleagues found that for a light source of angular sizes of 0.3º or more the glare model requires the inclusion of the glare source luminance to predict glare with higher accuracy (2011):

$$DB = 6.6 - 6.4\log DG + 1.4\log(50{,}000/L_L) \qquad \textbf{(2-13)}$$

Where

DB – is the De Boer discomfort glare scale rating;

DG – is the discomfort glare as calculated in formula (2-11);

L_L – is the luminance of the light source, in cd/m^2.

These formulas **(**2-11**)**, **(**2-12**)**, **(**2-13**)** have been developed fairly recently and use only illuminances and glare source luminance as predictors of discomfort glare. Therefore, they need further experimental validation.

2.3.5 The Unified Glare Rating (UGR) (CIE 117-1995)

The Unified Glare Rating (UGR) formula assesses discomfort glare from normal size sources (0.0003 to 0.1 sr) in interior lighting (CIE 117-1995). However, since the UGR small source extension is based on the UGR, the UGR is covered in this section.

The UGR was developed by the CIE in response to a request to create a practical, widely used discomfort glare evaluation system. The UGR is composed of the best parts of the major formulae in terms of practicability and familiarity with the results of glare prediction at the time. The UGR combines the Einhorn and Hopkinson formulae, the Guth position index, the aspects of the CIE Glare Index (CGI) and the British Glare Index (BGI) to evaluate glare sensations of electric lighting systems (CIE 117-1995, Wienold and Christoffersen 2006). The UGR formula is given as follows (CIE 117-1995):

$$UGR = 8log \cdot [\frac{0.25}{L_b} \cdot \sum \frac{L^2 \cdot \omega}{p^2}] \quad \textbf{(2-14)}$$

Where

L_b is the background luminance, in cd/m^2;

L is the luminance of the luminous parts of each luminaire in the direction of the observer's eyes, in cd/m^2;

ω is the solid angle of the luminous parts of each luminaire at the observer's eyes, in sr, and;

p is the Guth position index for each luminaire (displacement from the line of sight).

In the calculation of the background luminance the glare sources are excluded. Background luminance (in cd/m^2) is the uniform luminance of the whole surroundings, which produces the same illuminance on a vertical plane at the observer's eyes as the visual field under consideration (CIE 117-1995). It is defined as follows:

$$L_b = \frac{E_i}{\pi} \quad \textbf{(2-15)}$$

Where

E_i is the indirect illuminance at the eyes of the observer, in lx.

Errors in background luminance do not influence the UGR values much. For example, an error of +33% in background luminance results in an error of the UGR of 1 unit, which is the least detectible step. The practical range of the UGR scale is from 10 to 30.

The luminance of the luminaire, L, is defined by:

$$L = \frac{I}{A_p} \quad \textbf{(2-16)}$$

Where

I is the luminous intensity of the luminaire in the direction of the observer's eyes, in cd;

A_p is the projected area of the luminaire, in m^2.

The solid angle is calculated through the projected area and the distance from the observer to the center of the luminous parts of the luminaire:

$$\omega = \frac{A_p}{r^2} \quad \textbf{(2-17)}$$

Where

ω is the solid angle of the luminous parts of each luminaire at the observer's eyes, in sr

A_p is the projected area of the luminaire, in m^2;

r is the distance from the observer to the center of the luminous parts of the luminaire, in m.

The UGR is an interval scale, which means that only differences in glare ratings are meaningful; they represent the perceptible difference in psychological value – discomfort glare. High values indicate significant discomfort glare, while low values indicate little discomfort glare. If UGR < 10, then it is assumed that there is no discomfort. The UGR is limited to solid angles in the range of 0.0003 to 0.1 sr (CIE 117-1995).

The correlation of UGR ratings with subjective appraisals of discomfort glare has been tested in at least two studies (Boyce et al. 2003, Akashi et al. 1996). For example, Akashi et al.

examined the correlations of UGR with subjective glare ratings from a single light source and multiple light sources in a full-scale simulated office room (1996). They found high correlations between the UGR values and subjective ratings with a single glare source (r = 0.96), as well as the UGR values and subjective ratings with multiple glare sources (r = 0.95). However, Akashi et al. also found that multiple glare sources are overestimated by the UGR. Therefore, to account for overestimation, the authors proposed a modification to the UGR formula to include the multiplication of the term ($n^{-0.006}$), where n is the number of glare sources.

A number of exploration attempts to extend the UGR formula to various applications was made previously: to large sources (Sendrup 2001), to daylighting (Fisekis et al. 2003), and to LED sources of matrix arrangements that have non-uniform luminance (Takahashi et al. 2007). In 2014, the CIE organized a workshop on "Glare of LED Lighting Products" with the goal to develop a correction to the UGR formula that accounts for non-uniformity.

Einhorn recognized the merits of the UGR formula such as its simplicity (1998). However, he also outlined the following limitations: (1) UGR is applicable for normal size luminaires, because for small light sources it overestimates glare, and for large sources it underestimates glare; (2) the position of the light source has to be at least 5º off the line of sight; (3) the adaptation level is debatable, because the UGR does not include the direct illuminance at the eyes, which also contributes to adaptation.

To address the first issue outlined above, the CIE published a standard "Glare collection" (CIE146,147-2002) which proposed extensions for small, large, and complex light sources. The following section covers the UGR small source extension, because this study focuses on small sources.

2.3.5.1 The UGR Extension for Small Light Sources (CIE146,147-2002)

The internationally accepted UGR formula is valid for normal sources with solid angles in the range of 0.0003 to 0.1 sr (CIE 117-1995). However, because the UGR predicts intolerable glare for small sources such as incandescent lamps which are widely accepted by the public, the CIE proposed an extension for small sources (CIE 146,147-2002).

The CIE defined a small source as one that has a projected area of 0.005 m^2 (CIE 146,147 - 2002). This corresponds to a disc of diameter 80 mm at interior lighting distances. This area was the result of a study by Paul and Einhorn, who showed that small sources viewed off the line of sight at interior distances have a constant effective area (1999).

In their study (1999), Paul and Einhorn tested whether the effective size of a small source should be expressed in terms of a solid angle or an area. The experimenters were changing the background luminance (and as a result the indirect illuminance at the eyes), while the participants were changing the intensity of a light source (and as a result the direct illuminance at the eyes) at a given background luminance, such that the subjective assessment had to correspond to the 'just intolerable' criterion. The tests were done at different interior distances. The researchers re-expressed the UGR formula (equation (2-14)) by substituting L_b with $\frac{E_i}{\pi}$ as follows:

$$UGR = 8log \cdot [\frac{0.785}{E_i} \cdot \sum \frac{L^2 \cdot \omega}{p^2}] \qquad \textbf{(2-18)}$$

The UGR was reformulated further, assuming one source. Since $L = \frac{E_d}{\omega}$, equation (2-18) becomes:

$$UGR = 8log \cdot [\left(\frac{0.785}{p^2}\right) \cdot \left(\frac{E_d^2}{E_i}\right) / \omega] \qquad \textbf{(2-19)}$$

And after substituting the solid angle as $\frac{A}{R^2}$, equation (2-19) becomes:

$$UGR = 8log \cdot [\left(\frac{0.785}{p^2}\right) \cdot \left(\frac{E_d^2}{E_i}\right) R^2/A] \quad \textbf{(2-20)}$$

The next step was to show how the term $\frac{E_d^2}{E_i}$ varied with distance. For a constant position index (p), if the term (E_d^2/E_i) remains constant with the change of distance, then the 'constant omega' hypothesis is true, if not then 'constant area' one is. Paul and Einhorn found support for the 'constant area' hypothesis. For a small light source the projected area was determined as 0.005 m^2. This means that any source with a projected area of less than 0.005 m^2 should be considered to have a constant effective area equivalent to 0.005 m^2, when viewed off the line of sight. Since luminance can be expressed with equation (2-21), after substituting the projected area with 0.005 m^2, one obtains the equation (2-22). When this new area is substituted into the solid angle equation (2-17), then one obtains equation (2-23)

$$L = \frac{I}{A_p} \quad \textbf{(2-21)}$$

$$L = \frac{I}{0.005} = 200 \cdot I \quad \textbf{(2-22)}$$

$$\omega = \frac{0.005}{R^2} \quad \textbf{(2-23)}$$

Substitution of luminance and solid angle as expressed in equations (2-22), (2-23) into the UGR equation (2-14) results in the modified UGR formula for small light sources:

$$UGR = 8log \cdot [\frac{0.25}{L_b} \cdot \sum \frac{200 \cdot I^2}{R^2 p^2}] \quad \textbf{(2-24)}$$

This formula is restricted to small sources more than 5° off the line of sight at interior lighting distances; glare from these sources is determined by their intensity (CIE 146,147-2002).

2.4 Measurement of Discomfort Glare

Discomfort glare is usually assessed using subjective measures. However, subjective responses are known to have high variability (Bennet 1977b). Since the correlations of predicted levels and individual or group ratings of discomfort glare are typically low (Boyce 2014), it is highly desirable to have an objective (or physiological) measure of discomfort glare that has the potential to increase the reliability of data. It is critical to understand which method(s) should be used in this research to obtain reliable results. Therefore, the sections below discuss subjective and objective discomfort glare measures that have been used in glare research in the past.

2.4.1 Subjective Measurements

Most discomfort glare research was done with subjective scales. There are four methods available to obtain a subjective measure of discomfort glare with human subjects (Xia et al. 2011): (1) a rating method using a semantic differential scale; (2) a paired comparison method; (3) a single-label method; and (4) categorization. Below is a summary of these methods which became the basis for the subjective measurement choice in this study.

2.4.1.1 Semantic differential scale

The first method is a rating method using a semantic differential scale. Most studies utilize a 7- or 9- point scale for subjective glare appraisals (CIE 55-1983, CIE 112-1994, Hargroves 1986, Akashi 1996, etc.). According to Reis et al. (2000), for unipolar scales reliability and validity are optimized for approximately 5-7 points.

In outdoor nighttime environments, the most frequently used scale is the 9-point De Boer scale (Table 2-1) (or modifications thereof), which was originally published in Dutch (Olson 1991). Schreuder argued that this scale has several problems, which, when combined, are likely to lower the reliability and validity of the scale (2008). First, this scale is counterintuitive, meaning that higher numbers represent lower level of experienced glare. Second, it is not known whether the original Dutch version of the scale was an interval scale, which is desirable for performing routine mathematical and statistical operations. For example, appraisals made by two observers as '6', one as '7', and one as '8', might not be appropriate to average to 27/4 = '6.75', although it always has been done this way (Schreuder 2008).

Table 2-1. The 9-point De Boer scale

1 Unbearable
2
3 Disturbing
4
5 Just acceptable
6
7 Satisfactory
8
9 Just Noticeable

The anchors of the De Boer scale do not indicate an interval scale, in which the differences are the same. Consider, for example, the difference between "satisfactory" and "just noticeable" or between "disturbing" and "unbearable". In a related study, participants reported that the term '*satisfactory'* discomfort was ambiguous, and it was often interchanged with '*just noticeable'* discomfort in the scale (Gellatly and Weintraub 1990).

In the Gellantly and Weintraub study, the researchers explored whether the De Boer scale was effective in predicting the amount of glare, and if not, attempted to determine potential improvements (1990). The authors concluded that subjects most frequently assign higher numbers to more uncomfortable situations, unlike in the De Boer scale where higher numbers mean less discomfort. For the US population increasing numerical values are associated with (1) increasing levels of what is measured, or (2) an increasing degree of positive value of what is measured (e.g. the higher grade point average (GPA) the better). However, since a higher level of discomfort glare is less desirable, the numerical assignment might become ambiguous. The authors proposed to add zero to the scale with a descriptor of *'no discomfort'*. This anchoring of the scale at the lower end reduces user's ambiguity. In addition, Reis et al. suggest that data quality is better when all scale points are labeled with words (2000). These labels should have meaning that divide up the continuum into approximately equal units (Reis et al. 2000).

Gellantly and Weintraub highlighted that an equal-interval and unidimensional psychological scale is desirable. They pointed out that the labels of the De Boer scale may be referring not only to the level of discomfort, but also to what they call value of discomfort acceptability. Subjects might agree on the magnitude of discomfort, but disagree whether it is acceptable or not. These two values may or may not lie on the same psychological continuum. The authors proposed to improve the rating scales by using labels that refer to the levels of discomfort only. Related to this, Boyce mentioned that individual variability is due to the fact that observers have to perform two tasks when they are asked to identify when a condition becomes uncomfortable (2014). These tasks are discrimination – tell when a condition occurred, and an assessment – decide if it is uncomfortable or not. The discrimination part of the process is likely to be determined by the characteristics of the visual system, which has individual variability. However, the assessment adds another kind of variability based on past experiences and expectation of the subjects (Boyce 2014).

The meaning of "glare" should be well articulated to the subjects, because participants define and understand it differently from researchers (Clarke et al. 1991). If different participants have their own definitions of the word "glare", this contributes random or error variance to grouped glare ratings, which results in poor correlations between individuals' ratings and the glare prediction systems. In Clarke and colleagues' study, the authors showed that when defining glare, people place great emphasis on reflections and brightness. Oftentimes in their descriptions, subjects talked about extreme situations; it is easier to agree on the extremes of glare than on intermediate (mild or moderate) discomfort glare conditions. The authors indicated that it is important to inform subjects about the different components of glare such as brightness, reflection, discomfort, etc.

Even though there are some problems with this scale, the data obtained with it are valid, suggesting that subjects are primarily guided by the numbers not the adjectives (Olson 1991, Narisada and Schreuder 2004). "When the observers are not familiar with the physical units, the only option they have is to discriminate between the stimulus magnitudes" (Poulton 1989).

2.4.1.2 Paired comparison

The second method of obtaining a subjective measure of discomfort glare with human subjects is paired comparison. In this method, subjects indicate which of the two stimuli simultaneously present in the field of view causes more discomfort when looking at the fixation point (Eble-Hankins and Waters 2009). This is a ranking method. In contrast to a rating question, which asks one to compare different stimuli separately using a common scale, a ranking question asks one to compare different stimuli directly to one another (Reis et al. 2000).

In a study of discomfort glare from non-uniform luminance sources, the paired comparison method showed less variability than the subjective scale assessment (Eble-Hankins and Waters 2009). Ranking data are generally more reliable and validated than rating data (Reis et al. 2000). Despite the fact that this method has little variability, it has two major drawbacks.

First, the resulting outcome is mainly a ranking of different stimuli, unlike in the ratings method that shows the differences between the observer's evaluations of stimuli. Therefore, in a paired comparison method, in order to obtain more information about the relative difference in discomfort between the ranked stimuli, subjects can be requested to score the difference in discomfort between the two stimuli (e.g. on a five-point numerical scale). The second drawback of paired comparison is the time it takes to rank all possible stimuli. The number of presented pairs grows quadratically in the number of conditions. The number of pairs from a set of n conditions is calculated as follows:

$$F(n)=n(n-1)/2 \text{ (n choose 2)} \qquad \textbf{(2-25)}$$

For example, for 36 lighting conditions there are 630 possible pairs to assess. In addition, if one wants to account for a potential left/right bias to compare each stimulus to itself, one should add an additional 36 stimuli to the total number (Eble-Hankins 2008).

Another challenge with this method is to accommodate paired comparison for the 0º position in this research. The spatial distribution of the cones in the fovea has a dramatic drop-off. The foveal field of view can be approximated as 2˚ (Schreuder 2008). Therefore, subjects can look directly at only one glare source at a time; two sources cannot be viewed by the foveal vision simultaneously. However, the main intention of using the 0º position is to study glare for the foveal vision. To accommodate the paired comparison method in this case, special considerations have to be given to the presentation technique. When two glare sources have to be located at the 0˚ position, one source should be slightly shifted to the left from the center and the other to the right, but both in the same plane as the eye level. In this case, instead of looking at the fixation point between the light sources, a subject has to look directly at one source at a time in a counterbalanced order to make sure one uses the foveal vision for the discomfort glare assessments. The drawback of this method is that it might be confusing for the subjects to know where to look first - right or left. In addition, it is not clear how to account for adaptation in this case. Considerations of the cost, time, and methodology exclude paired comparison.

2.4.1.3 Single-label method

The third method is the single-label method, in which subjects adjust a level of the variable until it meets a predefined criterion. For example, one can change the luminance of the light source until it creates a perception of the borderline between comfort and discomfort (BCD), first used by Luckiesh and Guth (1949). In related studies, subjects tune the characteristics of the light source in the periphery to match the luminance of the light source in the direct line of sight (e.g. Putnam and Gillmore 1957).

It is a long task with large variations between subjects. The problem with this method is that a single label (such as BCD) must be accurately defined, and subjects have to manipulate the glare stimulus themselves (De Boer and Schreuder 1967). Multi-label scales are found to better represent the amount of glare (De Boer and Schreuder 1967). In addition, as Lulla and Bennett showed, the presented range influences subjects' adjustments of BCD (1981).

2.4.1.4 Categorization of comfort

The final method is categorization of comfort. In this method, subjects answer questions such as "Is the light comfortable? Yes or no?" (Boyce 2003). The proportion of subjects answering Yes/No indicates whether this lighting condition is comfortable or not. It is only a rough indication of whether comfort increases or decreases.

After reviewing the subjective methods, a rating scale method was chosen. The choice of the specific scale is provided in section 3.2.

2.4.2 Objective Measure

The underlying mechanism that is responsible for discomfort glare is unknown. However, it is highly desirable to have an objective measure of discomfort glare that may offer the potential for higher reliability of glare predictions. In general an objective variable may be measured as precisely as the measuring equipment allows (Putnam and Gillmore 1957). On the other hand, a subjective measure is limited in accuracy due to the large differences among individuals and more moderate variations within the individuals themselves (Putnam and Gillmore 1957).

Discomfort glare may cause little apparent change in the eyes or facial muscles, blinking, frowning, and even lacrimation (Hopkinson 1956). Researchers have been looking at potential measures such as changes in pupil size and pupillary oscillations (for example, Hopkinson 1956, Howarth et al. 1993, Fry and King 1975, Lin et al. 2015, Stringham et al. 2011), facial muscle responses (Berman et al. 1994), eye movements (Lin et al. 2014, Lin et al. 2015), etc.

Several authors explored the pupil's response to glare. The pupil diameter is controlled by two sets of smooth muscles in the iris (Sirois and Brisson 2014). The sphincter muscle forms a ring around the pupil and contracts it. A set of dilator muscles radiate from the sphincter to the circumference and dilate it (Schreuder 2008, Rea 2013). The function of these changes in diameter is to modulate the amount of light that reaches the retina, thus to optimize vision (Sirois and Brisson 2014). Hopkinson did not find a relationship between the pupil diameter and discomfort glare (1956). He indicated that the pupil diameter by itself cannot be an objective measure of discomfort. Other factors such as illumination received at the eyes change pupil diameter. He hypothesized that discomfort glare might be, in part, related to the opposing actions of sphincter and dilator muscles in the presence of a glare source that highly stimulates a part of the retina as opposed to the other parts of the retina that are adapted to a lower background luminance.

Based on Hopkinson's idea - discomfort originates from the antagonistic actions of the sphincter and dilator muscles, Howarth and colleagues tested the hypothesis that the dynamic characteristics of pupillary hippus could be different in discomfort glare conditions versus in no-glare conditions (1993). Since the iris is sensitive to pain (Fugate 1957), the iridomotor system could be involved in the sensation of discomfort felt in the presence of glare sources. Note that in Howarth's et al. paper, they used the term 'hippus' to describe changes of normal healthy pupil size under steady conditions. Rea, for example, mentions that a normal pupil is in a state of constant movement (2013). However, rhythmic contractions and dilations of the pupil can be associated with a much more marked condition such as epilepsy. Howarth and colleagues tested three observers at various steady illuminance levels (1993), and concluded that pupillary hippus is not directly responsible for discomfort. The iris movement does not seem to cause discomfort.

Unlike Hopkinson, in Stringham's et al. study with twenty-six subjects, the authors found a correlation between visual discomfort glare ratings and pupil diameters ($r = -0.429$, $p = 0.037$), which they called unexpected (2011). On average, the higher the discomfort, the smaller the subject's pupils. Stringham et al. assumed that since pain-signaling fibers of the trigeminal nerve (the fifth cranial nerve that is responsible for sensation in the face) innervate the dilator and constrictor muscles of the iris, it could be that during visual discomfort the iris experiences intense stretching and maximum constriction. The authors also hypothesized that Howarth et al. (1993) did not find the relationship between visual discomfort and hippus because they used only one subject.

The same trend – the greater the discomfort, the greater the pupil constriction – was shown in another study (Lin et al. 2015). The authors found a correlation between subjective responses on the De Boer scale and relative pupil size (RPS) ($r = -0.61$, $p < 0.001$). This correlation showed that the pupil becomes smaller when the glare source is presented compared to the initial no-glare condition. The authors also pointed to the fact that the glare source affects the trigeminal nerve and pupil muscles.

In other studies on objective measures of discomfort, the researchers hypothesized that discomfort glare is accompanied by a contraction or spasm in the extraocular muscles (e.g. Murray et al. 2002). Muscles contract in response to nerve impulses and produce force (Rosenbaum 1991). Muscles' activity is measured by electromyography (EMG), a technique for recording the electrical activity of muscles using electrodes. Muscle responses can be measured, for example, with the Focus EMG machine (TeleEMG website).

In a 1994 study, Berman et al. examined the EMG activity of facial muscles around the eyes. They hypothesized that discomfort glare causes a subtle, involuntary contraction of these muscles in response to glare. In their study the authors measured the EMG activity of orbicularis oculi (muscles responsible for closing the eyes) of twenty subjects. This objective measure correlated well with subjective perceptions. However, the authors believe that it is unlikely that this facial muscle is the source of discomfort, it might well be, for example, a nerve fiber.

In two related studies, Lin et al. examined the relationship between discomfort glare evaluated on the De Boer scale and the average eyeball movement speed (AEMS) characterized by fluctuations of the electrooculogram (EOG) (2014, 2015). The objective data were also collected through electrodes attached to the subjects. The higher the AEMS, the faster the eye moved. Lin et al. found a correlation between subjective responses and AEMS. In more glary conditions the AEMS was higher than in less glary conditions, especially for the senior subjects.

Multiple physiological measures were assessed in recent years, yet no clearly identifiable, suitable objective measure has been established. However, such a measure would be clearly useful, since control of discomfort can be achieved through an understanding of the processes which give rise to it (Boyce 1981).

2.5 Summary of the Research Gaps

Discomfort glare has been studied for decades, however, it is rarely calculated in lighting practice. LEDs are finding widespread use in outdoor applications. These sources have the potential to cause more glare than conventional lighting systems due to LEDs' high luminance. The first step in the direction of facilitating discomfort glare calculations from small, high luminance sources in outdoor nighttime environments is to examine four variables – the luminance of the glare source, its solid angle, its position, and the background luminance – with regards to their effect on humans' judgements of discomfort glare. Since subjective responses are known to have high variability (Bennet 1977b), it is highly desirable to include objective measures of discomfort glare (in addition to a subjective measure) that may offer an increase in the predictive reliability of data. Previous studies showed that some objective (physiological) measures correlate well with discomfort glare perception (Berman et al. 1994, Lin et al. 2014, Lin et al. 2015). Moreover, studying subjective and physiological measures simultaneously might give a deeper insight into the humans' responses to discomfort glare.

If multiple metrics are available, one might wonder why not to use one of them when assessing discomfort glare from small, high luminance glare sources? The main reason is that the predictive utility of existing discomfort glare formulae for this specific application of nighttime outdoor environments is questionable due to their limitations.

The CIE outdoor sports and area lighting glare formula (1994) is restricted to the viewing directions below eye level, and glare becomes infinitely large when one looks directly at the glare source - the angle between the light source and the line of sight appears in the denominator.

The Schmidt-Clausen and Bindels formula (1974) for automobile headlamps also approaches infinity when one looks directly at the glare source. In this case, neither metric produces meaningful results.

Bullough's et al. outdoor discomfort glare model is based solely on illuminances (2008). In Bullough's et al. further studies (2011, 2012), the authors found that, in addition to illuminance, glare source luminance plays a significant role in discomfort glare when the light source is larger than 0.3º in visual size. Bullough's et al. metric does not directly consider other factors, such as the solid angle of the glare source, that are known to significantly contribute to the perception of discomfort glare. In addition, this metric is new and needs further validation.

One other discomfort glare metric applicable to outdoor nighttime environments is the road lighting formula (CIE-31 1976), which was developed for specific road lighting installations. Therefore, it is only applicable for very limited conditions (for example, the minimum number of light sources per kilometer has to be 20). Moreover, according to the later CIE document (115-2010) "it resulted in anomalies". Therefore, this metric was excluded from this research.

The UGR is used in many countries, and it is the most promising metric in interior lighting (Boyce 2014). It comprises the best parts of discomfort glare formulas known at the time (CIE-117 1995). A number of exploration attempts to extend the UGR formula to various applications were made previously (Sendrup 2001, Fisekis et al. 2003, Takahashi et al. 2007). Therefore, it seems like a logical step to test the performance of the UGR small source extension (sources with an area of 0.005 m^2 or less) and to investigate whether it can be extended to outdoor nighttime environments. Consequently, this accomplishes another task – validation of the UGR small source extension with human subjects in dark environments, which was not fully validated before (Eble-Hankins and Waters 2004).

To encourage the use of a discomfort glare metric, the first step is to determine which existing metric predicts discomfort glare best when compared to humans' judgements in the given application.

CHAPTER 3 – METHODOLOGY OF THE EXPERIMENT

The most certain way to succeed is always to try just one more time.
-Thomas A. Edison

This chapter covers the methodology used for the discomfort glare experiment in this research. Variables, levels, and methods are described along with the reasoning behind the choices. A detailed description of the apparatus, measurement equipment, and the controls software is provided. The calibration of the apparatus and the measurements collected are explained. The EMG integration and eye tracking analysis software are described. Finally, a justification of the excluded subjects, a detailed description of the subject sample, and a thorough description of the data collection procedure concludes this chapter.

3.1 Independent Variables and Levels

Four independent variables were used in this study: luminance of the glare source, its position in the field of view, its solid angle, and luminance of the background. It has been shown in the literature that these variables are likely to have a significant effect in outdoor nighttime environments, because they are the major factors that are known to influence discomfort glare perception (Benz 1966).

3.1.1 Luminance of the Light Source

Three levels of light source luminance were chosen: 20,000; 205,000; and 750,000 cd/m^2 (Table 3-1). The idea was to study small, bright sources such as LEDs that can have very high luminances (Tyukhova and Waters 2014). The highest luminance level in this study was determined based on three factors: field measurements; duration of afterimages; and source uniformity.

First, in June 2014, field measurements were completed using a luminance meter (LS-110) and high dynamic range imaging (HDRI) technology at Westside Tennis Courts in Omaha, Nebraska - as one example of outdoor nighttime lighting - to estimate the luminaires' luminance in outdoor LED projects. Luminances as high as approximately 537,000 cd/m^2 were measured, which served as the basis for the highest luminance used in this study.

Second, the higher the luminance, the stronger the afterimage effect. Therefore, a longer adaptation time is needed to minimize the aftereffect. Since the focus of this research is discomfort glare, the highest luminance had to be chosen such that it does not create long lasting afterimages (scotomatic glare (Mainster and Turner 2012)). Otherwise, a longer adaptation time would be necessary, which would prolong the test, fatigue the subjects, and influence the results (see section 3.5). Therefore, the highest luminance had to be balanced with the duration of the required adaptation time.

Third, during the developmental stages of the apparatus, it proved to be difficult to create a uniform light source of high luminance. Therefore, a balance between the required highest source luminance and the maximum source uniformity had to be found. For the highest luminance in this research (750,000 cd/m^2), the luminance achieved at the center was 20% higher than the luminance at the circumference of the source, which was considered acceptable in this study (Wallace and Lockhead 1987).

The three luminance levels (see Table 3-1) were chosen as perceptually equally spaced based on the approximate relationship between luminance and brightness known as Stevens's power law (DiLaura et al. 2011). For a single surface seen in isolation, brightness is computed as follows:

$$B = \alpha \cdot L^{0.33} \quad \textbf{(3-1)}$$

Where

B is brightness;

α is a constant;

L is the object luminance, in cd/m^2.

Table 3-1. Variables and levels used in this study

Luminance of the light source (average)	**20,000; 205,000; 750,000 cd/ m^2**
Position of the light source	**0°; 10°**
Solid angle of the light source	**10^{-5}; 10^{-4} sr**
Luminance of the background (average)	**0.03; 0.3; 1 cd/m^2**
Number of sources in the field of view	**1**
Color temperature of the light source	**5700 K**
Task/no task for the subjects	**No Task**
Uniformity of the light source	**Uniform light source (about 20% non-uniformity)**
The distance between the subject and the light source	**1 meter**
Viewing technique	**Momentary. 3 flashes (1.2 seconds “on”; 1.2 seconds “off”)**
Adaptation time in one condition	**49.2 seconds**

3.1.2 Position of the Light Source

Two levels of position were chosen for this study: 0˚ and 10˚ (Table 3-1). These two positions represent conditions when subjects look directly at the glare source (direct viewing) and close to the point of fixation (peripheral viewing) respectively.

A position of 0˚ accounts for a frequently occurring situation when subjects look directly at the glare source (e.g. Putnam and Faucett 1951, Bullough 2008). It is a situation in which the outdoor sports and area lighting discomfort glare metric (CIE 112-1994) and the motor vehicle lighting metric (Schmidt-Clausen and Bindels 1974) predict infinitely large glare, and, therefore, become inaccurate. In his comments to Bullough’s et al. 2008 paper, Boyce mentioned that viewing light sources directly is not natural behavior, although this is a controversial point. Vos, for example, suggests that observers tend to look at the glare sources directly (2003). The author proposed the idea that people might have a “phototactic” reaction (attraction) to light, and that discomfort might be caused by the conflict between this attraction reaction to light sources and the avoidance of them (Vos 2003). A position of 10° accounts for the peripheral viewing. This level was previously used in other research papers (e.g. Benz 1966). A glare source at 10° has the potential to cause more glare than a source located farther from the line of sight (Benz 1966), therefore, it is also included in this research.

3.1.3 Solid Angle of the Light Source

Two levels of solid angle (size) were chosen for this study: 10^{-5} and 10^{-4} sr (Table 3-1). Both sizes fall under the definition of small source (CIE 146,147-2002) and fall into the range of angles found in outdoor lighting such as $1.1\text{x}10^{-3} – 10^{-6}$ sr (Putnam and Faucett 1951). Sources smaller than 10^{-5} sr were not of interest in this study. For example, as Putnam and Faucett showed (1951), glare sources smaller than 10^{-5} sr create very high BCD brightness. This means that very high BCD may not be uncomfortable, if the source is extremely small.

3.1.4 Luminance of the Background

Three levels of background luminance were chosen for this study: 0.03; 0.3; and 1 cd/m^2 (Table 3-1). These levels were based on field measurements completed in outdoor nighttime environments and previous studies with low background luminances (e.g. Putnam and Gillmore 1957, Bennett 1976, Li et al. 2006).

In June 2014, field measurements of background luminances were completed at two locations: Westside Tennis Courts and on a parking lot near the TD Ameritrade Park baseball stadium in Omaha, Nebraska (as two examples of outdoor nighttime environments). The luminance of the sky directly overhead was in the range of 0.01-0.09 cd/m^2 and that of the sky that appears brighter in the immediate surround of luminaires was in the range of 0.19-10 cd/m^2.

Previous studies were also guiding the choice of levels. For example, Li et al. demonstrated that dark backgrounds in residential areas have luminances of approximately 0.2 cd/m^2 and in administration areas 2 cd/m^2 (2006). In other studies, the adaptation (background) levels for outdoor lighting were approximately in the range of 0.034 – 34.26 cd/m^2 (Putnam and Fauccett 1951, Putnam and Gillmore 1957).

Based on the measurements and previous studies, the initial idea was to look at 0.01 cd/m^2 as the lowest background luminance. However, during the early stages of the apparatus development, background luminances lower than 0.03 cd/m^2 were not possible to create due to equipment limitations (see section 3.6.1). Therefore, based on 0.03 cd/m^2 as the lowest level, the investigator chose the remaining levels such that they are perceptually equally spaced, similar to section 3.1.1.

3.2 Dependent Variables

Three dependent variables were used in this study: a subjective measure – the differential scale reported in Fischer's paper (1991); and two physiological measures – the pupil diameter and the EMG recordings of orbicularis oculi (the principle muscle responsible for closing the eyes).

A differential scale method was chosen for this study. In general, this method has its shortcomings, but it produces valid data (refer to section 2.4.1). Among a great variety of available differential scales, the scale from Fischer's paper was chosen (1991, it appeared in Bodmann et al. 1966 with slightly different labels) (Table 3-2). The reasons for this choice are described in the following paragraphs.

Table 3-2. Subjective scale used in this study (Fischer 1991)

0	No discomfort glare
1	Glare between non-existent and noticeable
2	Glare noticeable
3	Glare between noticeable and disagreeable
4	Glare disagreeable
5	Glare between disagreeable and intolerable
6	Glare intolerable

Despite the fact that the De Boer scale and its modifications are most frequently used in outdoor nighttime environments, the De Boer scale seems to be confusing for subjects. In 1990, Gellatly and Weintraub conducted an experiment in which subjects had to order five descriptors in the way they perceived that these labels describe different degrees of glare. Most of the subjects reversed the scale when compared to the De Boer scale; they assigned higher numbers to more uncomfortable situations. For clarity Gellatly and Weintraub proposed to have zero in the scale with a descriptor of *'no discomfort'*.

There is some evidence that subjects are able to reliably distinguish between approximately seven categories of a unidimensional stimulus, and this is apparent for a broad range of sensory judgments (Miller 1994). With more than seven categories confusions become more frequent (Miller 1994).

The scale (Fischer 1991) meets three recommendations mentioned above, namely - smaller numbers in the scale mean less discomfort; the scale has a category of zero with the label "no discomfort glare"; and it has seven categories. In addition, previous research showed that oftentimes subjects could not reconstruct the scale from memory, even if they had worked with the scale before (Gellatly and Weintraub 1990). Using Fischer's scale, subjects have to remember only four categories – no discomfort glare, noticeable, disagreeable, and intolerable (the other three labels lie between them). Data quality is better when all scale points are labeled with words, and this is also the case in the scale reported in Fischer's paper (1991).

The procedure and instructions can significantly affect subjects' discomfort glare assessments (Bennett 1972b). Clear instructions should be provided to the subjects, since even commonly used terms are frequently misunderstood (Maruyama and Ryan 2014). For this reason, carefully phrased instructions and practice trials were used in this study (section 3.12).

Two physiological measures were collected: pupil diameter, measured with a video-based eye tracking device (ETL-100 by ISCAN), and EMG activity of orbicularis oculi recorded with the Focus EMG Machine (by TeleEMG).

With the available technology, tracking and recording of the pupil diameter is relatively straightforward. Even though the role of the pupil in discomfort glare is not very clear, recording the pupil diameter is worth the effort. As recent papers show, there is a significant correlation between pupil diameter and discomfort glare (Stringham et al. 2011, Lin et al. 2015).

Berman and colleagues demonstrated that the EMG activity of the muscles around the eyes showed some correlation with subjective assessments (Berman et al. 1994). Therefore, EMG readings were also recorded in this study. The goal was to explore the relationship between the discomfort glare responses and muscular activity, expressed through the Muscle Activation Index (MAC) (see section 3.9).

3.3 Control Variables

The number of glare sources in the field of view, the color temperature of the glare source, the uniformity of the glare source, and the presentation technique were controlled. Subjects did not have any additional task during glare assessments.

Subject individual-difference variables such as age, eye color, gender, sensitivity to light, and others were not controlled, although this information was collected for each subject. Other variables related to the subject, for example, mood, amount of caffeine intake, or amount of sleep were not controlled, nor was that type of information collected.

3.4 Viewing Technique

The momentary viewing technique of the stimulus was chosen for this study. This technique was selected from the three available viewing techniques as specified by Bennett (1971), namely – continuous viewing, momentary viewing, and the look-up technique. A number of authors used the momentary technique in their experiments (e.g. Putnam and Faucett 1951, Luckiesh and Guth 1949). Typically, the flashing sequence consists of three one-second "on" periods each separated by one-second "off" periods, with this sequence followed by a five-seconds "off" period. In this research, the sequence consisted of three 1.2 seconds "on" periods separated by 1.2 seconds "off" periods, with this sequence followed by a 4.8 seconds long "off" period until the start of the adaptation time of the next experimental condition (see sections 3.6.3.2 and 3.6.3.3 for details).

The idea of this research was to mimic glancing at the light source, because - as Putnam and Faucett noted in their paper - a steady fixation on glare sources rarely happens in lighting practice (1951). In outdoor nighttime environments, drivers, for example, might glance at the oncoming car headlights or at fixed road lighting as they drive by. In another example, pedestrians located "off-site" the illuminated property (for example, a baseball stadium viewed from a residential property located near the stadium) may briefly look directly at the luminaires located near the line of sight.

Putnam and Faucett (1951) claimed that it is easier to evaluate the sensation of brightness from a short versus a prolonged exposure. In addition, Hopkinson pointed out that the flashing/momentary technique gives reliable results (1957). Bennet said about the two techniques

– momentary and continuous – “the differences among the techniques are quite small, one is tempted to say ‘negligible’ ” (1971). Momentary exposure keeps the observer’s adaptation close to that of the background brightness and reduces the foveal adaptation change involved in a steady fixation (Putnam and Faucett 1951), both of which are desirable.

3.5 Adaptation Time

Adaptation is a process that changes the sensitivity of the visual system; it is one of the most controversial issues in glare research (Poulton 1991). For example, Einhorn mentioned that in the UGR the adaptation luminance (L_b) is debatable, because it does not include the direct illuminance at the eyes that also contributes to adaptation (1998). For the visual system to be able to function well, it has to be adapted to the prevailing lighting environment (DiLaura et al. 2011). Therefore, it is crucial to understand how much time a subject needs to adapt between the conditions.

The adaptation time in each experimental condition was 49.2 seconds. It is the time between the start of each experimental condition and the time when the flashing sequence starts (see Figure 3-34). It was determined as the balance between two key issues: the duration of afterimages and the length of the session.

The first issue was concerned with the duration of afterimages after viewing high luminance stimuli. An afterimage is a visible trace of a primary stimulus that appears even though the stimulus is no longer present (Virsu 1977). If the glare luminance is too high, then potential carry over effects may exist, affecting subsequent discomfort glare assessments. Therefore, one needs to allow sufficient time for adaptation to occur. The second issue to address was to make sure the experiment was not too tiring. Bennett mentioned that it is important to make sure the experiment is not too long, so that the observers do not get fatigued (1979b). In his study, observers reported discomfort glare experiment as “boring, long, nebulous, confusing, hurt eyes, etc.” (1979b).

To examine the impact of afterimages, one needs to understand the range of luminances presented in this study – at the lower end, the luminance is determined by the dark background (0.03 cd/m^2); at the higher end by the glare source (750,000 cd/m^2). The low end falls into the range of mesopic vision, when both cones and rods are active (DiLaura et al. 2011). According to the IESNA Lighting Handbook, “a few minutes are sufficient for adaptation to occur”, when the change in retinal illumination happens within the range of operation of the cone photoreceptors (2011). The cone threshold is at 0.001 cd/m^2 (DiLaura et al. 2011); therefore, a few minutes should be adequate for this study. At the highest end of the luminance range used in this research are glare sources that are viewed directly at the line of sight, which might cause afterimages (scotomatic glare) (Mainster and Turner 2012, Feresin 1992). Reidenbach showed that an afterimage on a human retina after an exposure from a white high-brightness LED (approximately 110,000 cd/m^2) remains nearly constant with a slight decrease during approximately 10 minutes (2007). However, he argues that the effect of the afterimage on visual acuity is eliminated within 30 to 60 seconds.

A pilot study with five subjects in this research showed that the duration of afterimages after an exposure to three flashes (1.2 seconds “on” periods separated by 1.2 seconds “off” periods) in the worst-case scenario was about 3-5 minutes (until afterimages fully disappeared) as reported by the subjects. The worst-case scenario was caused by the largest glare source ($\omega = 10^{-4}$ sr) directly on the line of sight with the LED operating at a current of 850 mA. Luminance of the LED operating at a current of 850 mA was measured, but found inaccurate due to the equipment problem that was revealed later. However, it would be well over 1,000,000 cd/m^2.

Note that the current used in this pilot study was twice as high as the one actually used in the main experiment (410 mA, 750,000 cd/m^2). An adaptation time of 1-3 minutes was considered to be reasonable in this study.

To finalize the choice of the adaptation time, the experimenter had to determine how long a subject can be attentive in a dark environment between conditions. A pilot study showed that long periods between flashing sequences (more than one minute) in a steady position in a dark environment without a task caused fatigue in some cases and, therefore, might have influenced the assessments. Therefore, the adaptation time served as a compromise between allowing sufficient adaptation time and minimizing fatigue. The adaptation time used in this study was 49.2 seconds. The entire experimental session per subject was scheduled for 1.5 hours.

3.6 Apparatus

The light bulb was an invention with 1000 steps.
-Thomas A. Edison

This section describes the apparatus that was custom-designed and custom-built with the assistance of Musco Sports Lighting specifically for this research to study discomfort glare from small, high luminance light sources in outdoor nighttime environments. Four primary factors that affect discomfort glare perception – glare source luminance, its size, its position, and background luminance – were controlled through a laptop via custom controls software. Fast and convenient controls were implemented to decrease the duration of the experiment and fit a larger number of experimental conditions in a given period of time. The apparatus was designed to have the flexibility to conduct glare research beyond the current study. For example, the solid angles of the glare sources could be changed from 10^{-6} sr to 10^{-3} sr.

3.6.1 Description of the Apparatus and its Capabilities

The apparatus consisted of several major parts (Figure 3-1 through Figure 3-7): a large sphere, a subject positioning station, two glare sources, a background source, the measurement equipment, and the supporting structures/mounts for the equipment.

Many authors have previously used a sphere/hemisphere in the studies of discomfort glare (e.g. Putnam and Gillmore 1957, Luckiesh and Guth 1949, Lulla and Bennett 1981), because it provides a uniform adaptation luminance. For this reason, a sphere became a logical choice in this study.

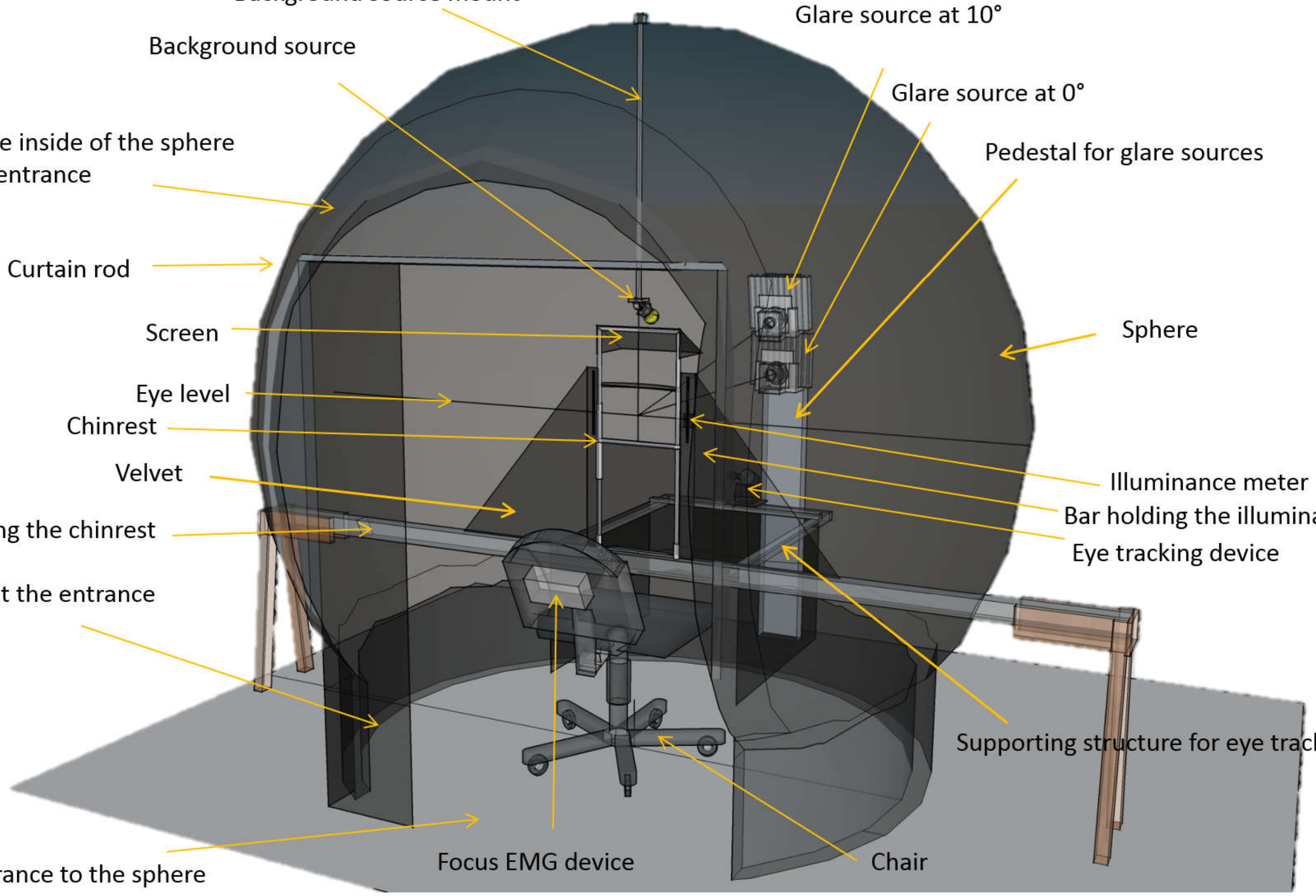


Figure 3-1. Three-dimensional model of the apparatus (not to scale).

Shown in semitransparent shading

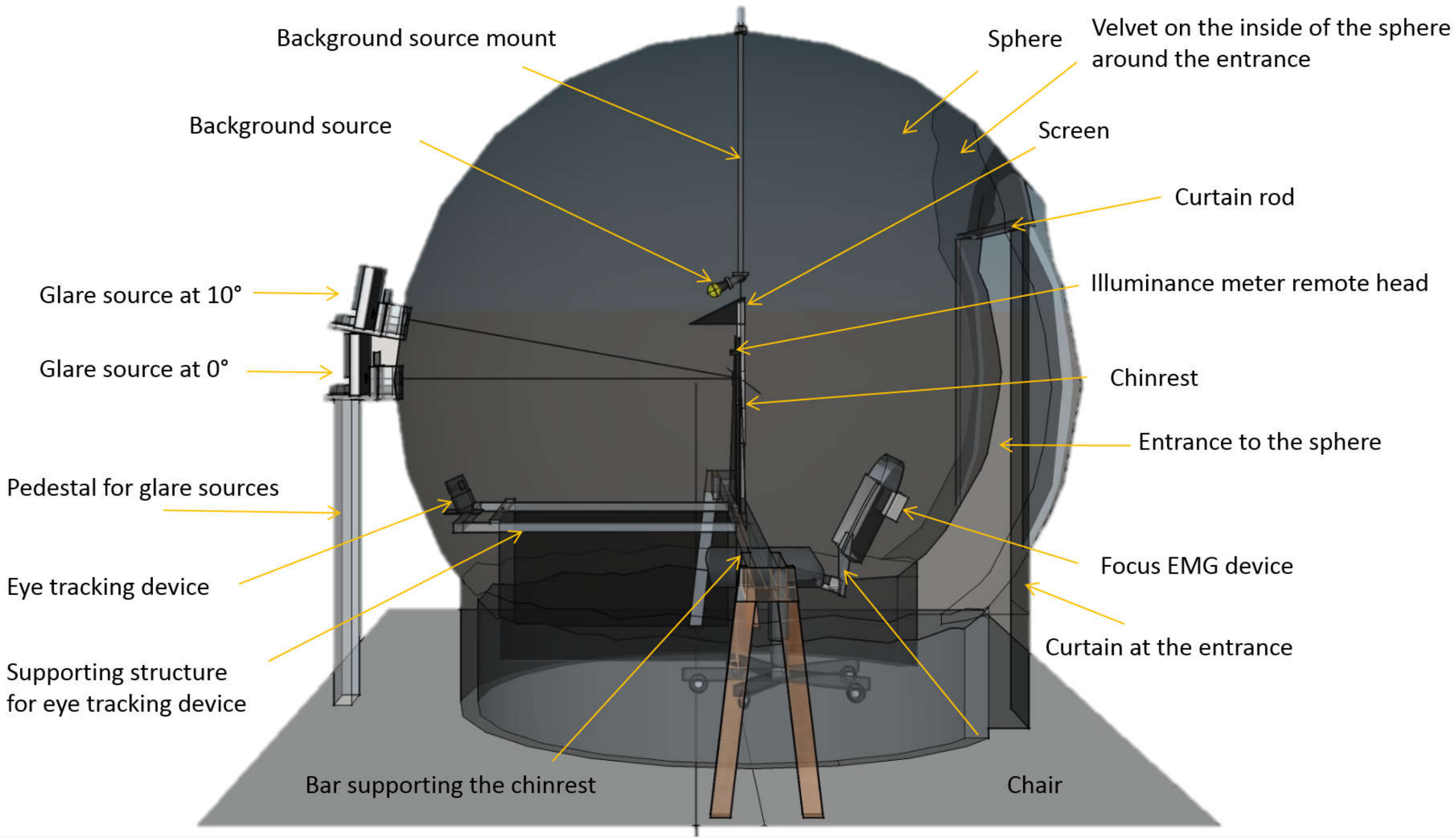


Figure 3-2. Elevation view of the apparatus (not to scale). Shown in semitransparent shading

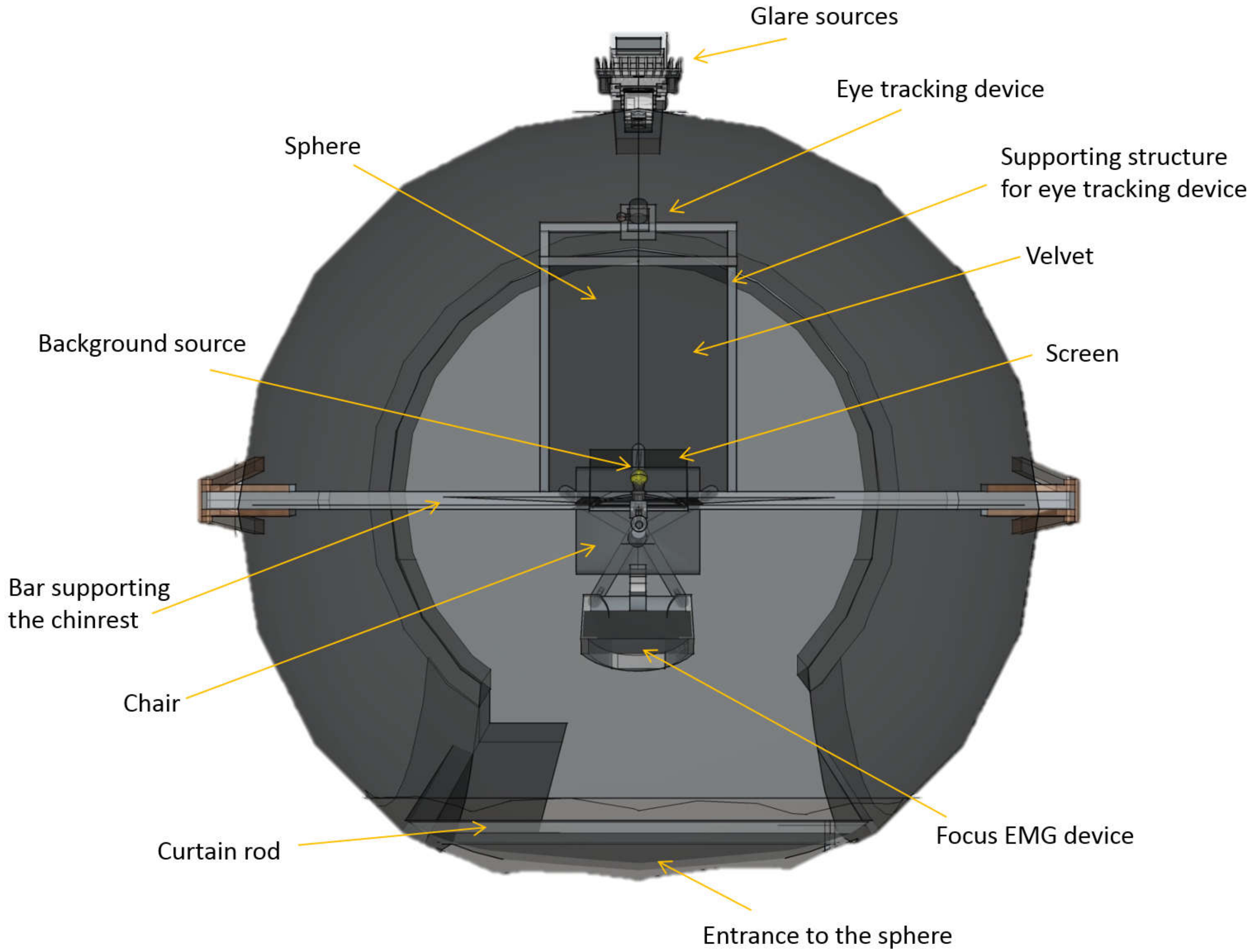


Figure 3-3. Plan view of the apparatus (not to scale). Shown in semitransparent shading

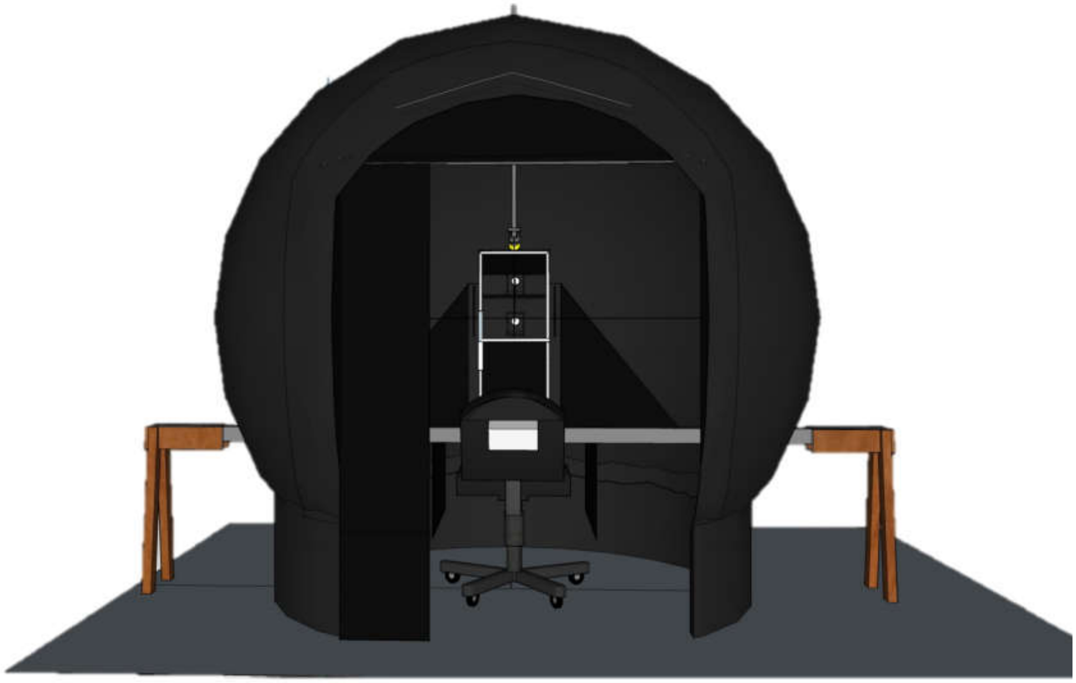


Figure 3-4. Front view of the apparatus (not to scale)

Figure 3-5. Apparatus from behind the subject

Figure 3-6. Front view of the apparatus with a glare source switched on

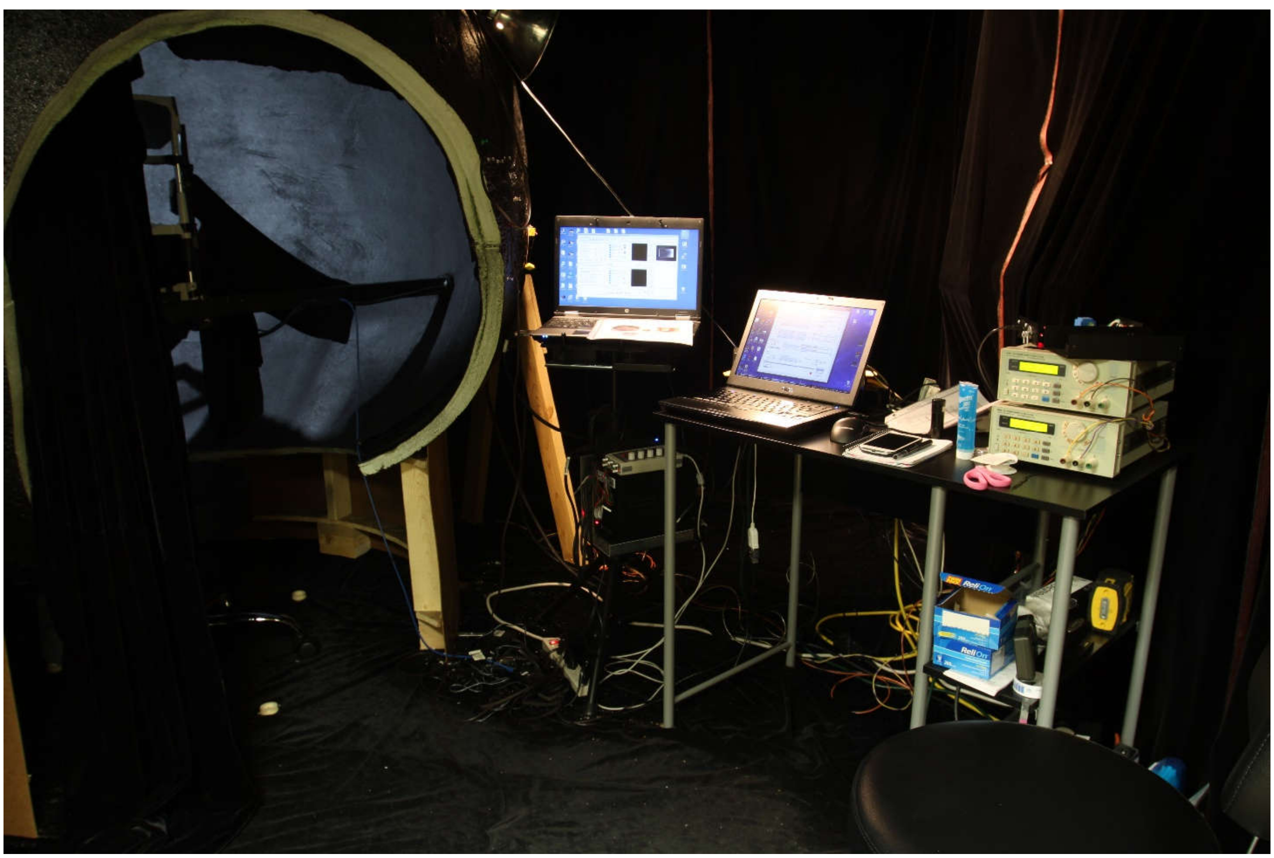


Figure 3-7. Apparatus, equipment, and the controls software

The custom-made sphere was 2 meters in diameter. Due to the time and cost consideration, an affordable way to construct a uniform sphere was devised. The core of the sphere was made from a helium parade balloon (Figure 3-8). While constantly inflating the balloon, the sphere was coated with a thin layer of Line-X (spray-on rubber protective coating). After the coating hardened, it was covered with multiple layers of Closed Cell Spray Polyurethane Foam to give the sphere structure. After 24 hours of cure time, an additional layer of Line-X was applied to protect the foam from damage during transit to the research facility. Once the final layer of Line-X cured, openings were cut, so that the subject could enter the hollow sphere. The sphere had to be cut into two parts, so that it could be brought into the lab (a dark room about 4.6 m x 4.6 m x 4.3 m in size, covered with black felt (ρ=0.006)). Once inside, the parts of the sphere were connected, reinforced with straps, and placed on a stand. The inside of the sphere was coated with multiple layers of black paint.

Figure 3-8. Core of the sphere made from a helium parade balloon (left), sphere during the early stages of construction (right)

The subject positioning station consisted of a chinrest and a chair. A chinrest was used to fix the subject's head position; chinrest was mounted on a support bar intersecting the sphere (Figure 3-1). The observer's eyes were located at the center of the apparatus, so that the distance between the observer's eyes and the glare sources (or radius of the sphere) was 1 m. The expected position of the eyes was estimated with a rotary laser level (Figure 3-9) and the chinrest was accurately marked. During the experiment the subjects had to adjust, if necessary, the height of the chair to match their eye level and the mark on the chinrest (this was checked by the experimenter).

The glare sources were mounted on a metal pedestal behind the two openings in the sphere, which were located in the visual field of the subject (Figure 3-10, Figure 3-11). One of the openings was on the direct line of sight (the 0º position), and the second one was at 10º above the fixation point. The estimation of the glare source position at 0° was done with a laser pointer (Figure 3-12). During the flashing sequence, the subjects always looked at the 0º position, which could either be a glare source or a fixation point, depending on the experimental condition. This was checked through the eye tracking camera. During the adaptation time subjects could move their eyes without moving their heads.

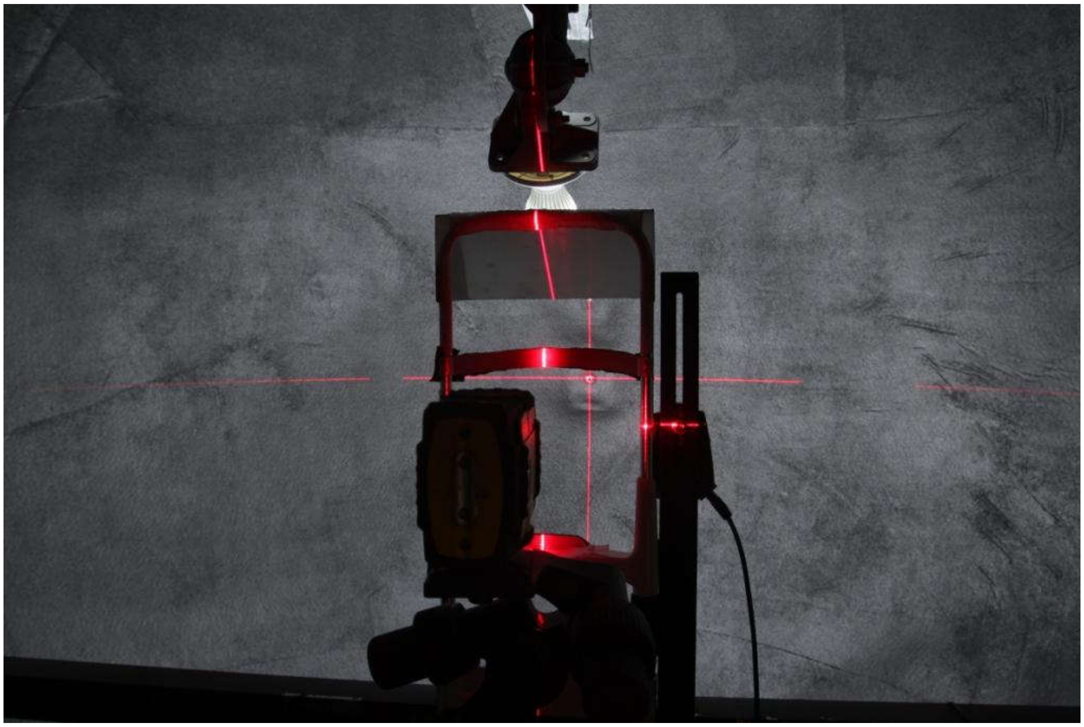


Figure 3-9. Estimating the eye level with a rotary laser level and marking the chinrest

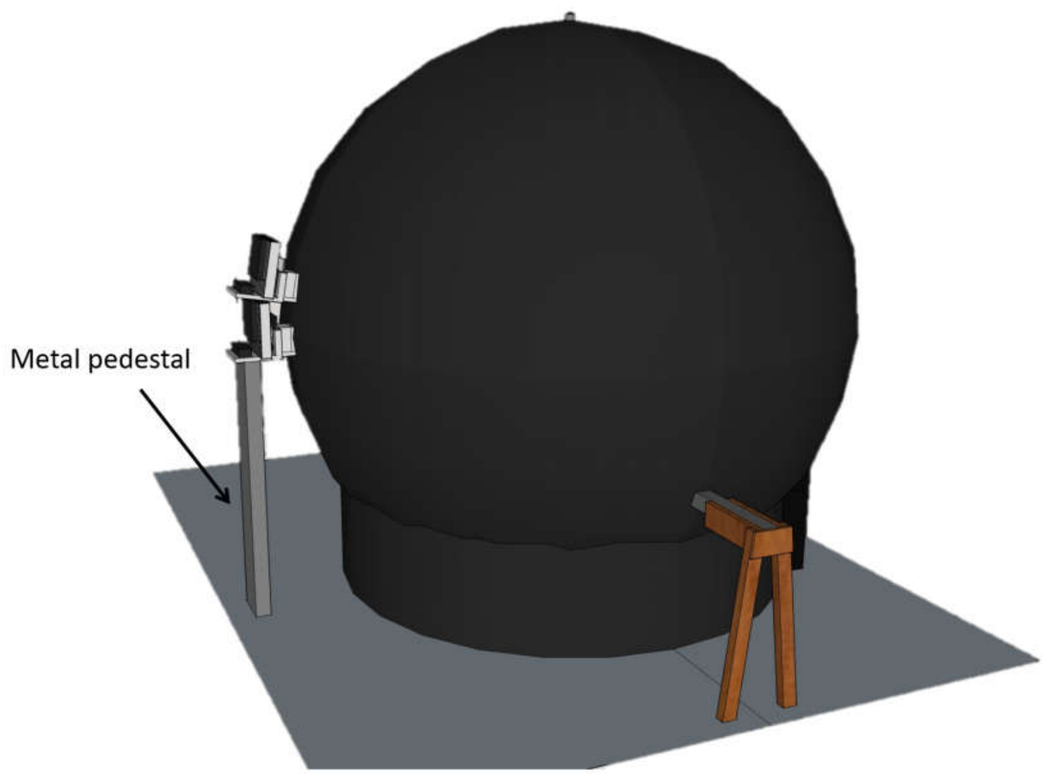


Figure 3-10. Mounting of the glare sources on the metal pedestal (not to scale)

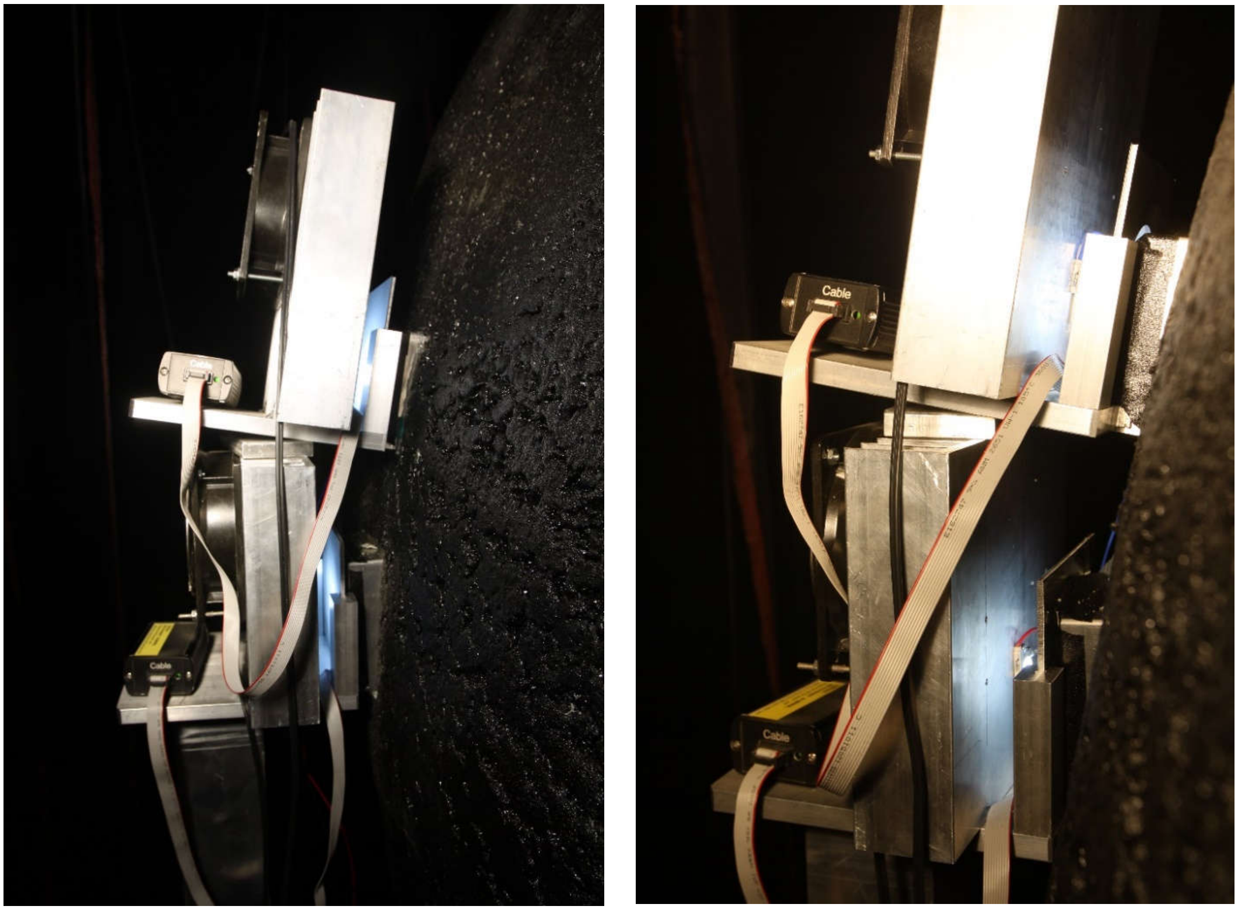


Figure 3-11. Mounting of the glare sources behind the sphere

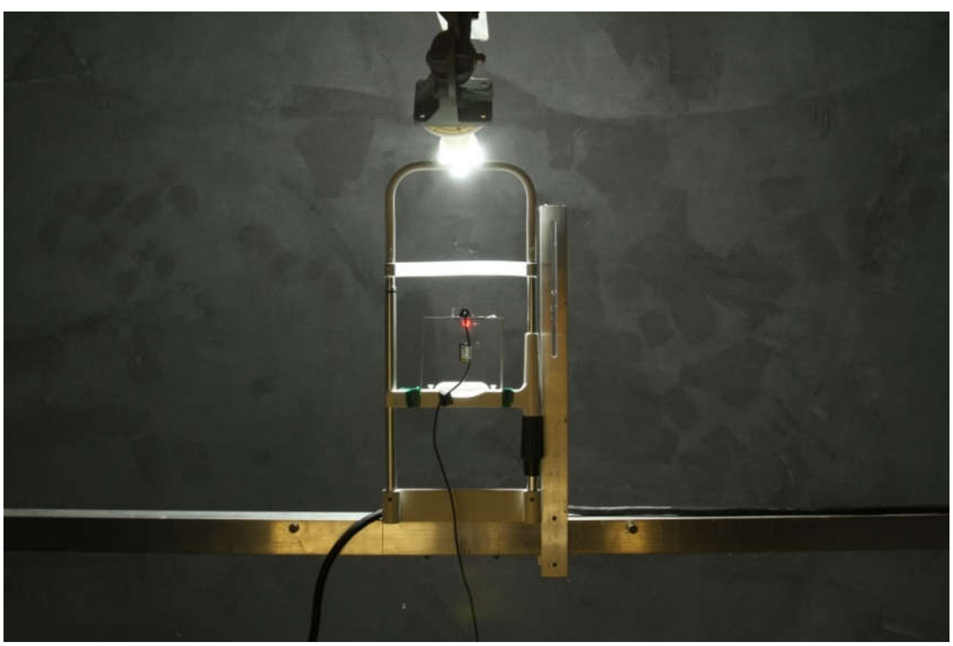


Figure 3-12. Estimation of the glare source position for the 0° view

The luminance of the background was controlled with a 9-Watt A19 5700K LED lamp (by Magic Lighting Inc.) mounted above the subject's head. To achieve the highest uniformity of the background luminance possible, the background source should be located exactly at the center of the sphere. However, because the position of the subject's eyes was more critical (to have the same distance from the eyes to the glare sources located at different positions), the subject's eyes were located at the center instead. The light from this background source was shielded from the subject with a screen mounted on the chinrest, such that no spilled or scattered light entered the subject's eyes (Figure 3-13). Black velvet (ρ=0.006) covered the chinrest and the screen to absorb any unwanted spill light (Figure 3-14).

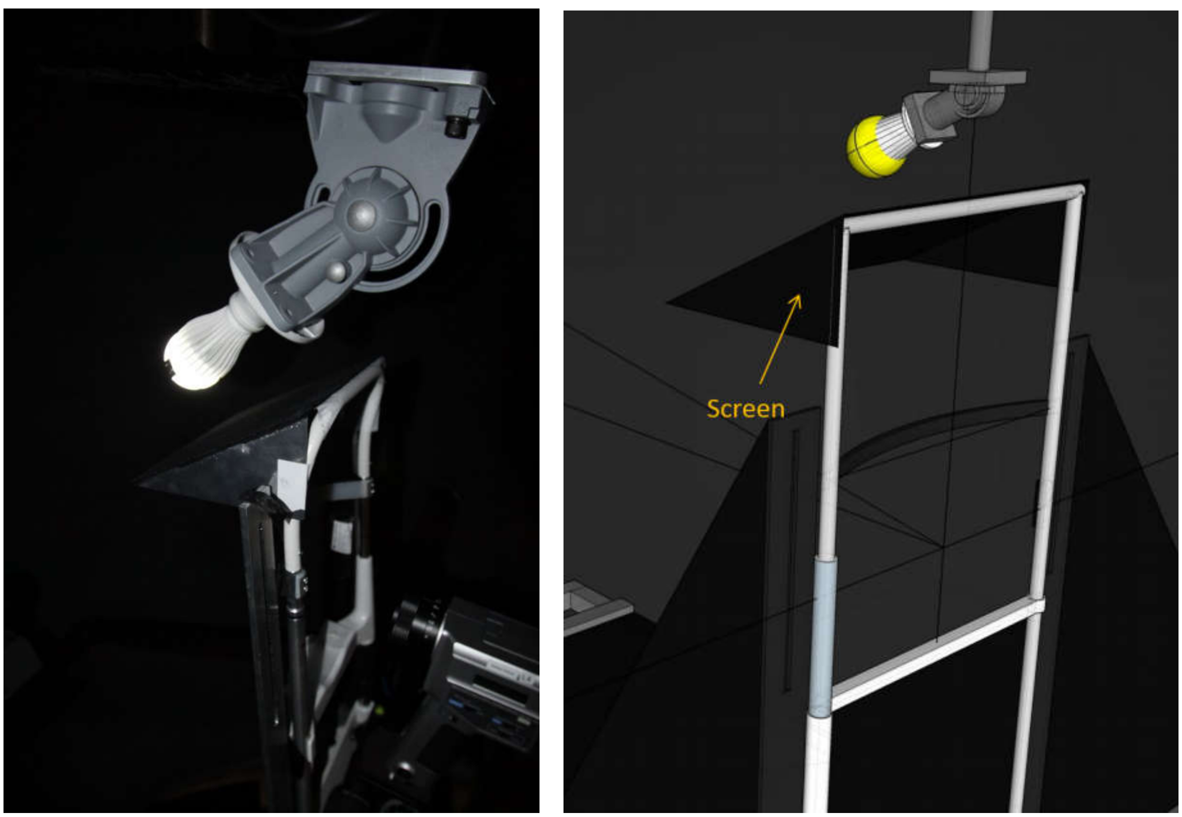


Figure 3-13. Screen mounted on the chinrest

Figure 3-14. Chinrest and the screen covered with black velvet (ρ=0.006)

The measurement equipment that was present in the sphere during the experiment included the following: the Focus EMG Machine that was attached to the back of the chair, the illuminance meter head attached to the vertical bar on the right side of the subject, and the eye tracking device placed on the supporting structure in front of the subject (see section 3.6.2).

The shape of the background source was chosen as close to a sphere as possible (A19 LED light bulb) to uniformly illuminate the background. The inherent imperfections of the balloon core made the sphere look non-uniform. Initially, to provide a highly uniform background luminance, the inside of the sphere was supposed to be covered with black velvet (ρ=0.006). In that case, the initially desired lowest luminance (0.01 cd/m^2) was easily achieved. However, the highest background luminance (1 cd/m^2) was not achievable with the available equipment. In addition, it was unclear how to cut the fabric to eliminate seams in the subject's field of view, and how to attach the fabric to the sphere. Any other type of fabric with higher reflectance would still lead to the same problem of cutting and attaching it to the sphere.

The next trial attempted to use iron-on backing material with black fabric on top of it. The white backing material contained glue particles that melted and attached to another fabric when heat was applied to it during ironing. The backing material was glued onto the sphere with spray adhesive, and the black fabric was ironed onto the sphere afterwards. This method worked well for small test patches. However, large pieces of fabric were required, such that few seams were present in the subject's field of view. Nevertheless, ironing on the large pieces of fabric created multiple bubbles and imperfections thus creating unacceptable non-uniformity.

As the final solution, backing material glued to the sphere was painted with black paint (6258 Tricorn, Sherwin-Williams) at least four times to achieve maximum uniformity (Figure 3-15). HDRI images of the resulting background luminances are given in Appendix A.

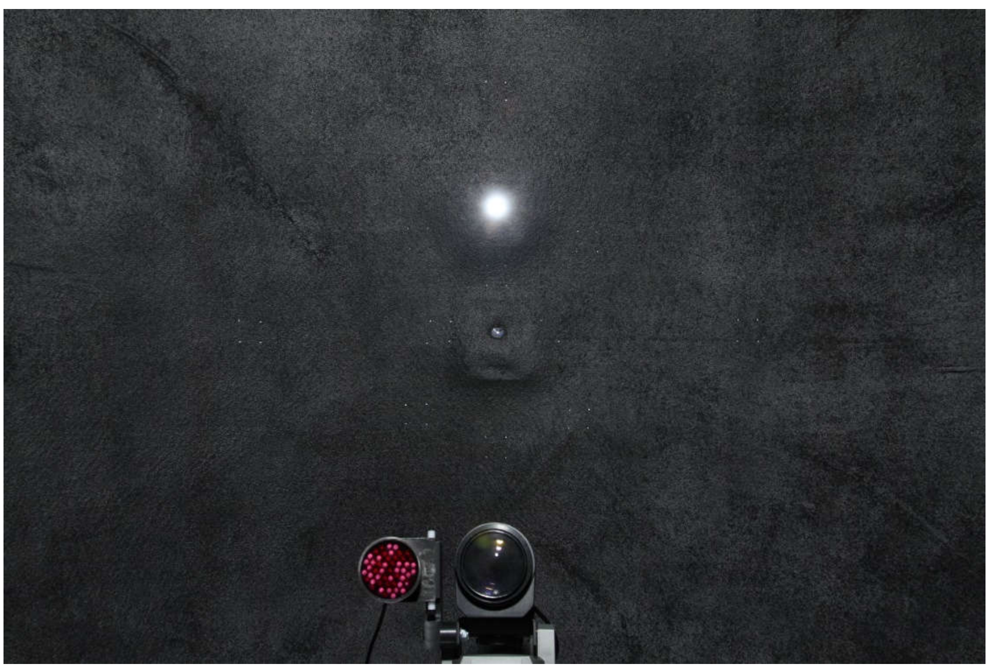


Figure 3-15. View from the position of the subject

Light from the glare sources reflected off of the black sphere, chinrest, and subjects' clothing increased the background luminance by an amount that was difficult to estimate. For this reason, in addition to placing the glare sources outside the sphere, spill light in the sphere was minimized by covering the sphere's entrance with black velvet ($\rho = 0.006$) and hanging a curtain of the same material on a bar over the entrance (Figure 3-1). All parts that were facing the glare source were either painted black or covered with velvet (Figure 3-14). Black velvet was also stretched from the chinrest to the sides of the support bar intersecting the sphere (Figure 3-6). This minimized the light reflected from the subjects' clothing.

Two power supplies, the background source controller, and two laptops - one for the controls software, another one for eye tracking - were placed on a little table to the right of the sphere (Figure 3-7). The experimenter had easy access to all control devices, and the subject in the apparatus was visible through an opening in the curtain to verify that the experiment ran correctly.

3.6.1.1 Glare sources

Each glare source consisted of the following elements: an LED chip mounted on a heat sink, a diffuser, a black baffle, a motorized aperture, a metal plate (the base of the glare source), and a box covered in black velvet on the inside (Figure 3-16 through Figure 3-20). Due to time constraints and limited availability, two different apertures were used (one with the maximum diameter of 36 mm and one with 50 mm). The two glare sources had equivalent characteristics, except that the box and the aperture were bigger in one case. However, the openings and the distances between the parts in both cases were the same.

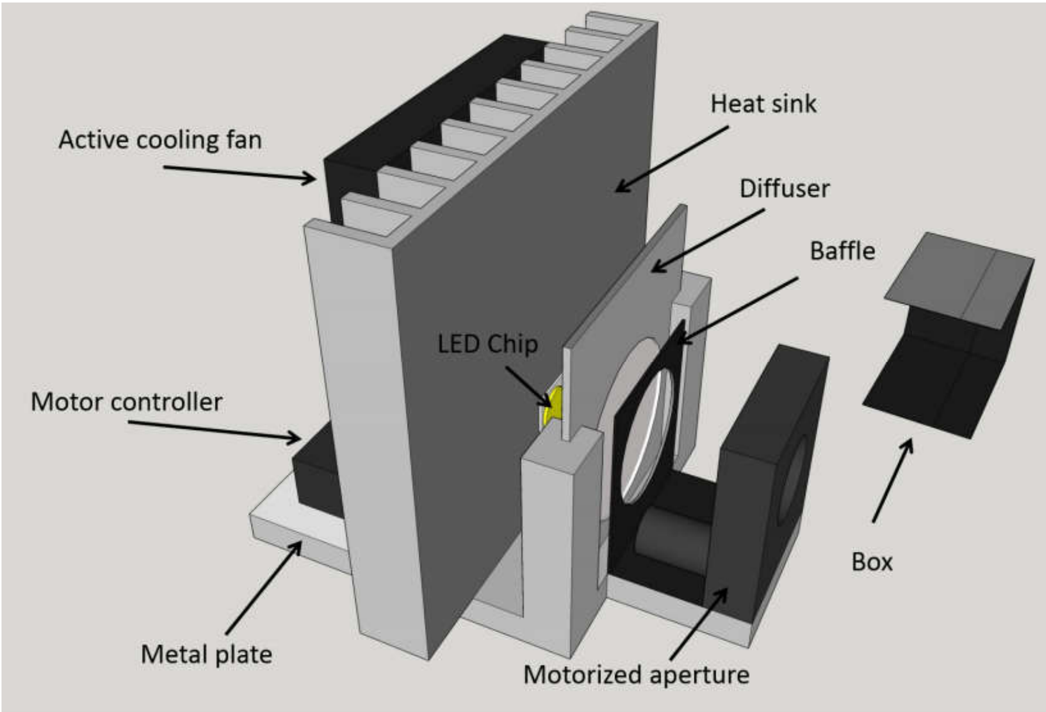


Figure 3-16. Three-dimensional model of the glare source with the box removed (not to scale)

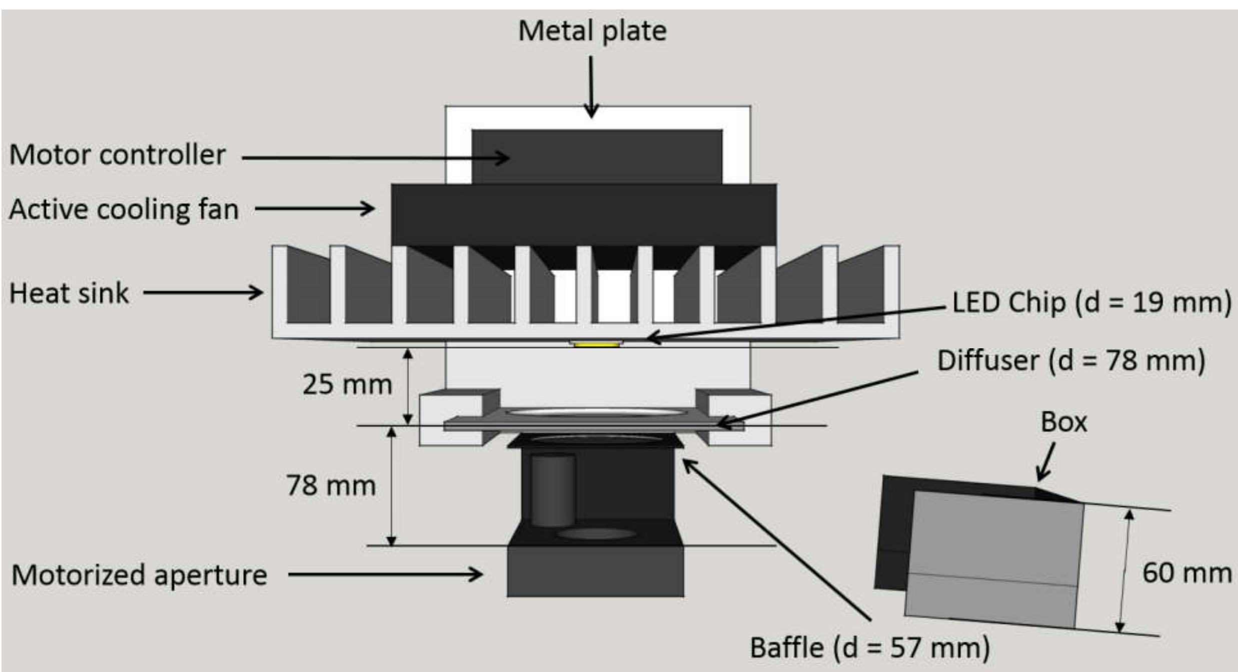


Figure 3-17. Plan view of the glare source with the box removed (not to scale)

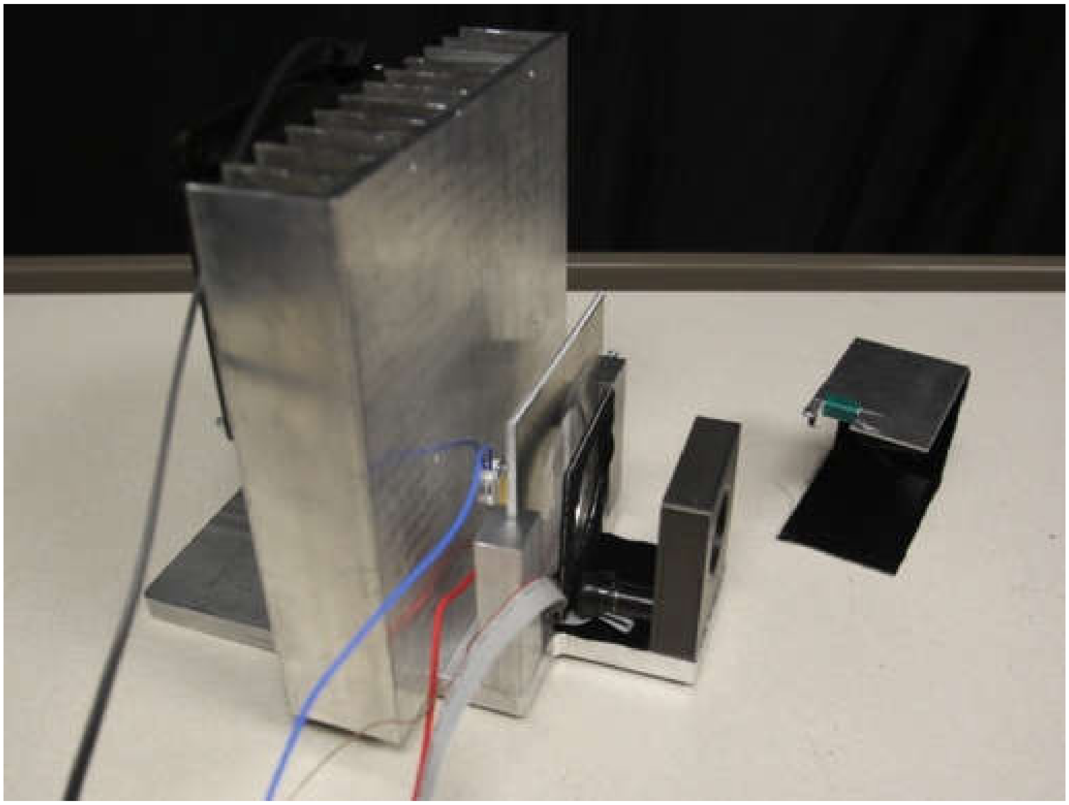


Figure 3-18. Photograph of the glare source with the box removed

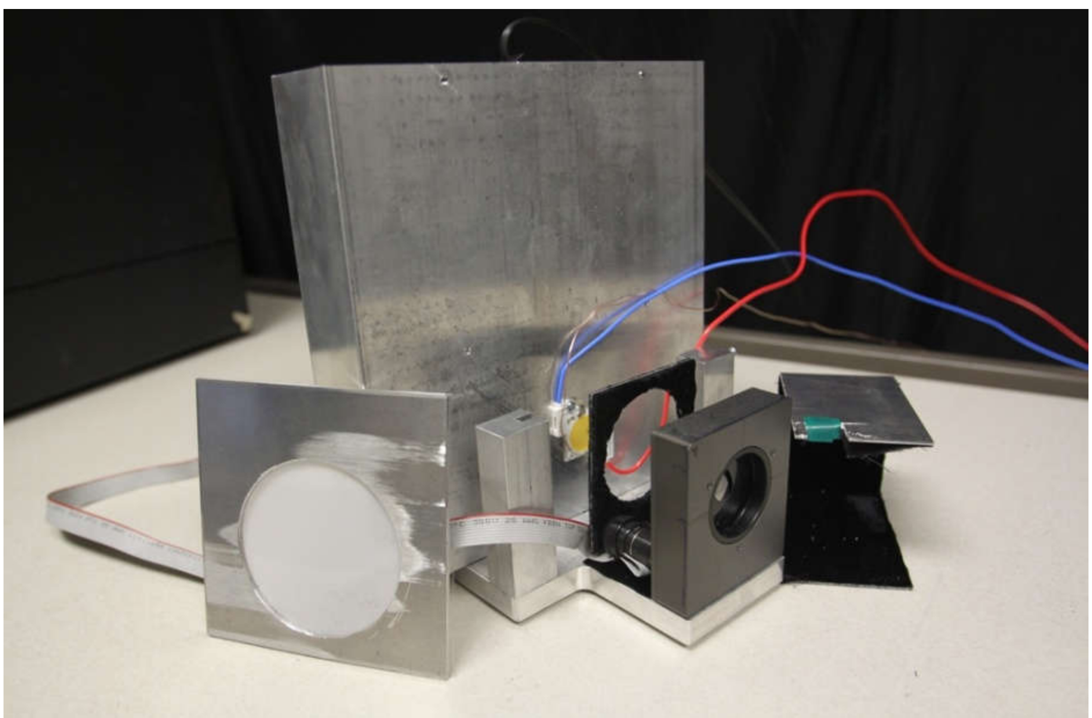


Figure 3-19. Photograph of the glare source with the box and the diffuser removed

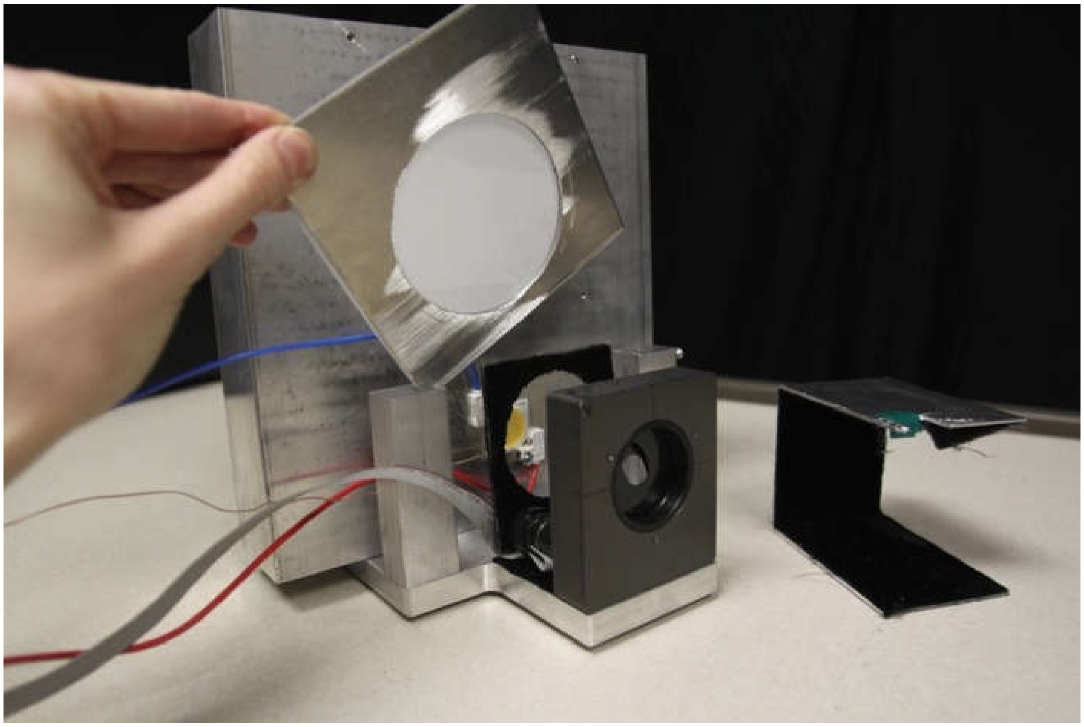


Figure 3-20. Photograph of the glare source while inserting the diffuser

Each glare source was built around the Cree XLamp LED chip (CXA2590) (Table 3-3) mounted on a large heat sink (custom configured 5052-H34 - Aluminum mounting platform/heatsink). Figure 3-21 shows how the temperature of the LED chip was measured. The heat sink was crucial for the operation of the chip, since without it the case temperature of the LED reached approximately 60º C within minutes after switching it on and kept growing rapidly. In addition to using a large heat sink, an active cooling fan was also added (Figure 3-22). The metal plate, the base of the glare source, was wider in the back so that it could accommodate the LED chip placed on the heat sink (Figure 3-16, Figure 3-18).

Table 3-3. Main characteristics of Cree XLamp LED chip (CXA2590)

Characteristic	Value
Forward voltage	69 V
Maximum drive current	1800 mA
Color temperature	5700 K
CRI	80
Luminous flux at 1200 mA	9000-9500 lm

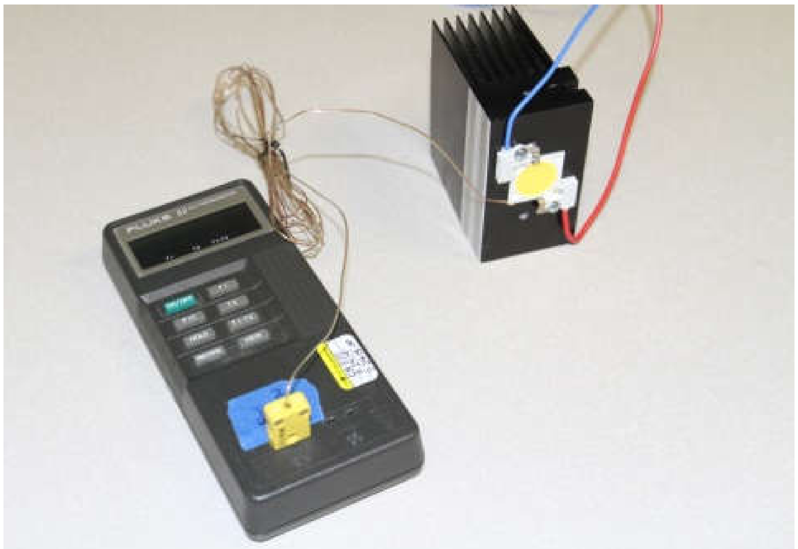


Figure 3-21. Measuring the case temperature of the LED chip with a thermocouple

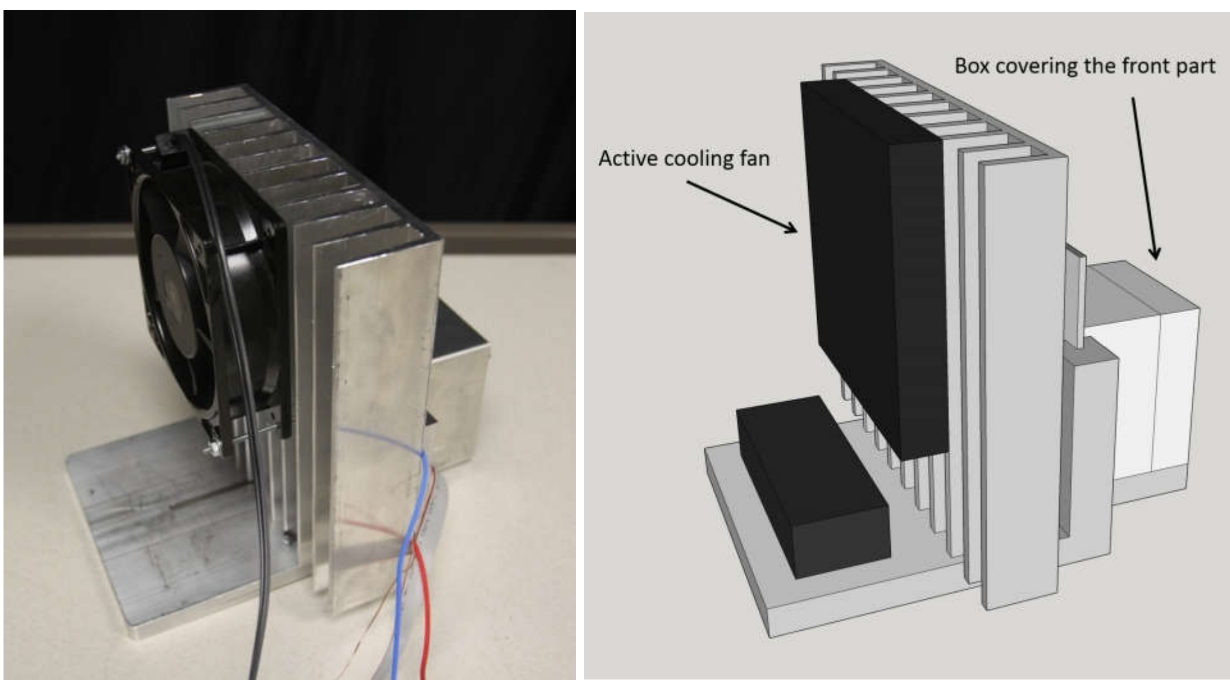


Figure 3-22. Active cooling fan of the glare source – photograph (left) and 3D model (right, not to scale)

For the purpose of this study, the glare source had to have a high luminance and be uniform. Achieving both factors simultaneously was a challenging task. Most light sources are non-uniform, and when a diffuser is used to increase uniformity, it reduces the source's luminance considerably. Therefore, a balance between the desired maximum source luminance and uniformity had to be found. The diffuser, a 60˚ Light Shaping Holographic Diffuser (by Luminit), was placed in front of the LED chip, which resulted in non-uniformity of approximately 20% between luminance in the center and the circumference of the source (measured with a luminance mapping camera P501F by Westboro Photonics).

The baffle was located between the motorized aperture and the diffuser. The main purpose of the baffle was to absorb any undesired spill light. Baffles were cut out of 0.5 millimeter thin metal sheets (Aluminum 5052-H34) on an industrial cutting machine (Prototrak Edge K2). These baffles were then sprayed with a general performance spray adhesive (Loctite) and covered with black velvet with a reflectance of $\rho = 0.006$ (Figure 3-23, Figure 3-24). The metal box that covered the front part of the plate extending from the aperture to the diffuser (Figure 3-16, Figure 3-22) was also covered with velvet on the inside using the same procedure to absorb any unwanted spill light. At the given distance between a subject and the glare source the diameter of the opening in the baffle had to be large enough ($d = 57$ mm), so that it could not be seen by the subjects. Each baffle was fixed in a cavity on the metal plate with Loctite Epoxy Instant Mix.

The glare sources were placed outside of the sphere on a metal pedestal to minimize the potential spill light (Figure 3-10, Figure 3-11). Initially, the base of the light source was longer, meaning that the LED chip was placed farther outside the sphere. Three black baffles were used in front of the diffuser to further minimize the effect of any potential spill light. However, because of the ocular dominance problem described below, the design of the glare source had to be modified. The base plate was cut shorter, such that the distance between the aperture and the LED chip changed from 305 mm to 103 mm.

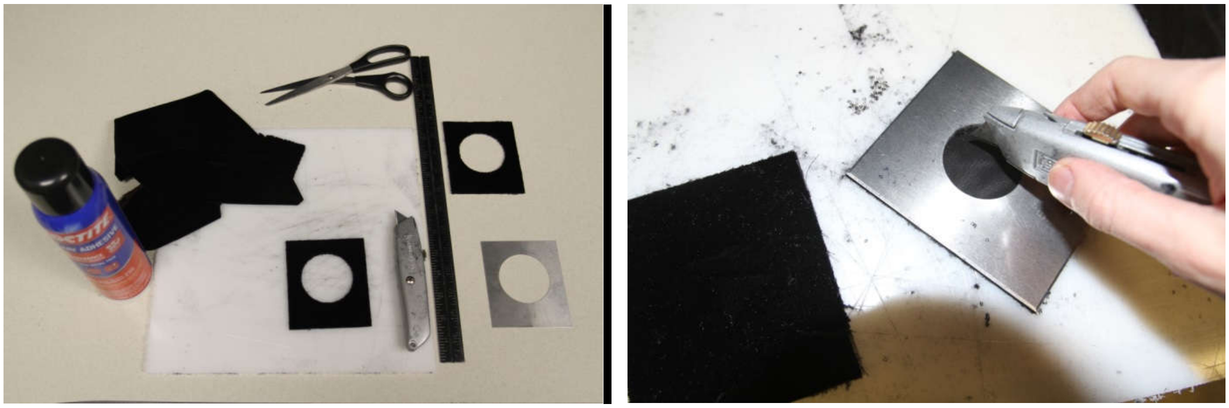


Figure 3-23. Covering baffles with black velvet

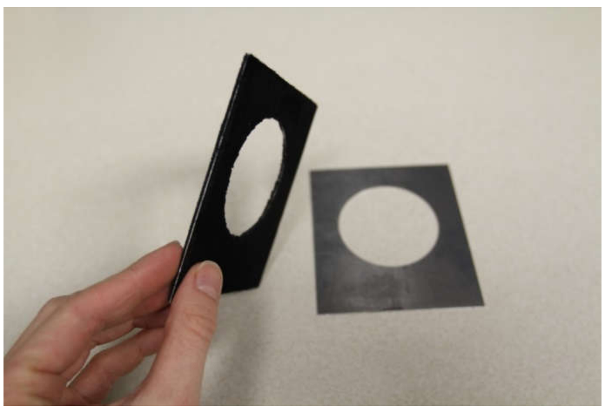


Figure 3-24. Baffles before being covered with velvet and after

An adjustable motorized aperture (by SK Advanced Group) that changed the solid angle of the glare source was located at the front end of the metal plate. Figure 3-25 shows the aperture in front of the diffuser with the LED chip switched on. Figure 3-26 shows the aperture set at various solid angles. Because of time constraints and limited availability, two different apertures were acquired. The first one had a diameter range of 0 to 50 mm (08IDM-050M, controller 08SMC-1) for the glare source located at 0°, and the second one had a range of 0 to 36 mm (08IDM-1M, controller 08SMC-1) for the glare source located at 10°. The main advantage of using motorized apertures was the ability to change conditions fast and precisely and thus decrease the duration of the experiment. Moreover, the subjects experienced less fatigue than during longer experiments that would have been the result of using manual apertures.

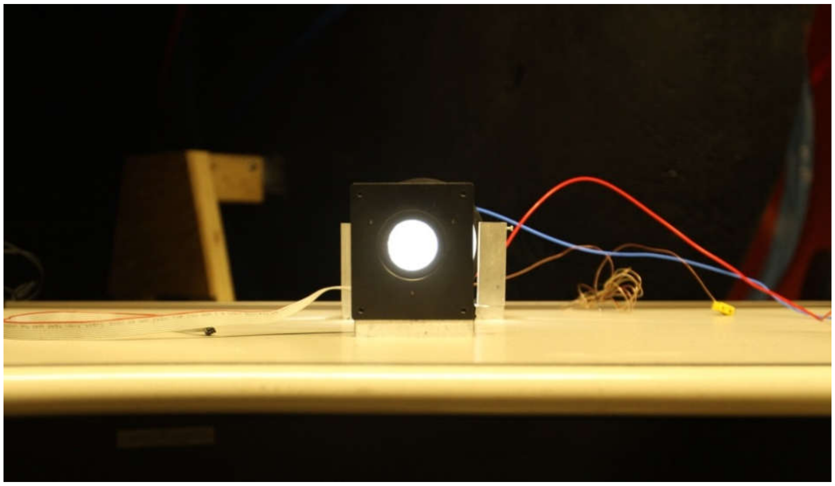


Figure 3-25. Motorized aperture (0 – 36 mm) in front of the diffuser and the LED chip

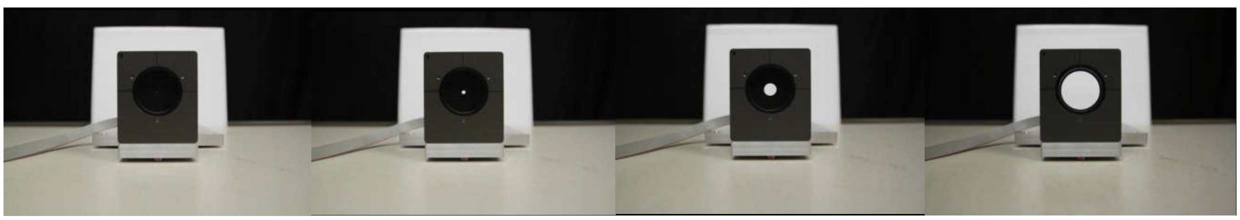


Figure 3-26. Motorized aperture (0 – 36 mm) set to various solid angles.
From left to right – fully closed, 10^{-5} sr, 10^{-4} sr, 10^{-3} sr (based on 1 m viewing distance)

Placing the light sources behind the sphere helped to reduce the amount of spill light. However, a new problem arose – ocular dominance (Sekuler and Blake 1990), which is the relative strength of the visual cortex connection to both eyes. Some cortical cells respond more vigorously to left eye stimulation, others to right eye stimulation (Sekuler and Blake 1990). Ocular dominance makes the aiming of the glare source placed deep behind the sphere a critical issue. If the ray of light were not perfectly aimed at the nose between the eyes, then the experimental conditions would not be the same for both right and left ocular dominant people. This causes an additional source of variability not attributable to the studied phenomenon. One had to assure that both eyes see the same luminance. Therefore, the source was placed closer to the sphere by shortening the front part of the base plate. The distance between the sphere and the light source was determined based on the compromise between ocular dominance and spill light issues. Appendix B provides readings of the background luminance with and without spill light for the final design of the glare source. These measurements show how using the above mentioned techniques helped minimize the influence of spill light.

3.6.2 Measurement Equipment

Two different sets of measuring equipment were used – one set during the experiment, and another between the tests with subjects.

The measurement equipment used during the experiment with subjects included an illuminance meter with the remote head, a Focus EMG Machine, and a video-based eye tracking device. The illuminance meter was a Konica Minolta T-10 meter (body serial # 36621105) with a remote head (serial # 56611034). The meter was calibrated by Konica Minolta on May 28, 2014, which was valid for a year (calibration certificate no. KMSA-001-00-019059). The remote head was installed inside of the sphere on a bar on the right side of the observer (Figure 3-14, Figure 3-9). It measured the illuminance from the background source that was reflected off of the background when the glare source was switched off (the direct component was occluded), and the total illuminance when the glare source was on during each of the three flashes (see section 3.6.3.2). The illuminance measurements served as a quality check to verify that subjects saw stimuli in the expected ranges.

Another piece of equipment was the Focus EMG Machine (by TeleEMG, LCC). Prior to the start of each experiment, the electrodes were placed on the subject's face, and plugged into the Focus EMG machine. The device was then attached to the back of the subject's chair with

Velcro (Figure 3-27). The EMG machine comes equipped with its own software that allows manual control of the device. However, to enable automated data collection, it was integrated into the controls software written specifically for this study (section 3.9)

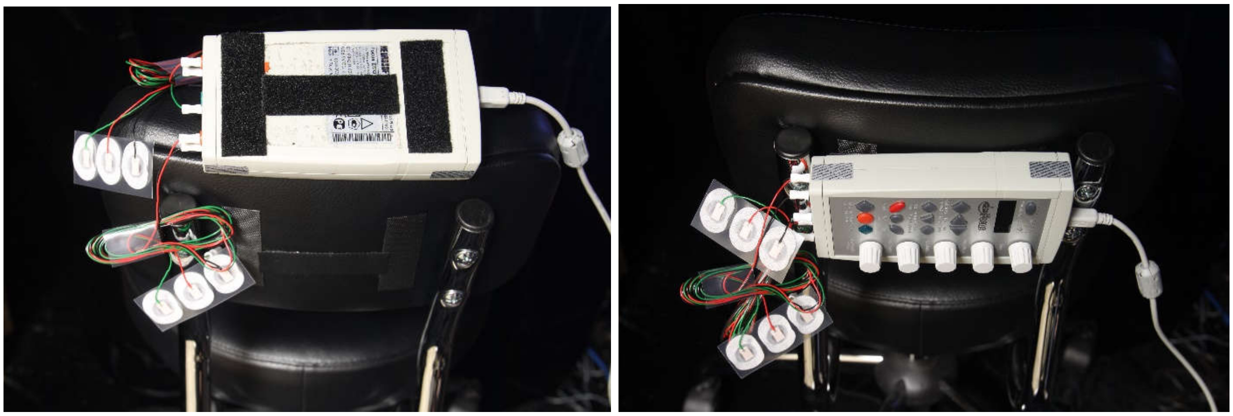


Figure 3-27. Placement of the Focus EMG Machine on the back of the subject's chair

Finally, the piece of equipment used during the experiments was the eye tracking device (ETL-100 Remote by ISCAN). It was located on a stand attached to a support bar intersecting the sphere (Figure 3-1). The device was aimed at the subject's eye, and it recorded data at a rate of 60 data points per second. The communication with the eye tracking software was done through the included ISCAN software (see section 3.6.3.1).

The measurement equipment used between the experiments with the subjects included an illuminance meter (same as mentioned above), two luminance meters, a camera with a MAC laptop for HDRI photography, and an imaging photometer. This equipment was used to additionally check the apparatus consistency over time and to acquire the measurements necessary for discomfort glare metrics calculations (see section 4.1.2).

The luminance meters were a 1/3º Minolta LS-110 (serial # 79923018) and a 1º Minolta LS-100 (serial # 78913009). The meters were calibrated by Konica Minolta on November 20, 2014 and on May 28, 2014 respectively, and were valid for a year (LS-110 calibration certificate no. 001-00-021899; LS-100 no. KMSA001-00-019060). The meters measurements of the glare sources and background luminances were conducted to ensure that the apparatus' characteristics did not change over time.

The camera used for taking HDR images of the background luminance was a Canon Rebel T1i with a 16-35 mm Canon lens. Two software programs – Photosphere and Radiance – were used for processing the images on the Mac laptop.

The imaging photometer used was a P501F model (by Westboro Photonics). Note that the photometer was not calibrated and hence only used for relative measurements, for example, uniformity of the source. Also, the aiming of the glare sources was verified with the imaging photometer.

3.6.3 Controls Software

Software specifically written for this research controlled all the equipment, randomized the conditions presented to the subjects, and automatically recorded all data, except the eye tracking data that had to be recorded separately and manually. Such automated control of the conditions made the experiment fast, efficient, and convenient.

The three following sections describe the software capabilities, the controls scheme, and the software creation and improvement. The latter section explains the rationale of some implementation choices. For example, a flashing sequence with one-second "on" and one-second "off" periods was initially targeted. However, for both "on" and "off" periods 1.2 seconds was actually used instead.

3.6.3.1 Software Capabilities

The software controlled two power supplies - one for each glare source, the controller for the background source, and two controllers for two motorized apertures (Table 3-4, Figure 3-28).

The software recorded inputs from both power supplies, illuminance meter, and the Focus EMG Machine. The eye tracking data were recorded on a separate laptop.

Depending on which one of the predefined 36 lighting conditions was presented to the subject, the devices were set to the necessary levels (Appendix C). The power supplies determined the luminances of the glare sources. They also defined the position of the glare stimulus (0˚ or 10˚); depending on the condition, the position was changed by applying the necessary current to the glare source under test. The controller for the background light source changed the background luminance. Two motorized apertures changed the solid angles of the glare sources.

Table 3-4. Equipment controlled by the custom software

Device	Characteristics/number	Manufacturer
Power supply	3646A DC Power Supply 0-72V/0-1.5A	Circuit Specialists, Inc.
Controller	P02C1-100_USB USB Light Dimmer, AC Light Dimmer 200W 2-Channel x 100W 120VAC 60Hz Single Circuit with a USB Interface	National Control Devices, LLC
Motorized aperture controller	08SMC-1	SK Advanced Group
Motorized aperture	08IDM-050M and 08IDM-1M	SK Advanced Group
Illuminance meter	T-10	Konica Minolta
EMG machine	Focus EMG Machine	TeleEMG, LLC

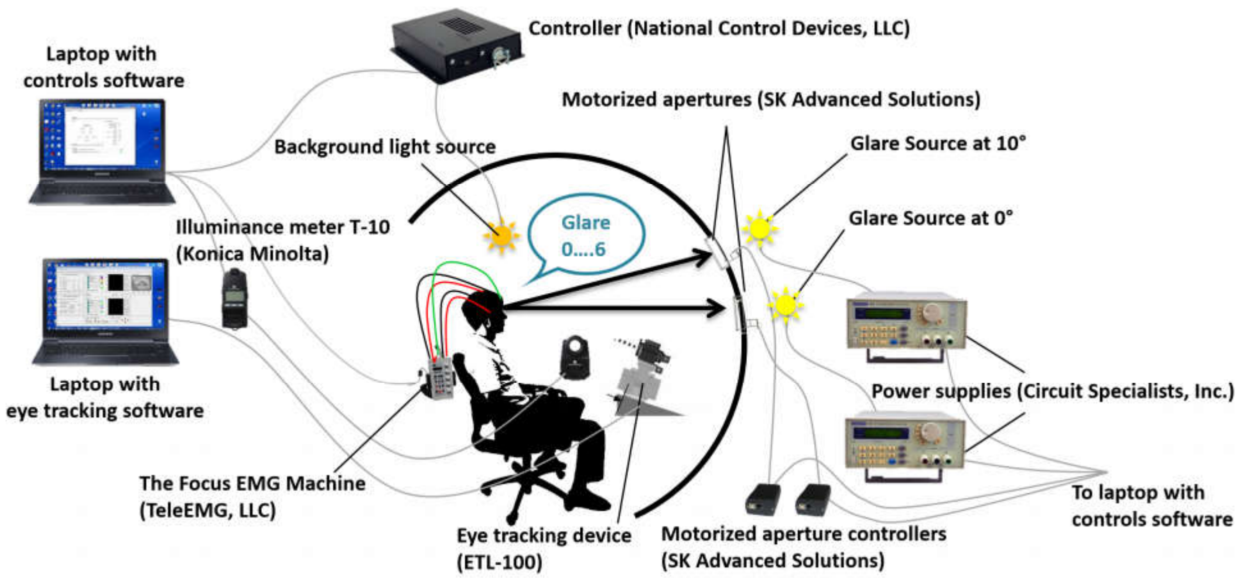


Figure 3-28. Controls software scheme

The software was written in C Sharp and enabled two modes of control – a manual control mode allowing the manual selection of the parameters for the experimental condition, and the auto test mode. The manual mode was mostly used during the development stage of the software and for preliminary testing of the stimuli. The auto test mode was used during the main experiment of this study.

In the manual mode, the experimenter changed the conditions by moving the sliders or typing the numbers in the appropriate boxes (Figure 3-29). In the auto test mode, the predefined 36 conditions were presented in a randomized order (through the Fisher–Yates shuffle algorithm) with minimal input from the experimenter (Figure 3-30). Subjective responses were entered manually through a pop-up window by the experimenter. The auto test ran without stops to ensure the same duration of the experiment for each subject. Nonetheless, a “Pause” button allowed stopping and resuming the experiment to handle unexpected situations.

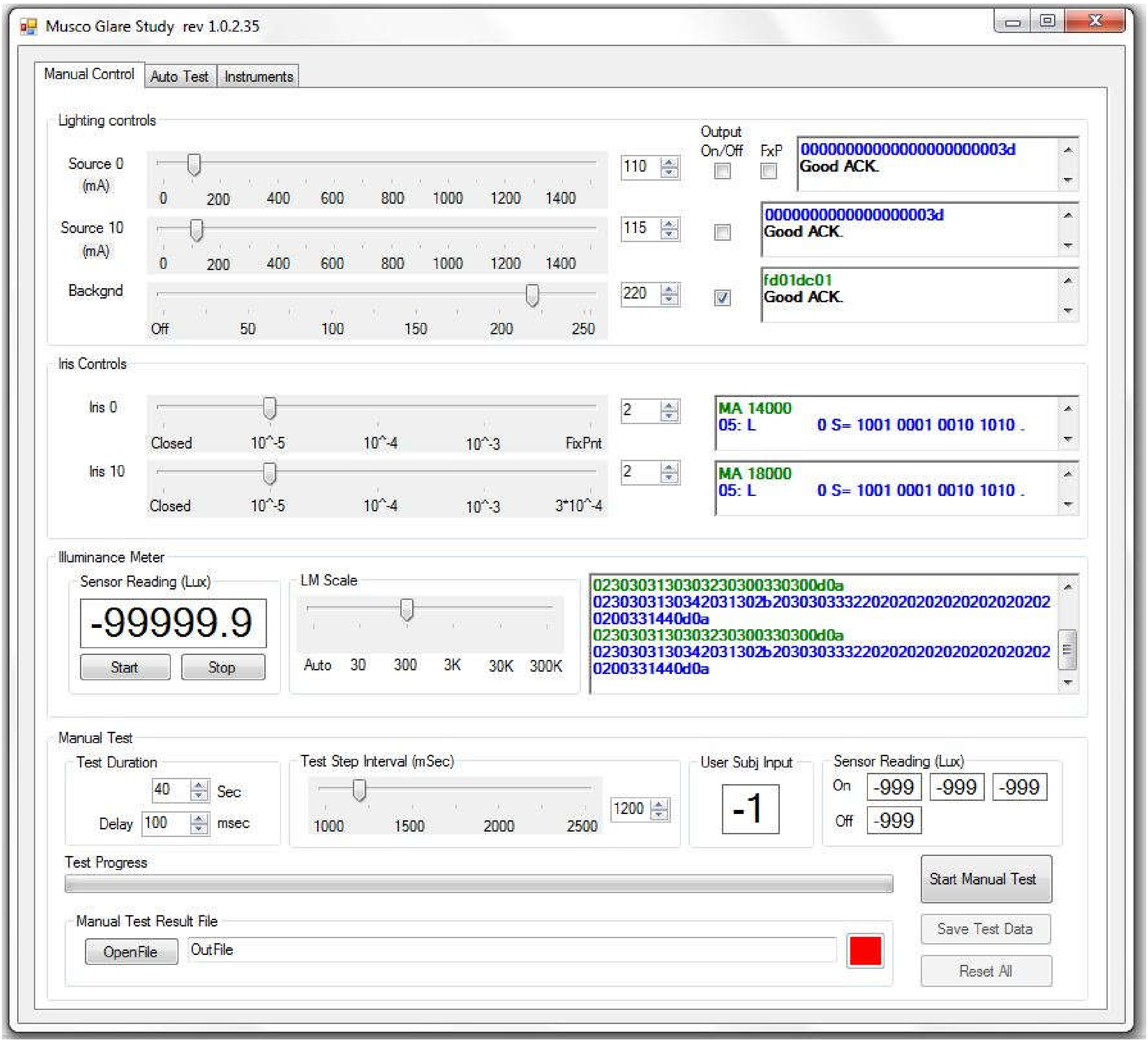


Figure 3-29. User interface of the manual mode of the controls software

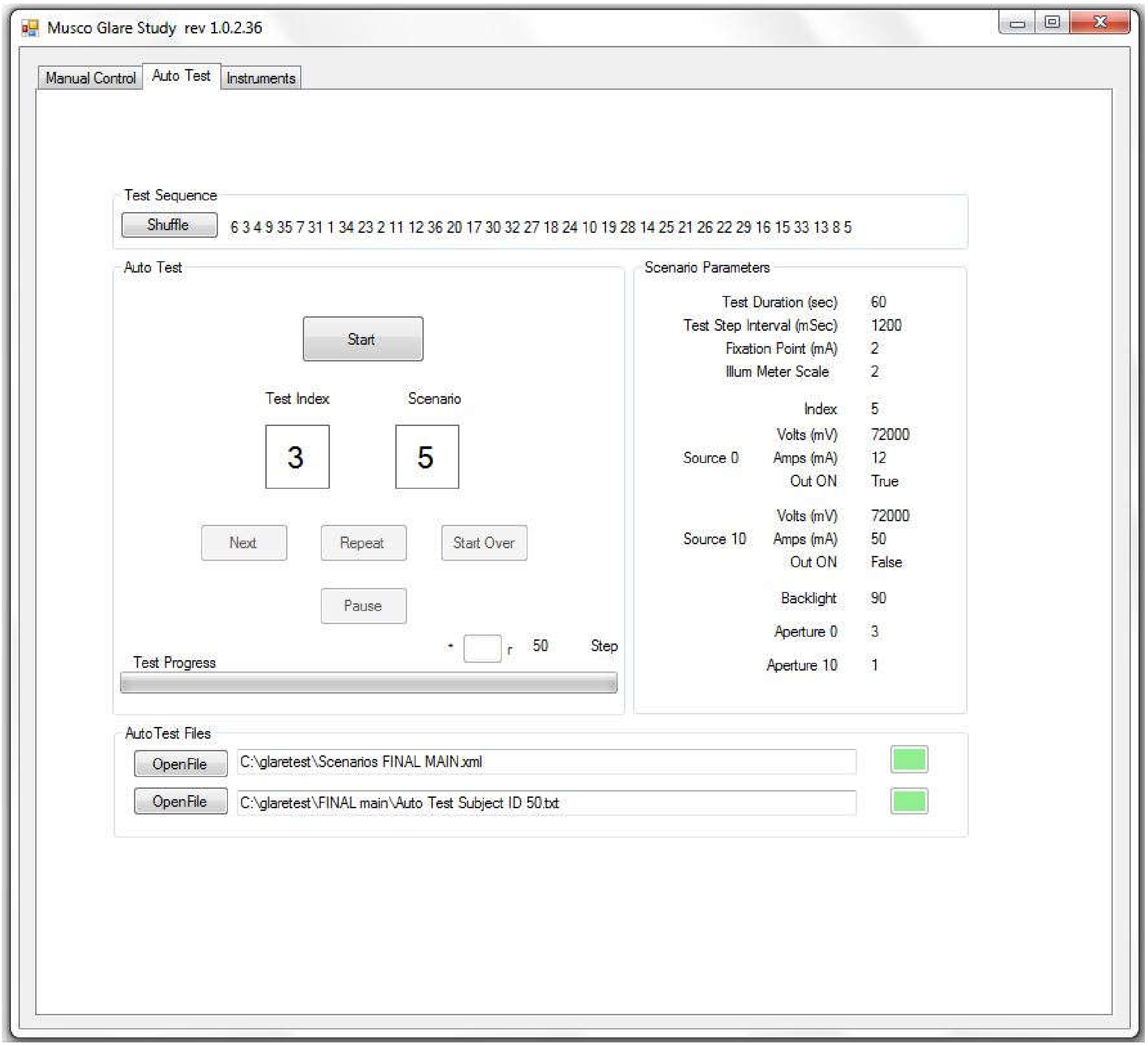


Figure 3-30. User interface of the auto mode of the controls software

Once the experimenter loaded the software, the first step was to open the USB ports to establish communication links between the software and the devices (Figure 3-31, Appendix D). The next step was to load the parameters file, which contained values for the state of all devices at the beginning of each condition (Appendix E).

In the next step, if the manual test mode was used, the experimenter chose a file to which the data from the test were saved. After the experimenter set all the devices to their desired settings, the condition was presented to the subject. In the auto test mode, the experimenter chose a file containing a list of all predefined conditions, and a file to which the subject's data were stored. The settings for the flashing sequence of condition 17 (taken from the file with predefined settings for all 36 conditions) are shown in Table 3-5. The settings during the adaptation time in each condition were specified in the code of the software.

Table 3-5. An example of the settings for the condition 17

Code of the predefined scenario #17	Explanation
<Scenario Code="17">	
<Source0>	*Light source at 0˚*
<voltage>72000</voltage>	*72 Volts on the light source*
<current>110</current>	*110 mA on the light source*
<output>On</output>	*Light source would be switched on during the flashing sequence*
</Source0>	*End of settings for light source at 0˚*
<Source10>	*Light source at 10˚*
<voltage>72000</voltage>	*72 Volts on the light source*
<current>50</current>	*50 mA on the light source (this setting would not matter in this case, see the next line)*
<output>Off</output>	*Light source would NOT be switched on during the flashing sequence*
</Source10>	*End of settings for light source at 10˚*
<backlight>90</backlight>	*Background light source set to 90 (see calibration tables in Appendix F)*
<Aperture0>3</Aperture0>	*Aperture at 0˚ set to 3*
<Aperture10>1</Aperture10>	*Aperture at 10˚ set to 1*

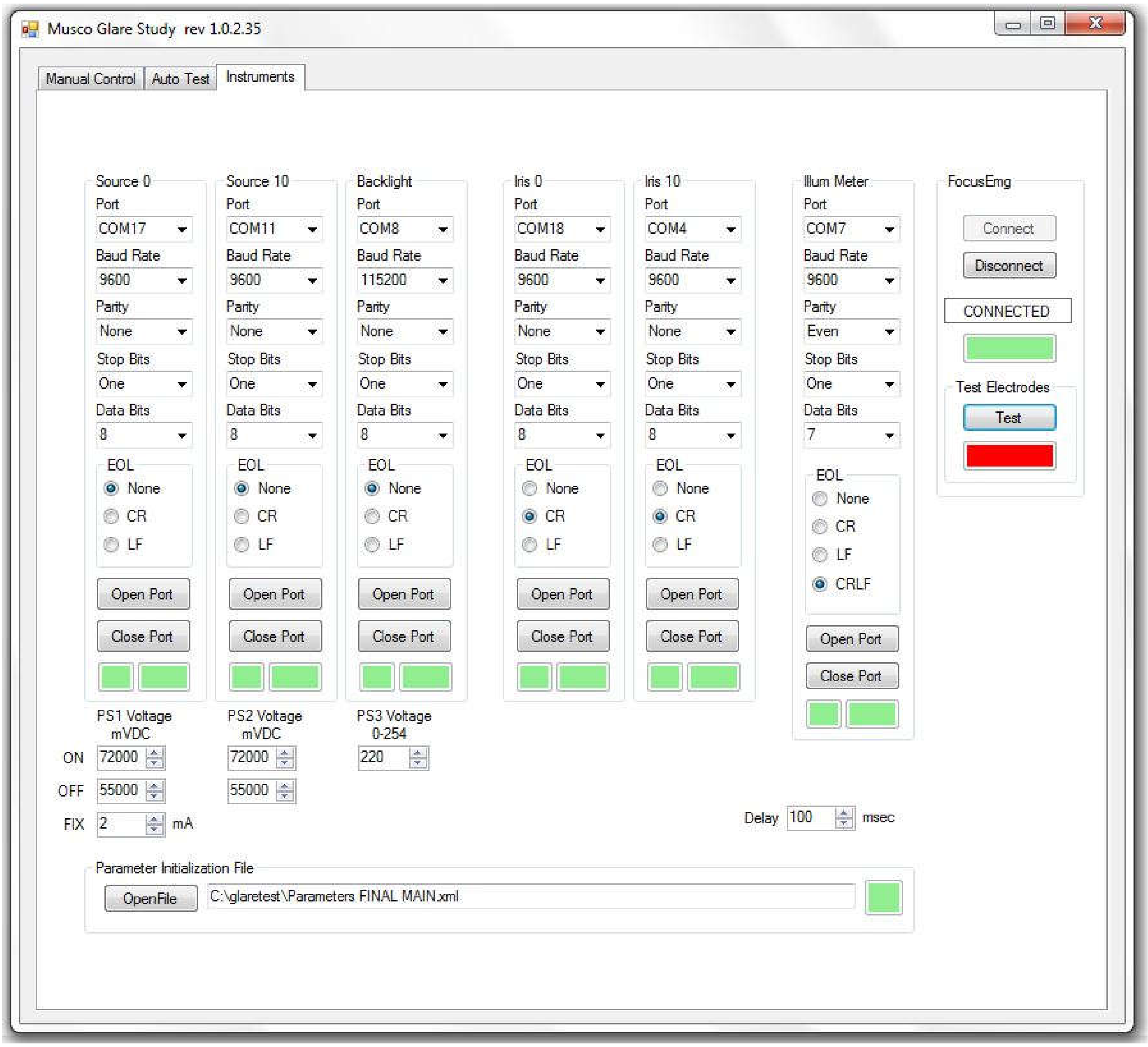


Figure 3-31. Opening USB ports to establish communication links between the devices and the controls software

For each condition and each subject the software recorded multiple data points and saved these data in a text document. A Microsoft Excel template parsed this text file and automatically calculated whether the illuminances recorded to the right of the observer's eyes (Figure 3-32) fell outside the predefined ranges (Appendix G). This range was determined as ± 10% of the baseline values measured before the study had started. For every experimental condition, the controls software recorded the date and time when it occurred, the randomized condition number and the actual sequence number indicating when the condition was presented (the test index increasing from 1 to 36). Another data point recorded a subjective response. Additionally, the time stamp and illuminance when the glare source was off (during the adaptation) were recorded. The time stamps, illuminances, voltages, currents, and power from both power supplies during the three flashes were also recorded. Finally, the last data point indicated whether the EMG data were valid, based on the electrodes impedance test. This test indicated whether the electrodes were properly attached to the subject's face.

The eye tracking device required its own laptop due to the technical constraints of the software - it did not run on any other laptop than the one it was initially installed on. Therefore, these data were recorded manually for each subject and each condition. The interface of the software is shown in Figure 3-33. Pressing the "Start Record" radio button started the recording at 60 Hz for a number of points defined a priori (Eye tracking laboratory manual). The recording automatically stopped after 12 seconds (720 data points) in this study. The file was saved through "Save ISCAN ASCII Data File as" option. An example file is too lengthy to include here, but a part of a file is shown in Appendix H.

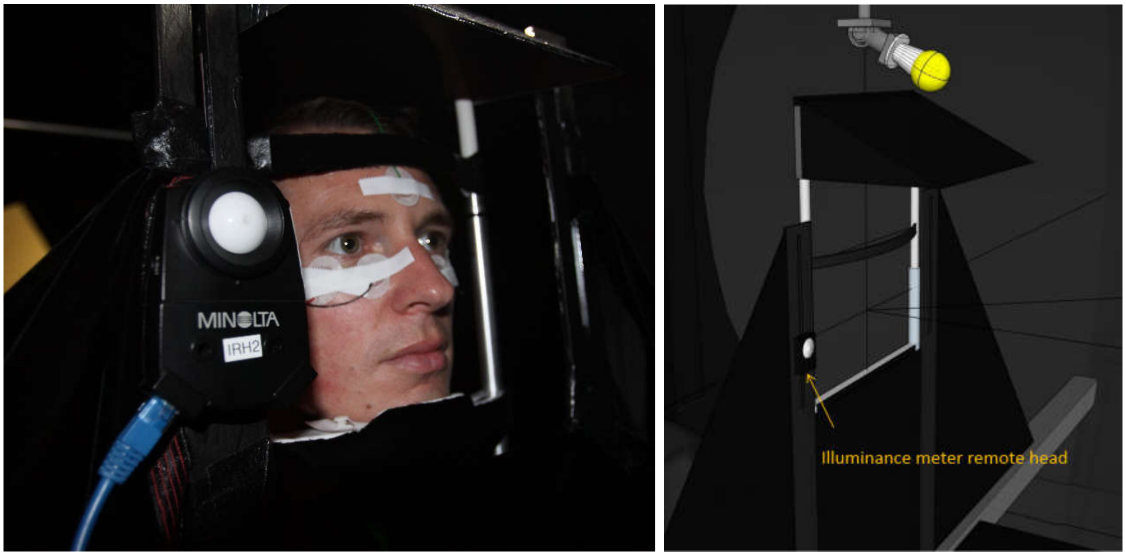


Figure 3-32. Subject on the chinrest with electrodes attached to the face during the experiment

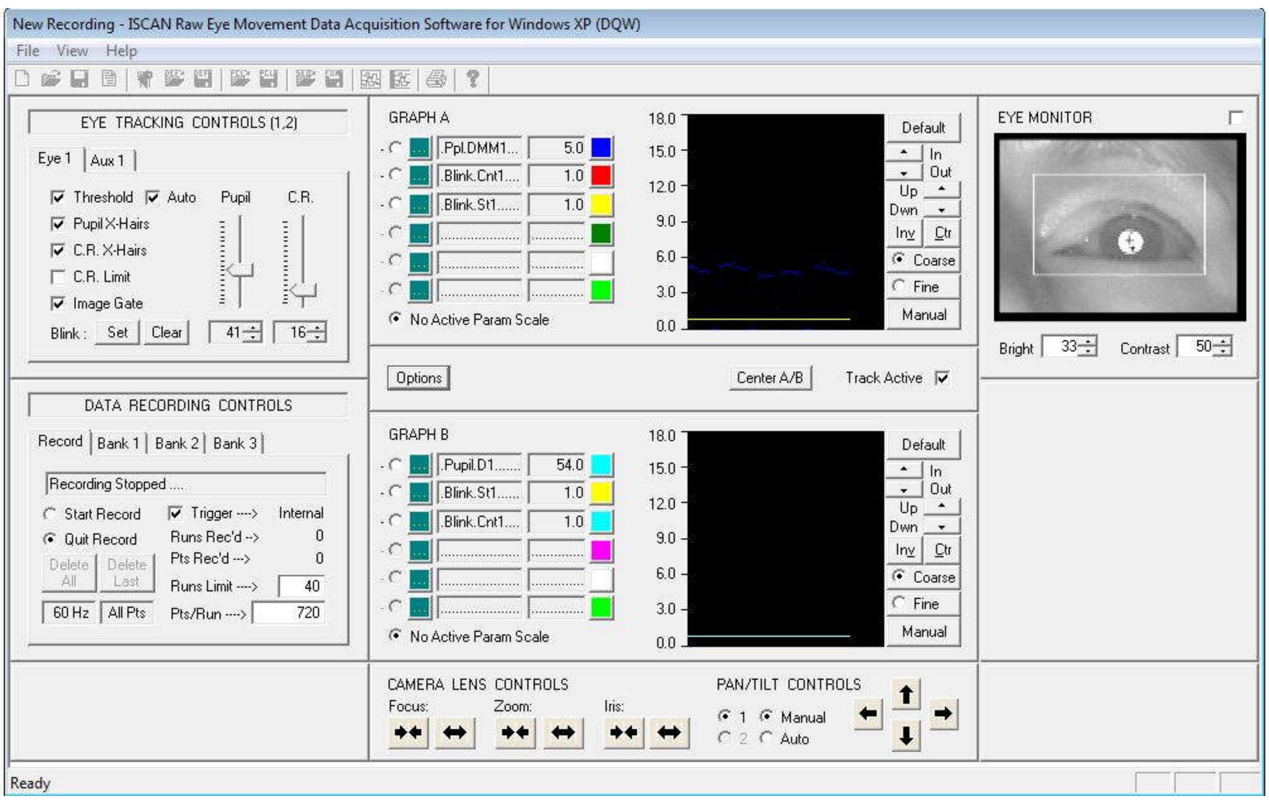


Figure 3-33. ISCAN raw eye movement aquision software interface

3.6.3.2 Controls Scheme

The duration of one experimental condition was 60 seconds or 50 time steps (one time step = 1.2 seconds). A time step concept was used since the controls software code utilized half time steps. The simplified scheme of the events occurring during one experimental condition is shown in Figure 3-34.

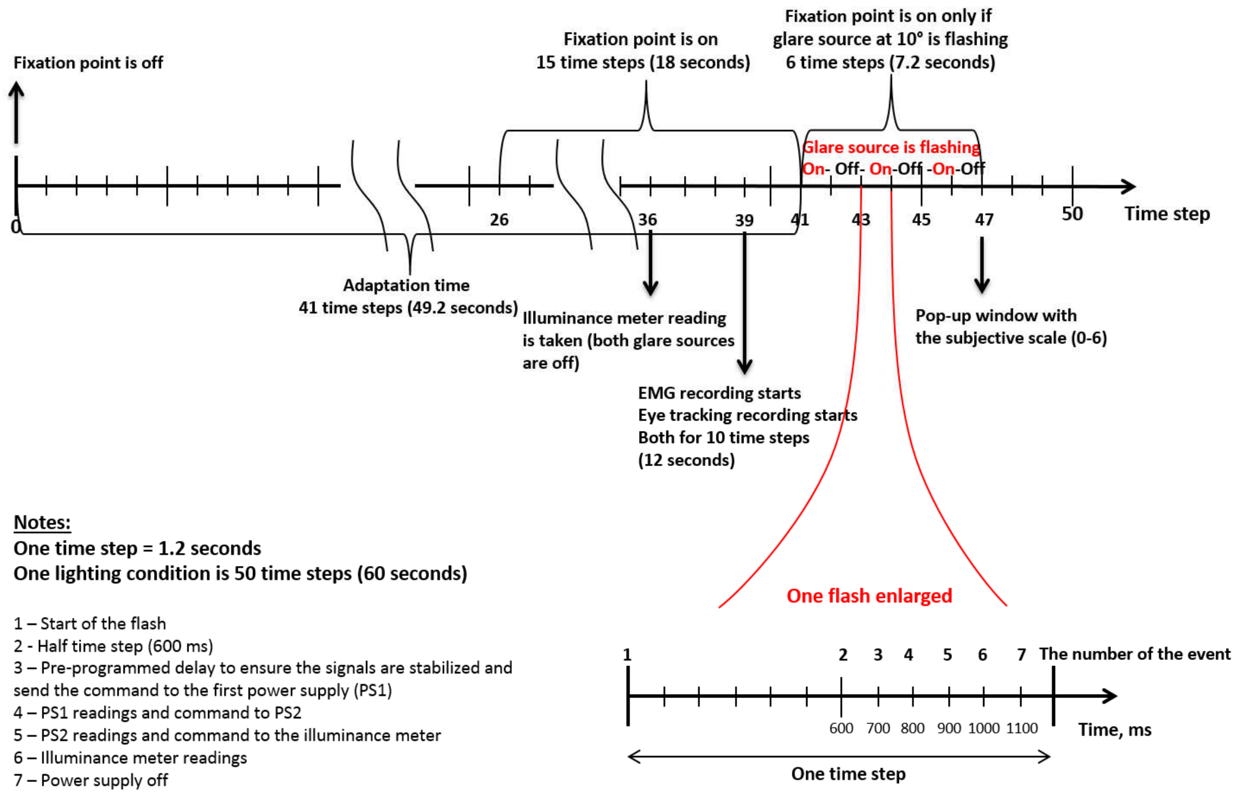


Figure 3-34. Timeline during one experimental condition

<u>Events during one lighting condition</u>

1) At the beginning of each condition, the software read the scenarios (conditions) file (the main settings are shown in Appendix C), and sent the commands to all devices accordingly (e.g. to the controller of the background source to set the background luminance to 0.3 cd/m^2). The initial state of both apertures was closed. The background source was on; it created the

background luminance (adaptation) necessary for the experimental condition under test. The glare sources were in the "off" state (55 V, 0 mA).

The subject adapted to the background luminance for 49.2 seconds (41 time steps). During the first 31.2 seconds (26 times steps) the subjects were allowed to look around without moving their head; the head was positioned on the chinrest. This helped subjects to relax their eyes, avoid fatigue, and boredom.

2) At 31.2 seconds (the 26th time step), the fixation point (source at 0° position) was switched on. At this point, the subjects had to look at it at all times; the experimenter monitored the subjects through the eye tracking camera.

3) The illuminance reading was collected at 43.2 seconds (the 36th time step) - the glare source was off, while the background source was on.

4) At 49.2 seconds (the 41st time step), depending on the condition, one of the glare sources started to flash. If the glare source at the 10º position flashed, the fixation point at the 0º position (on the line of sight) remained in the 'on' state. However, if the glare stimulus was presented at 0º, the fixation point was switched off, and the glare source at 0º started to flash. The software read currents, voltages, and power from both power supplies, and illuminances from the illuminance meter during each flash.

5) After the flashing sequence, at 56.4 seconds (the 47th time step), a radio button window appeared for at most 2 minutes allowing the input of the subjective response.

6) At 60 seconds (the 50th time step), if the subjective response were entered into the pop-up window, then the software would proceed to the next condition until all 36 conditions were completed.

In case of unpredictable events, the experimenter could pause the automatic test sequence and resume upon resolution of the event. If the "Pause" button was pressed during the adaptation time, the software stopped immediately and waited for further actions. If "Pause" was pressed during the flashing sequence, the software did not stop immediately; it continued until the end of the sequence. At that time, the experimenter had a choice of either repeating the condition or proceeding to the next random condition.

3.6.3.3 Software Creation and Improvement

The two major challenges of creating such sophisticated controls software were to ensure reliable communication between the laptop and a number of devices that use different communication protocols, and to synchronize their performance. Many decisions during the development of the software were based on overcoming equipment limitations. This section addresses the major issues.

Reproducibility and consistency of the light source presentations were of crucial importance. The experimenter had to ensure that all subjects saw the same stimuli. As previously mentioned, illuminances collected during the adaptation time and the three flashes served as a quality check for the consistency of stimuli (Figure 3-14, Figure 3-32). The voltage, current, and power readings of the sources were recorded for each experimental condition for each subject as additional quality metrics.

During the software debugging stage, it was noted that the fixation point did not appear at all, despite the fact that it was programmed to do so. It happened because the aperture failed to change from the closed state (0 mm) to the fixation point state (approximately 2 mm in diameter) - the aperture blades needed a higher initial momentum to open. Therefore, in the auto sequence, the aperture was programmed to open up to a larger diameter first, and then to decrease the diameter of the opening to the fixation point position, which solved the problem.

During the calibration stage, it was noticed that illuminance readings differed significantly when measured multiple times during the same lighting condition. Illuminance measurements depended on whether the aperture's current diameter was set from a previously larger diameter or a smaller one. For example, if in condition 15 the aperture was set to a solid angle of 10^{-5} sr from a condition with a solid angle of 10^{-4} sr, the illuminance at the eyes was 5.7 lx. However, if the aperture was set to the solid angle of 10^{-5} sr from the fixation point state, then illuminance was 4.6 lx. Therefore, to ensure consistency, the aperture diameter was programmed to always increase from a smaller diameter to the diameter of interest. The only exception was the fixation point state mentioned above; it was always set from an initially larger diameter.

The next challenge was the limitation of the LED/power supply reaction time. The predefined flashing sequence of the glare source was 1 second on – 1 off – 1 on – 1 off – 1 on, similar to previous studies (e.g. Putnam and Faucett 1951). The initial LED current was set to 1000 mA in the "on" position, and 0 mA in the "off" position. However, ramping up the LED current to 1000 mA took the LED/power supply more than five seconds. Therefore, the LED current (thus the luminance of the flash) at the end of one second resulted in seemingly random numbers (e.g. 800 or 910 mA). This inconsistency was unacceptable when presenting stimuli to the subjects. The current seemed to reach saturation at higher values. For this reason, the experimenter had to find the current that could be reached almost instantly and reliably. A current of 850 mA was the maximum consistent current that could be reached in a time period of less than one second.

The next challenge was similar in nature to the high current problem, but now for small currents. When the current was set to 10 mA, the LED did not flash at all. In this case, one second was not long enough for the power supply to ramp up to 10 mA. To enable proper presentation of all three flashes, a minimum voltage of 55 V was applied to the LEDs throughout the experiment. This new starting voltage allowed the LEDs to reliably ramp up to the full output in the given time frame.

During the early stages of testing, the software crashed almost every single time when the experimenter ran the set of the 36 lighting conditions. Troubleshooting made it clear that the USB cables to the apertures were causing the issue. Since the apertures were located behind the sphere (Figure 3-10, Figure 3-11), they were connected to the laptop via the USB extension cables and a USB hub. These cables exceeded the maximum length allowed for passive USB cables. By specification, a passive USB cable has a limited maximum length that is based the propagation properties of electromagnetic fields. Therefore, an active extension cable was used (Tripp Lite model U026-016), which solved the instability problem of the software.

The initial plan for the flashing sequence was 1 second "on" and 1 second "off" periods. During the time when the flash occurred, multiple communication steps took place between the devices. The glare source was set to its full output first (Figure 3-35), then voltage, current, and power readings were recorded from the first power supply and then from the second one. Finally, the illuminance during the flash was recorded. If the "on" period were too short, the data acquisition from all devices during the time when the source was fully on would not be completed. Instead, the readings resulted in random inconsistent numbers that were not representative of the actual condition. In this case, reliability could not be guaranteed. The solution is described in the paragraphs below.

Initially, the commands to both power supplies and the illuminance meter were sent right after switching the glare source on, but this resulted in inconsistency of the readings. One had to account for the time it takes the LED to achieve its full output. Therefore, additional software was written to test the shape of the voltage and current waveforms, and the consistency of the illuminance readings (the user interface is shown in Figure 3-36 to Figure 3-38).

The voltage waveform for the glare source positioned at 10° and set to 20 mA is shown in Figure 3-35. Note that the duration of the stimulus in this case was longer than in the actual experiment, because acquiring the shape of the waveform required a higher recording frequency. Since this frequency was limited, the program took 20 readings as fast as possible which resulted in the longer stimulus duration. However, this was not an issue, because the front part of the waveform was of primary interest in understanding how long it takes the LED to reach its full output.

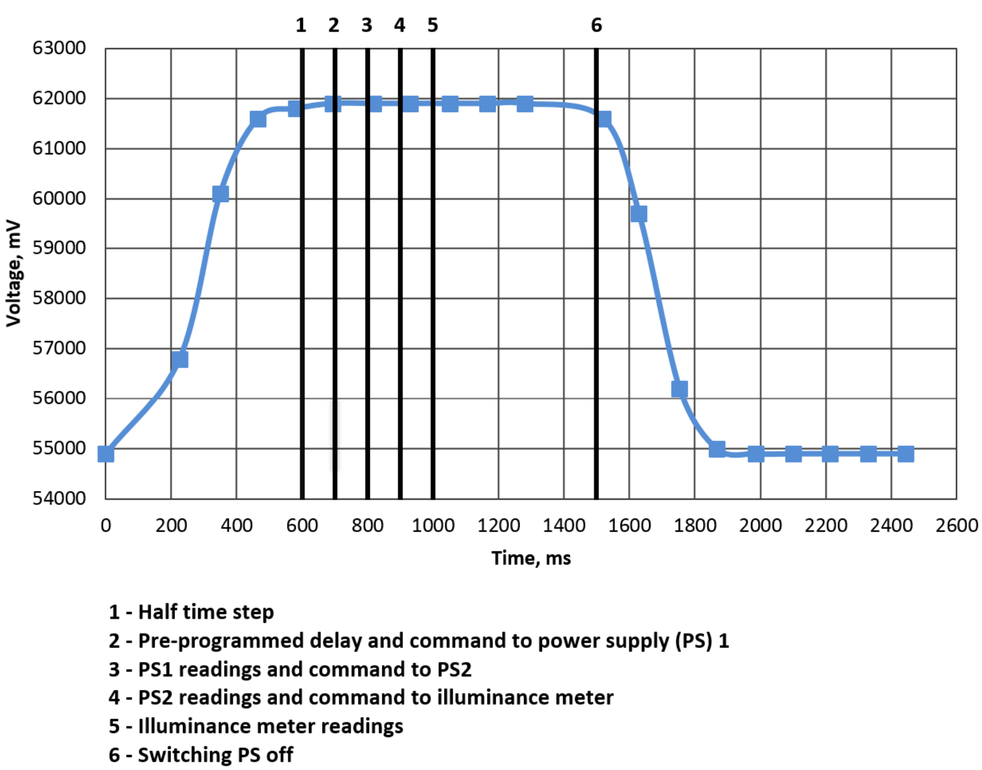


Figure 3-35. Voltage waveform for the glare source positioned at 10° and set to 20 mA

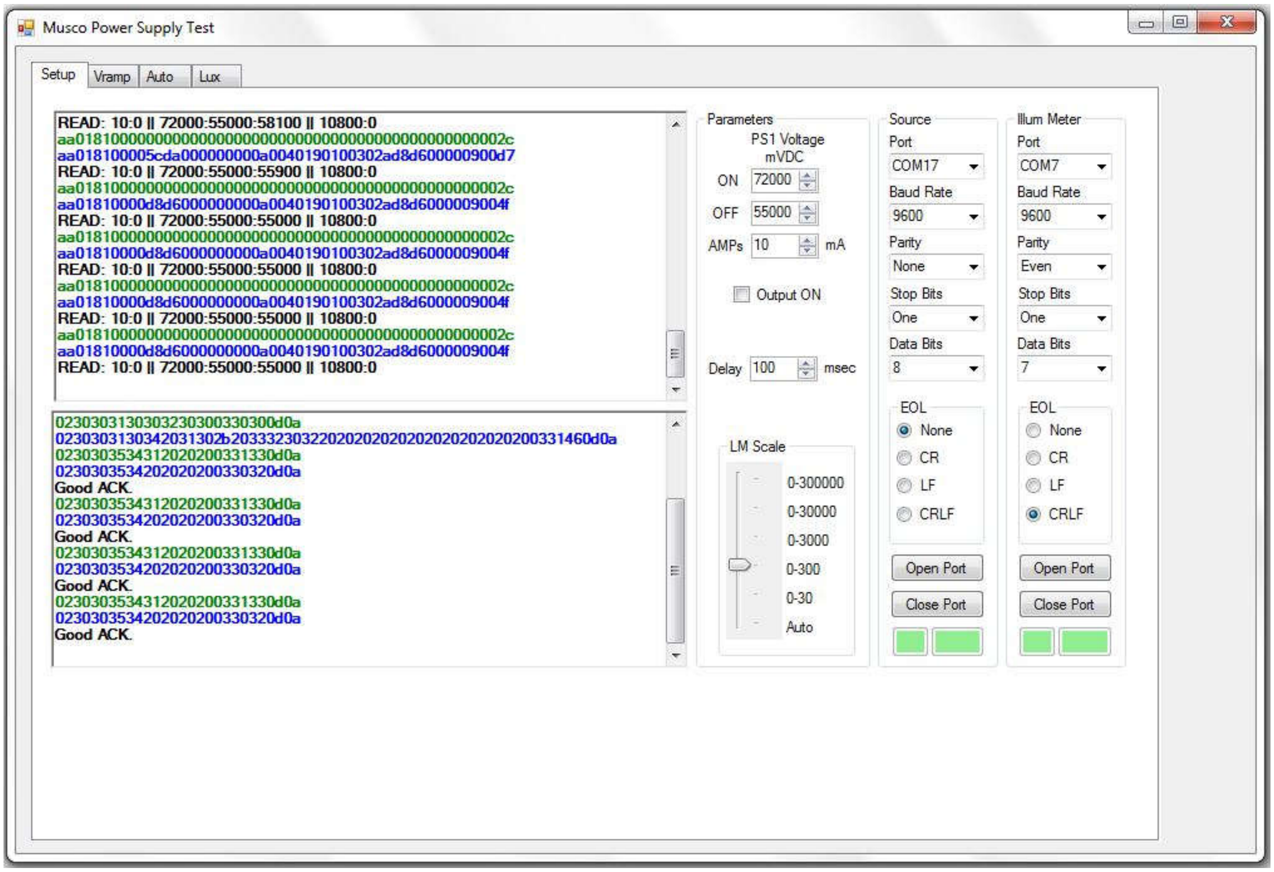


Figure 3-36. Software to test the consistency of voltage, current, and illuminance readings

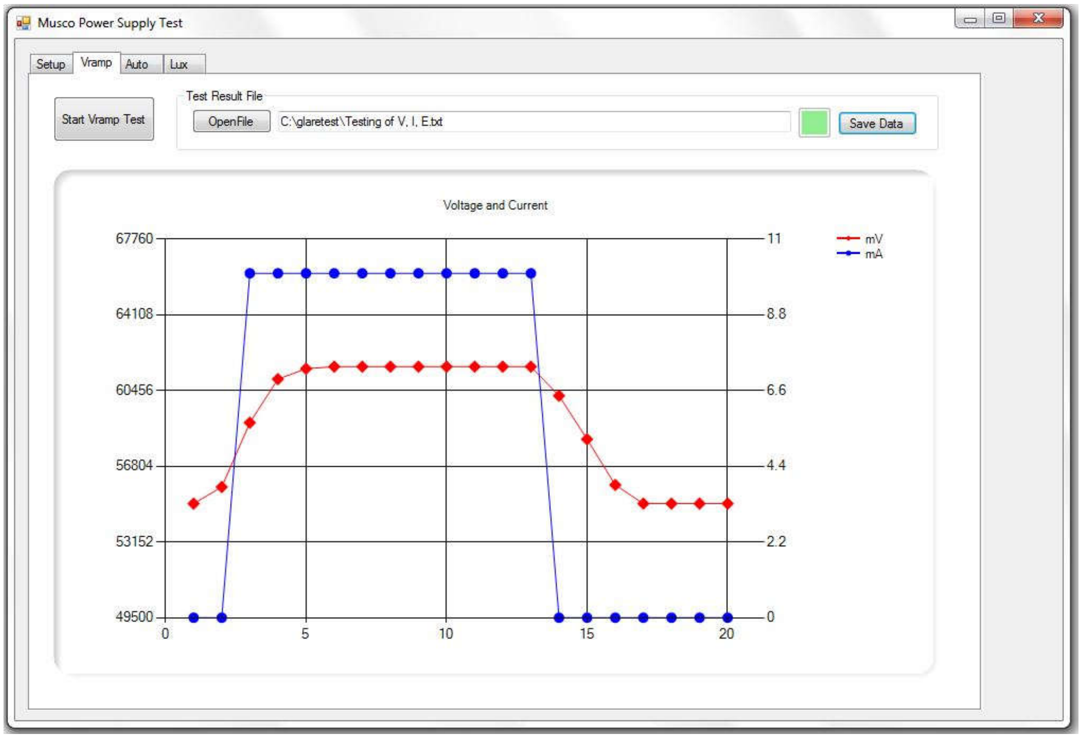


Figure 3-37. Software to test the consistency of voltage and current readings

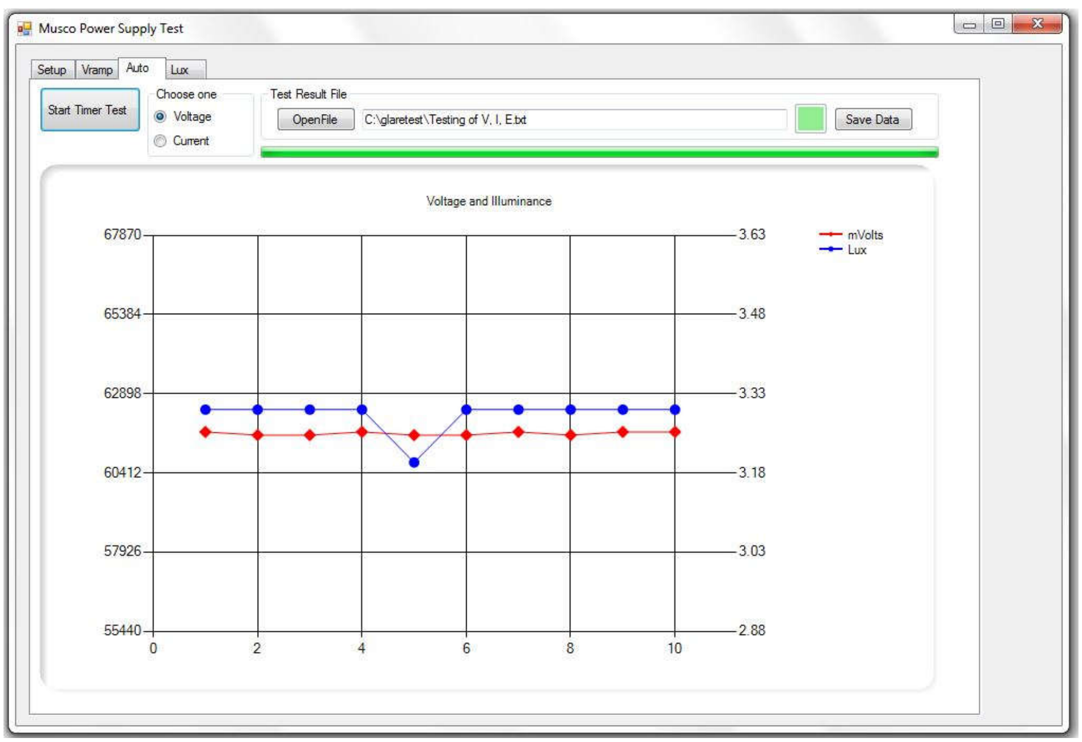


Figure 3-38. Software to test the consistency of illuminance readings

Based on the voltage and current waveforms (Figure 3-35, Figure 3-39), the timing for each device was determined that guaranteed stable readings. Figure 3-40 shows how fast the illuminance meter responded to a command to record illuminance during the time when the light source was on. Due to the limitations of the devices' response-latencies, the time of the "on" and "off" periods had to be increased from 1 second to 1.2 seconds to enable the consistent collection of all desired measurements.

The total duration of one flash was 1200 ms; a half time step was 600 ms. No readings were taken during the first half time step, because the LED was not at its full output yet. At approximately 700 ms, the command was sent to power supply one (PS1) to acquire the voltage, current, and power readings of the glare source at position 0°. The same command was sent to power supply two (PS2) at approximately 800 ms, and, at the same time, the readings from PS1 were recorded. The readings from PS2 were recorded at approximately 900 ms, and at the same time, a command to the illuminance meter was sent. At approximately 1000 ms the illuminance of the flash was recorded. Finally, the light source was switched off at 1200 ms which concluded one "on" increment (one flash).

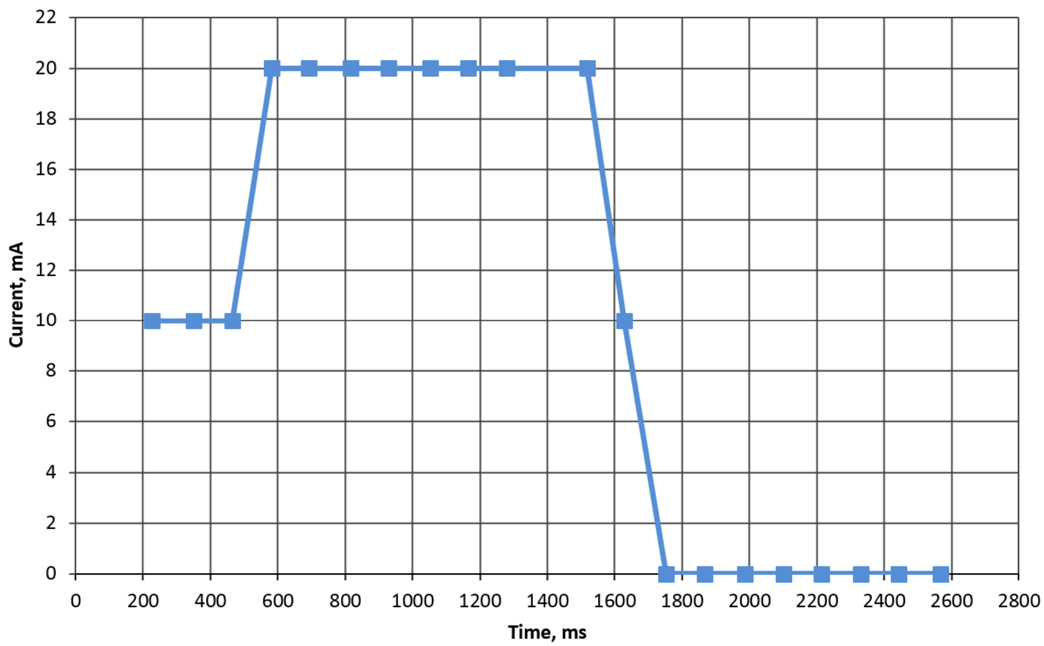


Figure 3-39. Current waveform for the glare source positioned at 10° and set to 20 mA

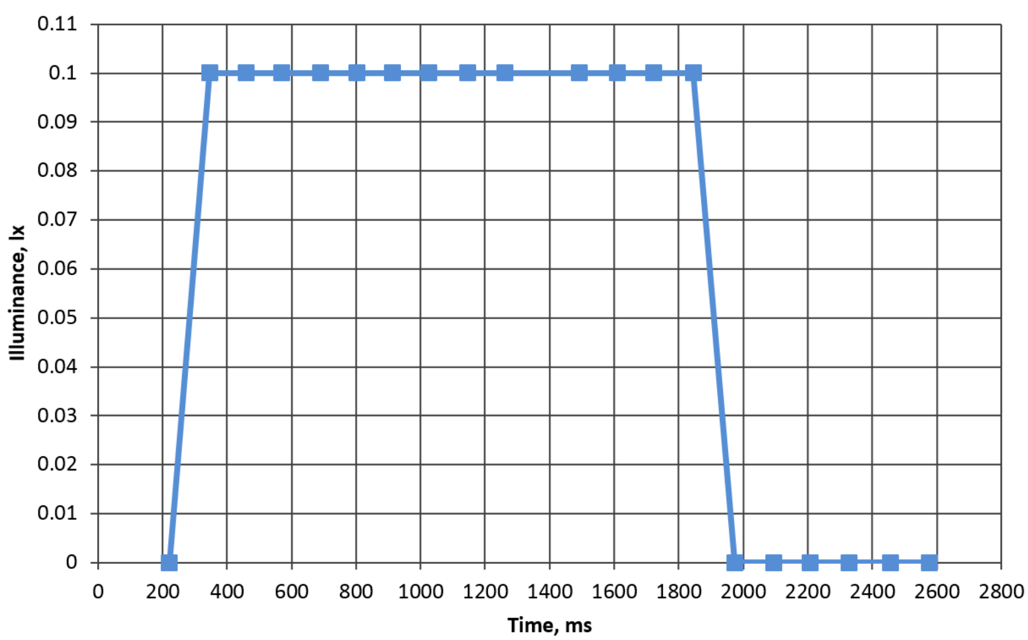


Figure 3-40. Illuminance meter response to a command to record the illuminance when the glare source positioned at 10° was set to 20 mA

Despite the fact that illuminances were collected during the stable part of the flash (at approximately 1000 ms in Figure 3-40), the illuminance inconsistency persisted. The problem was related to the measuring mode of the meter. Konica Minolta's illuminance meter (T-10) has five options related to the measuring ranges (Illuminance meter manual). By default, the measuring range is automatically switched from one range to another during the measurements. The code that determines the range on the meter was unknown. However, the assumption was that when one measures illuminance in the auto measuring range, the meter requires some time to determine the 'correct' range and display the value. The meter consequently checks whether the value fits into a measuring range until it finds the appropriate one. Searching for the appropriate range took longer than the flash duration. When a constant stimulus was presented, the illuminances measured in sequence resulted in random numbers (Figure 3-41). The maximum illuminance at the eyes did not exceed 299.9 lx in this experiment. Therefore, instead of using the auto measuring range option, the meter was set to the range #2 (0.0-299.9 lx), which solved the inconsistency issue. Figure 3-42 shows the illuminance readings for a constant stimulus recorded in sequence when the measuring range #2 was set on the meter (as opposed to the auto measuring range in Figure 3-41).

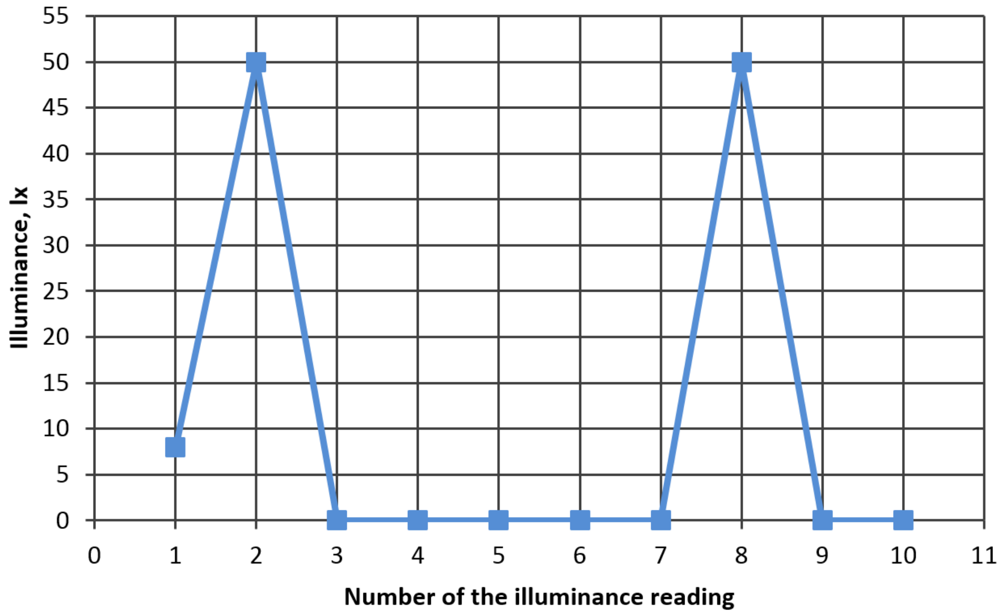


Figure 3-41. Illuminance readings of a constant stimulus recorded in sequence using the meter's automatic measuring range

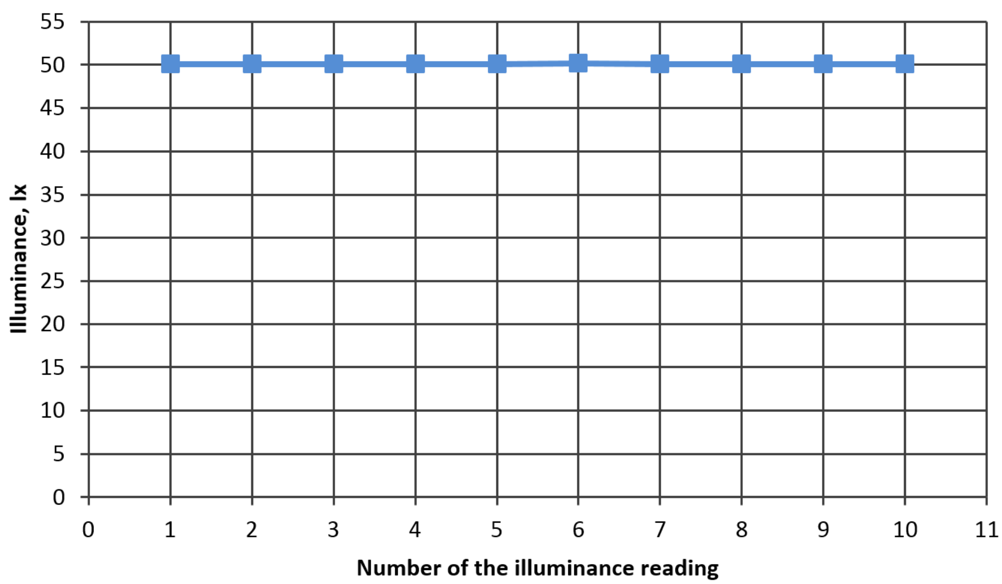


Figure 3-42. Illuminance readings of a constant stimulus recorded in sequence using the meter's measuring range #2 (0.0-299.9 lx)

3.7 Calibration and Measurements

This section describes calibration measurements of the apparatus completed before the experiment started and a set of measurements collected four times over the course of this study (after 18, 34, 44, and 56 subjects) to ensure reliable performance of the apparatus over time and the quality of the acquired data. In addition, these measurements enabled discomfort glare metrics calculations. For example, for Bullough's et al. metric (2008), it was necessary to measure the light source illuminance, ambient illuminance, and surround illuminance (section 2.3.4).

The following measurements were recorded:

- Background luminance with a luminance meter at 11 points at all background luminance levels;
- HDRIs of the background luminance at all background luminance levels;
- Luminance of both glare sources at all luminance levels;
- Spill light caused by the glare source at its highest output and largest size used in this study - the increase in background luminance when compared to the state without the glare source;
- Illuminances at the left and the right eye at all glare source luminance levels;
- Illuminances at the right bar measured for all 36 conditions. These measurements served as the quality check – the baseline for the illuminances measured for each subject during the experiment;
- Illuminance at the eyes (center) caused by the background source reflected off of the background (ambient illuminance);
- Total illuminance at the eyes (at the center) for 36 conditions;

- Only the direct component of illuminance from each glare source (0˚ and 10˚ position) at the eyes for 36 conditions;
- Illuminance at the eyes from the glare sources after reflection from surrounding surfaces for 36 conditions (surround illuminance); the direct component was blocked.

Each of the glare sources consisted of seven components (see section 3.6.1.1), two of which were calibrated – the motorized aperture and the LED chip.

The motorized aperture that changed the solid angle of the glare source used its own unit system (e.g. the smaller aperture had the range of 0 - 170,000 control steps), which was mapped to mm using a caliper (Appendix F). Since two apertures were not the same model, setting the apertures to the same solid angle required different numbers in their unit system. For example, for the aperture located at 0˚, 14,000 mapped to 3.6 mm (a solid angle of 10^{-5}sr for a distance of 1 meter), but for the aperture at 10˚, the same solid angle was achieved at a setting of 18,000.

The currents on LEDs were mapped to luminances (Appendix F). Since the LED chips did not exhibit the exact same characteristics, different currents were applied to the LEDs to create the same luminance.

To enable consistent measurements of the background luminance with the luminance meter over time, the investigator had to mark a set of points on the background. Eleven points were arranged in three circles around the fixation point (5˚, 10˚, and 20°) (Figure 3-43). According to Boyce (2003), if the subject has one point of fixation, then the average luminance within approximately 20º of the fixation point is a reasonable estimate of the adaptation luminance. The background luminance was calculated as the average across these eleven points.

The investigator initially used pins to mark the points of interest. Once the marks were checked with the laser level (Figure 3-44), the points of interest were marked with a silver permanent marker. These marks were visible enough to acquire consistent readings over time (Figure 3-45). In addition to eleven points measured with the luminance meter, HDRIs were taken to acquire background luminances of the entire field (Appendix A). For a detailed description regarding the HDRI measurements method, refer to the paper by Tyukhova and Waters (2014).

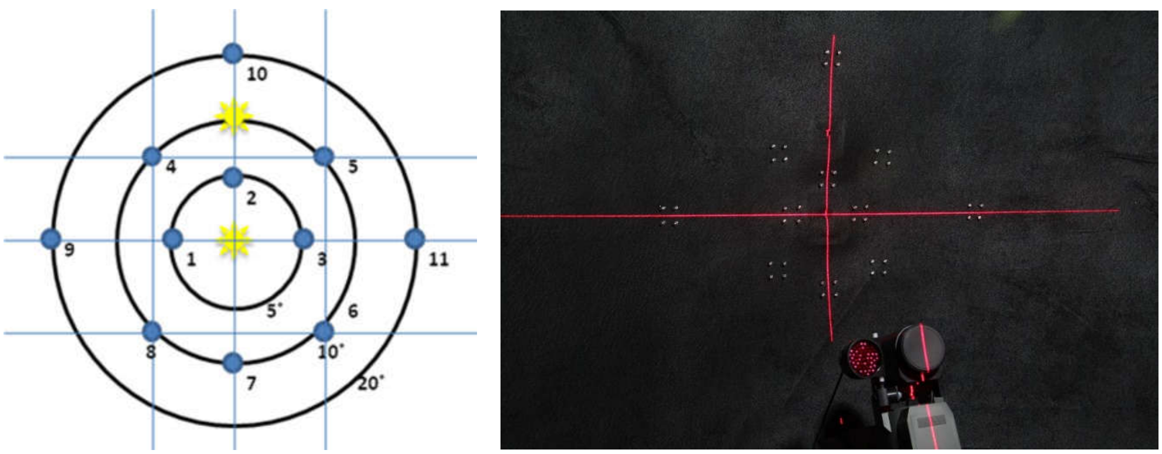


Figure 3-43. Schematic representation of eleven points of interest to test the uniformity of the background luminance and consistency over time (left) and actual eleven points in the apparatus shown together with laser level marks (right)

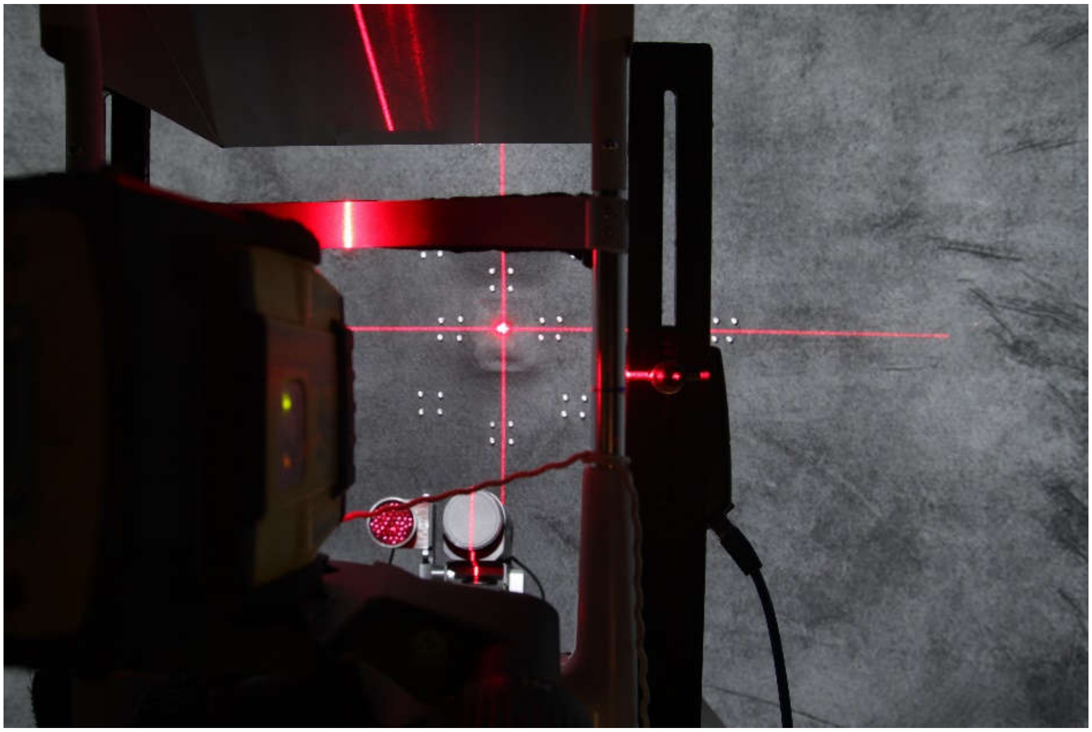


Figure 3-44. Checking the markings of eleven points with the laser level

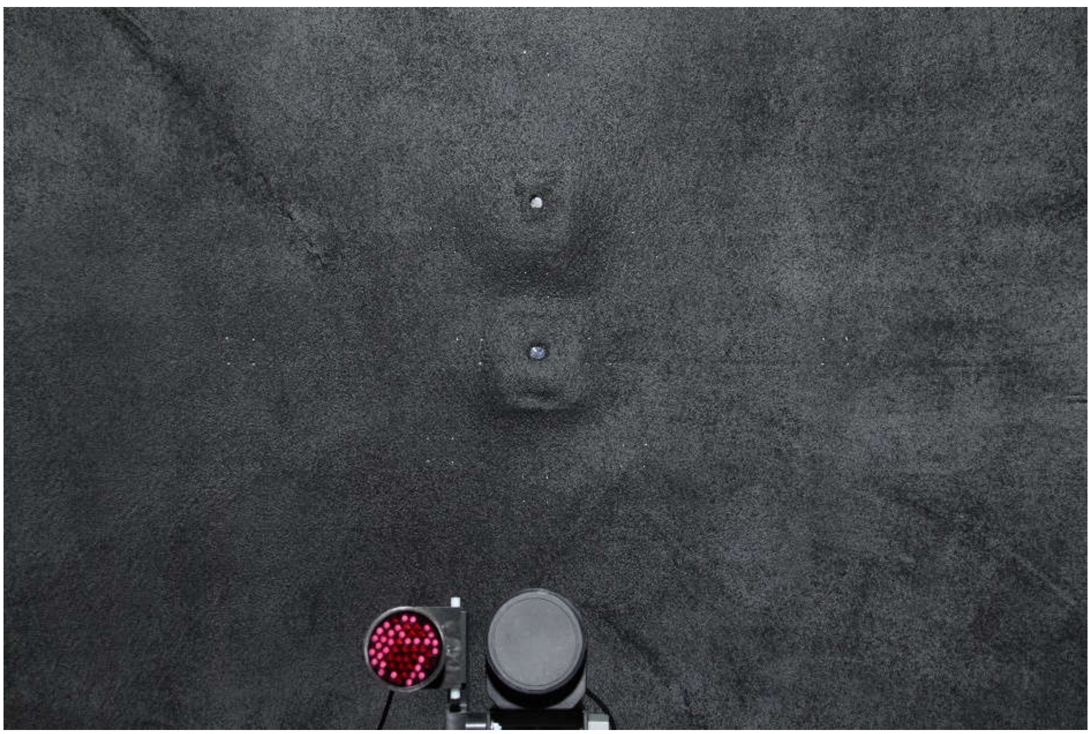


Figure 3-45. Eleven points of interest marked with a silver permanent marker (view from the subject's position)

Ensuring consistent measurements of the glare source and background luminances between the experiments with subjects required the same positioning of the luminance meter for every set of measurements. A tripod was essential for this purpose. Since the measurements were scheduled between the tests with subjects, the tripod was relocated a number of times. To ensure the same tripod position across the measurements, caster cups were attached to the floor (Figure 3-46). In addition, to ensure a consistent distance from the floor to the luminance meter, marks were added to the tripod legs. The length of the tripod legs was left unchanged throughout the experiment.

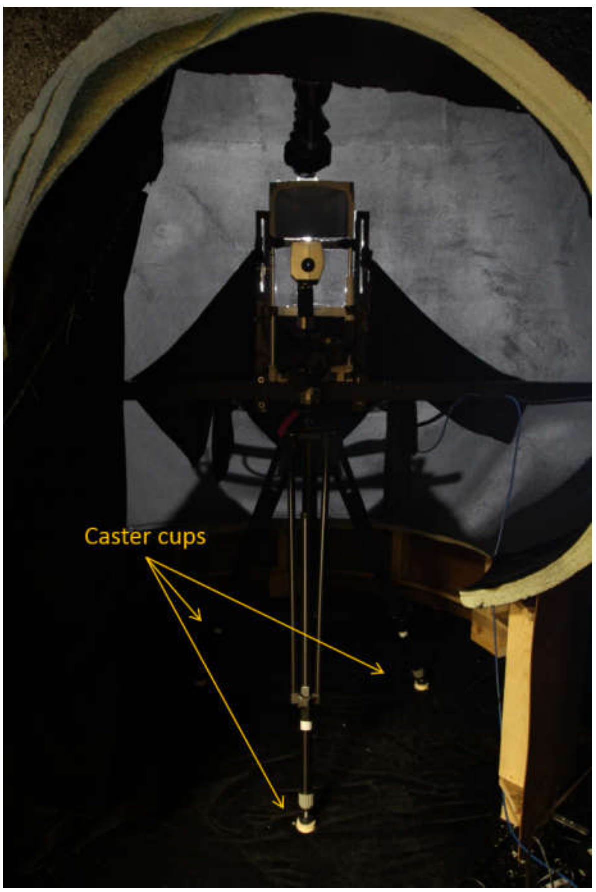


Figure 3-46. Caster cups attached to the floor allowed consistent positioning of the luminance meter on the tripod over time

Ideally, the focal-plane of the luminance meter would be positioned exactly where the subject's eyes were located – at the center of the sphere. However, this was not possible due to limited physical space. The dimensions of the tripod and construction of the bar across the sphere did not allow the placement of the luminance meter at the position of the subject's eyes (one meter distance from the glare sources). Therefore, the location of the luminance meter's focal-plane was behind the eye level (Figure 3-47). This difference between the desired one meter distance and the actual distance from the glare source to the focal-plane of the luminance meter was accounted for with the focus distance setting (1.17 m) on the luminance meter.

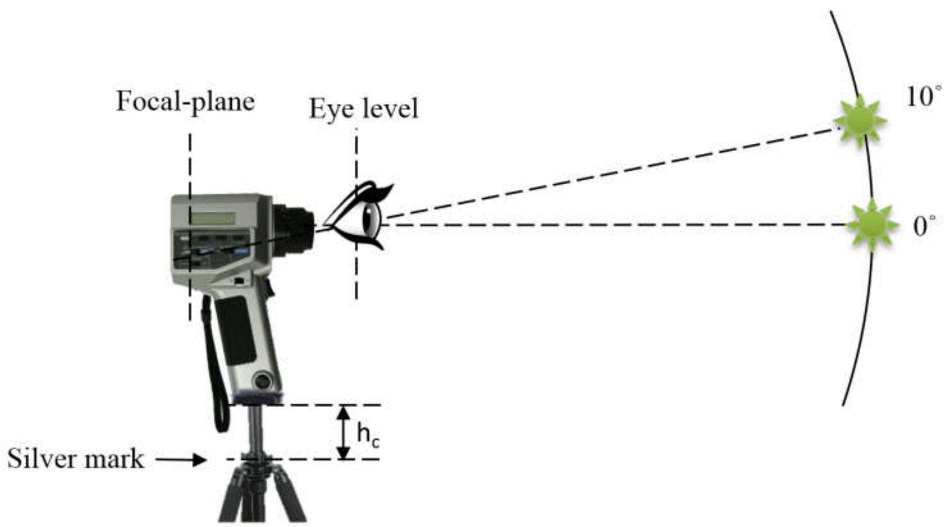


Figure 3-47. Position of the luminance meter during the measurements of the glare source at 0° between the tests with the subjects

Another issue to consider was the need for the variable height of the tripod's column (h_c in Figure 3-48, Figure 3-49) for the measurements of the two light sources. Since the luminance meter was not positioned at the center of the sphere, any tilting of the tripod shifted the meter's acceptance area above the actual position of the top light source (at 10˚) by an amount shown as "A" in Figure 3-48. Therefore, to measure the glare source at 10˚, the tripod's column was positioned at the lowest setting (Figure 3-49), and for the glare source at 0˚, the column was extended up to the silver mark made during the calibration stage (Figure 3-47).

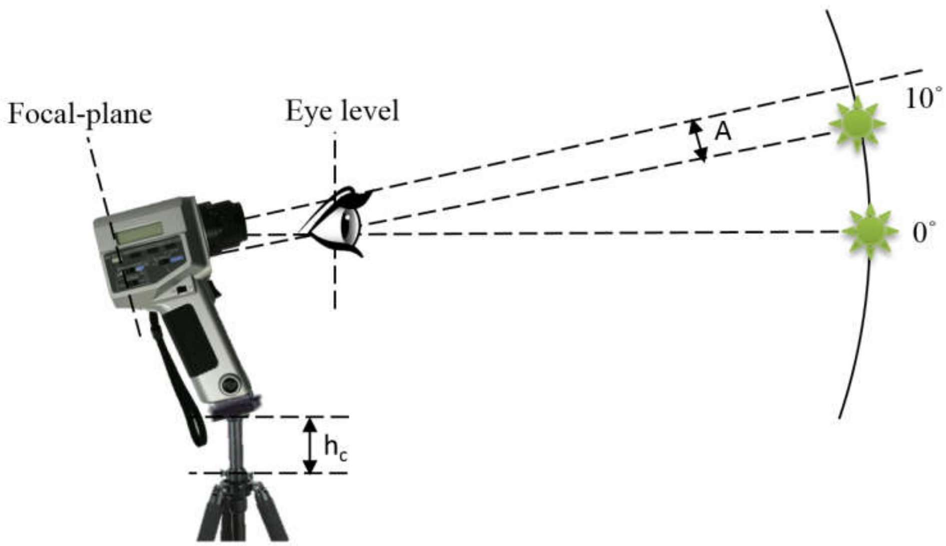


Figure 3-48. Acceptance area of the luminance meter is shifted up when the tripod is tilted

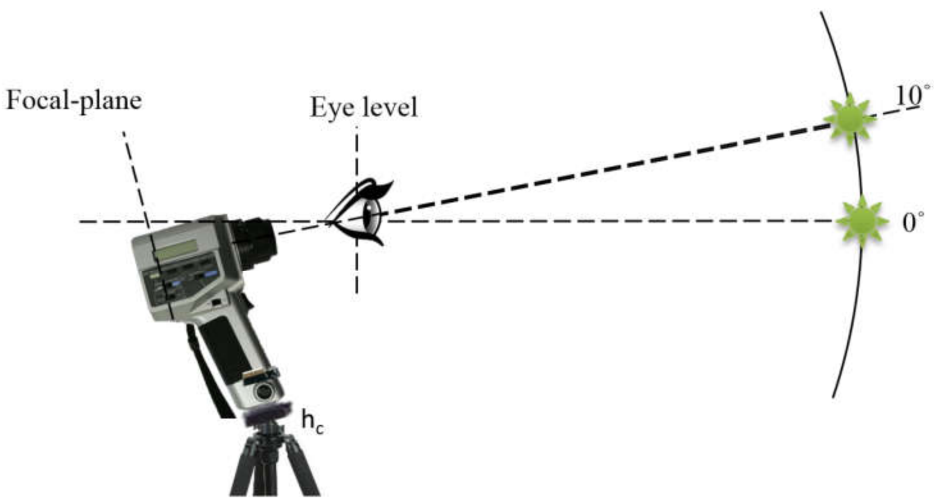


Figure 3-49. Position of the luminance meter during the measurements of the glare source at 10° between the tests with the subjects

During the measurements the experimenter verified that the eye level marks on the chinrest, the glare source, and the luminance meter were aligned in one plane (Figure 3-50 through Figure 3-52). Views of a background point and a glare source through the luminance meter are shown in Figure 3-53.

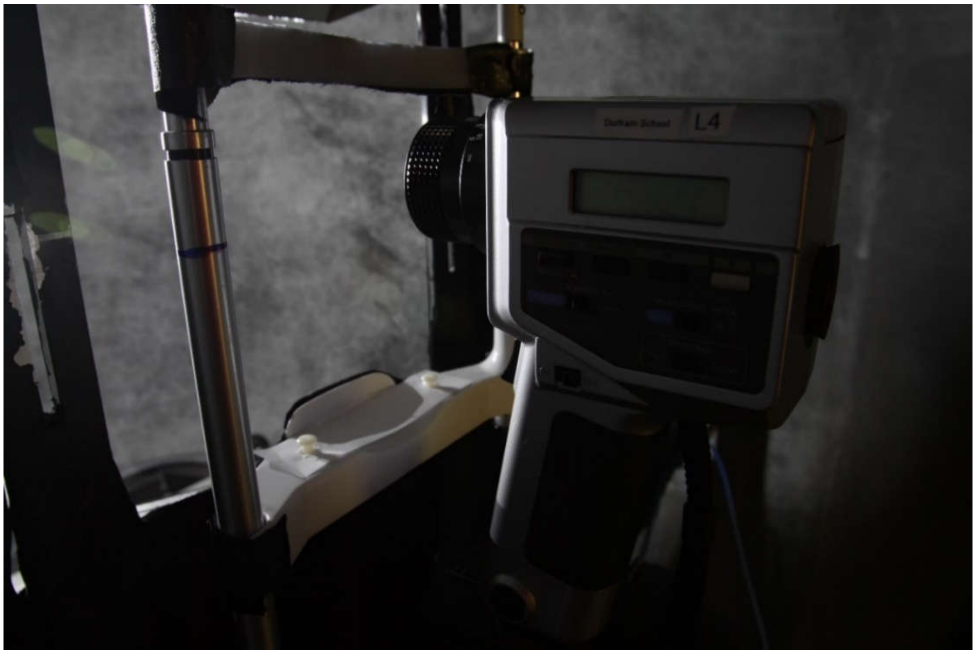


Figure 3-50. Positioning of the luminance meter for the measurements taken between the subjects

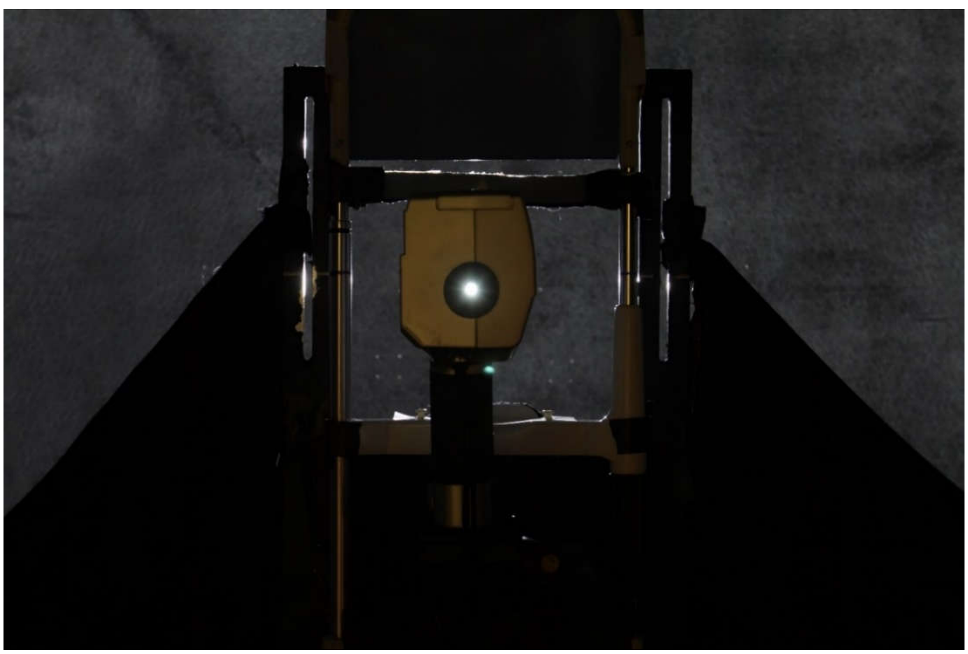


Figure 3-51. Measurements with the luminance meter

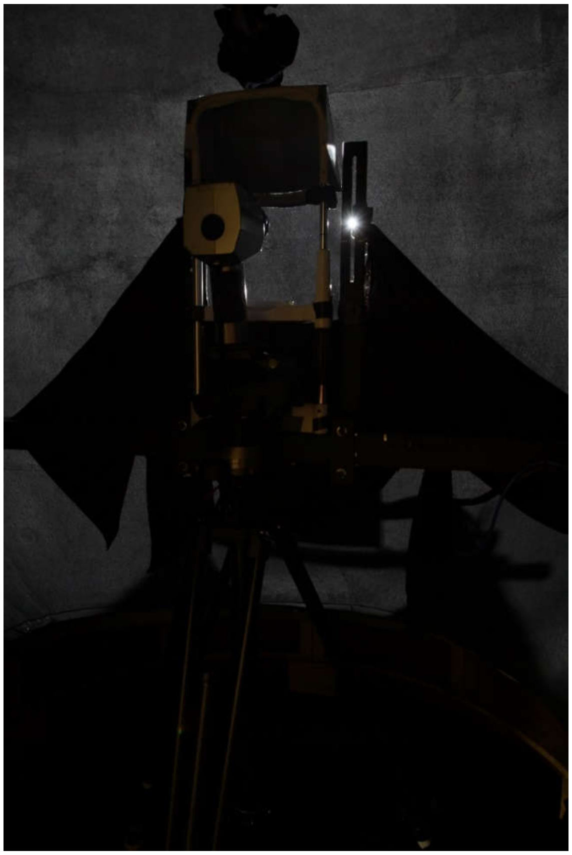


Figure 3-52. Luminance measurements from the side

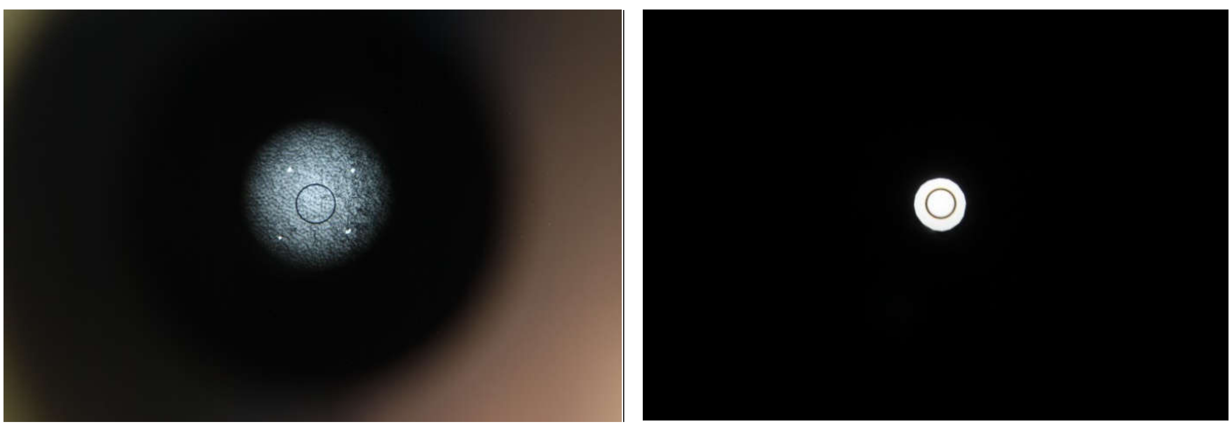


Figure 3-53. Views through the luminance meter

Left - Aiming at a background point marked with a silver permanent marker

Right - Aiming at a glare source

Spill light from the glare sources was a concern in this study, because it could increase the luminance of the background by an unknown amount. Therefore, it was measured. According to the luminance meter manual, light sources outside of the luminance meter's acceptance area influence measurements only slightly. However, practice showed that in the case of dark environments the background luminance measurements were considerably influenced by the glare source (instead of 0.03 cd/m^2, the meter measured an average of 1.82 cd/m^2 across eleven points), instead of the actual spill light. For this reason, a special "occluder" was built (Figure 3-54). It was mounted in the center between the glare source and the luminance meter on an additional bar of the eye tracking device supporting structure. The occluder was used to block the direct view of the glare source; this allowed accurate measurements of the background luminance with and without spill light (Figure 3-55) (Appendix B).

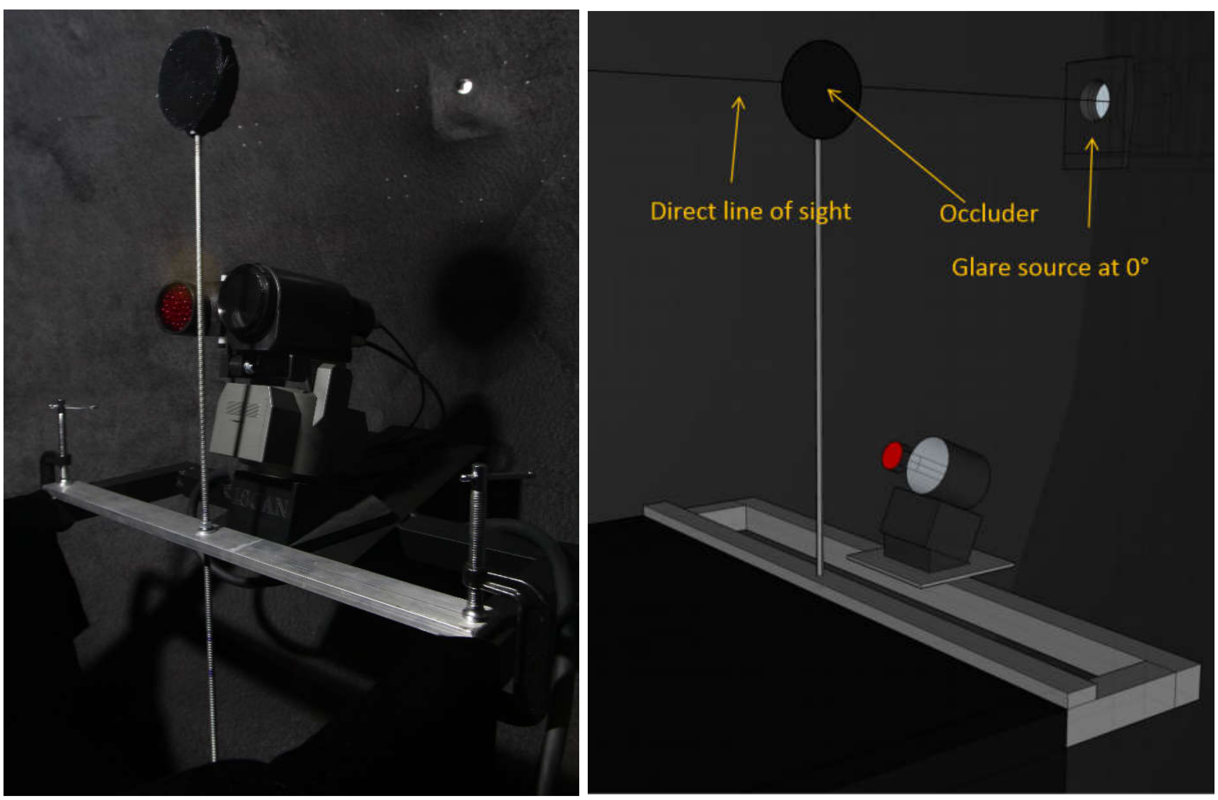


Figure 3-54. Occluder blocks the direct view of the glare source

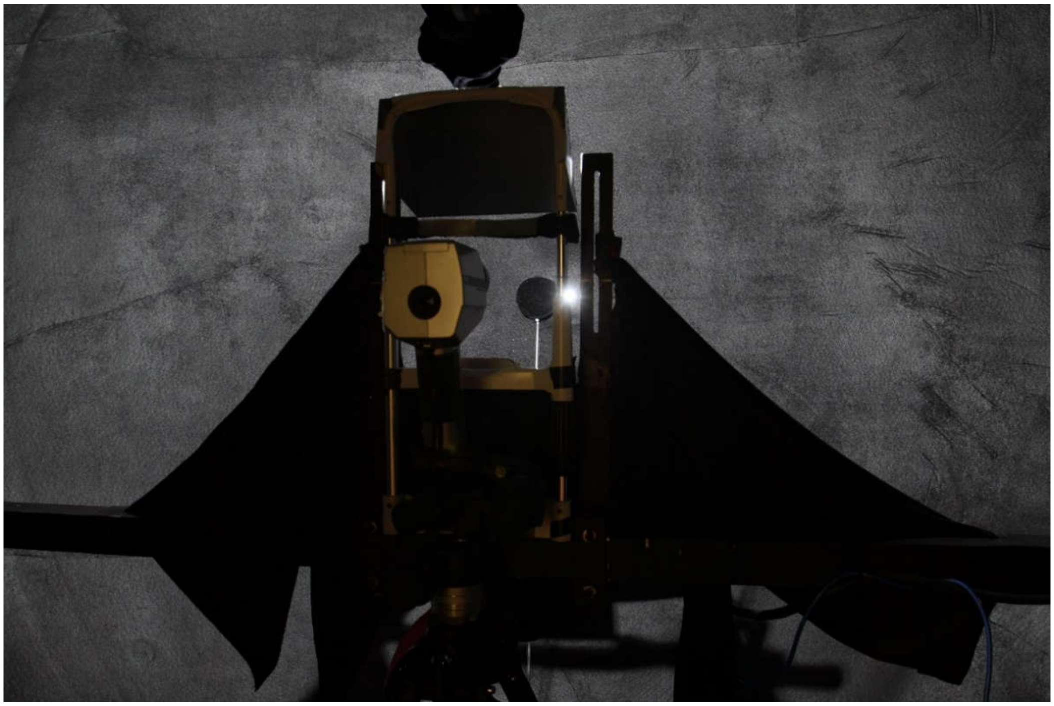


Figure 3-55. Occluder during the spill light measurements

The illuminance measurements were taken to check the consistency of the apparatus performance over time. To perform the illuminance measurements at the subject's eyes location (between the experiments), custom bars were constructed and placed on the right and left hand side of the chinrest for the whole duration of the experiment (Figure 3-56). The purpose of these two bars was to support a third temporarily installed bar that held the illuminance meter remote head between the tests. The location of this third bar matched the mark on the chinrest that corresponded to the eye level (in line with the 0° source) (Figure 3-57, Figure 3-58).

The distance between the eyes was measured for three people in a pilot test (about 60.3 mm between the centers of the pupils), and it was assumed to be an acceptable approximation for the test subjects. During the calibration stage, silver marks were added to the bar that matched the eye level at approximate locations of the left eye, the right eye, and at the center. To ensure equal illuminance at both eyes, illuminances were measured at the left and right marks on the bar (Figure 3-59).

During the actual subjects testing, the illuminance meter head was placed on the bar to the right of the chinrest. Four readings were taken during each condition for each subject (one in the no-glare state and three during each of the three glare source flashes). The expected illuminances were measured ahead of time, so that a comparison between the baseline and the actual readings could be made. Acceptable illuminance ranges were verified with an automated Excel spreadsheet (a tolerance of +/-10% was allowed) (Appendix G).

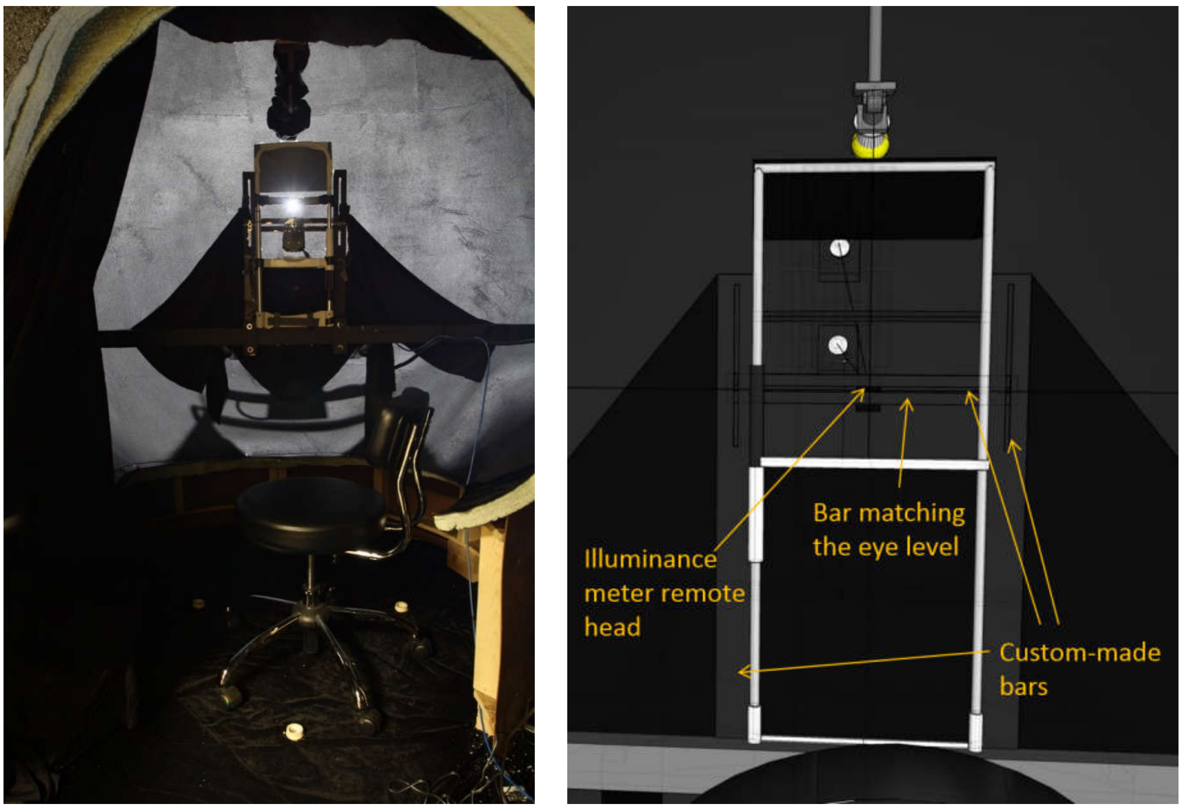


Figure 3-56. Illuminance meter remote head installed on the bar at the eye level

Figure 3-57. Illuminance meter installed on the bar at the eye level (close-up)

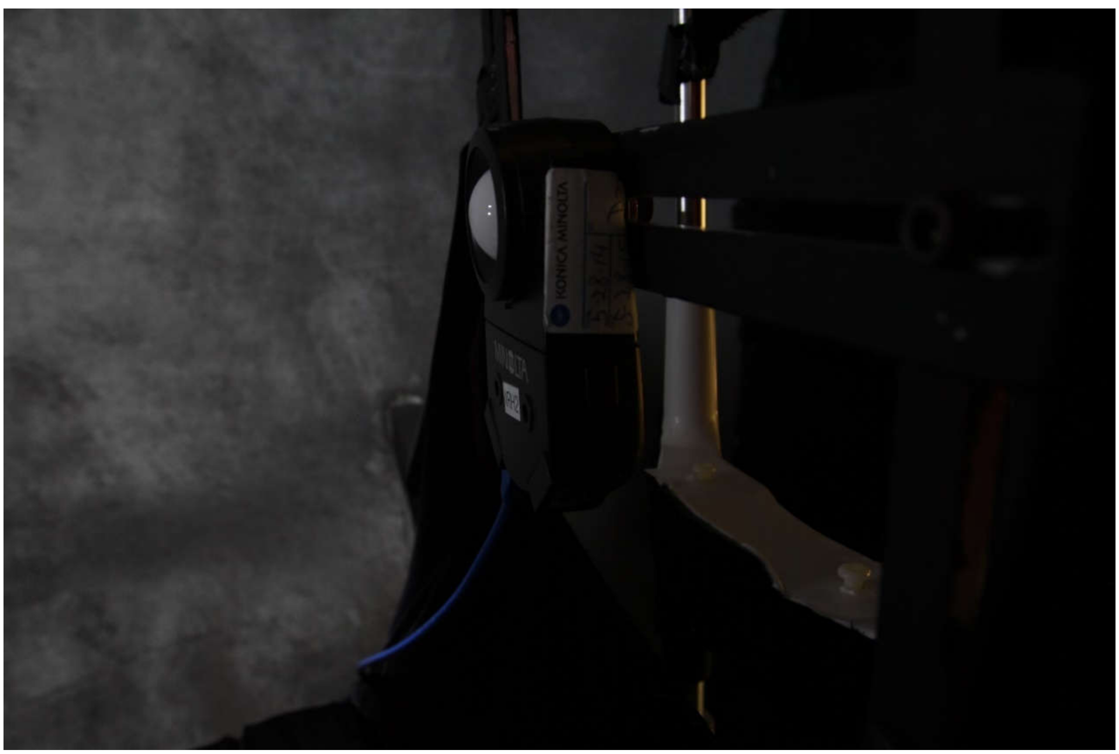


Figure 3-58. Illuminance meter installed on the bar at the eye level (side close-up)

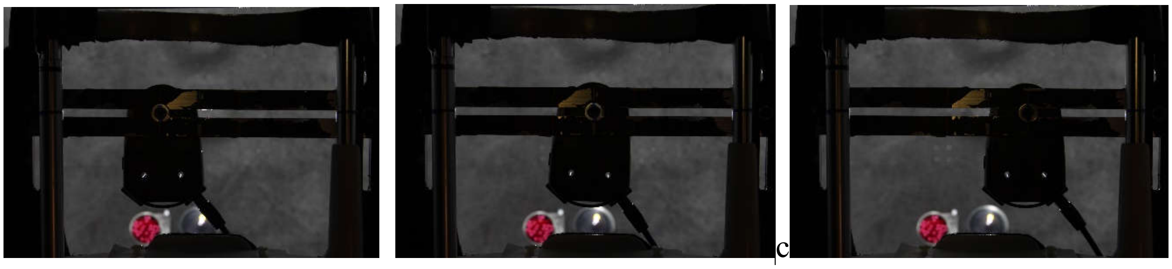


Figure 3-59. Illuminance meter installed at the left, center, and right marks

Additional illuminance measurements enabled the calculations of discomfort glare by Bullough's et al. (2008) metric, which required the measurements of very specific illuminance components – namely, ambient, surround, and direct.

Ambient illuminance in Bullough's experiment was measured by switching the light source under consideration off, while measuring the illuminance from other sources in the environment. In this study, it was the reflected component of the illuminance from the background source. Since three levels of background luminance were studied in this research (0.03, 0.3, and 1 cd/m^2), three illuminance readings with both glare sources switched off were measured at the location of the subjects' eyes (at the center).

The second illuminance was the surround illuminance. In Bullough and colleagues' paper, this is the ambient and the direct components subtracted from the total illuminance at the center, which essentially is the reflected illuminance from the glare source. In order to measure this component, the occluder from the spill light measurements was used (Figure 3-54). The occluder assured that the direct component of the illuminance from the glare source was blocked; the meter sensor was in the shadow of the occluder. The background source was off.

Finally, the third component was the direct component of the illuminance from the glare source. A special tube with black baffles placed inside was mounted on a tripod to collect this measurement (Figure 3-60). The main challenge was to align the tube with the glare source and the meter (Figure 3-61). Improper alignment resulted in incorrect illuminance readings due to the shadow on the meter. Therefore, the following method was used to measure this direct illuminance accurately.

A tripod holding the tube was placed in front of the illuminance meter. After sliding the meter to the side of the bar, the glare source was visually centered through the tube from the illuminance meter position (a silver mark on the bar) (Figure 3-61, Figure 3-62). Then the meter was moved back to the center, and velvet ($\rho = 0.006$) was placed over the meter and the tube to absorb unwanted light (Figure 3-63). The experimenter carefully lifted the velvet to verify that when the glare source was on, no part of the illuminance meter was in the shadow (Figure 3-64).

The aiming of the glare sources was critical in this study. Inappropriate aiming could result in higher illuminance at one eye than the other. Therefore, it was important to verify that the glare sources were aimed properly. The easiest way to do this was to use a luminance mapping camera (Figure 3-65).

Multiple measurements of the apparatus served as a quality check, which verified that the apparatus did not change over time and guaranteed that all subjects were responding to the same stimuli.

Figure 3-60. Tube for measuring the direct illuminance component from the glare source

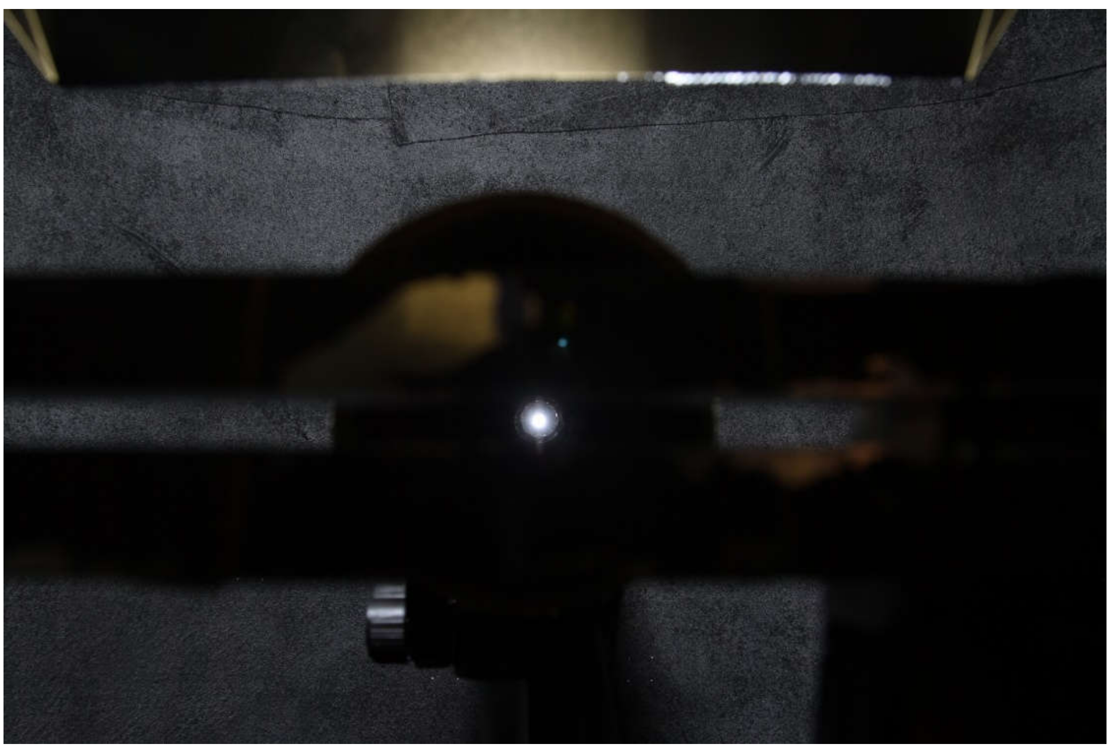


Figure 3-61. Visual alignment of the glare source, tube, and the illuminance meter (focused on the source)

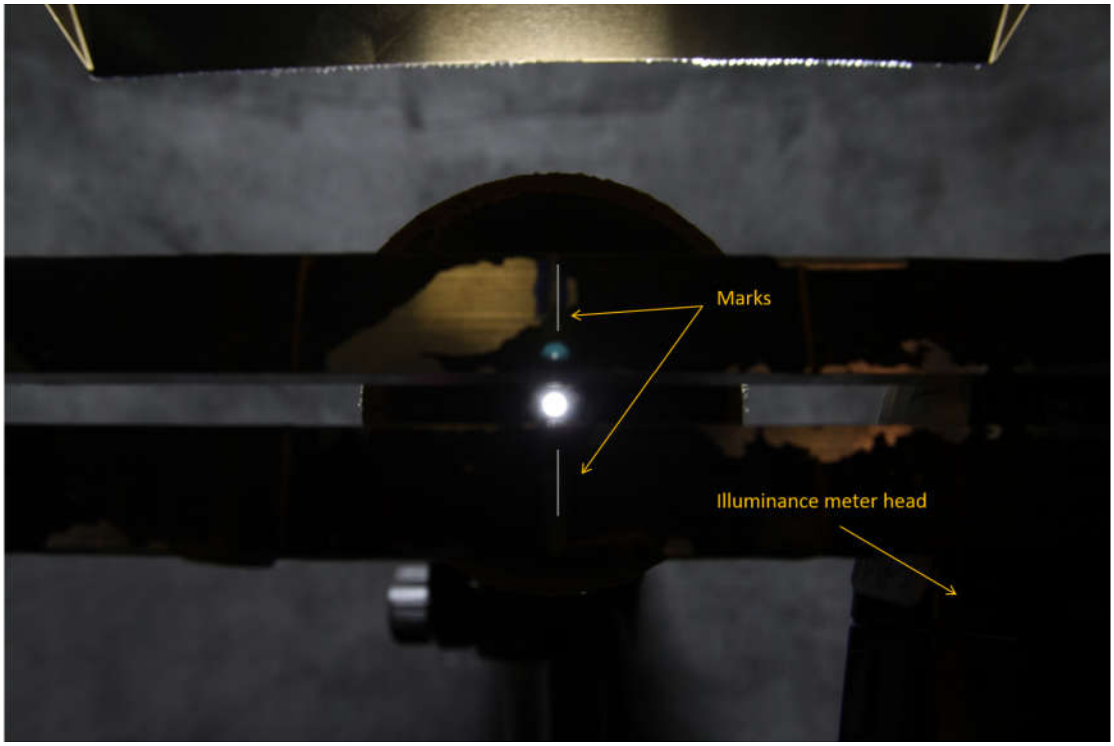


Figure 3-62. Visual alignment of the glare source, tube, and the illuminance meter (focused on the bar)

Figure 3-63. Black velvet placed over the tube and the meter

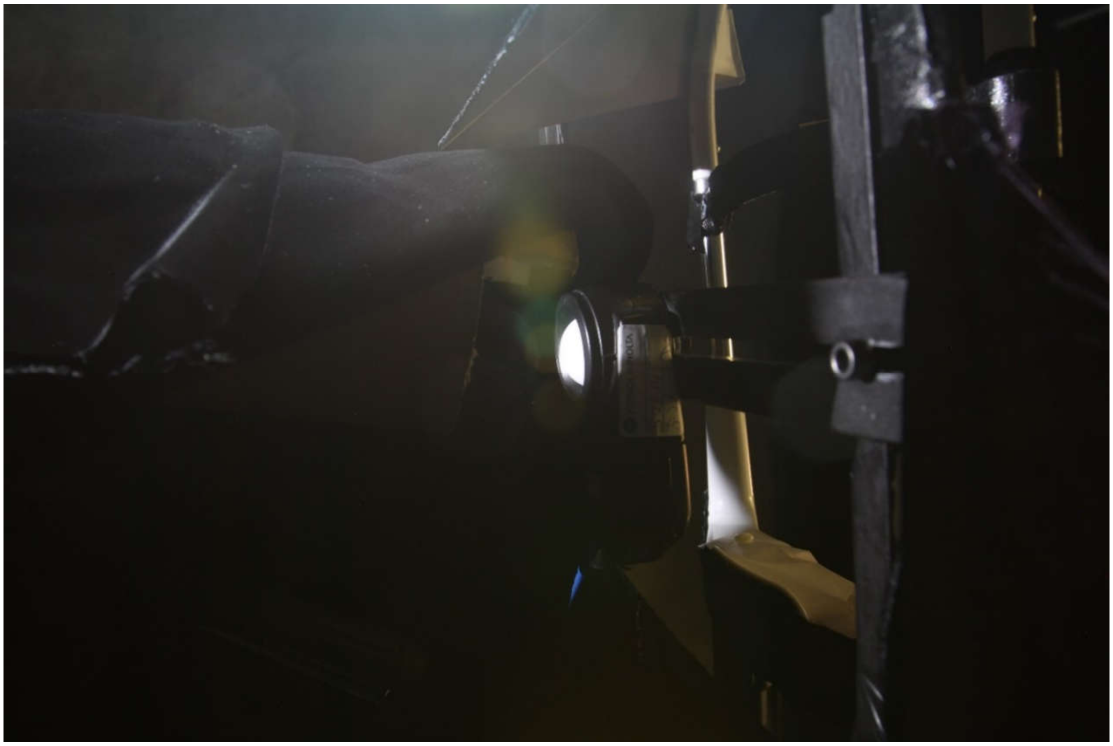


Figure 3-64. Illuminance meter is in “full” view of the glare source (no shadows)

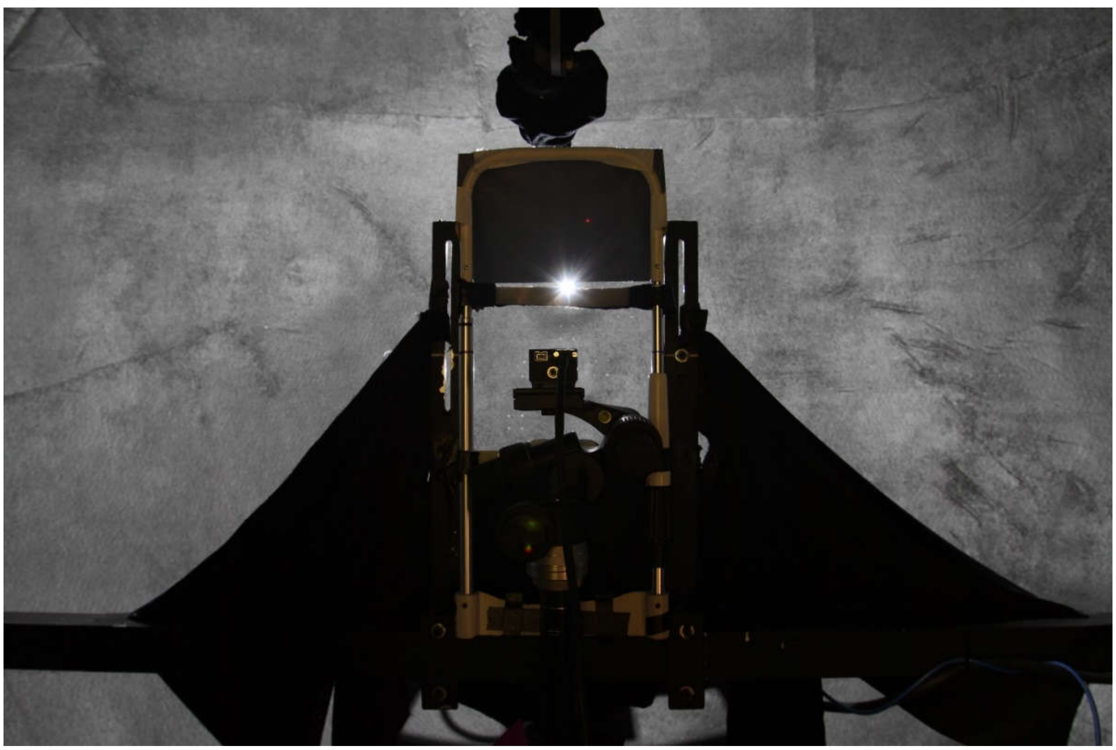


Figure 3-65. Luminance mapping camera (at the eye level) used for checking the aiming of the glare sources

3.8 Apparatus Performance over Time

A decrease in the glare source luminance (for the source located at 0˚ and set to 12 mA) was noticed during the course of the experiment. These settings of the glare source were used in the first six lighting conditions (Appendix C). The stimuli were measured before the start of the experiment, and after subjects 18, 34, 44, and 56. Before the first subject was tested on April 11, 2015, the average luminance of the source was 21,820 cd/m^2. After the last subject was tested on May 16, 2015, the glare source luminance was 18,890 cd/m^2, a difference of 13.4 %.

If the decrease in luminance over time influenced subjects' judgements (i.e. was associated with lower glare ratings) then a significant negative correlation between the subjective responses and time would be expected. Correlations for all six conditions were calculated (Table 3-6), and none of the coefficients was significant. However, the correlation coefficient for condition 5 would be considered by some to be marginally significant.

Table 3-6. Correlation coefficients between the subjective responses and time for six conditions

Lighting condition	Correlation	P value for H_0
1	0.237	0.109
2	0.177	0.234
3	0.13893	0.352
4	-0.205	0.166
5	**-0.272**	**0.064**
6	-0.235	0.110

One of the quality measures used in this apparatus for ensuring consistency was the illuminance meter installed to the right of the subjects (Figure 3-14). The subjective responses were plotted over time (which is equivalent to subjects' IDs) on the same graph as the illuminances that were recorded at the time of each subject's testing (Figure 3-66). The decrease of illuminance over time was within 12% (minimum 2.2 lx, maximum 2.5 lx). The decrease in subjective responses over time was not obvious, however, condition 5 was investigated further.

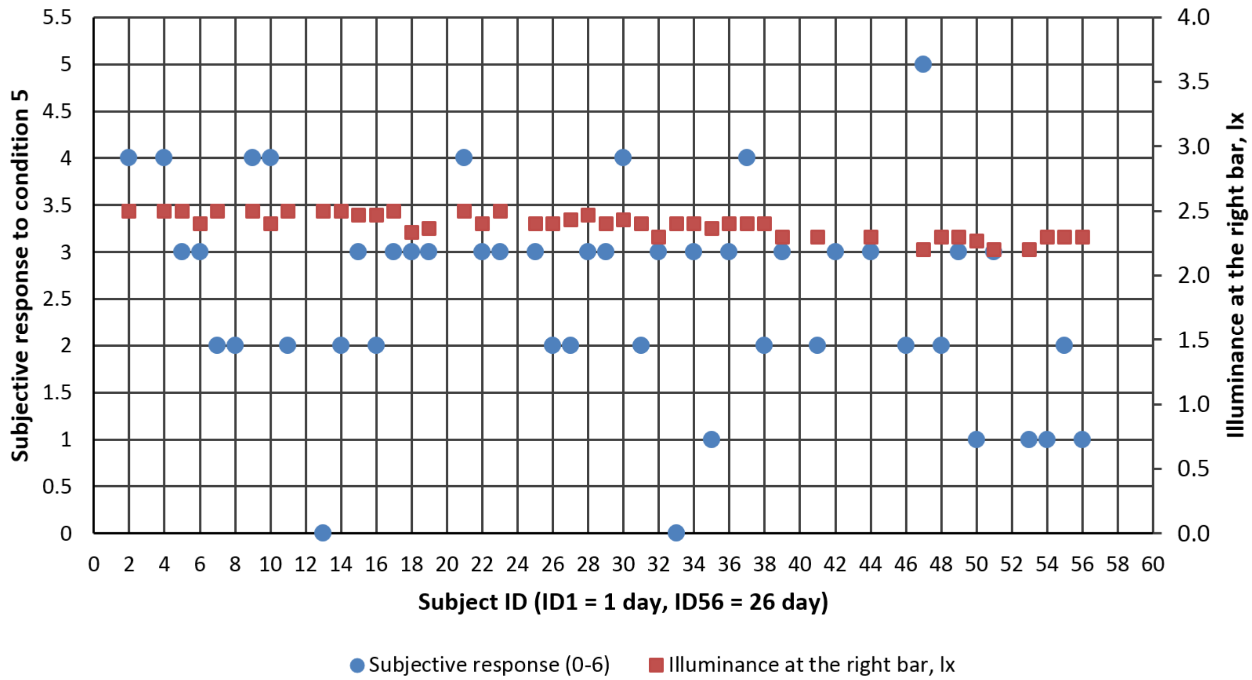


Figure 3-66. Subjective responses and the average illuminances for condition 5 over time

If the decrease in luminance affected the subjective responses, then one would expect that the apparatus also affected the pupil data. However, there was no relationship between the relative pupil size and the time in condition 5 ($F = 0.05$, $p = 0.823$).

In addition, if the apparatus influenced the subjective responses, then the sign of the correlations in all six conditions (Table 3-6) is expected to be negative. This would mean that the decrease in luminance would most likely cause subjective ratings to be lower. However, the correlations in three of the six conditions were positive.

Overall, then, there was little evidence that this minor problem with the apparatus influenced the conclusions.

3.9 EMG Integration into the Controls Software

The Focus EMG machine is typically used in nerve conduction studies in medicine to help diagnose problems such as pain in the lower back (the TeleEMG website) (Figure 3-67). Usually a nerve or a muscle is stimulated and the response is recorded via electrodes. Based on previous studies (see section 2.4.2), it was hypothesized that by stimulating the subjects with a glare source, muscles around the eyes would display a noticeable response.

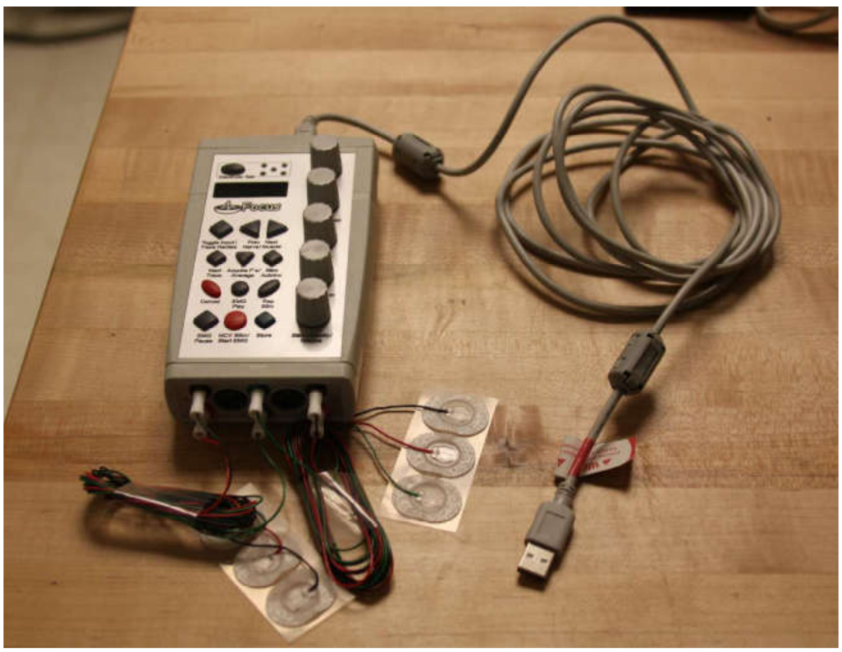


Figure 3-67. Focus EMG machine

The EMG device was connected to the laptop via USB. The accompanying software allows only manual recording of the EMG data by pressing “Start EMG” and then the “Store” button on the device. The shape of the EMG signal was displayed on the computer screen (Figure 3-68). The software running on the computer calculated the Muscle Activation (MAC) Index, which is the sum of all absolute voltages sampled at 20 KHz acquired over one second (20,000 points) (equation (3-2)). In this research, the intention was to examine the MAC indices during the glare source presentation and to compare them to the baseline – the state without glare. Increased muscle activity was expected in the glare state.

$$MAC_{sampled\ at\ 20KHz} = \sum_{0}^{t=1s} |voltage_t| \quad \textbf{(3-2)}$$

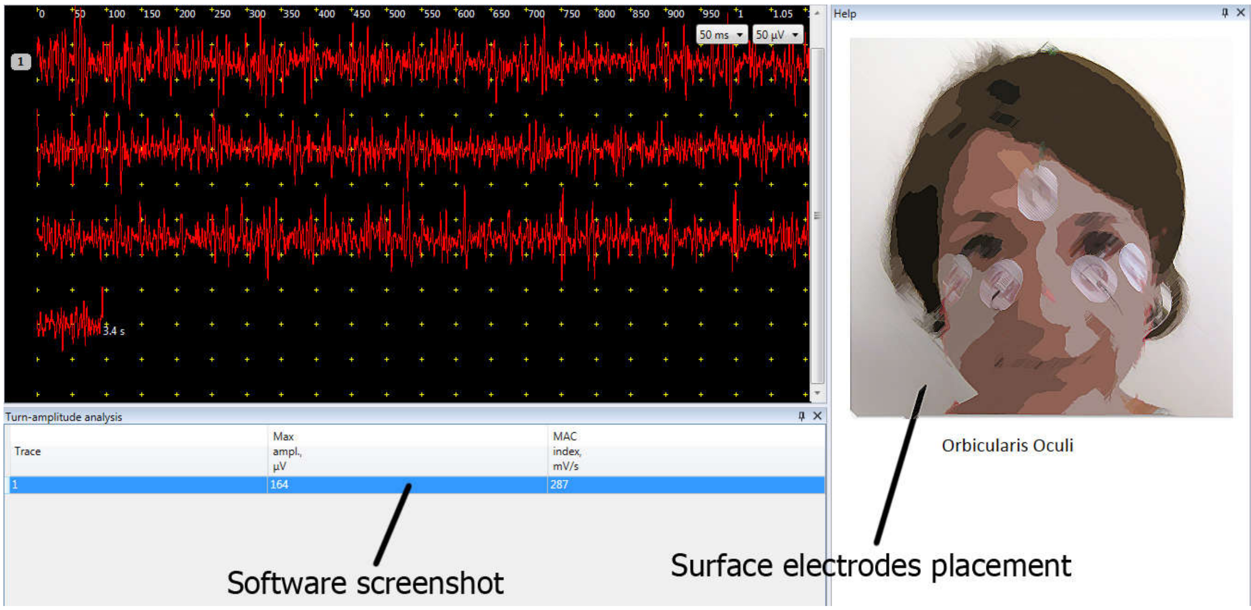


Figure 3-68. Focus EMG software

The computation of the MAC index requires three steps. First, the EMG device needs to be activated by pushing the "Play" button, which starts displaying the signal on the screen in real time (Figure 3-68). Second, pressing the "Start" button starts recording the data, and, lastly, pressing the "Stop" button stops recording, after which the software computes the MAC index. In order to collect reliable data, one needs to verify that the MAC indices accurately map to the actual events such as the presence or absence of glare. However, since in this research there were multiple events that happened during each lighting condition (such as three flashes) (Figure 3-34), it would not be possible to manually and accurately collect and store the MAC indices. Therefore, it was essential to integrate the EMG data acquisition into the controls software, and record the raw EMG signal over a desired period of time. Subsequently, based on the parts of the signal that represent the muscles activity during the glare- and no-glare states, the MAC indices can be calculated and compared. Without such integration and synchronization of the EMG data with the other data signals, manual recording of the MAC index would be meaningless or require extensive manual alignment of signals.

The integration of the EMG data collection into the controls software was a challenge, because no technical information or additional documentation about the EMG device was available. After some experimentation, a driver was identified in the existing EMG software as the module that communicates directly with the EMG machine via a USB port. To enable automated data collection on a computer, a custom dynamically linked library (DLL) was written in C Sharp that referenced the existing driver in the software of the EMG machine. The driver supported essential functions such as turning the EMG machine on/off and starting/stopping the EMG data collection.

After establishing communication with the device, a small pilot test with human subjects allowed the recording of facial movements such as squinting of eyes, which could be identified in the EMG data. The data could be recorded for various durations. The electrodes impedance test, which checked if the electrodes were attached to the face properly, was also working. Based on the settings used in the provided software, the following settings were used for the final recording: signal Input Range 20 mV, Low Frequency (high pass filter) 20 Hz, High Frequency (low pass filter): 10,000.00 Hz, Notch Filter On, Notch filter type Recursive, High Harmonics filter Off, Sampling rate 20 KHz. Once the DLL proved to be working reasonably well, it was integrated into the controls software. Due to time constraints, a proper pilot test with all 36 conditions running one after another was not completed.

3.10 Eye Tracking (Pupil) Data Processing Software

Special software for pupil data processing was written. Each pupil data file consisted of 720 data points, which is equivalent to 12 seconds of recording (at 60 Hz sampling rate), over all trials (for an example of a partial pupil data file see Appendix H). The initial diameter ($d_{initial}$) was the condition of the pupil before any glare source was shown to the subject (Figure 3-69). It was influenced by one of the three background luminances used in the study (0.03, 0.3, and 1 cd/m^2). Steep drops in the pupil diameter represented the appearance of the flashes in the subject's field of view (after accounting for the pupil's latency). Three minima (d_{min}) represented the full output condition of the light source (flash). Since the pupil data were recorded manually by pressing the button, a certain amount of human error was present at the beginning of each condition.

Custom software for pupil data processing was written in Matlab (Figure 3-70). Once the experimenter chose the data of a subject and pressed the "Load from the list" button, the software loaded all 36 conditions for this subject, with one condition displayed at a time. The default pupil scale was set to the range of 1.5 to 8.5 mm, which covered the typical range of pupil diameters for young people (2-8 mm (Boyce 2014)). However, if necessary, the scale could be changed. Anything that fell outside of the 1.5-8.5 mm range was cut off and considered "noise" (e.g. a blink or glasses reflections). The subject's ID number, condition number, and the run number (the order of the condition) were displayed at the top of the interface during the data processing.

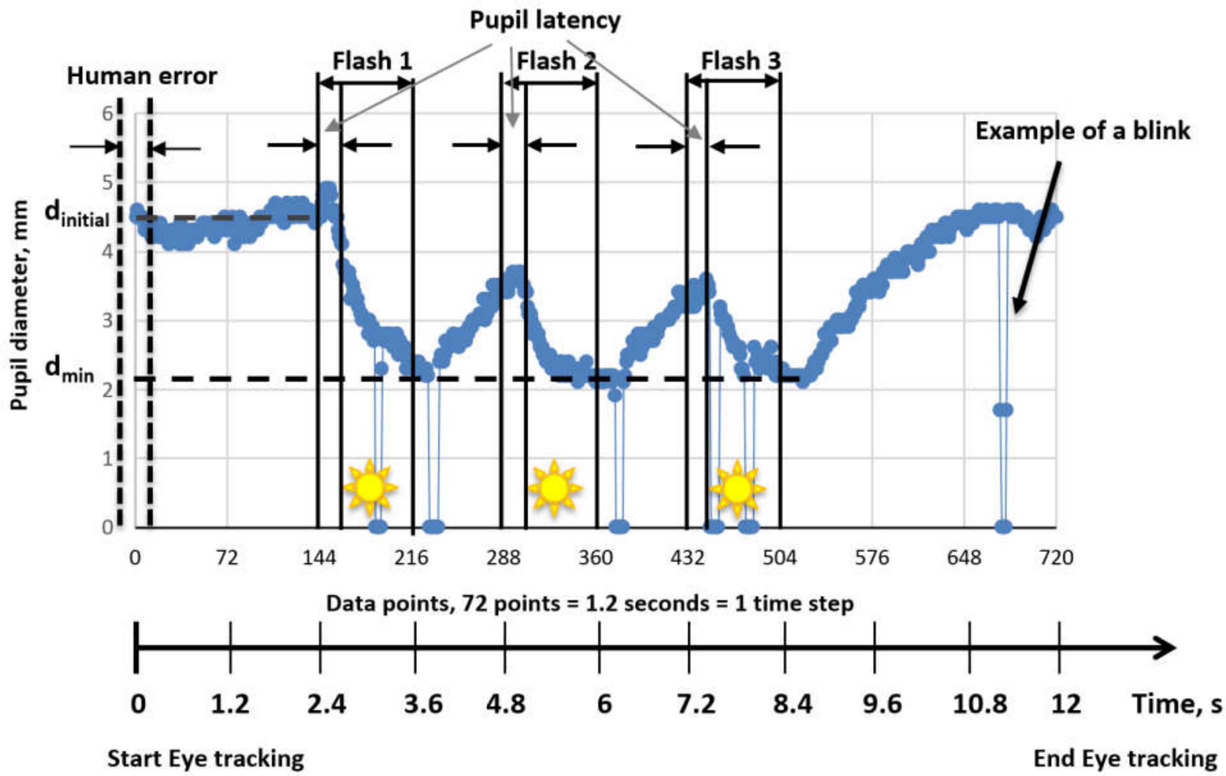


Figure 3-69. Timing of the pupil data file during one condition

The experimenter had to add seven marks to the graph to indicate the initial diameter (Figure 3-70), the start of each of the three flashes with an unknown error for pupil's latency (Figure 3-71), and the three minima of the pupil diameter for each subject and each condition. The initial diameter and the marks of the three minima of the pupil diameter were used to compute the relative pupil size that was analyzed in this research (section 4.2). The experimenter selected points that represented the initial diameter with a rectangular box (excluding the blinks) before the start of the first flash, and the software calculated the average pupil diameter in the initial state (Figure 3-70). The marks at the start of the three flashes were added in an attempt to align the pupil and EMG data (Appendix W).

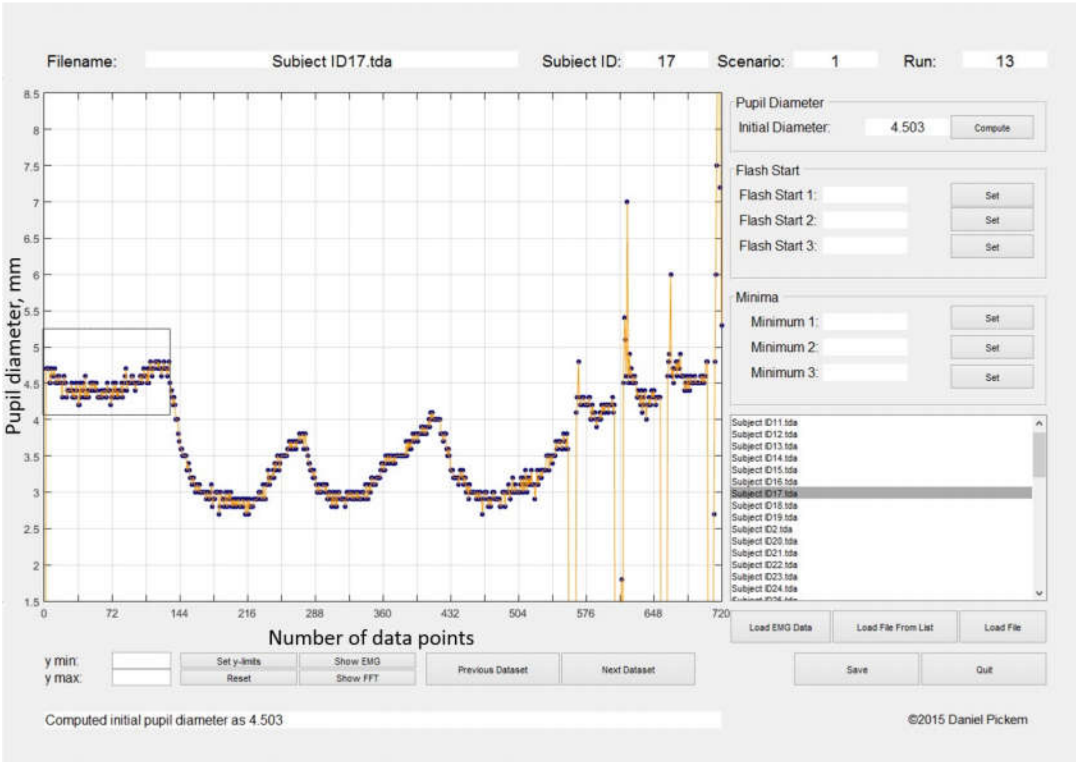


Figure 3-70. Eye tracking (pupil) data processing software (in Matlab)

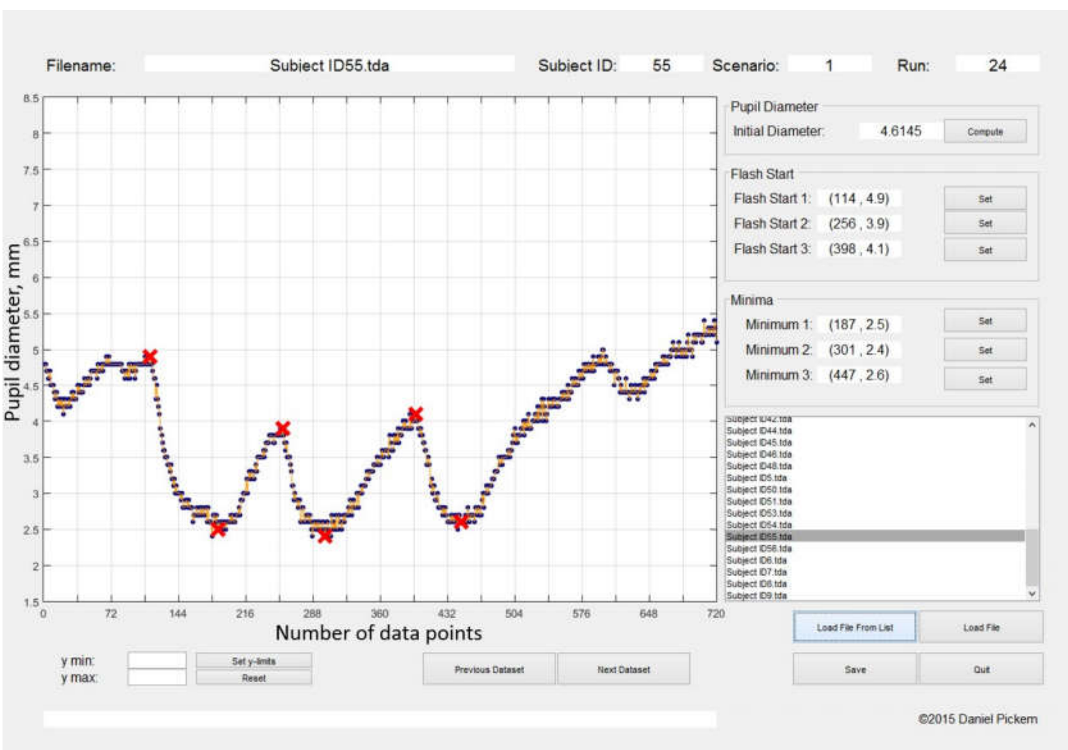


Figure 3-71. Example of the pupil file with the marks for one condition

3.11 Subjects

A total of 73 subjects signed up for the experiment of which a total of 56 subjects actually participated in the experiment. Data from only 47 subjects were analyzed.

Seventeen of 73 subjects who signed up did not participate in the main experiment: eleven subjects did not pass the vision test; two were not comfortable doing the test after reading the consent form (older than 75); one subject was under age (18); and three did not show up or cancelled the session.

The subjects were recruited using several methods: emails sent to Musco Employees by an HR manager, emails sent to students of William Penn University by the Vice President for Academic Affairs and Dean of Faculty, and through the direct relationships of Musco employees with members of the Oskaloosa community. Subjects signed up by visiting the website that was created for this study (www.lightingstudy.com) or emailing/calling the experimenter directly. On the webpage subjects had to provide general information (Appendix I). The study was voluntary; the subjects were not paid for their participation. Due to several factors, only 47 subjects were included in the data analysis.

3.11.1 Data Exclusion

The pupil data of nine of the 56 subjects were excluded from the analysis. Two subjects did not have any pupil data, three had poor quality data, and four had a missing condition and were excluded as well. These nine subjects are discussed in the paragraphs below.

The experimenter was observing the pupil data recording through the “EYE MONITOR” window in the eye tracking software (Figure 3-72). When the pupil was tracked properly, a crosshair in the middle and a white overlay fully covering the pupil were moving together with the pupil (Figure 3-73).

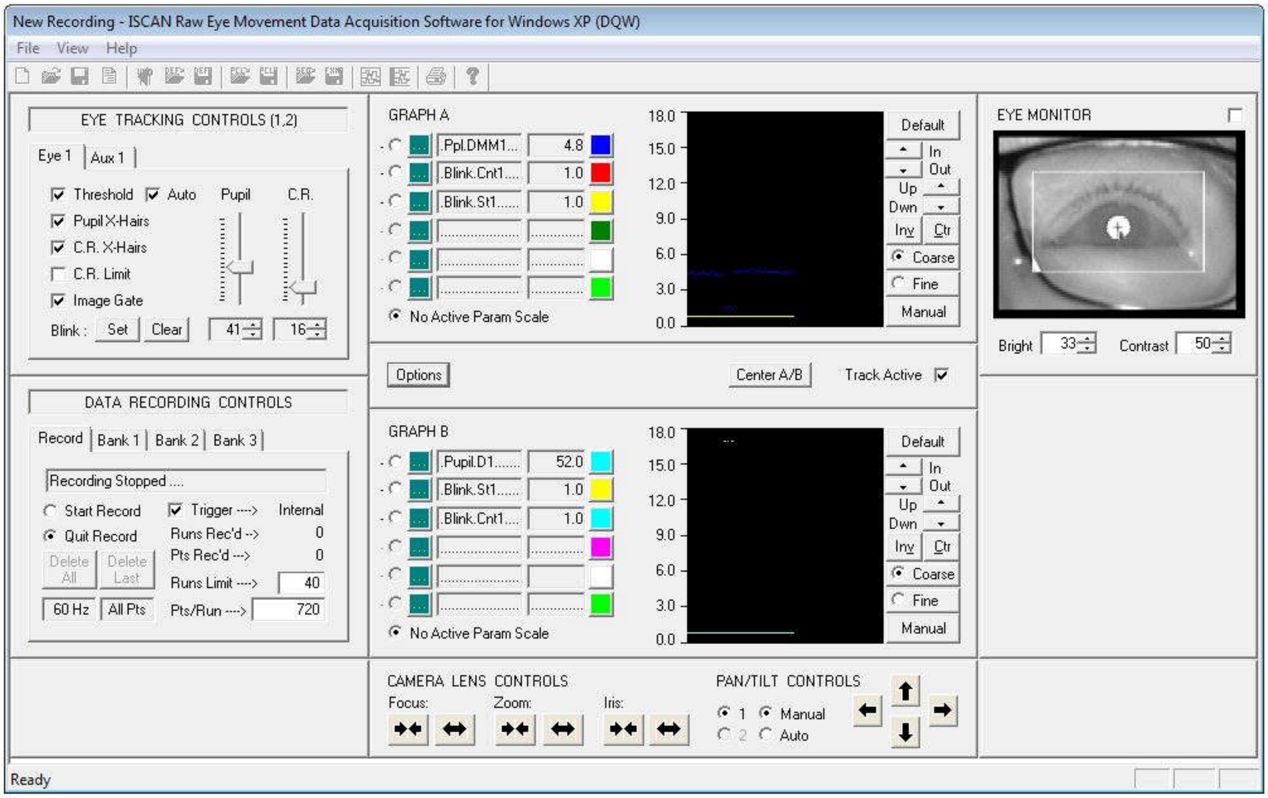


Figure 3-72. ISCAN Raw Eye Movement Data Acquisition Software for pupil size recording

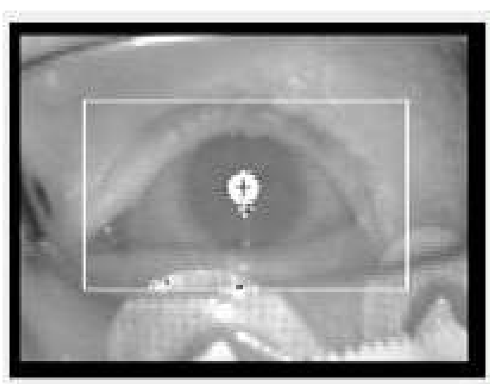


Figure 3-73. Example of good eye tracking (eye monitor enlarged)

Recording of pupil data for two subjects (ID 1 and 43) failed altogether. Any adjustments of the eye tracking device did not allow it to track the pupil correctly. Subject ID1 had thick eyeliner and heavy dark makeup, so that the eye tracking device confused the makeup with the pupil, and could not track it (Figure 3-74, left). Subject ID43 wore glasses that did not allow a proper tracking of the pupil presumably because of a special coating on the glasses (Figure 3-74, right). Following the recommendations of the eye tracking manual, the experimenter tried to change the angle between the observer and the camera of the device, but this did not result in any considerable improvement. Due to the apparatus setup, the eye tracking device could not be moved closer to the subject. Therefore, no data files were acquired for both subjects ID1 and 43.

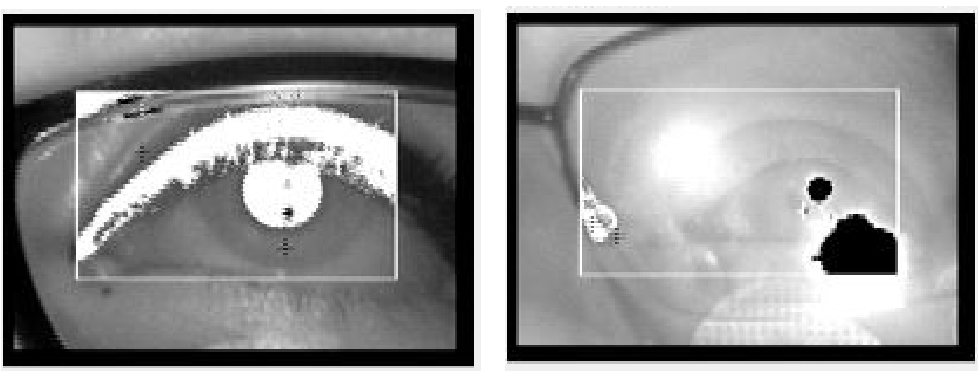


Figure 3-74. Low quality eye tracking
Left – Subject with heavy dark makeup (ID 1)
Right – Glasses with a special coating (ID 43)

Three more subjects (ID3, 24, and 52) were not included in the analysis due to the poor quality of the eye tracking data (for a description of the eye tracking graph see section 3.10). The eyes of subject ID3 were halfway open during the glare measurements (Figure 3-75, Figure 3-76). Subject ID24 was excessively blinking; eye tracking confused the pupil with the makeup (Figure 3-77). Finally, subject ID52 had many reflections due to tinted glasses (Figure 3-78, Figure 3-79). Therefore, data of these three subjects were excluded. Unlike during a typical blink with few vertical lines in the graph (e.g. Figure 3-69), in a problematic eye tracking condition there are multiple vertical lines that indicate that the tracking crosshair was “jumping” from the pupil to other dark objects in the EYE MONITOR window (for example, see Figure 3-75).

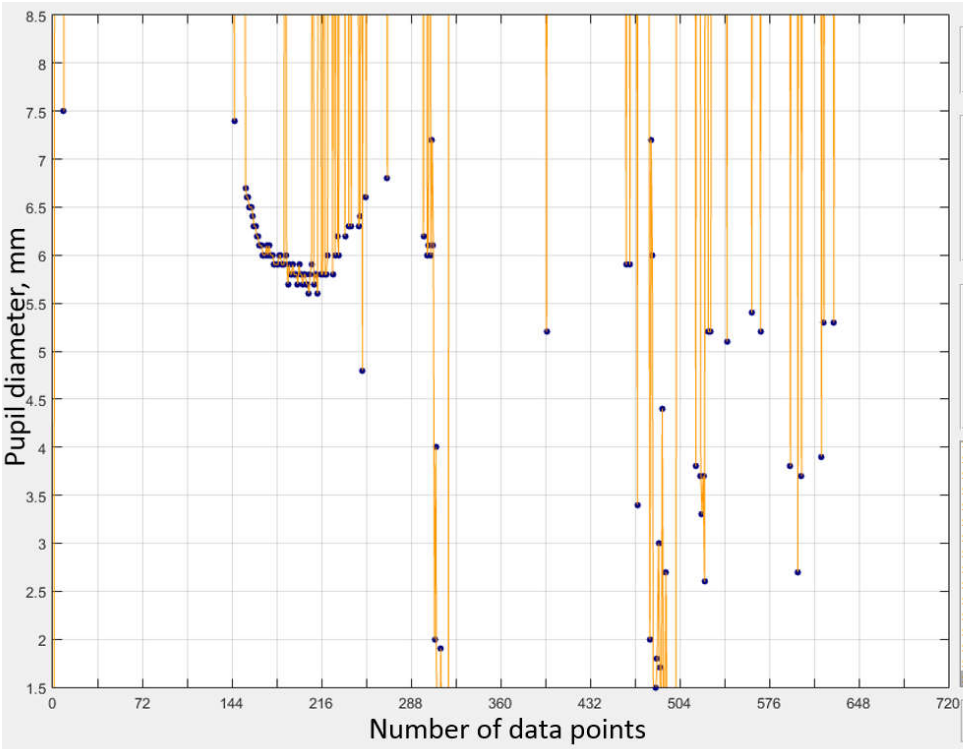


Figure 3-75. Poor quality of eye tracking data due to the halfway open eyes (Subject ID3, condition 15)

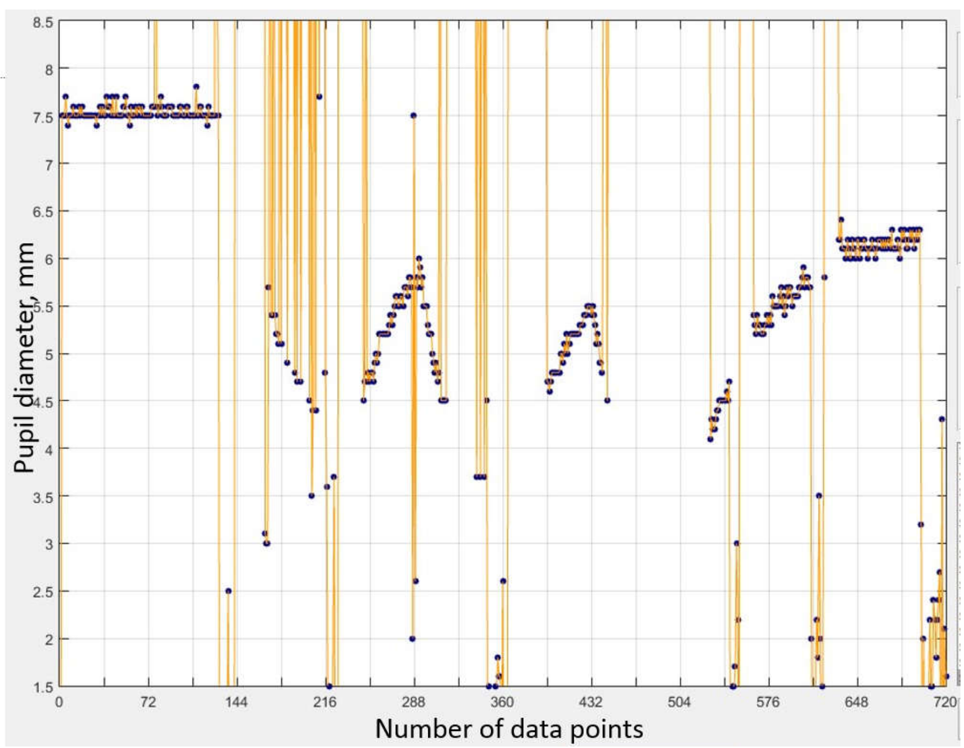


Figure 3-76. Poor quality of eye tracking data due to the halfway open eyes (Subject ID3, condition 28)

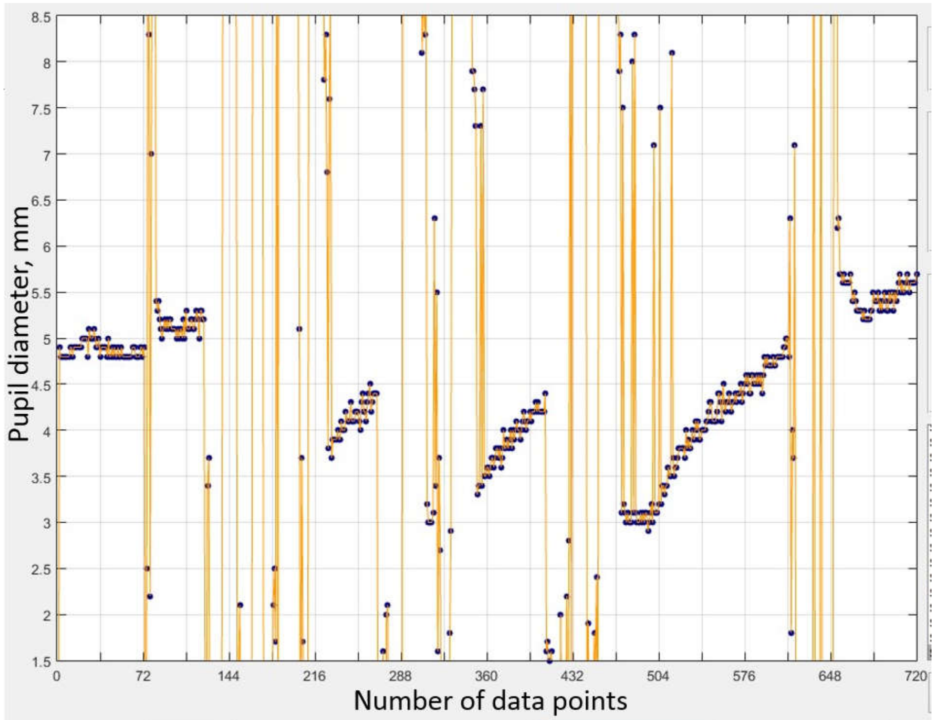


Figure 3-77. Poor quality of eye tracking data due to excessive blinking (Subject ID24, condition 29)

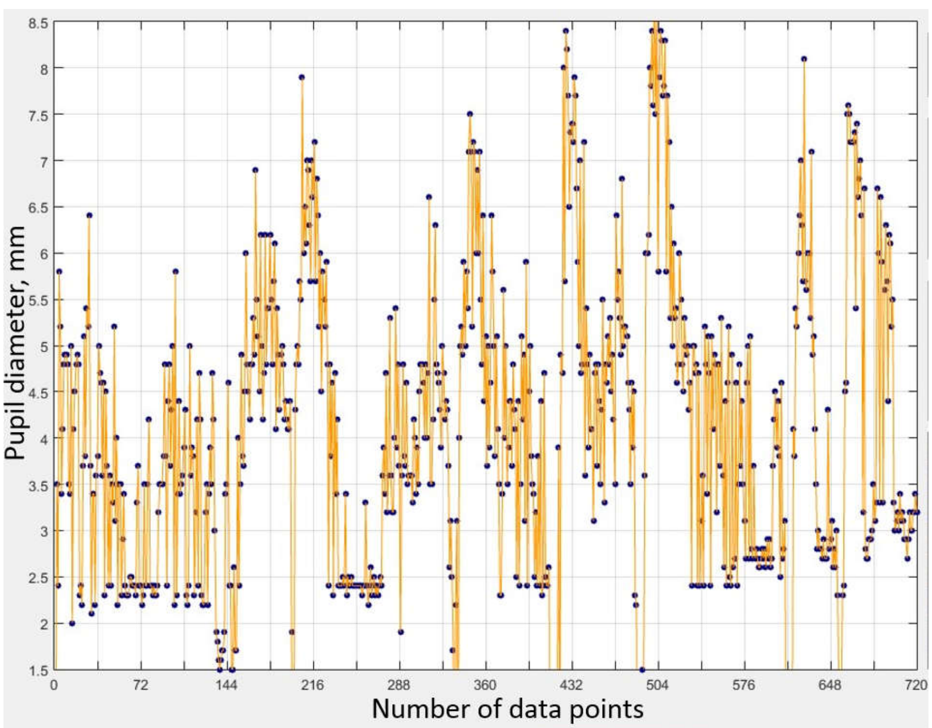


Figure 3-78. Poor quality of eye tracking data due to tinted glasses (Subject ID52, condition 24)

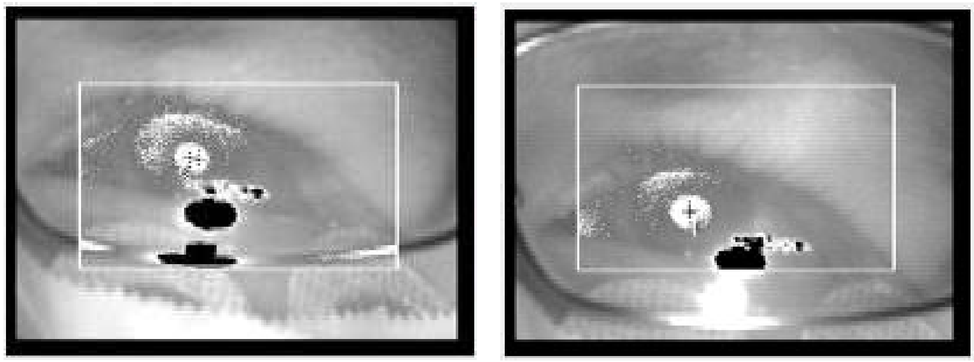


Figure 3-79. Poor quality eye tracking data (tinted glasses) (ID 52)

Four subjects (ID 12, 20, 40, and 45) had a missing condition. One subject had missing data in one condition due to a technical difficulty during the recording; three other subjects had missing data in one condition, because the noise in the recorded data (e.g. reflections from glasses) prevented the experimenter from identifying the necessary parts of the pupil file such as the minimum diameter. Initial eye tracking adjustments provided good tracking results. However, once the subjects slightly changed their position on the chinrest between the trials, it caused noise that prevented recording useful data in that condition. Therefore, these subjects were excluded from the entire analysis as well.

Forty-seven of the 56 subjects had complete datasets and were used both in the subjective and the pupil data repeated-measures ANOVA analysis.

There were some conditions for approximately five other subjects that also had problematic data. For example, one subject's data (ID38), which was still included in the analysis, exhibited "moderate" noise due to glasses reflections (Figure 3-80, Figure 3-81). However, to the best ability of the experimenter, the data were still marked.

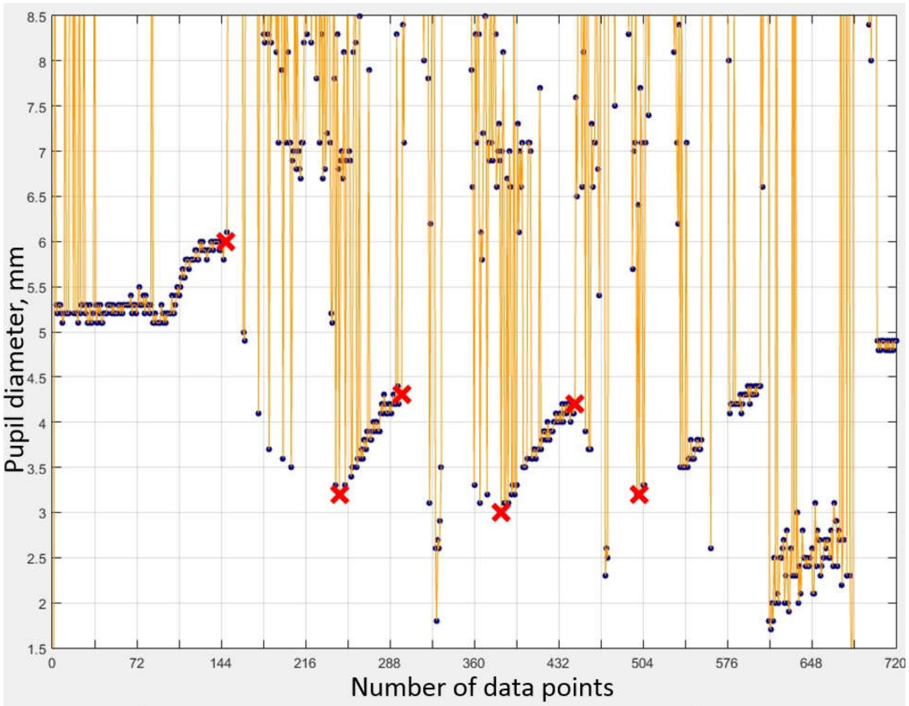


Figure 3-80. Problematic eye tracking file that was marked and used in the analysis (subject ID38, condition 17)

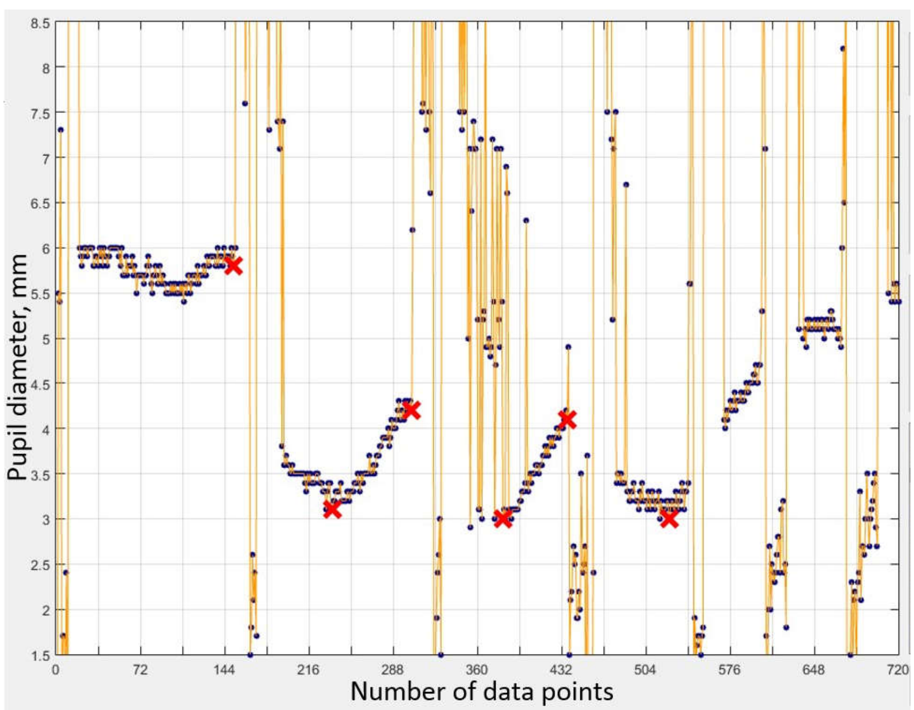


Figure 3-81. Problematic eye tracking file that was marked and used in the analysis (subject ID38, condition 22)

3.11.2 Description of the Included Participants

A total of 47 subjects were included in the analysis. All demographics information was self-reported via the General Information Survey form (Appendix M). The youngest subject was 20 years old and the oldest 76. The mean age was 39.3 years (Figure 3-82). Sixteen participants were female and thirty-one male. Forty-five subjects were Caucasian, one Hispanic/Latin American, and one Asian/Caucasian. The native language was English for 45 subjects, Spanish for one, and German for another one. Twenty-six subjects reside in Oskaloosa, IA, others in neighboring communities in IA, and one in Montezuma, MO.

The subjects were allowed to participate in the experiment if they had normal vision or normal vision with correction (contacts or glasses). Thirteen participants wore glasses. Thirteen wore contact lenses. Twenty-one subjects wore neither glasses nor contact lenses, but four of them wear reading glasses sometimes. At least two subjects mentioned that they had LASIK surgery done, and some reported cataract surgery.

The vision of a total of 67 subjects was checked. Eleven subjects did not pass the vision test. Forty-two participants passed the vision test on the first attempt (they scored in the expected ranges in the Keystone vision test, or were off by one, see Appendix K). If the participants failed in only a single vision target or were close to the passing zone on the related targets, the participants were given a second attempt at the end of their test. Ten people scored in the expected range after the second attempt. Finally, four subjects were "borderline" subjects (e.g. still 1 off from the passing condition on the second attempt), but they were also included in the experiment. A total of 56 subjects participated in the experiment; data from only 47 subjects were analyzed.

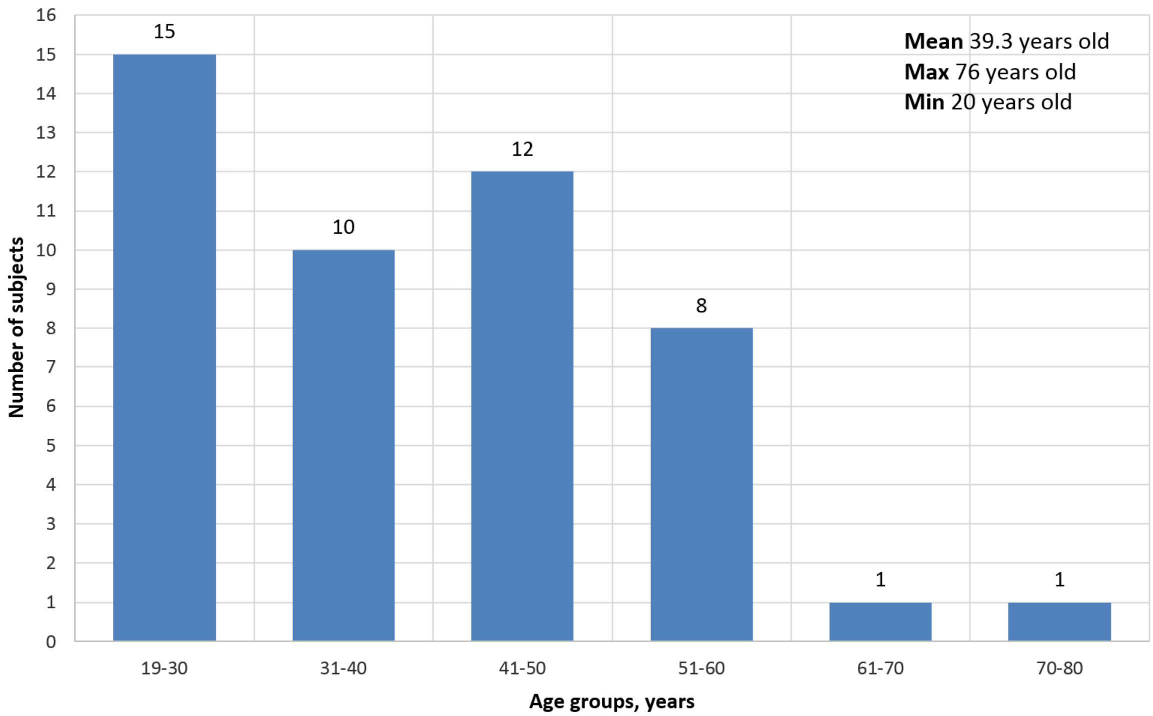


Figure 3-82. Number of subjects in each age group (a total of 47 subjects)

Sixteen subjects had blue eyes, 13 brown, 13 hazel, 4 green, and 1 blue/green. On the "sensitivity to light" question (on a scale of 1 (not at all) through 5 (very sensitive)), the majority of the subjects (nineteen) reported 3, sixteen reported 2, five subjects reported "not at all sensitive", four subjects reported 4, two subjects reported "very sensitive", and one reported between 3 and 4. Forty-three subjects had mostly indoor professions, two outdoor, and two more both indoor and outdoor equally. Thirty-seven participants were Musco employees (two of which were also students), six were students, and six were recruited from the Oskaloosa community. Thirty-two participants had not participated in a lighting research experiment before, fifteen had. Thirty-six participants had caffeine on the day of the test; eleven did not. Twenty-two participants did the experiment in the morning sessions, twenty-five in the afternoon.

3.12 Procedure

Before the main study a pilot testing was conducted on a small sample to identify potential problems, test stimulus materials, verify direction of the results, and to fine-tune the methodology. Due to time constraints the EMG was not tested during the pilot study. Both the pilot study and the main experiment were conducted at Musco Sports Lighting in Oskaloosa, IA.

Before the subjects arrived at the scheduled time, the experimenter had completed several preparation steps. Through the glare software, the experimenter established communication links between all devices and the controls software (Figure 3-28), loaded the parameters file (Appendix E), the conditions file (refer to Table 4-2 for 36 conditions), and the text file to which the data collected were stored. Additionally, the order of the lighting conditions presented to the subjects was randomized.

The eye tracking software (REMOTE ETL-100) was loaded on a separate laptop. During the very first time, the device was calibrated with an artificial pupil - a hole in a metal plate that acted as a sink to the infrared light illuminating it. Then a conversion from pixels to mm was applied and stored in the settings file in the software.

Each subject reported to the testing lab at Musco Sports Lighting in Oskaloosa, IA and was instructed to read and sign an Adult Informed Consent (Appendix J). A copy of the signed form was emailed to the subject (several subjects did not want the copy). After signing the form and agreeing to participate in the experiment, the subjects' vision was tested with the Keystone Visual Skills Screening Test (Appendix K, Appendix L). This test served to demonstrate the loss of specific visual skills, if they exist (see Keystone Visual skills test set instruction manual). The intent of this test was to verify that each subject's vision resided in the normal range (section 3.11.2).

Subjects that passed the vision test and agreed to participate in the study, filled out the General Information Survey (Appendix M). After a short introduction to the experiment (Appendix P), the subjects were seated next to the sphere. The experimenter explained the apparatus, the experimental procedures, and answered any questions (Appendix P).

After these instructions, the subjects were seated inside of the experimental sphere. The experimenter verified that the eye level matched the mark on the immovable part of the chinrest and adjusted the movable part of the chinrest, if necessary. Once the eye level matched the mark on the chinrest, the subject adjusted the chair to a comfortable position. The experimenter adjusted the eye tracking device to enable the proper tracking of the pupil and activated the tracking. After this initial set up, the subjective scale was explained to the participant. (Appendix N, Appendix O).

During the next step, the experimenter cleaned certain areas on the subject's face with sterile alcohol swabs (ReliOn), applied electrode gel (Spectra 360) to the EMG electrodes (silver/silver chloride electrodes (Ambu Neuroline 715)), and attached them to the subject's face. Two electrodes were placed under each eye, and one on the forehead (Figure 3-32). Channel 1 of the EMG device collected the input from the right eye; Channel 2 from the left eye. Adhesive tape was placed over the electrodes to avoid accidental removal during the experiment. After the electrodes were placed on the subject's face, the electrodes were connected to the Focus EMG Machine, which was then attached to the back of the subject's chair (Figure 3-27).

Before starting the main experiment, subjects were shown two stimuli on opposite ends of the discomfort glare sensation spectrum ("no discomfort glare" and "intolerable") to demonstrate the range of possible conditions in this study. This was done to "calibrate" the subjects' responses. As Lulla and Bennett showed, the range of stimuli used in a psychophysical experiment can influence subjects' responses (1981). Therefore, Tiller and Rea recommended that pre-experimental standards should be used to define the meaning of the upper and lower limits of a rating scale to observers, anchoring the response range to the stimulus range (1992). After the setup, the subject completed three practice trials to get familiar and comfortable with the procedure. Practice trials for the observers were employed to reduce the response variability associated with learning an unfamiliar task.

Finally, after the practice trials the main experiment started. The entire introduction up to the start of the main experiment took approximately 25-30 minutes. The experimenter closed the curtain (at the entrance to the sphere), so no light from the outside could enter the sphere. Each subject saw each of the 36 lighting conditions in a randomized order with every condition lasting approximately 60 seconds.

Before the start of each condition, the software checked the impedance of the electrodes. If it detected a problem, a pop-up window was shown to the experimenter indicating that the electrodes had to be re-attached.

At the beginning of each condition (refer to Figure 3-34 for the timeline), the background luminance was set to one of the three levels (0.03; 0.3; 1 cd/m^2) according to the experimental condition parameters. The adaptation time lasted approximately 49.2 seconds. During the first 31.2 seconds, when no fixation point was on, the subjects were allowed to move their eyes without moving their heads on the chinrest. This was an opportunity to relax their eyes, and increase the subjects' attention. At 31.2 seconds, the fixation point was switched on; the subjects had to fixate the gaze on the fixation point at all times.

At approximately 46.8 seconds, the experimenter pressed the "Start Record" button in the eye tracking software on the second laptop. At approximately the same time, the EMG recording started automatically and no additional input was needed from the experimenter. The eye tracking recording automatically switched itself off after 12 seconds as did the EMG.

At 49.2 seconds, the flashing sequence started either at the 0˚ or at 10˚ position, depending on the condition. After all three flashes were shown, the subject verbally rated discomfort glare on a scale of 0 through 6 (Appendix O), which the experimenter entered into the glare software.

Through the camera of the eye tracking device, the experimenter observed what the subjects were looking at. It was critical to verify that subjects looked at the fixation point when necessary and were not glancing at the upper source when they had to look straight ahead. Besides recording the pupil diameter, the eye tracking device proved to be a very valuable quality check – for example, to detect sleepiness of some participants, which was noted in the subject's file.

After all 36 lighting conditions were completed, each subject was asked to answer a one-question survey (Appendix Q), which concluded the experiment.

CHAPTER 4 – RESULTS

The task of data analysis is to build a story of what the data have to tell.
- Judd et al. 2009

The experiment generated three different bodies of data that cover different aspects of the human reaction to discomfort glare. The first one is the subjective assessment of discomfort glare reported by the subjects (the rating scale data). This is simply a rating for each of the 36 lighting conditions (or scenarios) by each of the 47 subjects included in the data analysis (the full dataset is shown in Appendix R and an example in Table 4-1).

Table 4-1. Results of the rating scale experiment for Subject ID32

Scenario number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Subjective response	**1**	**2**	**2**	**4**	**3**	**4**	**3**	**1**	**2**	**4**	**3**	**3**	**4**	**3**	**2**	**5**	**6**	**6**
Scenario number	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Subjective response	**2**	**3**	**3**	**5**	**5**	**5**	**5**	**5**	**5**	**6**	**6**	**6**	**3**	**4**	**3**	**5**	**5**	**5**

The second body of data is the pupil diameter data that were collected from the remote eye tracking device aimed at the left eye of the subject. In each condition the pupil diameter was recorded for 12 seconds, resulting in 720 individual data points (60 points per second) (Figure 4-1) (the full dataset of the relative pupil size is shown in Appendix U).

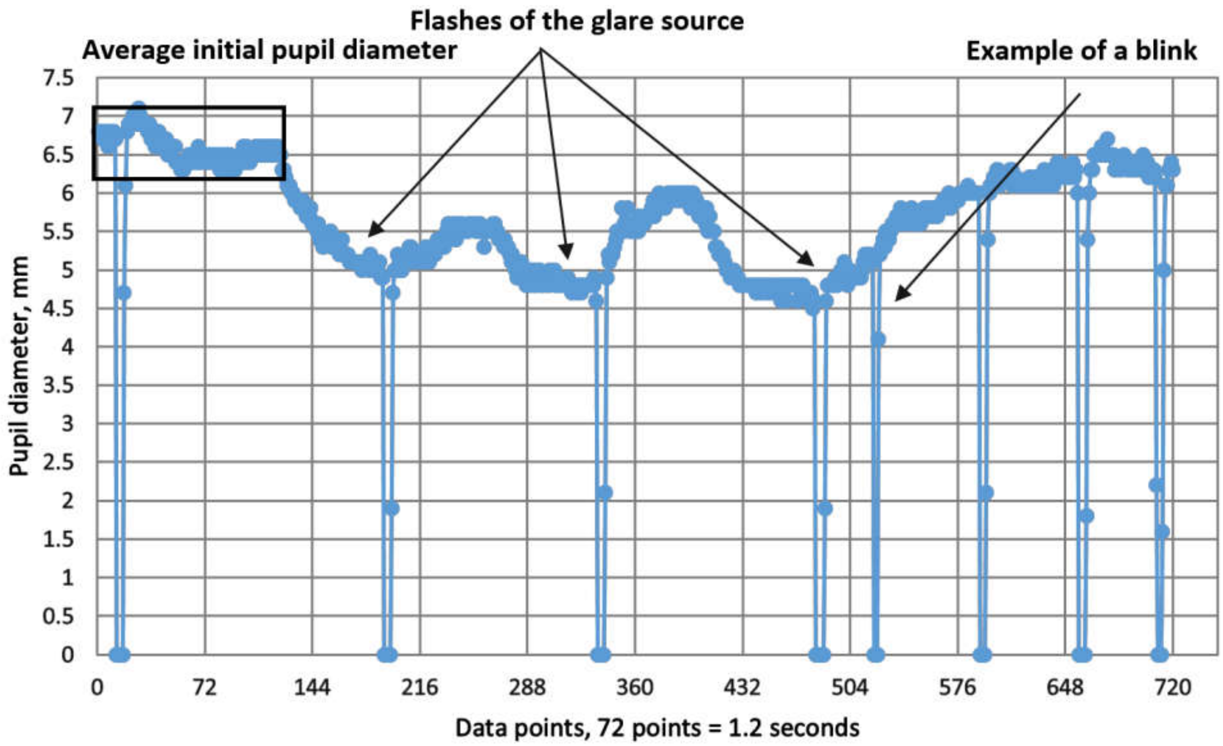


Figure 4-1. Example of pupil diameter recorded for 12 seconds for one subject and one condition (subject ID32, condition 15).

Finally, the third body of data is the set of EMG readings recorded through electrodes placed on the subjects' faces in the area of orbicularis oculi (Figure 3-32) – the muscle responsible for closing the eyes. The EMG readings were recorded for 12 seconds in each condition for each subject.

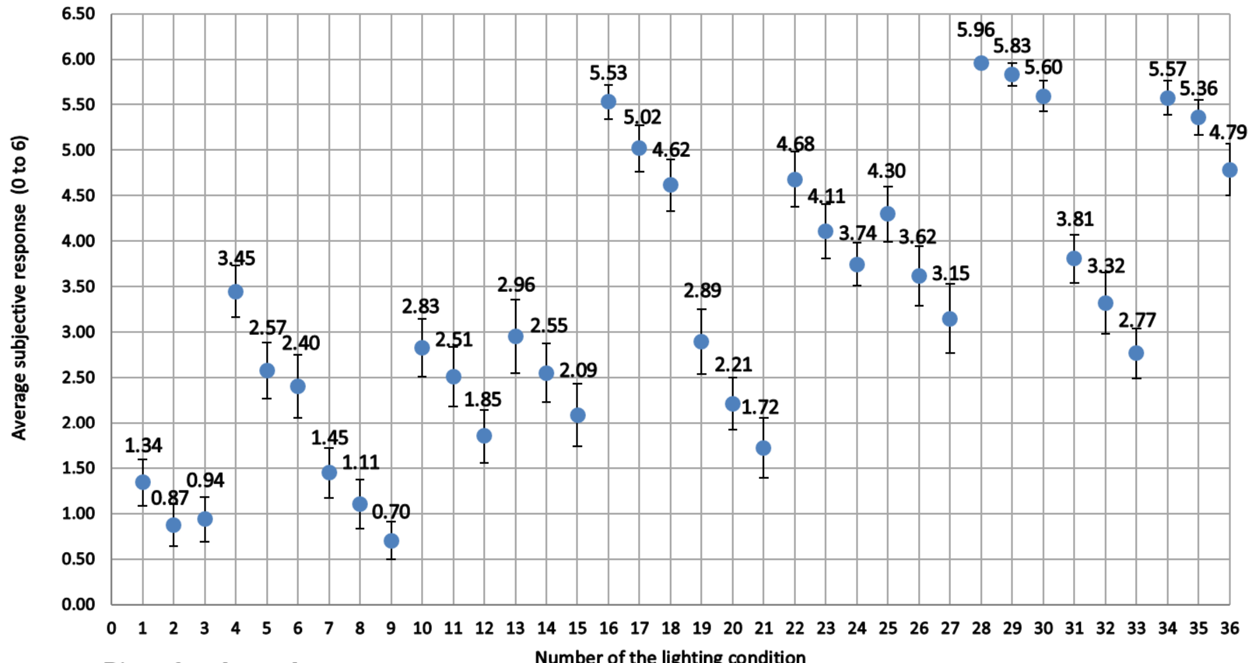
4.1 Rating Scale Analysis

A repeated-measures Analysis of Variance (ANOVA) was used for the analysis of the rating scale data. Prior to the discussion of the results acquired through ANOVA, one can gain a useful insight about the collected data by simply looking at the descriptive statistics. The subjective responses to discomfort glare given by 47 of the 56 subjects, who participated in the experiment, were included in the rating scale analysis (see section 3.11.1 on the data exclusion of 9 subjects). The responses were averaged across 47 subjects to determine a mean rating for each of the 36 lighting conditions (Table 4-2). The values were plotted in Figure 4-2 with 95% confidence intervals shown as errors bars.

Table 4-2. Thirty-six experimental lighting conditions

Number of condition (scenario)	Luminance, cd/m^2	Position, degrees	Background luminance, cd/m^2	Solid angle, sr
1	20,000	0	0.03	10^{-5}
2	20,000	0	0.3	10^{-5}
3	20,000	0	1	10^{-5}
4	20,000	0	0.03	10^{-4}
5	20,000	0	0.3	10^{-4}
6	20,000	0	1	10^{-4}
7	20,000	10	0.03	10^{-5}
8	20,000	10	0.3	10^{-5}
9 (min)	20,000	10	1	10^{-5}
10	20,000	10	0.03	10^{-4}
11	20,000	10	0.3	10^{-4}
12	20,000	10	1	10^{-4}
13	205,000	0	0.03	10^{-5}
14	205,000	0	0.3	10^{-5}
15	205,000	0	1	10^{-5}
16	205,000	0	0.03	10^{-4}
17	205,000	0	0.3	10^{-4}
18	205,000	0	1	10^{-4}
19	205,000	10	0.03	10^{-5}
20	205,000	10	0.3	10^{-5}
21	205,000	10	1	10^{-5}
22	205,000	10	0.03	10^{-4}
23	205,000	10	0.3	10^{-4}
24	205,000	10	1	10^{-4}
25	750,000	0	0.03	10^{-5}
26	750,000	0	0.3	10^{-5}
27	750,000	0	1	10^{-5}
28 (max)	750,000	0	0.03	10^{-4}
29	750,000	0	0.3	10^{-4}
30	750,000	0	1	10^{-4}
31	750,000	10	0.03	10^{-5}
32	750,000	10	0.3	10^{-5}
33	750,000	10	1	10^{-5}
34	750,000	10	0.03	10^{-4}
35	750,000	10	0.3	10^{-4}
36	750,000	10	1	10^{-4}

It is clear from the error bars that statistically significant effects are expected in this dataset. For example, a linear increase in the luminance of the glare source produced higher subjective ratings of discomfort glare (the first 12 conditions have a luminance of 20,000 cd/m^2, the second 12 – 205,000 cd/m^2, and the third 12 – 750,000 cd/m^2). Another example would be a source with the solid angle of 10^{-4} sr created more discomfort glare than did 10^{-5} sr (conditions 1-3, 7-9, 13-15, 19-21, 25-27, 31-33 have a solid angle of 10^{-5} sr and conditions 4-6, 10-12, 16-18, 22-24, 28-30, 34-36 have 10^{-4} sr (refer to Table 4-2)).



Discomfort glare scale
0 - No discomfort glare
1 - Between non-existent and noticeable
2 - Noticeable
3 - Between noticeable and disagreeable
4 - Disagreeable
5 - Between disagreeable and intolerable
6 - Intolerable

Figure 4-2. Average of 47 subjective responses for each of the 36 lighting conditions

4.1.1 Repeated-measures ANOVA

A repeated-measures Analysis of Variance (ANOVA) was used for the analysis of the rating scale data to compare the means of more than two groups. Based on a predefined alpha (α) level and appropriate degrees of freedom, the F-statistic is calculated for each group, and is compared to the critical value. If it exceeds the critical value, the null hypothesis (i.e. that the means for each group are the same) is rejected. ANOVA provides results for both the main effects and interactions. It is based on the following assumptions about the errors: (1) they are normally distributed, (2) they have constant variance, and (3) they are independent of each other (Judd et al. 2011). The first two are often seen as "robust" assumptions meaning that the violation of these assumptions does not result in major statistical errors (Judd et al. 2011).

The experiment in this study was designed as a 3x2x2x3, full-factorial, repeated-measures experiment - every level of one variable was combined with every level of all other variables (36 conditions in total). The null hypothesis for the effect of the luminance in the rating scale analysis is as follows:

$$\mu_{20,000\ cd/m^2} = \mu_{205,000 cd/m^2} = \mu_{7\ 50000 cd/m^2} \qquad \textbf{(4-1)}$$

Similarly, the null hypothesis for the effect of the position (the angle between the fixation point and the light source), the solid angle, and the background luminance are respectively:

$$\mu_{0^\circ} = \mu_{10^\circ} \qquad \textbf{(4-2)}$$

$$\mu_{10^{-5}} = \mu_{10^{-4}} \qquad \textbf{(4-3)}$$

$$\mu_{0.03\ cd/m^2} = \mu_{0.3\ cd/m^2} = \mu_{1\ cd/m^2} \qquad \textbf{(4-4)}$$

The means and standard deviations for each level of each variable are given in Table 4-3. Each subject rated discomfort glare on a scale of 0-6 for each of the 36 lighting conditions.

The data were entered into SAS for analysis. Both the data and the SAS commands used for analysis are shown in Appendix R – SAS Command File for Subjective Responses Analysis. Table 4-4 shows the main effects and all possible interactions together with significance levels.

Table 4-3. Means and standard deviations of the subjective responses data

Independent Variable	Level	Mean (μ) Discomfort Glare Rating	Standard Deviation (σ) of Discomfort Glare Rating
Luminance	20,000 cd/m^2	1.84	0.66
	205,000 cd/m^2	3.51	0.64
	750,000 cd/m^2	4.51	0.48
Position	0°	3.49	0.58
	10°	3.08	0.61
Solid angle	10^{-5} sr	2.32	0.66
	10^{-4} sr	4.25	0.47
Background luminance	0.03 cd/m^2	3.73	0.57
	0.3 cd/m^2	3.26	0.57
	1 cd/m^2	2.86	0.59

Table 4-4. Complete table of all effects from the ANOVA analysis of subjective responses data of 47 subjects

Source	df *	F	P
Main effects			
Significant			
Luminance	**2**	812.05	<0.0001
Linear effect	1	1139.57	<0.0001
Quadratic effect	1	56.94	<0.0001
Position	1	30.49	<0.0001
Solid angle	1	926.81	<0.0001
Background luminance	**2**	126.68	<0.0001
Linear	1	176.59	<0.0001
Non-significant			
Quadratic (background luminance)	1	1.25	0.2688
Two-way interactions			
Significant			
Luminance X Position	**2**	6.66	0.002
Linear luminance X Position	1	9.05	0.0042
Quadratic luminance X Position	1	5.19	0.0274
Luminance X Solid angle	**2**	18.95	<0.0001

Linear luminance X Solid angle	1	15	0.0003
Quadratic luminance X Solid angle	1	25.36	<0.0001
Linear luminance X Background luminance quadratic	1	4.66	0.0361
Position X Solid angle	1	20.27	<0.0001
Position X Background luminance	**2**	4.88	0.0097
Position X Quadratic background luminance	1	6.21	0.0164
Non-significant			
Luminance X Background luminance*	**4**	1.69	0.1539
Linear luminance X Background luminance linear	1	0.18	0.6771
Quadratic luminance X Background luminance linear	1	2.39	0.1289
Quadratic luminance X Background luminance quadratic	1	0.13	0.7163
Position X Linear background luminance	1	3.82	0.0567
Solid angle X background luminance	**2**	0.32	0.7276
Solid angle X Linear background luminance	1	0.36	0.5497
Solid angle X Quadratic background luminance	1	0.27	0.6038
Three-way interactions			
Significant			
*Quadratic luminance X Position X Solid angle**	1	4.51	0.0392
Quadratic luminance X Position X quadratic background luminance	1	5.47	0.0237
Luminance X Solid angle X Background luminance	**4**	5.16	0.0006
Linear luminance X Solid angle X Linear background luminance	1	19.54	<0.0001
Non-significant			
Luminance X Position X Solid angle	**2**	2.84	0.0634
Linear luminance X Position X Solid angle	1	1.75	0.1922
Luminance X Position X Background luminance	**4**	2.12	0.0798
Linear luminance X Position X linear background luminance	1	0.01	0.9202
Linear luminance X Position X quadratic background luminance	1	3.69	0.0608

Quadratic luminance X Position X linear background luminance	1	0.00	0.9532
Linear luminance X Solid angle X Quadratic background luminance	1	0.55	0.4605
Quadratic luminance X Solid angle X Linear background luminance	1	0.09	0.7595
Quadratic luminance X Solid angle X Quadratic background luminance	1	0.54	0.4669
Position X Solid angle X Background luminance	**2**	0.26	0.7742
Position X Solid angle X Linear background luminance	1	0.07	0.7874
Position X Solid angle X Quadratic background luminance	1	0.51	0.4766
Four-way interactions			
Significant			
Linear luminance X Position X Solid angle X Linear background luminance	1	7.74	0.0078
Non-significant			
Luminance X Position X Solid angle X Background luminance	**4**	1.62	0.1704
Linear luminance X Position X Solid angle X Quadratic background luminance	1	0.66	0.4214
Quadratic luminance X Position X Solid angle X Linear background luminance	1	0.64	0.4293
Quadratic luminance X Position X Solid angle X Quadratic background luminance	1	0.01	0.9272

*The denominator degrees of freedom for df = 1, df = 2, and df = 4 were 46, 92, and 186 respectively.

A potential violation of the homogeneity of variance assumption that underlies this analysis was assessed by examining the variances. According to Howell (2011), the general rule of thumb is that the variance in one condition should be smaller than four times the variance in other conditions. Additionally, if the sample sizes are equal, a violation of this assumption is unlikely to cause problems for statistical inference. Howell also points out that a factor of four is probably conservative, and using the standard approach seems appropriate when variances are considerably different (i.e., more than four times as large in one condition as in another) as long as the sample sizes are roughly equal.

By examining the variances of the subjective dataset, one can see three very small variances for conditions 28, 29, and 30 (Table 4-5). This means that subjects agreed on the worst conditions without much variability. These variances could potentially be problematic when testing differences between these and other conditions.

Table 4-5. Variances based on subjective responses for each lighting condition

Condition number	Variance	Condition number (continued)	Variance (continued)
1	0.795	**19**	1.575
2	0.636	**20**	0.997
3	0.713	**21**	1.335
4	0.992	**22**	1.135
5	1.163	**23**	1.097
6	1.463	**24**	0.673
7	0.948	**25**	1.127
8	0.880	**26**	1.285
9	0.518	**27**	1.782
10	1.231	**28**	**0.042**
11	1.299	**29**	**0.188**
12	1.043	**30**	**0.333**
13	1.998	**31**	0.854
14	1.253	**32**	1.352
15	1.471	**33**	0.922
16	0.428	**34**	0.424
17	0.804	**35**	0.453
18	0.981	**36**	0.997

However, the variances for the main tests and two-way interactions, which were the tests of the primary interest in this research, met the general rule of differing by no more than approximately a factor of 4 (Table 4-6). This means that the homogeneity of variance assumption was not violated for these tests. An examination of the variances, which were similar in magnitude, indicated that neither the homogeneity of variance nor the normality assumption was violated.

Table 4-6. Variances based on subjective responses in the main and the two-way interactions tests

Variable level	Variance	Variable level (continued)	Variance (continued)
Luminance 1	0.431	Luminance 1 Background luminance 3	0.473
Luminance 2	0.404	Luminance 2 Background luminance 1	0.629
Luminance 3	0.229	Luminance 2 Background luminance 2	0.482
Position 1	0.331	Luminance 2 Background luminance 3	0.471
Position 2	0.367	Luminance 3 Background luminance 1	0.216
Solid angle 1	0.441	Luminance 3 Background luminance 2	0.298
Solid angle 2	0.222	Luminance 3 Background luminance 3	0.437
Background luminance 1	0.323	Position 1 Solid angle 1	0.577
Background luminance 2	0.322	Position 1 Solid angle 2	0.260
Background luminance 3	0.349	Position 2 Solid angle 1	0.502
Luminance 1 position 1	0.439	Position 2 Solid angle 2	0.343
Luminance 1 position 2	0.593	Position 1 Background luminance 1	0.331
Luminance 2 position 1	0.604	Position 1 Background luminance 2	0.343
Luminance 2 position 2	0.492	Position 1 Background luminance 3	0.516
Luminance 3 position 1	0.262	Position 2 Background luminance 1	0.519
Luminance 3 position 2	0.400	Position 2 Background luminance 2	0.441
Luminance 1 solid angle 1	0.413	Position 2 Background luminance 3	0.354
Luminance 1 solid angle 2	0.620	Solid angle 1 Background luminance 1	0.601
Luminance 2 solid angle 1	0.678	Solid angle 1 Background luminance 2	0.489
Luminance 2 solid angle 2	0.355	Solid angle 1 Background luminance 3	0.554
Luminance 3 solid angle 1	0.523	Solid angle 2 Background luminance 1	0.224
Luminance 3 solid angle 2	0.125	Solid angle 2 Background luminance 2	0.306
Luminance 1 Background luminance 1	0.479	Solid angle 2 Background luminance 3	0.325
Luminance 1 Background luminance 2	0.574		

A set of four graphs for this 3x2x2x3 design was created to show all 36 cell means (Figure 4-3 to Figure 4-6).

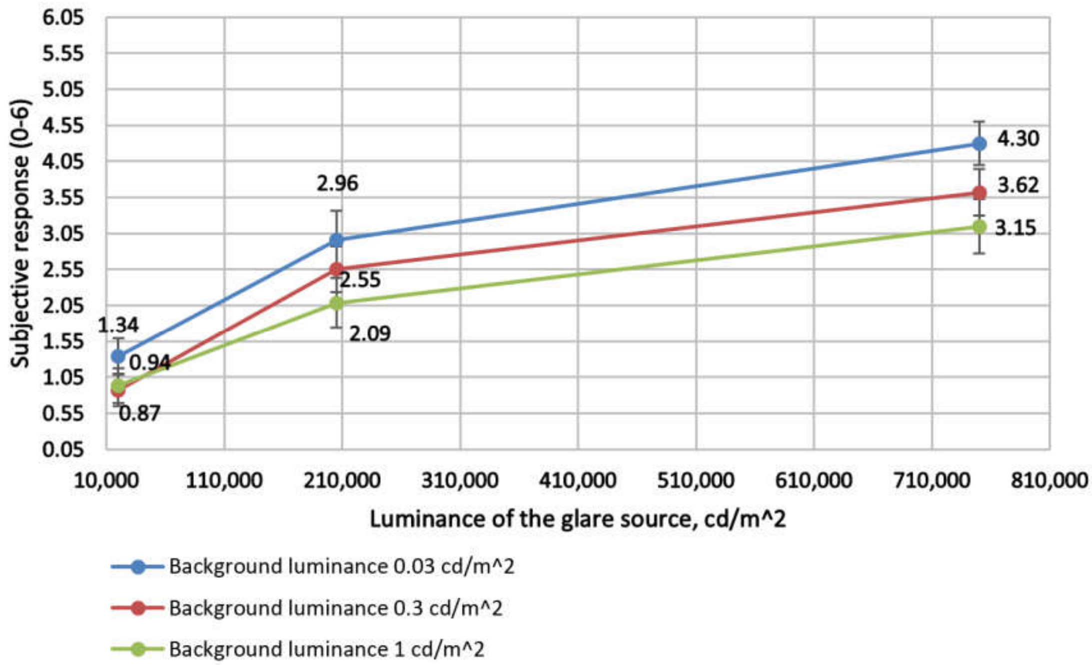


Figure 4-3. Interaction of the glare source luminance and the background luminance for position 0° and a solid angle of 10^{-5} sr

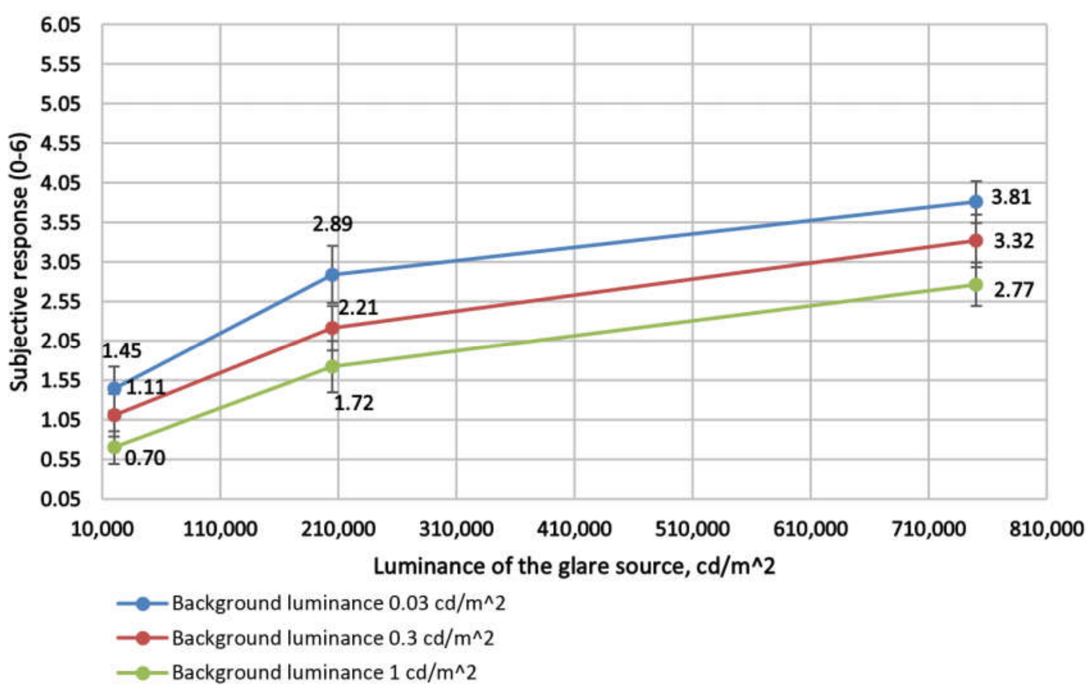


Figure 4-4. Interaction of the glare source luminance and the background luminance for position 10° and a solid angle of 10^{-5} sr

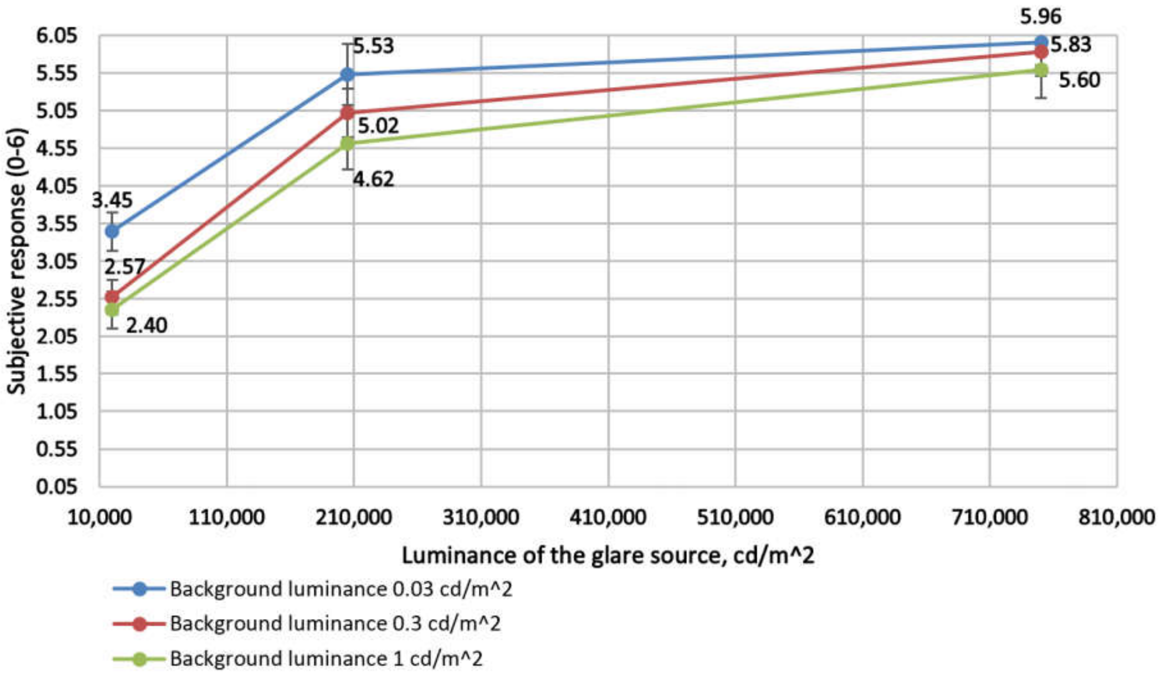


Figure 4-5. Interaction of the glare source luminance and the background luminance for position 0° and a solid angle of 10^{-4} sr

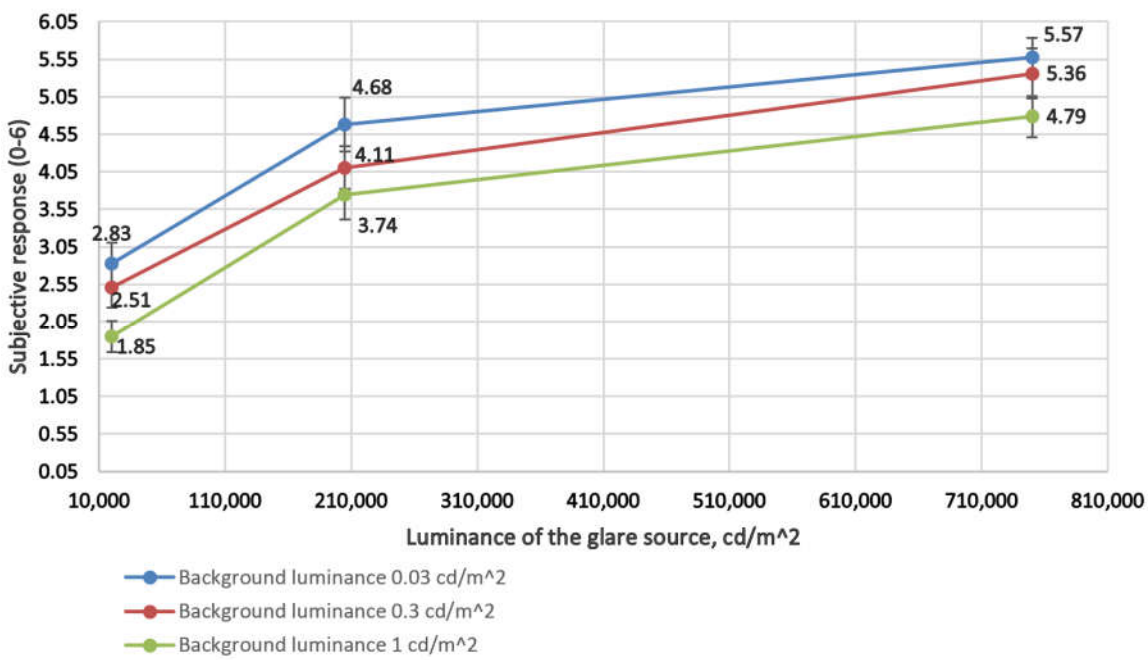


Figure 4-6. Interaction of the glare source luminance and the background luminance for position 10° and a solid angle of 10^{-4} sr

4.1.1.1 Significant main effects

The linear effect of the glare source luminance indicates that a greater luminance results in higher subjective ratings of discomfort glare. In other words, a luminance of 750,000 cd/m^2 results in subjective ratings of discomfort glare that are significantly higher than a luminance of 20,000 cd/m^2. The quadratic effect of glare source luminance indicates that subjective responses to discomfort glare increase as the luminance increases from 20,000 to 205,000 cd/m^2, after which the rate of increase is lower (from 205,000 cd/m^2 to 750,000 cd/m^2) (Figure 4-7).

The main effect of the position indicates that discomfort glare is greater for the source located at the 0° position (on the line of sight) than at the 10° position (Figure 4-8).

The main effect of the solid angle shows that discomfort glare is higher for the larger glare source (10^{-4} sr) than for the smaller source (10^{-5} sr) (Figure 4-9).

The linear effect of the background luminance shows that the lower the background luminance the greater the discomfort glare (Figure 4-10). Discomfort glare increases when the background luminance decreases from 1 cd/m^2 to 0.03 cd/m^2.

The analysis showed that discomfort glare increases with an increase of the luminance of the glare source, an increase of its size, a decrease of the angle between the fixation point and the glare source, as well as a decrease of the background luminance.

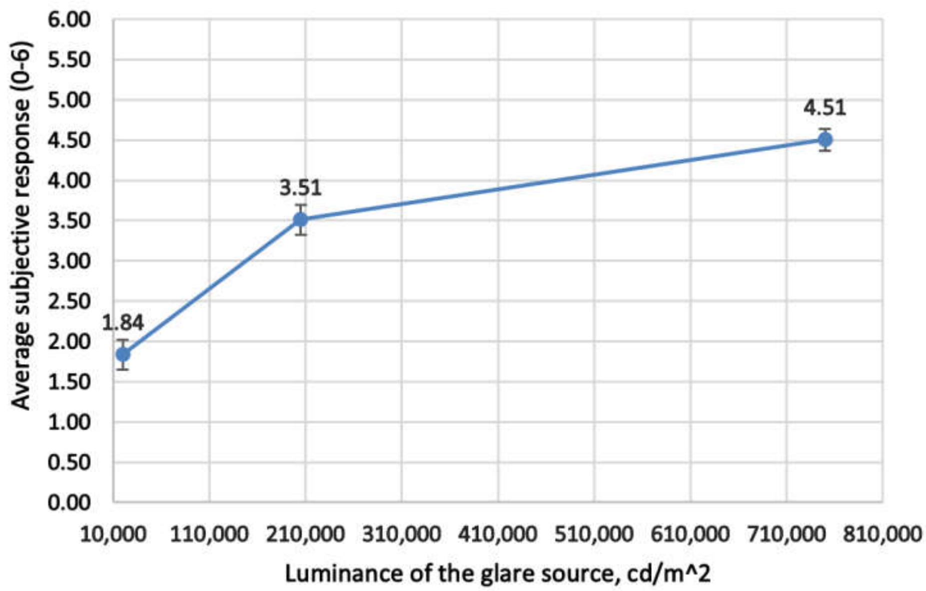


Figure 4-7. Main effects of the glare source luminance

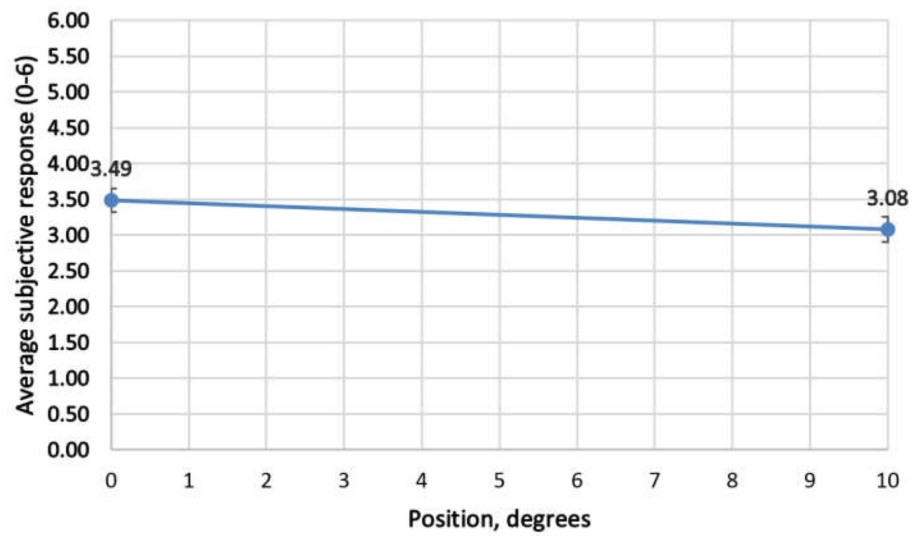


Figure 4-8. Main effect of the position

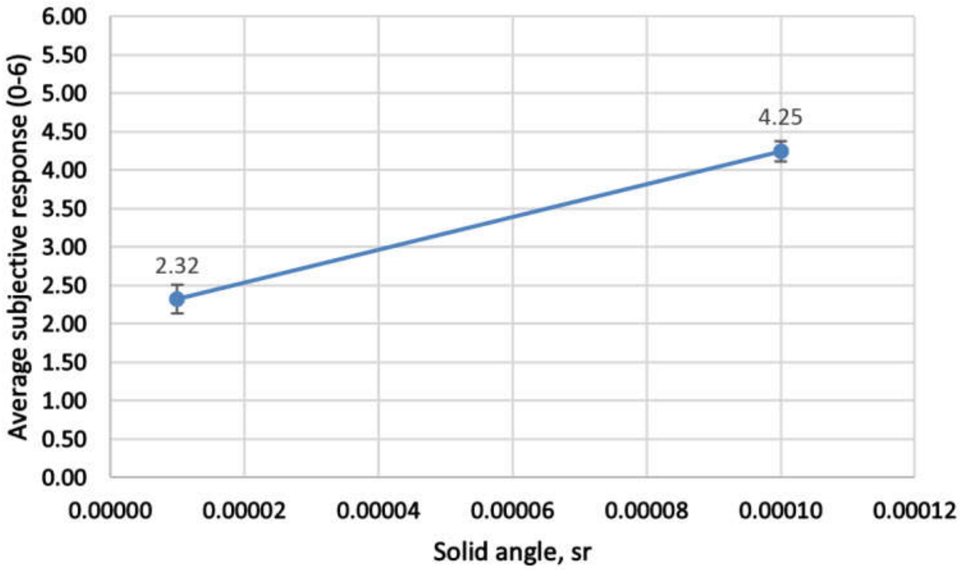


Figure 4-9. Main effect of the solid angle

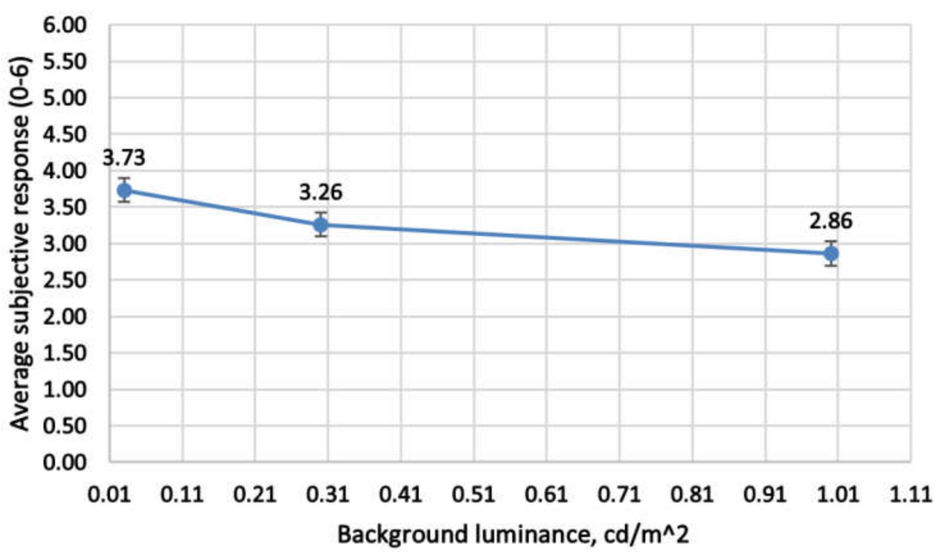


Figure 4-10. Main effects of the background luminance

4.1.1.2 Significant interactions

The significant interaction between the linear effect of the glare source luminance and the source position shows that the linear increase in perceived discomfort glare as a function of the luminance increase was especially true for a source located at the 0° position compared to the 10° position. The quadratic effect shows that the perception of discomfort glare increases more initially (from 20,000 cd/m^2 to 205,000 cd/m^2) than subsequently (from 205,000 cd/m^2 to 750,000 cd/m^2), especially for the 0° position when compared to the 10° position.

The linear increase in perceived discomfort glare as a function of the luminance was especially true for a glare source of solid angle 10^{-4} sr when compared to a source of solid angle of 10^{-5}. The quadratic effect between the luminance and its solid angle shows that the perception of discomfort glare is increased more initially (from 20,000 cd/m^2 to 205,000 cd/m^2) than subsequently (from 205,000 cd/m^2 to 750,000 cd/m^2), which is especially true for a larger source (10^{-4} sr) when compared to a smaller source (10^{-5} sr).

A significant two-way interaction between the linear effect of the glare source luminance and the quadratic effect of the background luminance shows that there is more discomfort glare when the glare source luminance is increased, especially when the background luminance decreases from 0.3 to 0.03 cd/m^2 compared to a decrease from 1 to 0.3 cd/m^2 (Figure 4-11).

The two-way interaction between the position and the solid angle of the glare source indicates that the perception of discomfort glare is higher for a larger source than for a smaller source, which is especially true for the source on the line of sight (0°) than for the source that is 10° above the line of sight.

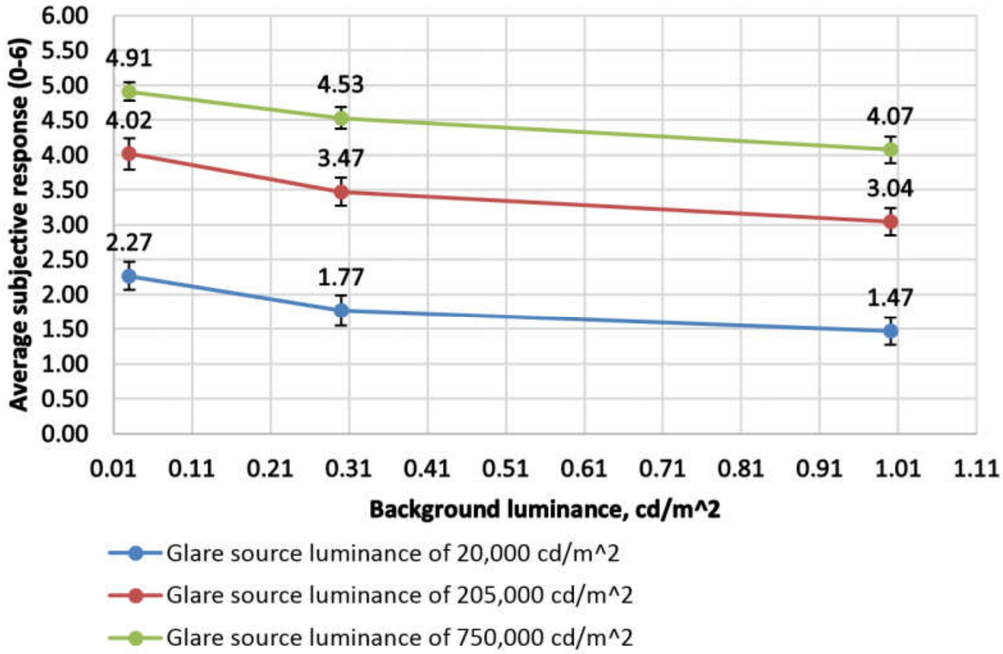


Figure 4-11. Interaction of the glare source luminance with the background luminance

The interaction between the position of the glare source and the quadratic effect of the background luminance shows that the perception of discomfort glare is higher from a glare source on the line of sight than one 10° above the line of sight, especially for the darker backgrounds (0.03-0.3 cd/m^2) than for the brighter ones (0.3-1 cd/m^2).

Finally, there are significant three-way interactions and one four-way interaction. The three-way interaction between the glare source position, its solid angle, and the quadratic effect of its luminance indicates that discomfort glare increases as luminance increases from 20,000 to 205,000 cd/m^2, after which the rate of increase is smaller (from 205,000 cd/m^2 to 750,000 cd/m^2), especially for a larger source (10^{-4} sr vs 10^{-5} sr) on the line of sight (0° vs 10°).

The perception of discomfort glare increases for the glare source on the line of sight (0° vs 10°) as the luminance increases from 20,000 to 205,000 cd/m^2, after which the rate of increase is less (from 205,000 cd/m^2 to 750,000 cd/m^2), especially true for darker backgrounds when compared to brighter ones (0.03 to 0.3 vs 0.3 to 1 cd/m^2).

The three-way interaction between the luminance, the solid angle of the glare source, and the background luminance shows that as the background luminance decreases from 1 to 0.03 cd/m^2, the perception of discomfort glare increases, in particular for a larger source (10^{-4} to 10^{-5}) of a higher luminance (the linear effect of luminance).

Although the four-way interaction between the luminance of the glare source, its position, its solid angle, and the background luminance is not of primary interest, it is significant. This interaction indicates that as the background luminance decreases from 1 to 0.03 cd/m^2, the perception of discomfort glare increases, in particular for a larger source (10^{-4} to 10^{-5}) on the line of sight (compared to 10°) as luminance of the glare source increases from 20,000 to 750,000 cd/m^2.

4.1.2 Correlation Analysis

Based on the subjective rating data, one can examine which discomfort glare metric correlates best with subjective responses to discomfort glare in the ranges of conditions tested in this study.

Predictions of discomfort glare by four existing metrics were compared to subjective responses for all 36 experimental lighting conditions in this study. The metrics used in the comparison analysis were the outdoor sports and area lighting metric – metric 1 (CIE 112-1994), the motor vehicle lighting metric – metric 2 (Schmidt-Clausen and Bindels 1974), the combination of two metrics by Bullough's et al. – metric 3 (2008, 2011), and the UGR small source extension – metric 4 (CIE146,147-2002).

Predictions by each discomfort glare metric were correlated with subjective responses across conditions for each subject. These correlations were transformed, using Fisher's z transformation, and compared, using dependent sample *t*-tests, to see which, if any, of the glare metrics correlated better with the subjective responses.

The first step was to calculate the metrics' predictions of discomfort glare for the 36 experimental conditions. During the course of the study, the experimenter collected multiple measurements of the apparatus to ensure the consistency of the stimuli (section 3.7). The averages of photometric measures collected over time were used in the calculations. For example, the background luminance was measured multiple times – before the start of the experiment, after subjects 18, 34, 44, and 56 (at the end of the study). Then, the background luminance measurements were averaged over time and used in each metric's calculation that incorporates a background luminance parameter in its equation (in this case, metric 1, 2, and 4).

Each of the four discomfort glare metrics has a validity range. Some existing metrics are not defined for certain input values and result in infinitely large numbers. For example, the outdoor sports and area lighting metric (metric 1) and the motor vehicle lighting metric (metric 2) cannot predict discomfort glare when a subject looks directly at the glare source. In this case, the angle between the line of sight and the position of the glare source is 0˚, and the discomfort glare prediction becomes infinite, which does not reflect reality. Therefore, meaningful substitutions of these problematic values had to be made in order to calculate and compare the predictions.

Two ways to address the problematic input values were considered. One way was to substitute these values with a small number that would allow the calculation of predictions. However, it should be acknowledged this kind of substitution would result in input values outside the validity range of some metrics. For example, a substitution of an angle different from 0°, such as 1 min. arc, is outside the validity range of the outdoor sports and area lighting metric as specified by the CIE (112-1994) – the angle should be between 1.5° to 60°. Another way to calculate the predictions was to substitute input values for the metrics with values that fall within their validity range. However, those substitutions would not be representative of the actual lighting conditions that the subjects assessed in this study. Therefore, the author chose the first method, because the goal was to determine which metric correlates best with subjective responses collected in this study. As such, the predictions should be calculated with values as close to the experimental conditions as possible.

Metrics 2 and 3 use inverted scales when compared to the subjective scale used in the current study (in metric 2 and 3, smaller values indicate more glare). This would result in a negative sign of the correlation coefficient, if a correlation indeed existed. To simplify the comparison, the scales were inverted by subtracting the resulting glare prediction as calculated by the metrics 2 or 3 from the number 10. This made the direction of the effect in all four metrics the same – larger numbers mean more glare. The step-by-step calculations of each metric's predictions for all 36 lighting conditions are discussed in Appendix S.

Table 4-7 shows the predictions of the 36 lighting conditions as calculated by each of the four tested metrics. Numbers in ***bold cursive*** fall outside the scale's range for that metric. The values were graphed in Figure 4-12. Since the scales of discomfort glare metrics are so different (e.g. 1-9 and 10-90 with values exceeding the maximum), two axes were used to better display the curves. Subjective responses, metrics 2 and 3 are shown on the left vertical axis (round markers). Metrics 1 and 4 are shown on the right vertical axis (triangular markers).

Table 4-7. Discomfort glare in the 36 lighting conditions as assessed in this study and calculated by four discomfort glare metrics

Number of the condition	AVERAGE subjective rating from this study	Calculations by the outdoor sports and area lighting metric 1994 (metric 1)	Calculations by the motor vehicle lighting metric 1974 (metric 2)	Calculations by the outdoor lighting installation (two equations 2008, 2011) (metric 3)	Calculations by the UGR small source extension metric 2002 (metric 4)
Scales (to the right)	0 – no DG 1 – between non-existent and noticeable 2 – noticeable 3 – between noticeable and disagreeable 4 – disagreeable 5 – between disagreeable and intolerable 6 – intolerable	10 – unnoticeable 20 30 –noticeable 40 50 – just admissible 60 70 - disturbing 80 90 - unbearable	9 – noticeable 8 7 – acceptable 6 5 – just admissible 4 3 – disturbing 2 1 – unbearable	9 –just noticeable 8 7 – satisfactory 6 5 – just permissible 4 3 – disturbing 2 1 – unbearable	10 – imperceptible 16 – perceptible 19 – just acceptable 22 – unacceptable 25 – just uncomfortable 28 – uncomfortable 31 – just intolerable (1999 Mistrick)
Scales inverted (to the right)			INVERTED 1 – noticeable 2 3 – acceptable 4 5 – just admissible 6 7 – disturbing 8 9 – unbearable	INVERTED 1–just noticeable 2 3 – satisfactory 4 5 – just permissible 6 7 – disturbing 8 9 – unbearable	
1	1.3	***179***	7.9	4.1	14.0
2	0.9	***158***	7.3	2.7	6.3
3	0.9	***147***	6.8	1.5	2.1
4	3.4	***205***	***10.0***	5.9	30.0
5	2.6	***184***	***9.4***	5.4	22.3
6	2.4	***173***	9.0	5.1	18.1
7	1.4	49	5.5	4.4	12.3
8	1.1	28	4.9	3.3	4.6
9	0.6	17	4.5	2.3	0.4
10	2.8	74	7.7	6.1	28.3

11	2.5	54	7.1	5.6	20.6
12	1.8	42	6.6	5.3	16.4
13	3.0	***205***	***10.0***	6.4	***30.3***
14	2.5	***184***	***9.4***	5.9	22.6
15	2.0	**173**	9.0	5.6	18.4
16	5.5	***231***	***12.2***	8.5	***46.3***
17	5.0	***210***	***11.6***	8.2	***38.6***
18	4.6	***199***	***11.1***	8.0	***34.4***
19	2.9	72	7.5	6.4	27.9
20	2.2	51	6.9	5.9	20.2
21	1.7	40	6.4	5.6	16.0
22	4.7	***98***	***9.6***	8.6	***43.9***
23	4.1	77	9.0	8.3	***36.2***
24	3.7	65	8.6	8.1	***32.0***
25	4.2	***218***	***11.1***	7.1	***39.1***
26	3.6	***197***	***10.5***	6.8	***31.4***
27	3.1	***186***	***10.1***	6.5	27.2
28	6.0	***244***	***13.3***	***9.7***	***55.1***
29	5.8	***223***	***12.7***	***9.4***	***47.4***
30	5.6	***212***	***12.3***	***9.3***	***43.2***
31	3.8	85	8.5	7.1	***36.5***
32	3.3	64	7.9	6.8	28.8
33	2.8	53	7.5	6.5	24.6
34	5.5	***111***	***10.7***	***9.7***	***52.5***
35	5.3	90	***10.1***	***9.5***	***44.8***
36	4.8	78	***9.7***	***9.3***	***40.6***

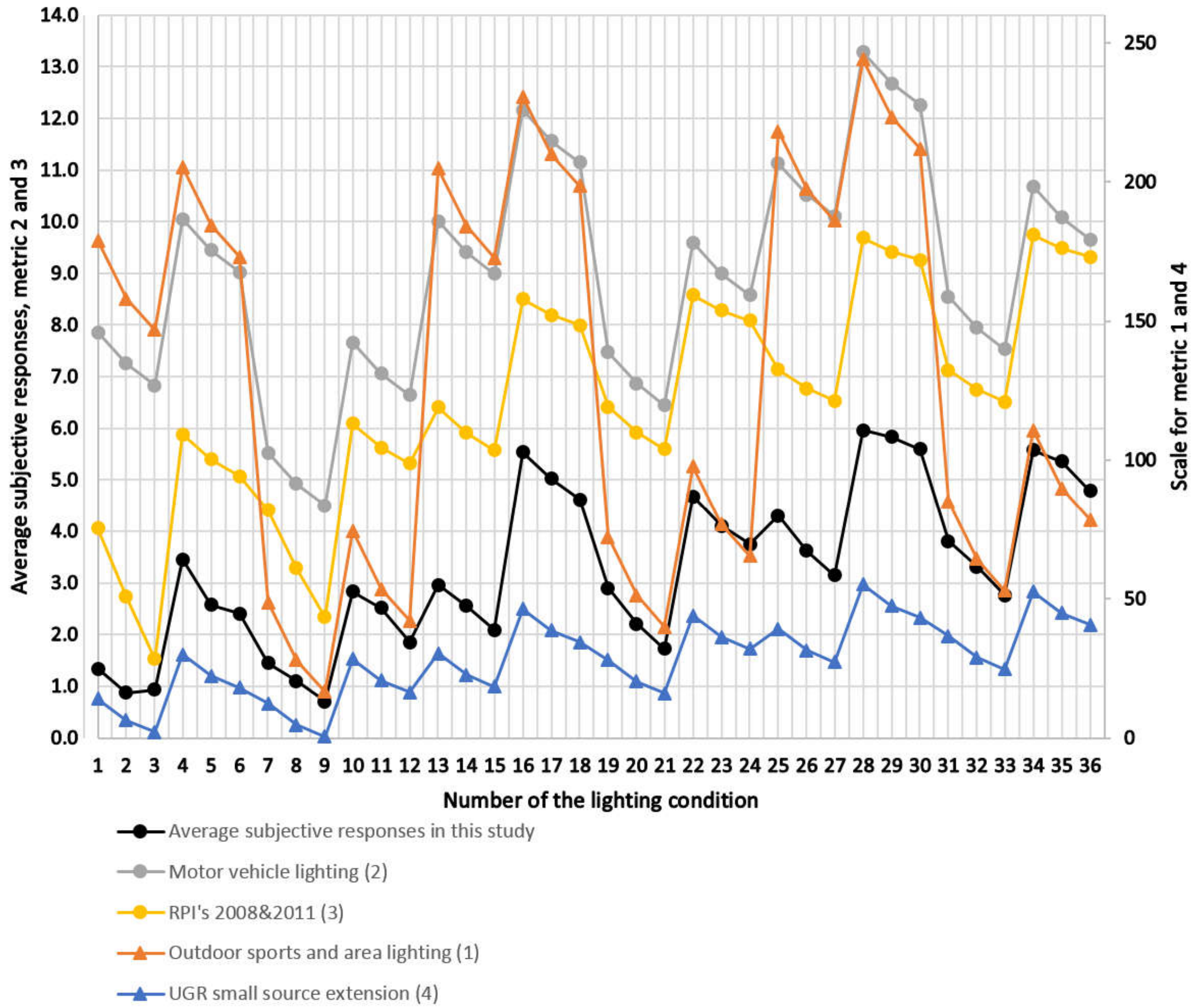


Figure 4-12. Predictions of discomfort glare by four metrics from the literature and subjective data from this study

The correlation analysis description

For each subject the correlation between subjective ratings and predictions of discomfort glare by each of the four metrics was computed across conditions (see the SAS code in Appendix T). Each of the 47 correlations (one for each subject) represented the magnitude and direction of the relationship between subjective ratings and one of the four metrics' predictions across the 36 conditions. To test whether the mean correlation differed from zero, Fisher's z transformation (equation (4-5)) was applied to the correlation coefficients. This transformation corrects potential violations of normality and homogeneity of variance, which are common when correlations are themselves the variables of interest (Judd et al. 2011).

$$\text{Fisher's z transformation} = \frac{1}{2} \cdot ln\left[\frac{1+r}{1-r}\right] \quad \textbf{(4-5)}$$

The correlation coefficient (converted from the z-transformed coefficient back to the original metric) between subjective responses and metric 1 is 0.405; between subjective responses and metric 2 it is 0.792; between subjective responses and metric 3 it is 0.860; finally, between subjective responses and metric 4 it is 0.879 (Table 4-8).

Table 4-8. Correlation coefficients between metrics' predictions and subjective responses in this study

Metric	Correlation with subjective responses, r
Outdoor sports and area lighting (1)	0.405
Motor vehicle lighting (2)	0.792
Bullough's et al. metrics (3)	0.860
UGR small source extension (4)	0.879

The z-transformed coefficients were treated as the dependent measures. The difference for each possible pair of correlation coefficients was tested for significance when compared to zero.

The differences of all pairs of correlation coefficients were statistically significant from zero (Table 4-9). This means that each correlation coefficient is significantly different from any other.

The UGR small source extension correlates best with subjective responses in the range of conditions tested in this study when compared to any other of the three metrics. The combination of the Bullough's et al. metrics correlates better than the motor vehicle lighting and the outdoor sports and area lighting metrics. Finally, the motor vehicle lighting metric correlates better with subjective responses than the outdoor sports and area lighting metric.

Table 4-9. Testing the difference between the correlation coefficients

Compared pair	Mean difference	T-test, p
Outdoor sports and area lighting (1) with Motor vehicle lighting (2)	-0.459	t = -56.6, p<0.0001
Motor vehicle lighting (2) with Bullough's et al. (3)	-0.153	t = -5.1, p<0.0001
Bullough's et al. (3) with Outdoor sports and area lighting (1)	0.611	t = 20.0, p<0.0001
UGR small source extension (4) with Outdoor sports and area lighting (1)	0.667	t = 23.8, p<0.0001
UGR small source extension (4)with Motor vehicle lighting (2)	0.208	t = 7.7, p<0.0001
UGR small source extension (4) with Bullough's et al. (3)	0.055	t = 5.5, p<0.0001

The best metric as determined by the above analysis is the UGR small source extension (r = 0.879) as seen in Figure 4-13. This means that the UGR small source extension accounts for a significantly larger variation in subjective responses than the other three metrics in the range of conditions tested in this study. However, the correlation coefficient for the combination of 2008 and 2011 Bullough's et al. metrics (second best) with subjective responses is also relatively high (r=0.860) (Figure 4-14).

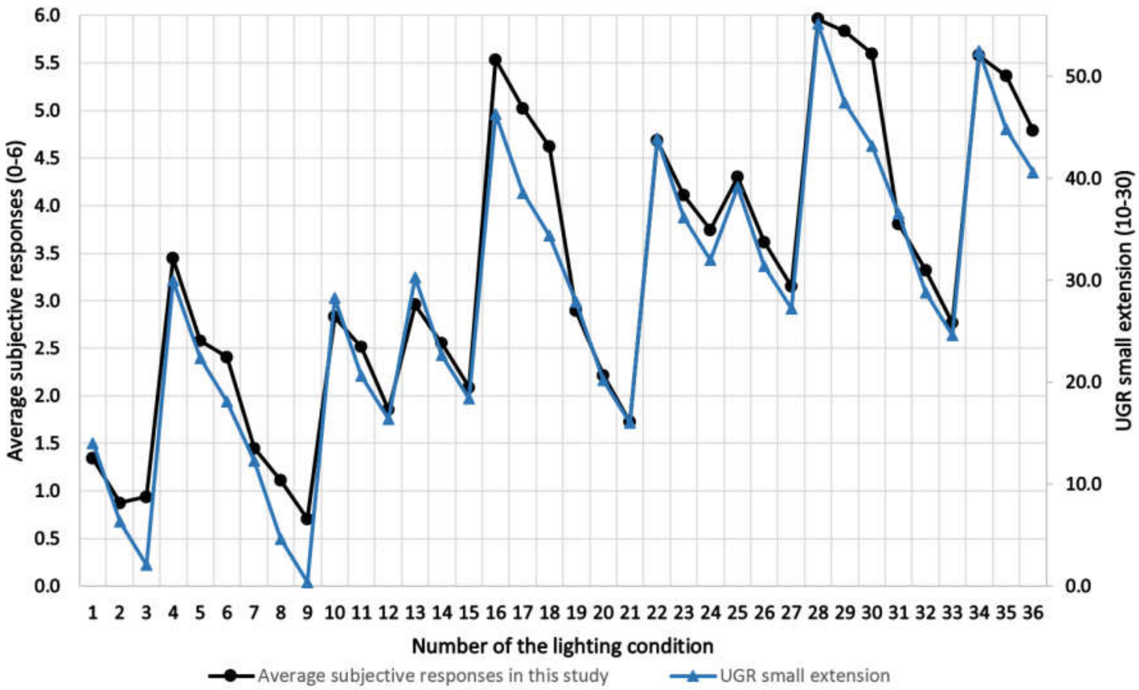


Figure 4-13. UGR small source extension predictions of discomfort glare and subjective responses in this study

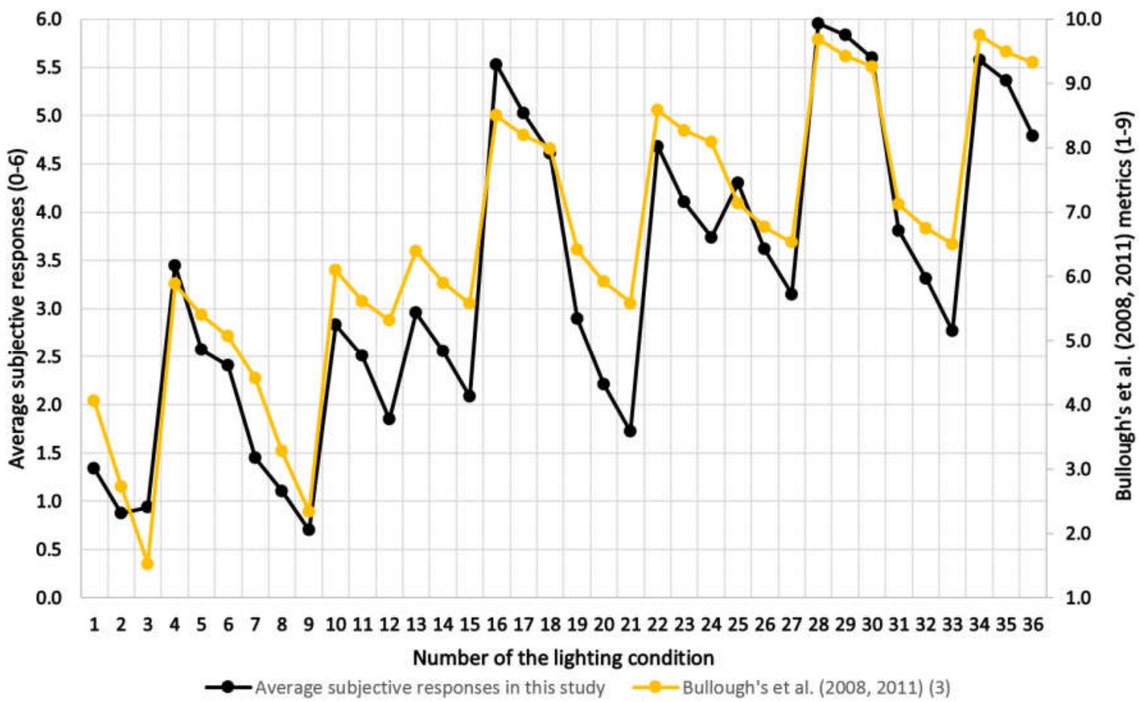


Figure 4-14. Bullough's et al. metrics (2008, 2011) predictions of discomfort glare and subjective responses in this study

4.2 Eye Tracking Data Analysis

The second body of data is the eye tracking (pupil) data that were collected with the remote eye tracking device ETL-100 (by ISCAN) consisting of an infra-red eye illuminator and a camera unit aimed at the left eye of the subject. The pupil diameter was recorded for 12 seconds (720 individual data points) for each condition and each subject (e.g. Figure 4-1).

Eye Tracking Data Statistical Analysis

A repeated-measures ANOVA was applied to the pupil data similarly to the rating scale data. Then, correlations between the pupil data and the rating data were examined.

4.2.1 Examination of the Pupil Data in the No-Glare State

The initial pupil diameter in this study is the diameter of the pupil when no glare source was present (Figure 3-69, Figure 4-1). It was averaged across all 36 conditions for each of the 47 subjects, and plotted as a function of the subject's age (Figure 4-15). A simple correlation of the average initial pupil diameter with the subjects' age indicated that older people had lower average pupil diameters than younger people, $r = -0.51440$, $p = 0.0002$. In addition to age, another self-reported measure was whether the subject had caffeine on the day of the experiment (Figure 4-15). The average initial pupil diameter for subjects who had caffeine (36 subjects) was 4.7 mm; for those who did not (11 subjects), it was 5.2 mm. No statistical tests were done with the caffeine data, because the mean in the no-caffeine group was based on only 11 subjects. These data were provided for descriptive purposes only.

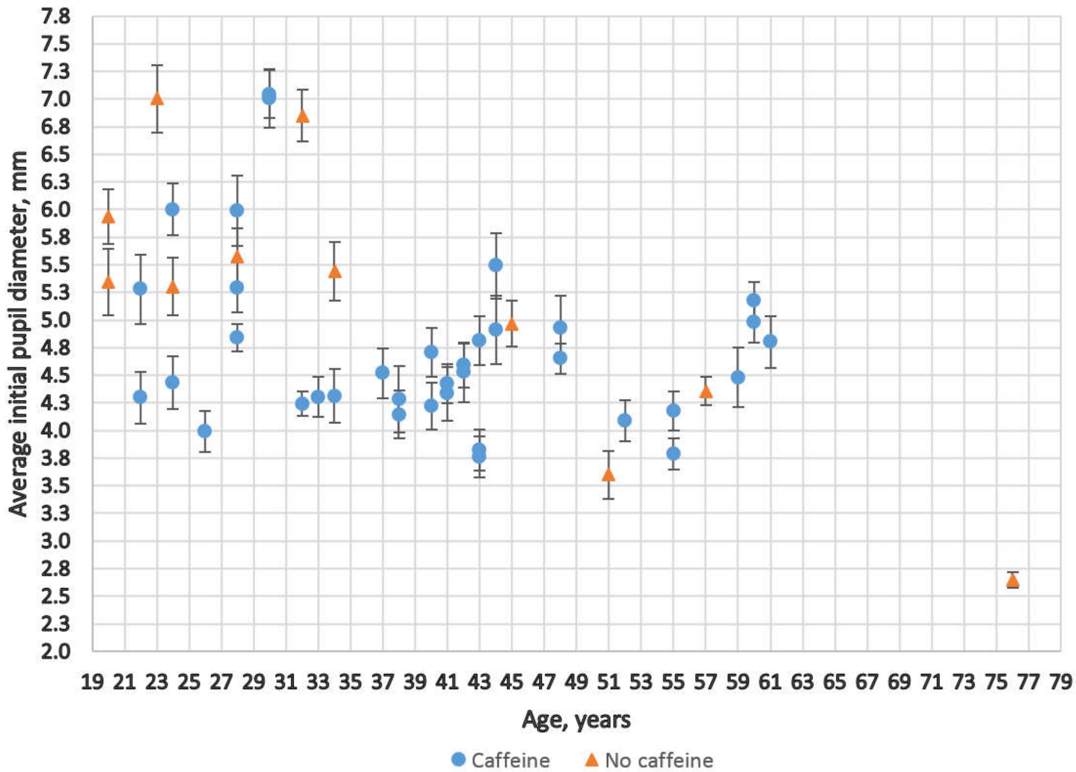


Figure 4-15. Average initial pupil diameter and age for each of the 47 subjects

The average initial pupil diameter for all 47 subjects in each of the 36 conditions is plotted in Figure 4-16. Since the initial pupil state is the no-glare state, the only difference between every block of three conditions (refer to Table 4-2 for the 36 conditions) in the figure is the background luminance (0.03; 0.3, 1 cd/m^2) - the darker the background luminance, the more dilated the pupil. These data correspond to the literature (Rea 2013). The average initial pupil diameter for the background luminance of 0.03 cd/m^2 is 5.4 mm, for 0.3 cd/m^2 is 4.8 mm, for 1 cd/m^2 is 4.3 mm.

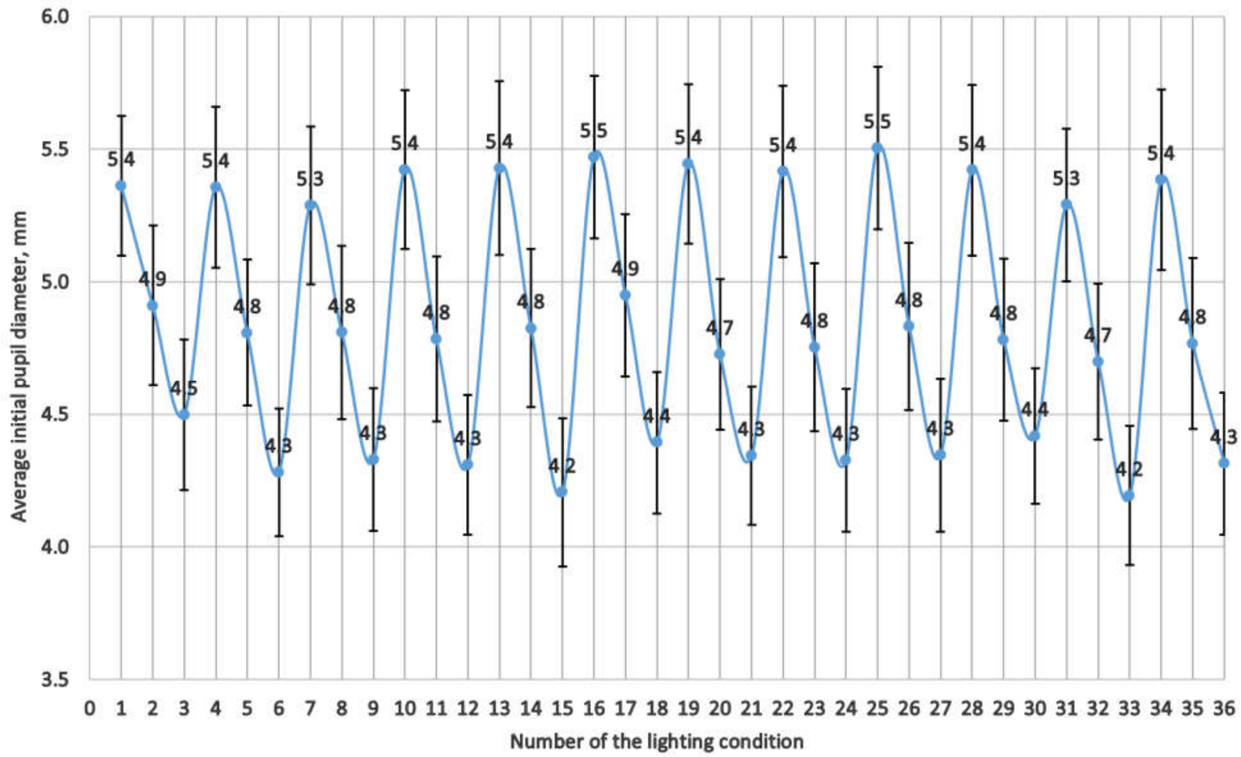


Figure 4-16. Average initial pupil diameter (during the adaptation stage) in each of the 36 conditions

4.2.2 Pupil Data Analysis

The relative pupil size (RPS) was chosen as a dependent variable in the analysis of the pupil data and was computed as follows:

$$RPS = \frac{(d_{init} - \frac{d_{min1} + d_{min2} + d_{min3}}{3})}{d_{init}} \quad \textbf{(4-6)}$$

Where

d_{init} is the average initial pupil diameter before a glare source was presented, in mm;

d_{min} is the minimum pupil diameter in a glare state (during each of the three flashes of the glare source) (Figure 4-1), in mm.

The RPS was chosen, because the absolute pupil size varies for subjects of different ages (Figure 4-15). It also depends on the adaptation luminance (DiLaura et al. 2011). This relative measure takes into account the pupil diameter before the glare was presented to the subjects - the adaptation state in this study. The RPS averaged across the 36 conditions for each of the 47 subjects is shown as a function of age in Figure 4-17.

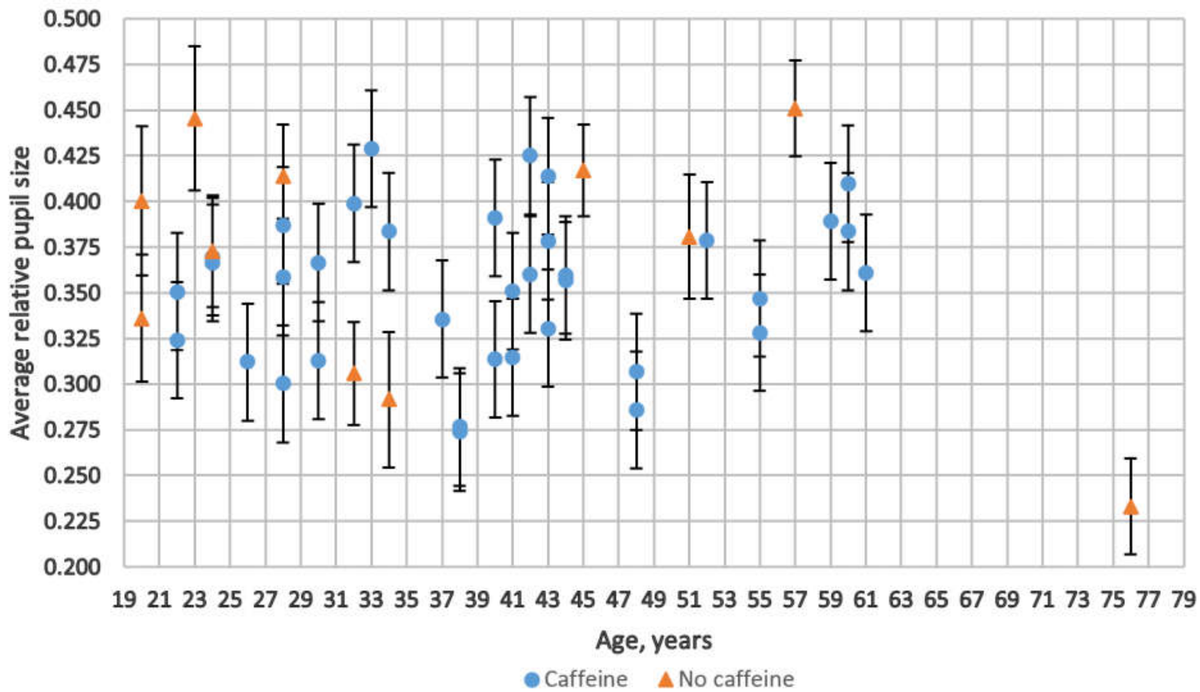


Figure 4-17. Relative pupil size (RPS) averaged across 36 lighting conditions and age for each of the 47 subjects

Descriptive statistics

Before proceeding to the ANOVA analysis, interesting insights can be gained simply by looking at the RPS means (Table 4-10). For example, an increase in the glare source luminance (more light enters the pupil) causes more pupil constriction (higher RPS). However, the difference in RPS is 0.087 when the luminance is increased from 20,000 to 205,000 cd/m^2, and only 0.032 when the luminance is increased from 205,000 to 750,000 cd/m^2. The expected direction of the effect (the more light at the eyes, the more the pupil constricts) was observed with the glare source luminance, its position and its solid angle effects. However, the background luminance effect indicated that the higher the background luminance, the smaller the RPS. This means that the lower the background luminance was, the more the pupil constricted during the glare presentation when compared to its initial state.

Table 4-10. Table with means and standard deviations of the pupil data

Independent Variable	Level	Mean (μ) RPS	Standard Deviation (σ) of RPS
Luminance	20,000 cd/m^2	0.288	0.054
	205,000 cd/m^2	0.375	0.050
	750,000 cd/m^2	0.407	0.052
Position	0°	0.386	0.053
	10°	0.328	0.048
Solid angle	10^{-5} sr	0.316	0.052
	10^{-4} sr	0.398	0.049
Background luminance	0.03 cd/m^2	0.426	0.048
	0.3 cd/m^2	0.350	0.053
	1 cd/m^2	0.294	0.055

Figure 4-18 demonstrates the RPS for each of the 36 conditions (refer to Table 4-2) averaged across 47 subjects with 95% confidence intervals shown as error bars. Each block of three conditions differs in the background luminance only. For example, the first three conditions all have luminance of 20,000 cd/m^2, position 0˚, solid angle 10^{-5} sr, but condition one has a background luminance of 0.03 cd/m^2, condition two has 0.3 cd/m^2, condition three has 1 cd/m^2.

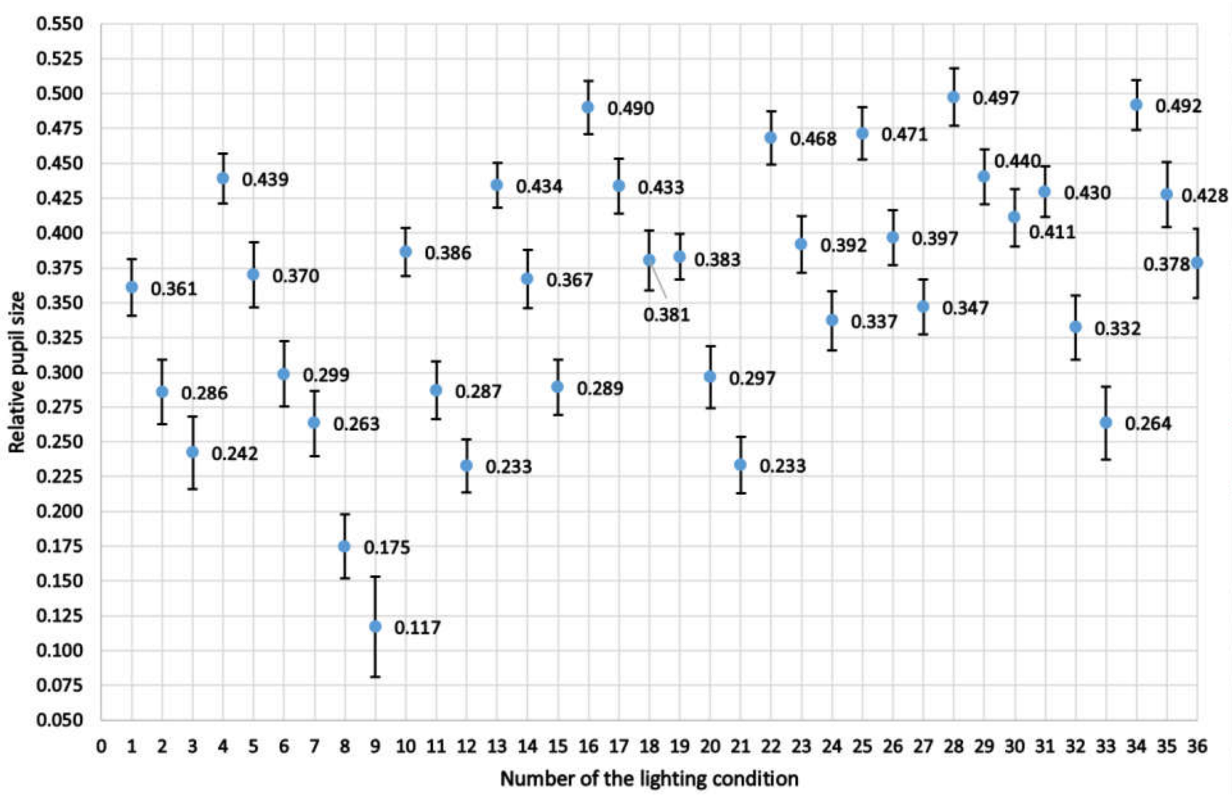


Figure 4-18. Relative pupil size averaged across 47 subjects for each of the 36 lighting conditions

The RPS data were examined for outliers. Outliers are extreme observations that are dramatically inconsistent with the other observations in a dataset. If not carefully examined, outliers can distort the results. In some cases, outliers can provide unexpected interesting insights about data (Judd et al. 2011).

Figure 4-19 shows a scatterplot of the RPS values and the subjective responses. There are four outliers (negative numbers) in the RPS dataset, one being very different from the other observations in this dataset (one outlier for each subject ID 8 and 41, and two for ID 46). The negative RPS value means that the pupil diameter was smaller in the initial state than in the glare state (Figure 4-20), which was not expected. The initial pupil diameter (in the no-glare state) was expected to be larger than during the glare presentation, since more light enters the pupil in the latter case. In four of the 1692 observations, this was not the case. The outliers might potentially arise from the pupil's condition in a half-awake state due to the observed "sleepy" behavior of a subject (e.g. subject ID 41). According to Rea, during sleep the pupils are always contracted (2013).

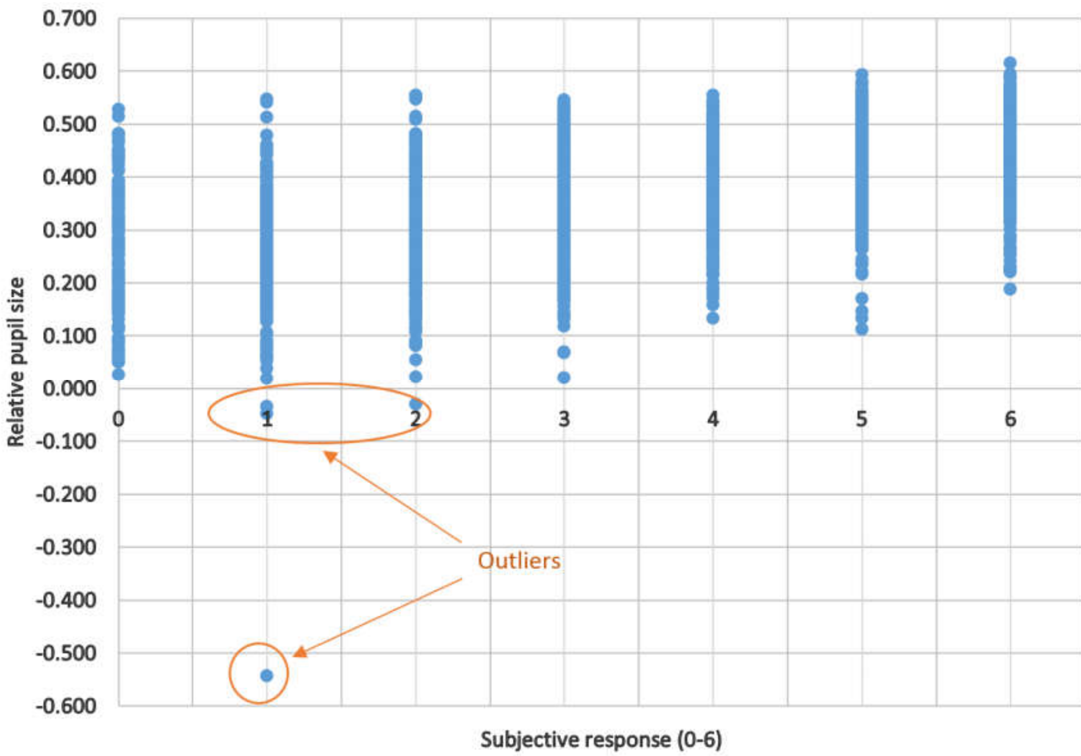


Figure 4-19. Scatterplot of subjective responses and relative pupil sizes for 47 subjects for 36 conditions

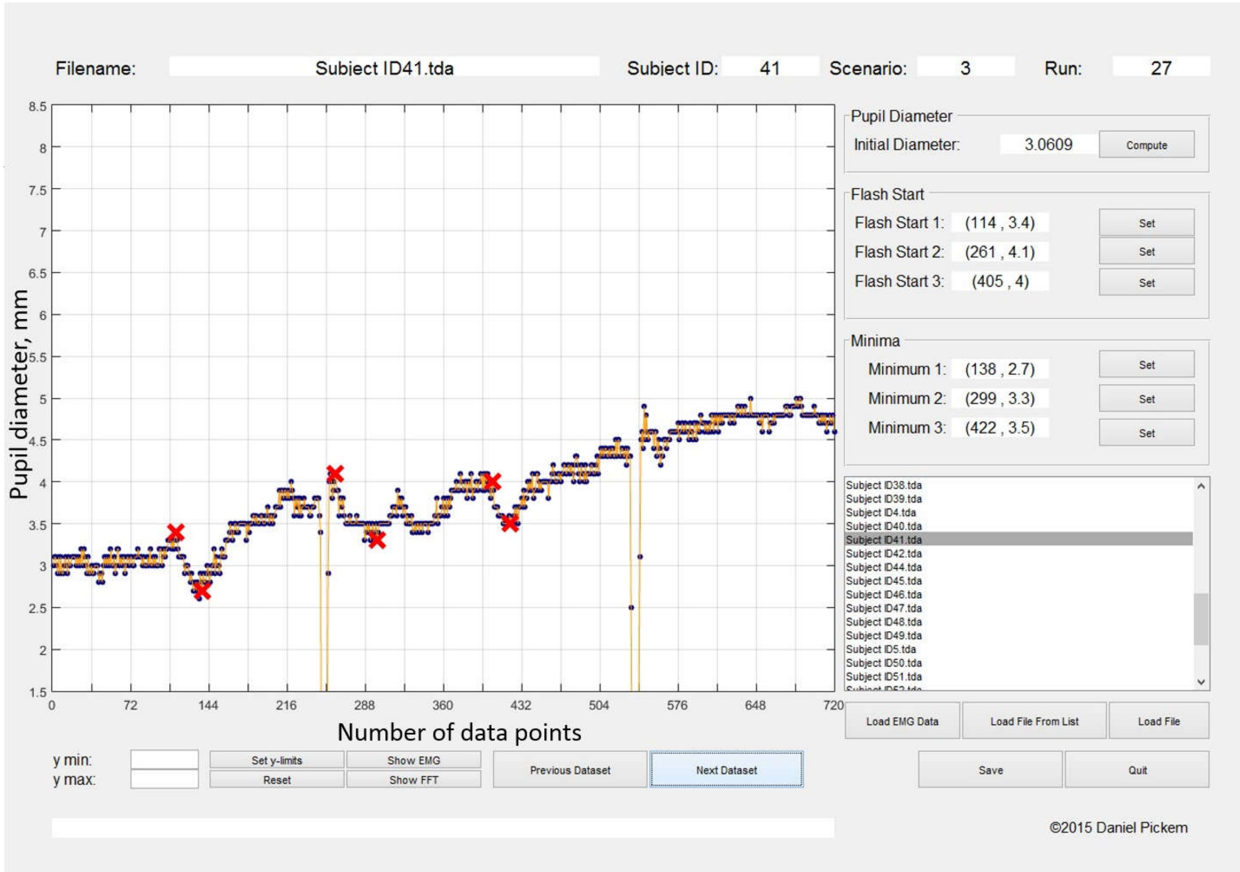


Figure 4-20. An example of a pupil file of a subject in the “sleepy” state. The initial pupil is smaller than the average pupil in the glare state.

However, after examining the notes for the other two subjects (ID 8, 46), no indication of the “sleepy” state was mentioned. The true reason for these outliers is unknown. One might hypothesize that there was a problem with the apparatus during the test. Unfortunately, illuminances during the test were not recorded for either of these subjects (ID 8 and 46) due to a communication error that happened during the test. The commands from the controls software were successfully transmitted to the devices to set the experimental conditions, but no readings were received in response. This happened for three of the 47 subjects (the third one being ID 42). However, the apparatus appeared to work correctly, because the pattern of the subjective judgements from these subjects did not show any abnormalities when compared to responses from other subjects in this study.

The main concern with the outliers is whether they influence the conclusions. If the conclusions are the same in the test with outliers and in the test without them, then the outliers are not a problem (Judd et al. 2011). The analysis with all 47 subjects including those with outliers and the analysis with 44 subjects without outliers did not change the main conclusions in this research. Of all effects tested, only one three-way interaction between the quadratic effect of luminance, position, and solid angle changed from marginally significant ($F = 4.57$, $p = 0.0378$) to insignificant ($F = 2.53$, $p = 0.1193$). Therefore, the subsequent analysis was conducted with the inclusion of the outliers (Judd et al. 2011).

4.2.3 Repeated-measures ANOVA

Similar to the ANOVA analysis of the subjective data (section 4.1.1), ANOVA was used for the analysis of the RPS data. It is a full-factorial 3x2x3x2 design. The experimenter analyzed RPS data of 47 subjects as a function of the glare source luminance, its size, its position, and the background luminance with repeated-measures on all factors. The main effects and all possible interactions with significant levels from the ANOVA analysis of pupil data are listed in Table 4-11.

Table 4-11. Complete table of all effects from the ANOVA analysis of pupil data of 47 subjects

Source	df *	F	P
Main effects			
Significant			
Luminance	**2**	309.56	<0.0001
Linear effect	1	364.37	<0.0001
Quadratic effect	1	100.25	<0.0001
Position	1	225.54	<0.0001
Solid angle	1	424.33	<0.0001
Background luminance	**2**	390.34	<0.0001
Linear	1	467.38	<0.0001
Quadratic	1	17.34	<0.0001
Two-way interactions			
Significant			
Luminance X Position	**2**	28.79	<0.0001
Linear luminance X Position	1	37.65	<0.0001
Quadratic luminance X Position	1	11.78	0.0013
Luminance X Solid angle	**2**	8.24	0.0005
Linear luminance X Solid angle	1	17.67	<0.0001
Position X Solid angle	1	40.10	<0.0001
Position X Background luminance	**2**	7.11	0.0013
Position X Linear background luminance	1	10.16	0.0026
Solid angle X background luminance	2	4.76	0.0108
Solid angle X Linear background luminance	1	7.6	0.0083
Non-significant			
Quadratic luminance X Solid angle	1	0.08	0.7795
Luminance X Background luminance	**4**	1.67	0.1593
Linear luminance X Background luminance linear	1	3.47	0.0687
Linear luminance X Background luminance quadratic	1	0.02	0.8761
Quadratic luminance X Background luminance linear	1	0.18	0.6763
Quadratic luminance X Background luminance quadratic	1	2.34	0.1326
Position X Quadratic background luminance	1	2.3	0.1364

Solid angle X Quadratic background luminance	1	0.08	0.7735
Three-way interactions			
Significant			
Quadratic luminance X Position X Solid angle	1	4.57	0.0378
Luminance X Solid angle X Background luminance	**4**	4.6	0.0015
Linear luminance X Solid angle X Linear background luminance	1	15.77	0.0002
Non-significant			
Luminance X Position X Solid angle	2	2.48	0.0893
Linear luminance X Position X Solid angle	1	0.04	0.8338
Luminance X Position X Background luminance	4	0.95	0.4364
Linear luminance X Position X linear background luminance	1	0.85	0.3623
Linear luminance X Position X quadratic background luminance	1	1	0.3235
Quadratic luminance X Position X linear background luminance	1	1.21	0.2780
Quadratic luminance X Position X quadratic background luminance	1	0.69	0.4114
Linear luminance X Solid angle X Quadratic background luminance	1	0.05	0.8314
Quadratic luminance X Solid angle X Linear background luminance	1	0.9	0.3488
Quadratic luminance X Solid angle X Quadratic background luminance	1	0.35	0.5591
Position X Solid angle X Background luminance	**2**	0.06	0.9461
Position X Solid angle X Linear background luminance	1	0.09	0.7710
Position X Solid angle X Quadratic background luminance	1	0.03	0.8625
Four-way interactions			
Non-significant			

Luminance X Position X Solid angle X Background luminance	**4**	1.12	0.3495
Linear luminance X Position X Solid angle X Linear background luminance	1	0.00	0.9995
Linear luminance X Position X Solid angle X Quadratic background luminance	1	1.96	0.1687
Quadratic luminance X Position X Solid angle X Linear background luminance	1	2.29	0.1369
Quadratic luminance X Position X Solid angle X Quadratic background luminance	1	0.89	0.3499

*The denominator degrees of freedom for df = 1, df = 2, and df = 4 were 46, 92, and 186 respectively.

In order to graphically show the 3x2x3x2 factorial design, a set of four graphs was used. The interactions of the glare source and the background luminances for the two positions and the two sizes are shown on the following four graphs (Figure 4-21 Figure 4-24).

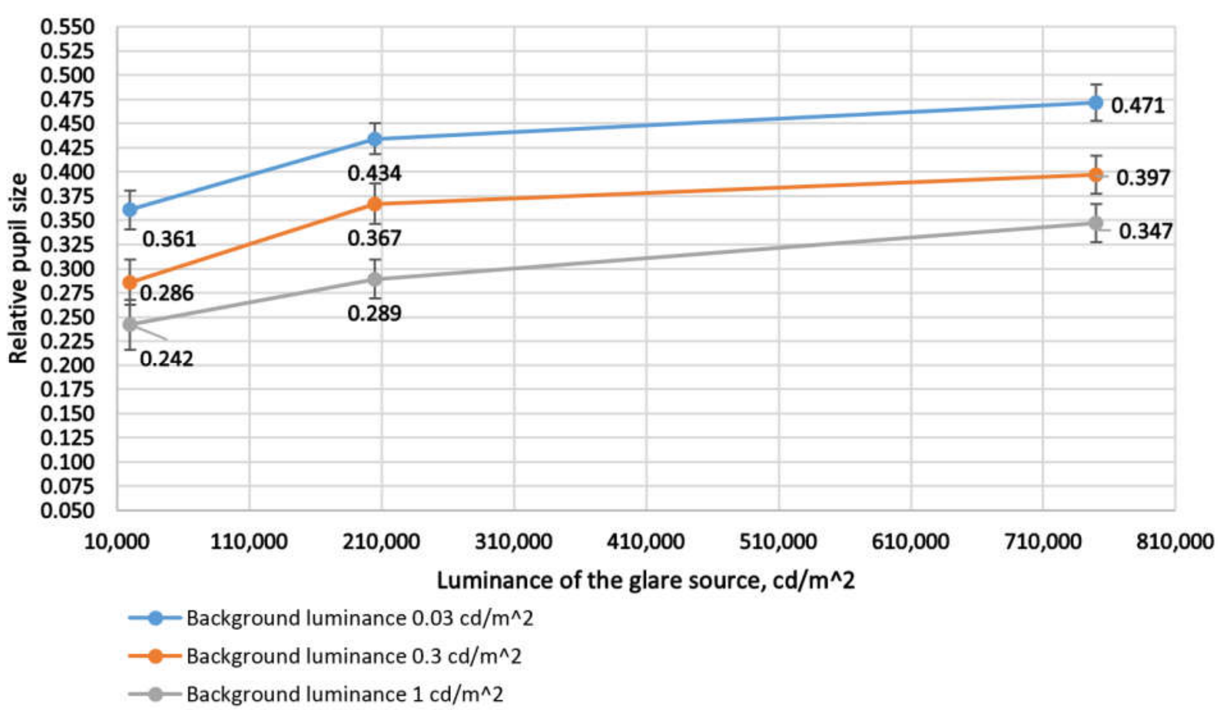


Figure 4-21. Interaction of the glare source luminance and the background luminance for position 0° and a solid angle of 10^{-5} sr

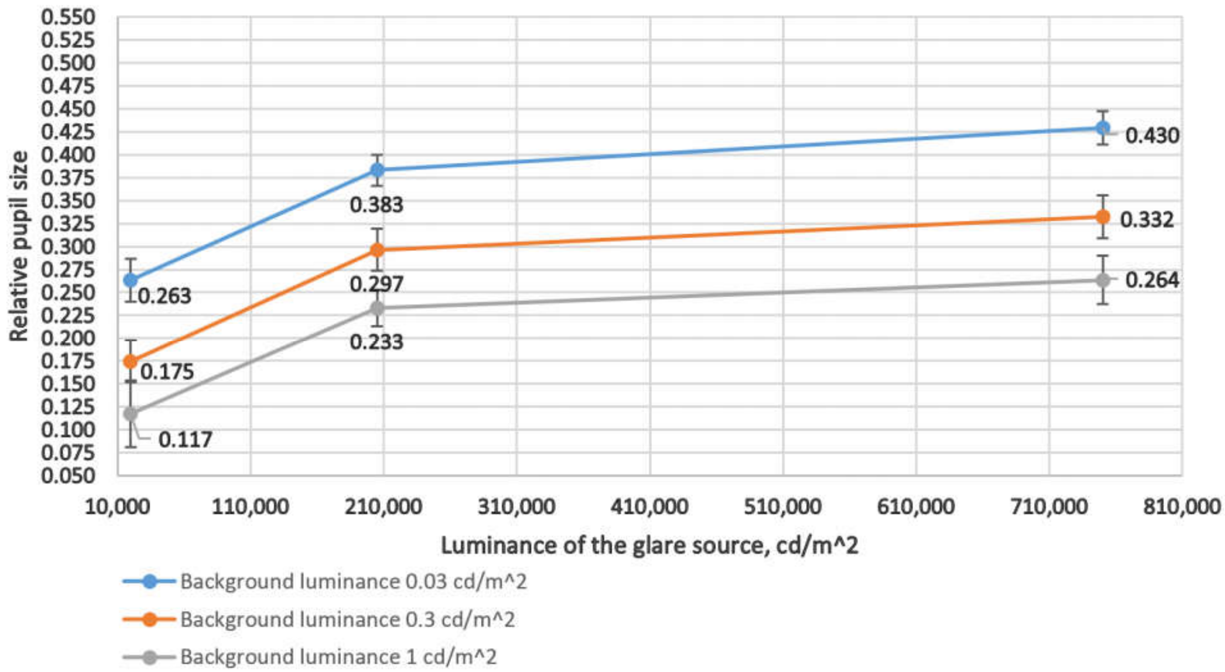


Figure 4-22. Interaction of the glare source luminance and the background luminance for position 10° and a solid angle of 10^{-5} sr

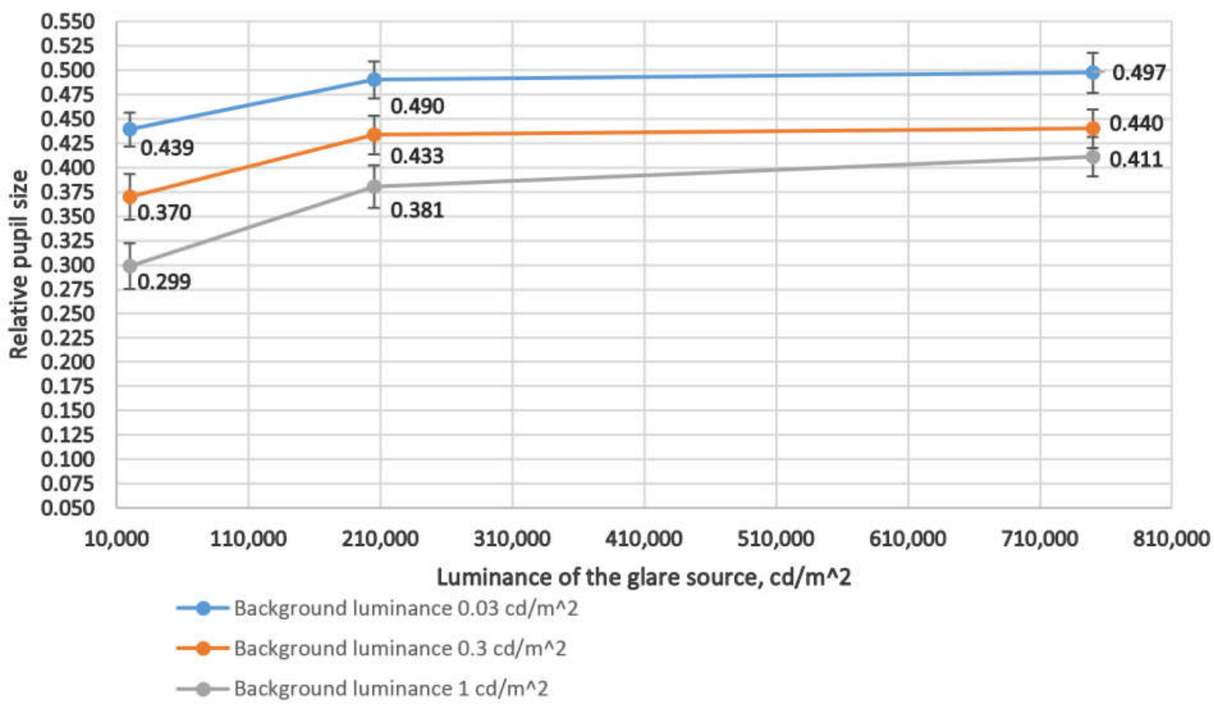


Figure 4-23. Interaction of the glare source luminance and the background luminance for position 0° and a solid angle of 10^{-4} sr

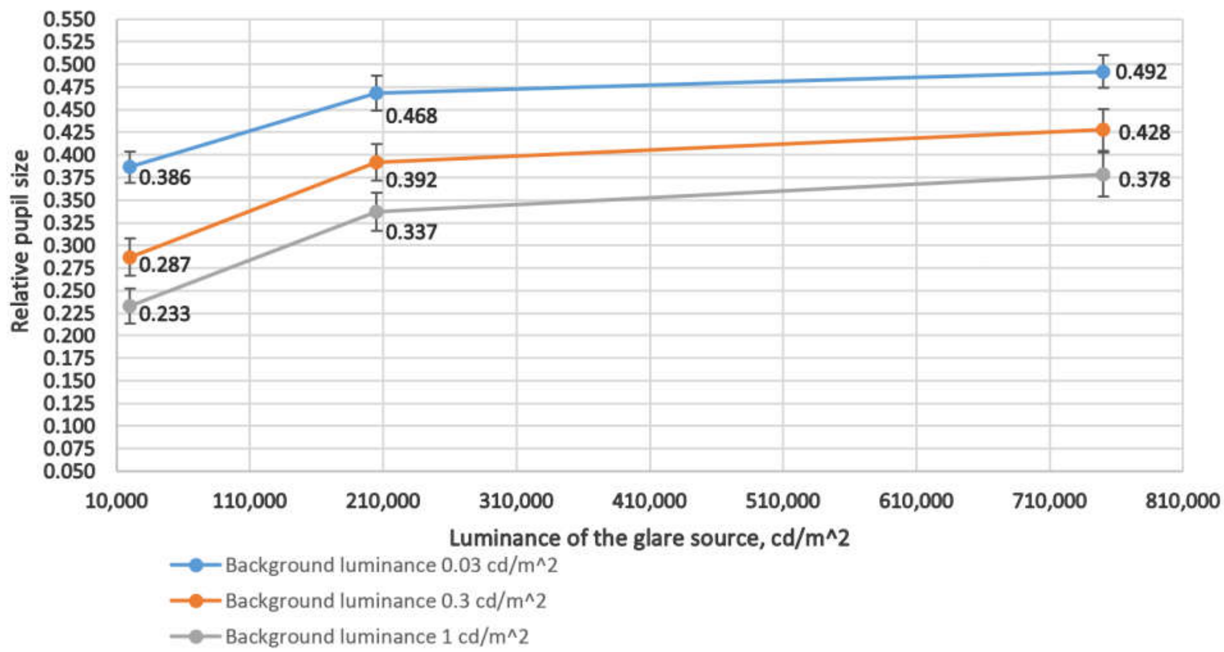


Figure 4-24. Interaction of the glare source luminance and the background luminance for position 10° and a solid angle of 10^{-4} sr

4.2.3.1 Significant main effects

The linear effect of the glare source luminance indicates that a greater luminance results in a greater pupil constriction, such that a luminance of 750,000 cd/m^2 constricts the pupil diameter significantly more than does a luminance of 20,000 cd/m^2. The quadratic effect indicates that the constriction of the pupil increases as the luminance increases from 20,000 to 205,000 cd/m^2, after which the rate of increase is lower (from 205,000 cd/m^2 to 750,000 cd/m^2) (Figure 4-25).

The pupil constriction is greater when a glare source is located at the 0° position when compared to the 10° position (Figure 4-26).

The pupil constriction is also greater for a larger glare source (10^{-4} sr) than for a smaller source (10^{-5} sr) (Figure 4-27).

The linear effect of the background luminance shows that the lower the background luminance the more the pupil constricts (Figure 4-28). The quadratic effects shows that the pupil constriction decreases more initially (when the background luminance is increased from 0.03 to 0.3 cd/m^2) than subsequently (from 0.3 to 1 cd/m^2).

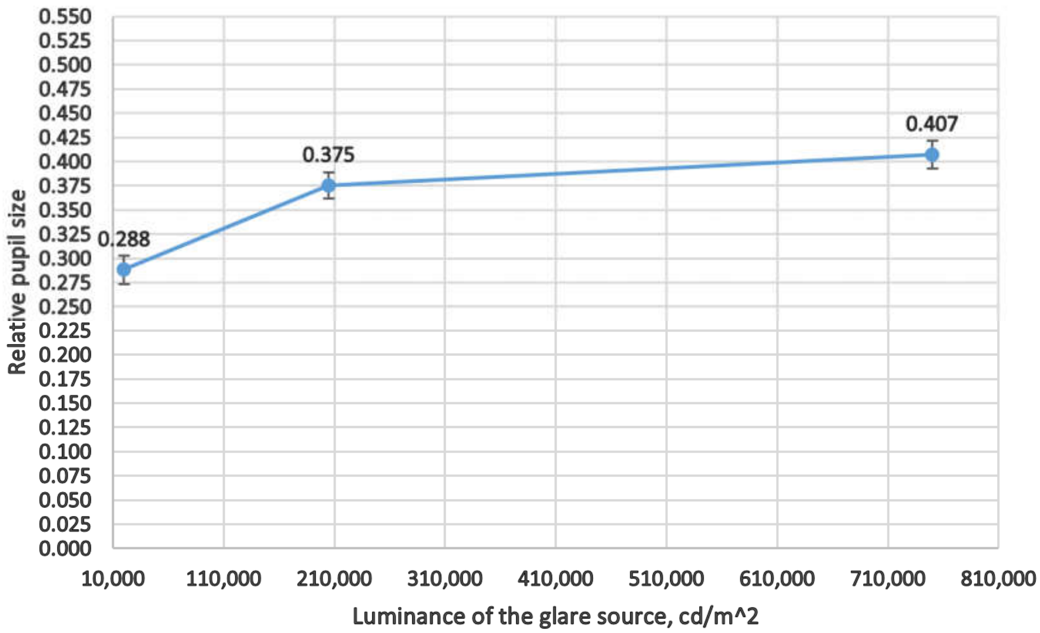


Figure 4-25. Main effects of the luminance of the glare source on the pupil data

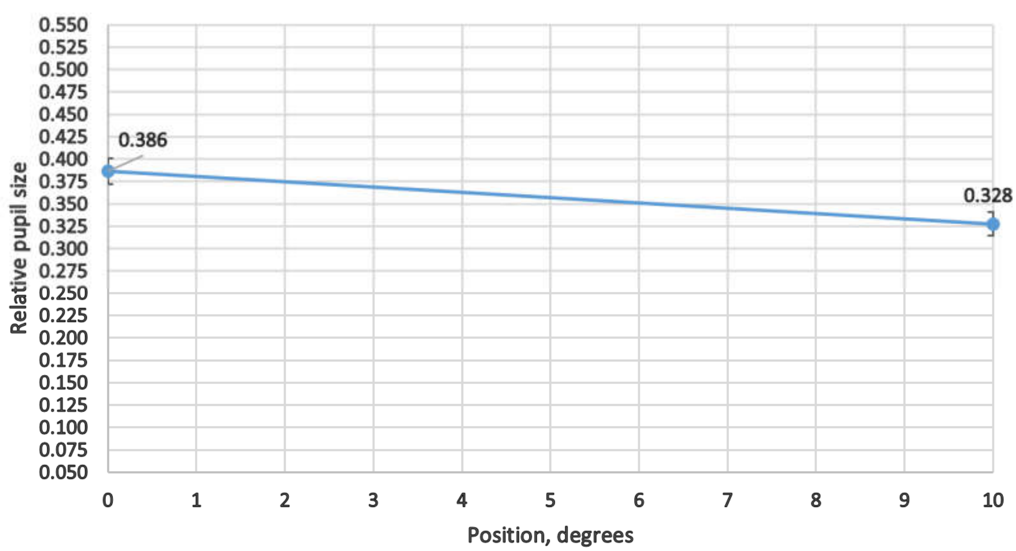


Figure 4-26. Main effect of the position on the pupil data

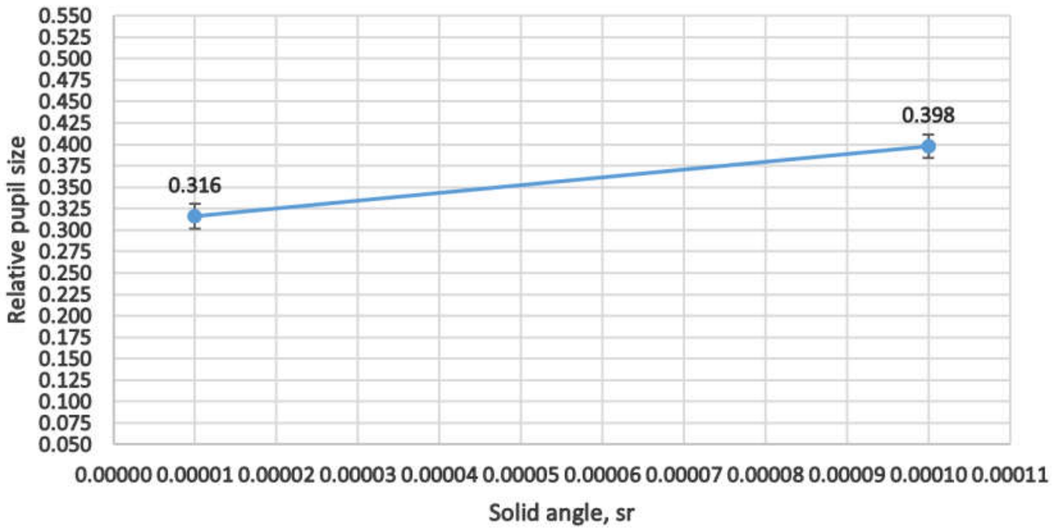


Figure 4-27. Main effect of the solid angle of the glare source on the pupil data

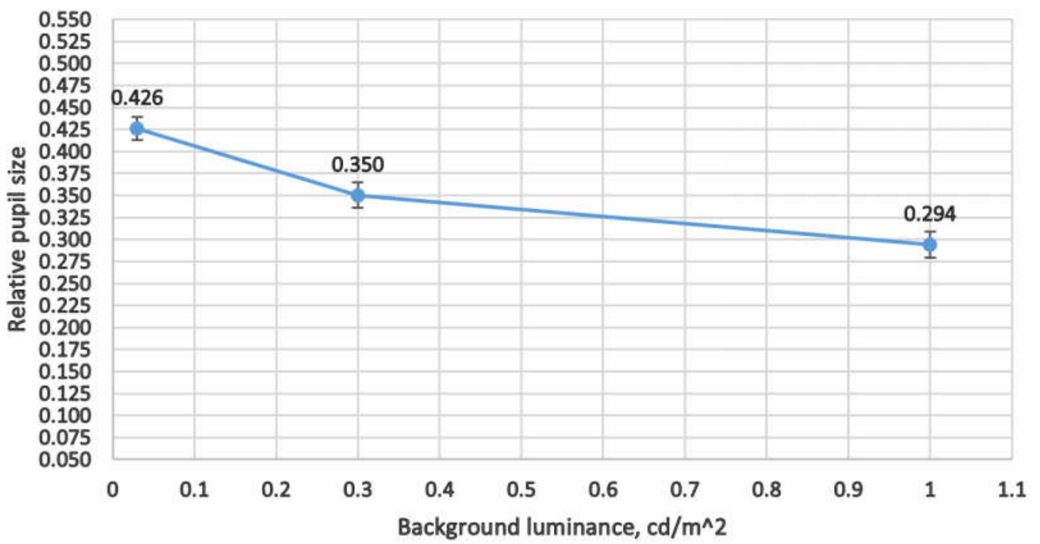


Figure 4-28. Main effects of the background luminance on the pupil data

4.2.3.2 Significant interactions

The larger the luminance the greater the constriction, this is especially true for a source located at the 0° position when compared to the 10° position. The quadratic effect shows that the pupil constriction increases more initially (from 20,000 cd/m^2 to 205,000 cd/m^2) than subsequently (from 205,000 cd/m^2 to 750,000 cd/m^2), especially for a source located at the 0° position when compared to the 10° position.

There is another significant two-way interaction between the luminance of the glare source and its solid angle, such that a higher luminance results in a greater pupil constriction, especially for the glare source with a solid angle of 10^{-4} sr when compared to a source with a solid angle of 10^{-5} sr.

A significant two-way interaction between the position and the solid angle of the glare source indicates that pupils constrict more when the glare source is positioned on the line of sight (when compared to the 10° position above the line of sight) for the source of size 10^{-4} sr versus 10^{-5} sr.

There is a significant interaction between the position of the glare source and the background luminance. For the glare source on the line of sight the pupil constriction is higher, especially if the background luminance is lower.

There is a significant interaction between the solid angle of the glare source and the linear effect of the background luminance. The pupils constrict more with the decrease of the background luminance, especially true for a larger glare source (10^{-4} sr vs 10^{-5} sr).

The three-way interaction of the quadratic effect of the luminance, position, and the solid angle of the glare source is significant. It shows that the pupil constriction increases more initially (when the luminance increases from 20,000 to 205,000 cd/m^2) than subsequently (when the luminance increases from 205,000 to 750,000 cd/m^2) from a glare source on the line of sight (vs 10°), especially for a larger glare source (10^{-4} vs 10^{-5} sr).

Finally, another three-way interaction of the glare source luminance, its solid angle, and the background luminance indicates that the increase in the glare source luminance causes a greater pupil constriction for the larger source (10^{-4} vs 10^{-5} sr), especially with the decrease in the background luminance.

4.2.4 Correlation of Pupil Data with Subjective Responses

For each subject the correlation between the subjective ratings and the RPS values across 36 conditions was computed. The analysis was similar to the correlation analysis of the subjective data (section 4.1.2). There is a statistically significant mean correlation (converted from the mean z-correlation coefficient back to the original metric) between the subjective responses and the RPS values $r = 0.659$ ($r^2 = 0.434$), $F = 584.92$, $p < 0.0001$ (SAS code is shown in Appendix V). About 43% of the variation in RPS is related to the variation in discomfort glare. In other words, on average, when subjects perceive more discomfort glare, their pupils constrict more when compared to the no-glare condition. This does not explain the causation however (discomfort might cause pupils to constrict, or the pupil constriction might cause discomfort, or a common cause is involved in the relationship).

4.3 EMG Data Analysis

The third body of data is the EMG readings recorded through electrodes placed on the subject's face in the area of orbicularis oculi (Figure 3-68). The EMG data were not analyzed in this study due to three major problems, the first two being of a similar nature. First, the actual timing of the EMG data was unclear. Therefore, it was not possible to identify which parts of the signal represent a glare/no-glare state and which parts should be included in the computation of the MAC indices. Second, there were randomly missing values in the recorded data files. Finally, it was unknown whether the data received from the EMG Machine were processed before being transmitted and recorded by the laptop. Each problem is explained in detail in Appendix W.

CHAPTER 5 – CONCLUSIONS

The retina derives from the same tissue out of which the brain itself develops.
It is a direct extension of the central nervous system.
- Sekuler and Blake 1990

5.1 Objectives

This research had four primary objectives. The overarching goal was to study discomfort glare from small, high luminance light sources, particularly from LEDs, in outdoor nighttime environments. Consequently, the second goal was to determine which existing outdoor discomfort glare metric correlates best with the subjective data collected in this study. The third intention was to examine the pupil's reaction to discomfort glare. Finally, the fourth goal was to measure the activity of the orbicularis oculi - the principle muscle responsible for closing the eyes - in response to discomfort glare, analyze the MAC indices, and compare them to the subjective and the pupil data. In this chapter, the results are discussed and future research directions are proposed.

5.2 Interpretations and Discussions

The following sections describe the interpretation of the results for each dataset separately and then provide a discussion of the overall framework.

5.2.1 Discomfort Glare from Small, High Luminance Sources in Outdoor Nighttime Environments

The subjective rating experiment confirmed the results from previous glare research that the glare source luminance, its position, its solid angle, and the background luminance have significant effects on discomfort glare. An increase in the luminance of the glare source as well as an increase in its solid angle cause more glare. Similarly, a decrease in the angle between the fixation point and glare source and a decrease of background luminance result in more glare.

In previous studies on small light sources in dark environments, researchers investigated the borderline between comfort and discomfort (BCD) sensation (e.g. Bennett 1977b, Putnam and Gillmore 1957). In this current study, glare was rated on a differential scale, because multi-label scales were found to better represent the amount of glare (De Boer and Schreuder 1967).

Bennett (1977b) studied the relationships between the BCD and the solid angle of the light source (10^{-3} - 10^{-6} sr), the background luminance (0.00343 - 34.26 cd/m^2), and the position (0º - 30º) with 97 observers. He found that subjects tolerate higher BCDs with an increase in background luminance, a decrease in the solid angle, and an increase in the source position. This study shows the same patterns in the data.

Other previous studies showed that the admissible glare luminance (BCD) increases with glare source position (Putnam and Gillmore 1951, Benz 1966, Bennett 1977b). This means that subjects tolerate higher glare when the angle between the fixation point and the glare source is larger. This current research showed a similar result, namely that the larger the angle between the fixation point and the glare source, the smaller the sensation of discomfort the subjects reported.

Background luminance reduces the amount of discomfort – subjects tolerate higher glare luminance with an increase in background luminance (Putnam and Faucett 1951, Bennett 1977b). Benz also found that higher ambient (background) luminances reduce unpleasant sensations, however, the effect was not significant in his study (potentially due to the small number of subjects – he only tested seven). This current research confirmed the effect of background luminance on discomfort glare. The data showed a significant linear effect of the background luminance on the perception of discomfort glare. The higher the background luminance, the less discomfort was reported.

Putnam and Faucett found that with an increase in the background luminance, the BCD values increased for various source sizes in their study with fifteen subjects (1951). The slopes for different solid angle curves were different in the relationship between BCD and background luminance. Examining the slopes of the curves essentially means examining the interactions between the variables, however, the authors did not report any statistic. In this current research, the interaction between the solid angle and the background luminance was not significant. Bennett also compared his work (1977b) to Putnam and Faucett's work (1951), and concluded that Putnam and Faucett's lower BCD values compared to Bennet's work could have potentially been influenced by specific instructions given to the subjects such as "BCDs should never be high".

5.2.2 Existing Metric that Correlates Best with Subjective Responses

The correlation analysis in this research validated the UGR small source extension (CIE 146,147-2002) and Bullough's et al. (2008, 2011) metrics with human subjects data within the ranges of the variables tested.

The UGR small source extension correlated best with the subjective responses collected in this study when compared to the other three outdoor discomfort glare metrics. The UGR small source values calculated for the 36 lighting conditions in this research were in the range of 0.4 to 55.1. Four of the 36 conditions resulted in values smaller than 10, and sixteen of 36 in values larger than 30 (Table 4-7). In the technical document (CIE 117-1995), the CIE specifies the range of 10 (imperceptible) to 30 (just intolerable) as being a "practical range … with most lighting systems producing values in that range". One might argue that all values above 30 should be considered intolerable glare. However, it is important to note that even though the UGR ratings of 45 and 65 both exceed the upper limit of 30 as specified by the CIE, any two installations with these UGR values do not create the same amount of intolerable glare. The UGR small extension values in this research (0.4-55.1) preserved the relative differences between the ratings of the lighting conditions, instead of equating the values larger than 30. As the CIE puts it – "the scale is reproduced here, not with the purpose of specifying glare restriction limits, but merely to offer, for glare evaluation purposes, insight in the practical meaning of differences in glare ratings" (CIE 112-1994).

Also, note that the UGR and its extensions were developed for interior lighting systems. A larger range of the UGR small source extension values in this study (0.4-55.1) when compared to the CIE's practical range (10-30) might be explained by the difference between the luminance ranges typically encountered in outdoor and indoor spaces. Outdoor nighttime environments with high luminance light sources have a larger luminance range than interior environments. According to the IESNA Lighting Handbook (DiLaura et al. 2011), the representative indoor luminances range from 0.3 to 3,100,000 cd/m^2 (from emergency lighting to tungsten lamp filament luminance respectively). Outdoor conditions, however, range from 0.001 cd/m^2 during a moonless clear night up to 19,000,000 cd/m^2 (Tyukhova and Waters 2014), if glare sources such as LEDs are present in the field of view. One can think about the difference in ranges encountered in outdoors versus indoors as the "range effect" (Lulla and Bennett 1981) - subjects adjust judgements based on the range presented. This effect suggests that there is no cut-off value of discomfort glare. An experimenter has to choose a range that is representative of the conditions experienced in a particular context.

Another point to remember is that subjective scales are arbitrary. During the training in the current study, subjects were shown the worst stimulus from the 36 lighting conditions and were told that this is "intolerable" glare and most people would rate it as 6 (Appendix P). This procedure served to anchor the subject's response range to the stimulus range - Tiller and Rea recommend to define the meanings of the upper and lower limits of a rating scale to observers (1992). When metrics were developed, "intolerable" glare could have been defined in different ways. For example, in this study the average subjective ratings of conditions # 4, 13, 19, 24, 26, 27, and 32 are all close to the mid-point of the scale – "between noticeable and disagreeable" (Table 4-7), specifically, they are 3.4; 3; 2.9; 3.7; 3.6; 3.1; and 3.3. These ratings correspond to the UGR small source extension calculations of 30; 30.3; 27.9; 32; 31.4; 27.2; and 28.8 respectively – all close to the scale's maximum. Therefore, the meaning of "just intolerable" in the UGR for interior assessments might be different from the definition of "intolerable" glare subjects used in this study.

The combination of Bullough's et al. 2008 metric for sources smaller than 0.3˚ and Bullough's et al. 2011 modification for sources larger than 0.3˚ was the second best metric to predict discomfort glare. It also showed a significantly better agreement with the subjective responses in this study than the predictions made by the motor vehicle lighting metric (metric 2), which agrees with the literature (Sammarco et al. 2011).

The correlation of predictions by the motor vehicle lighting metric (metric 2) and the subjective ratings in this study (r = 0.792) is similar to the correlations that Porter and colleagues found when they studied discomfort glare experienced by nighttime drivers (2005). Observers in their study drove on a test road that mimicked a real environment and then rated the experienced discomfort. The researchers used two variations of glare calculation: (1) through the maximum illuminance at the eyes experienced at some point on the test road, and (2) through the illuminance at the eyes that the observers experienced last on the test road. The correlation between subjective ratings and the calculations by metric 2 based on the maximum illuminance at the eyes was r = 0.74, and based on the illuminance experienced right before giving the rating r = 0.78.

The lowest correlation (r = 0.405) acquired in this study was between the outdoor sports and area lighting (metric 1) predictions and subjective responses, which might be explained by the limitations of metric 1 outlined in the CIE technical document (CIE 112-1994). The validity of the system is restricted to the viewing directions below the eye level. Moreover, the CIE 1994 glare formula does not differentiate between the two types of glare – discomfort and disability glare, but rather assesses the "general" glare through the veiling luminance components (see equation (2-7)). Veiling luminances are typically used for the assessment of disability glare. Therefore, it is not clear that using this CIE metric allows a valid estimation of discomfort glare.

5.2.3 Pupil Data Discussion

There is some controversy on the role of the pupil in discomfort glare estimation. Some studies suggests that the pupil's size is not related to discomfort glare perceptions (e.g. Hopkinson 1956), while others showed significant correlations (e.g. Stringham et al. 2011, Lin et al. 2015).

The pupil data analysis in this study suggests that the RPS is correlated with discomfort glare to some extent ($r = 0.659$, $p < 0.0001$). On the one hand, this contradicts previous result that showed that the pupil's reaction is not determined by the degree of glare, but rather by the level of illumination produced at the eyes by both the glare source and the background (Hopkinson 1956). On the other hand, the results of this current research match the results reported in other research papers (Lin et al. 2015, Stringham et al. 2011).

The contradictory results by Hopkinson indicated that in a no-glare state the pupil size decreased due to the background luminance that produced a higher level of illumination at the eyes. The difference between his results and the results in this study might be due to the fact that Hopkinson used only two subjects - the conclusions may be erroneously attributed to the studied phenomena instead of the sampling error. Also, Hopkinson used the absolute pupil diameter, which did not account for existing individual differences between the subjects such as age. This current research showed a significant negative correlation between the age and the absolute pupil diameter averaged across conditions. This trend corresponds to the literature indicating that under comparable conditions, older people tend to have smaller pupils than younger people (DiLaura et al. 2011). In addition, Hopkinson used a different methodology of slowly raising the stimulus until it met the specified criterion (e.g. "just perceptible"), allowed for adaptation and then made the final judgments. The pupil image was taken in the adapted state.

The results of this current research match the results reported in other research papers (Lin et al. 2015, Stringham et al. 2011). Stringham and colleagues found that greater visual discomfort is associated with greater iris constriction ($r = -0.429$, $p = 0.037$). Lin and colleagues also found that the relative pupil size correlates well with the De Boer rating, ($r = -0.61$, $p < 0.001$), indicating that when a glare source provides more discomfort, the pupil decreases in size compared to a no-glare state. Note that the correlation sign is negative, because the authors used the De Boer rating (smaller values mean more glare).

The ANOVA analysis performed on the pupil data demonstrated that all four variables (the glare source luminance, its position, its solid angle, and the background luminance) showed significant main effects (for the full summary of results refer to Table 4-2). The significant effects of the average glare source luminance and the viewing angle correspond to the results found by Zhu and colleagues (2013), who tested two of the four variables used in the current research.

In the current research, the luminance of the glare source, its position, and its solid angle showed significant effects in the expected direction, meaning that the pupil constricts more (i.e. larger RPS) in response to more light reaching the retina (Boyce 2014). These three significant effects correspond to one of the two normal pupil principal reactions - the direct light reflex (Rea 2013). The more light enters the pupil, the greater the constriction (Rea 2013, Rosenbaum 1991).

This research showed that the background luminance also has a significant effect on the relative pupil size, such that when the background luminance decreases, the RPS increases. This means that the lower the background luminance, the more the pupil constricts during the glare presentation when compared to its initial state. At the same time, as shown in this research, the lower the background luminance the higher the discomfort glare sensation. One needs to explore how, on average, the pupil reacts to the background luminance (the main effect) by examining the adaptation state before and after the glare occurred. The discussion on this issue is provided below.

Let the time before the glare source was presented be denoted as t_1, and the time after the glare source was presented as t_2. Figure 5-1 shows the average ambient illuminance at the eyes at t_1 graphed for the three levels of the background luminance. The average ambient illuminance is the illuminance from the background light source reflected off of the background and measured at the eyes. The darker the background, the smaller the ambient illuminance at the eyes. As was shown in section 4.2.1, the darker the background, the larger the absolute pupil diameter – for a background luminance of 0.03 cd/m^2 the average pupil diameter was 5.4 mm; for 0.3 cd/m^2 it was 4.8 mm; and for 1 cd/m^2 it was 4.3 mm.

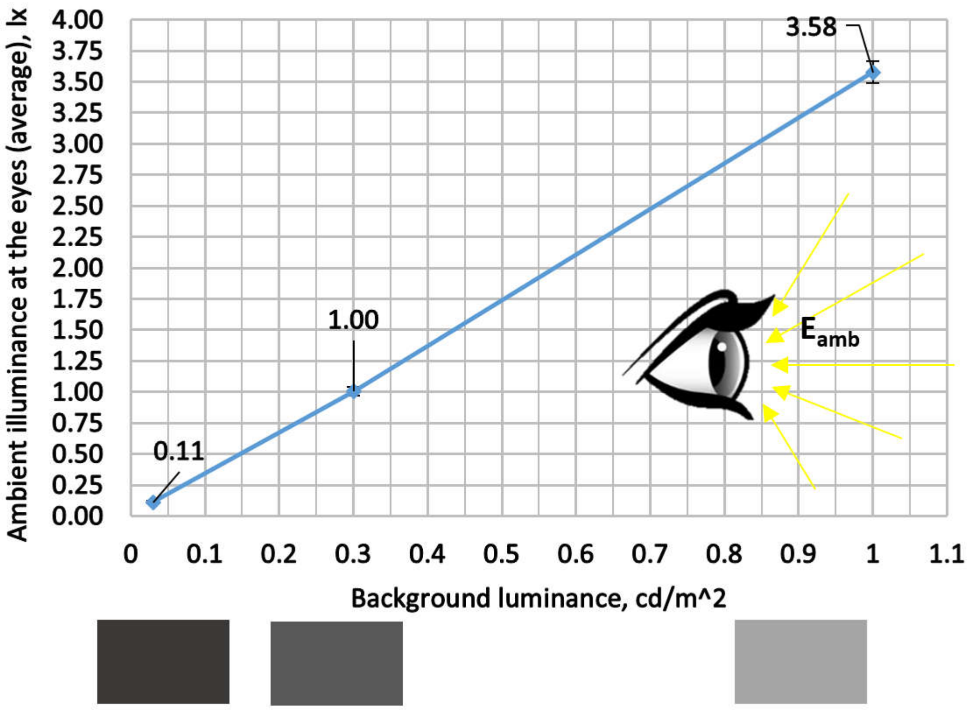


Figure 5-1. Average ambient illuminance at the eyes at three background luminance levels tested in this study (before the glare source was introduced)

When the glare source is shown in the field of view (at t_2), the illuminance at the eyes increased by the same amount for all three background luminances – by the illuminance caused by the glare source. Therefore, the absolute change in illuminance is the same for all three background levels. Figure 5-2 shows the total illuminance at the eyes after the subject is exposed to glare. The total illuminance at the eyes consists of the illuminance from the background source (ambient) and the illuminance from the glare source (both the direct and indirect components). For the highest background luminance used in this study (1 cd/m^2), the total illuminance at the eyes was the highest. Contrary to the expectation that the more light enters the pupil, the greater the constriction (Rea 2013, Rosenbaum 1991), the calculations of illuminances from the measurements in this study do not explain why pupils constricted less (smaller RPS) for the higher background luminance (refer to Table 4-10 for the main effect of the background luminance).

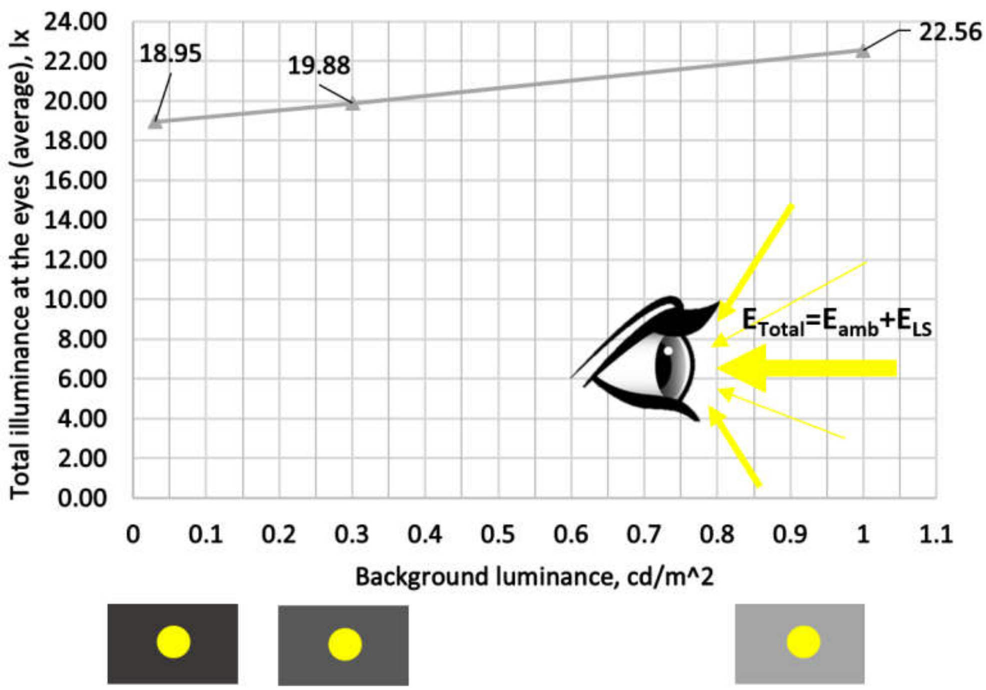


Figure 5-2. Average total illuminance at the eyes when the subject is exposed to glare

However, if one examines the relative change in illuminance at the eyes, the observed trend becomes clear. The relative change in illuminance is the absolute change in the illuminance at the eyes divided by the initial illuminance at the eyes (equations (5-1), (5-2)).

$$\Delta E_{relative} = \frac{|E_{t1} - E_{t2}|}{E_{t1}} \quad \textbf{(5-1)}$$

Where

$\Delta E_{relative}$ is the relative change in illuminance at the eyes;

E_{t1} is the illuminance at the eyes at time t_1 (before the glare was presented), lx;

E_{t2} is the illuminance at the eyes at time t_2 (after the glare was presented), lx.

Equation (5-1) can be further rewritten by substituting for the illuminance components E_{t1} and E_{t2} as follows:

$$\Delta E_{relative} = \frac{|E_{ambient} - E_{total}|}{E_{ambient}} = \frac{|E_{ambient} - (E_{LS} + E_{ambient})|}{E_{ambient}} = \frac{E_{LS}}{E_{ambient}} \quad \textbf{(5-2)}$$

Where

$\Delta E_{relative}$ is the relative change in illuminance at the eyes;

E_{amb} is the ambient illuminance at the eyes, lx;

E_{total} is the total illuminance at the eyes, lx;

E_{ls} is the illuminance at the eyes caused by the glare source, lx.

This relative change compares the change in illuminance from the no-glare state (t_1) to the glare condition (t_2) with the no-glare state being the baseline, which is the state with low background luminances (0.03; 0.3; and 1 cd/m^2). Essentially, the relative change takes into account the initial adaptation of the pupil to the low background luminance. Therefore, when a glare source was shown in the field of view with the lowest background luminance used in this study (0.03 cd/m^2), the relative change in illuminance was the highest – a value of 171 (Figure 5-3). In this case, the pupil constricted the most when compared to the initial dark-adapted state.

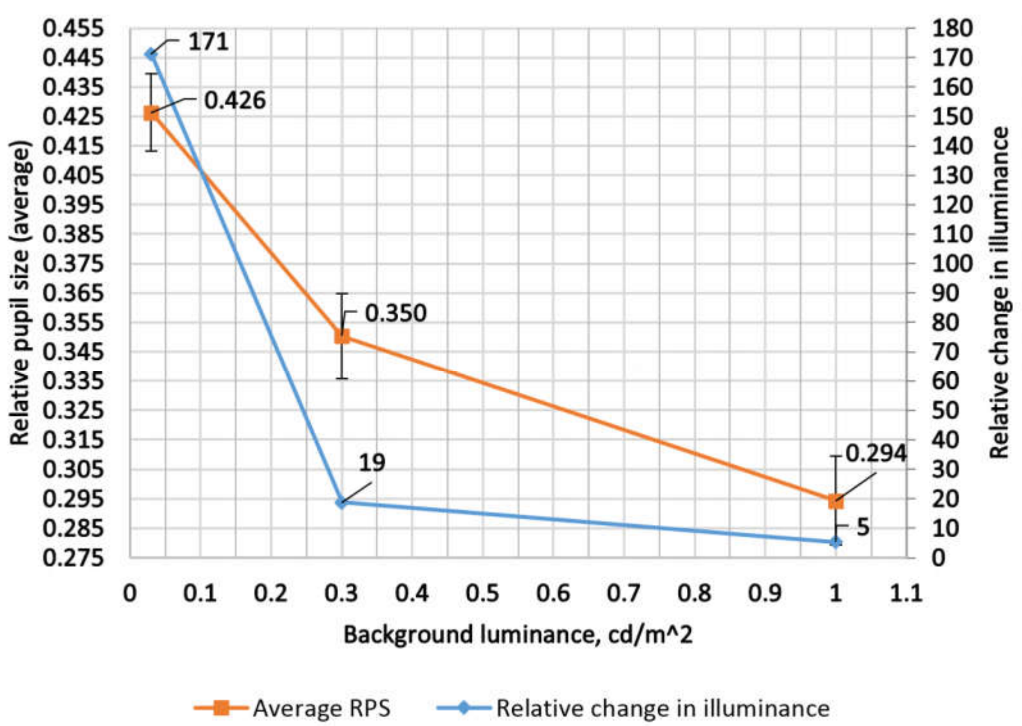


Figure 5-3. Average relative pupil size and relative change in illuminance for the three background luminances used in this study

The relative change in illuminance takes into account the initial adaptation by including the illuminance at the eyes before the glare source was shown to the subject in the denominator of equation (5-1) and the adaptation at t_2, which includes both the glare source and the background. In his initial proposal for the UGR formula (1979), Einhorn included the direct component of the glare source illuminance at the eyes (E_d) that accounts for the higher adaptation level due to the presence of the glare source. Einhorn mentioned that it is debatable to define adaptation in the glare condition through the indirect illuminance E_i at the eyes only (i.e. background luminance), since the direct illuminance at the eyes (E_d) also contributes to adaptation (1998). Einhorn mentioned that taking both illuminance components into account also avoids an anomaly of having infinitely large glare ratings in dark interiors (1979).

Figure 5-4 shows the average subjective responses to discomfort glare and the relative pupil size for the three levels of the background luminance examined in this research. The trends of the two curves demonstrate similar patterns. It means that when the background luminance is lower, the discomfort glare ratings are higher, and the pupil constricts more during the glare presentation compared to its initial state. According to Fugate, discomfort and pain are located on a continuum; discomfort is a mild degree of pain (1957). Any uncomfortable stimulus becomes painful if its intensity is sufficiently increased. Rea writes in her book that pain in the eye or in extraocular tissue is accompanied by contracted pupils (2013). This research supports Rea's statement by showing that the higher the discomfort glare, the larger the pupil constriction when compared to the initial no-glare state (Figure 5-4).

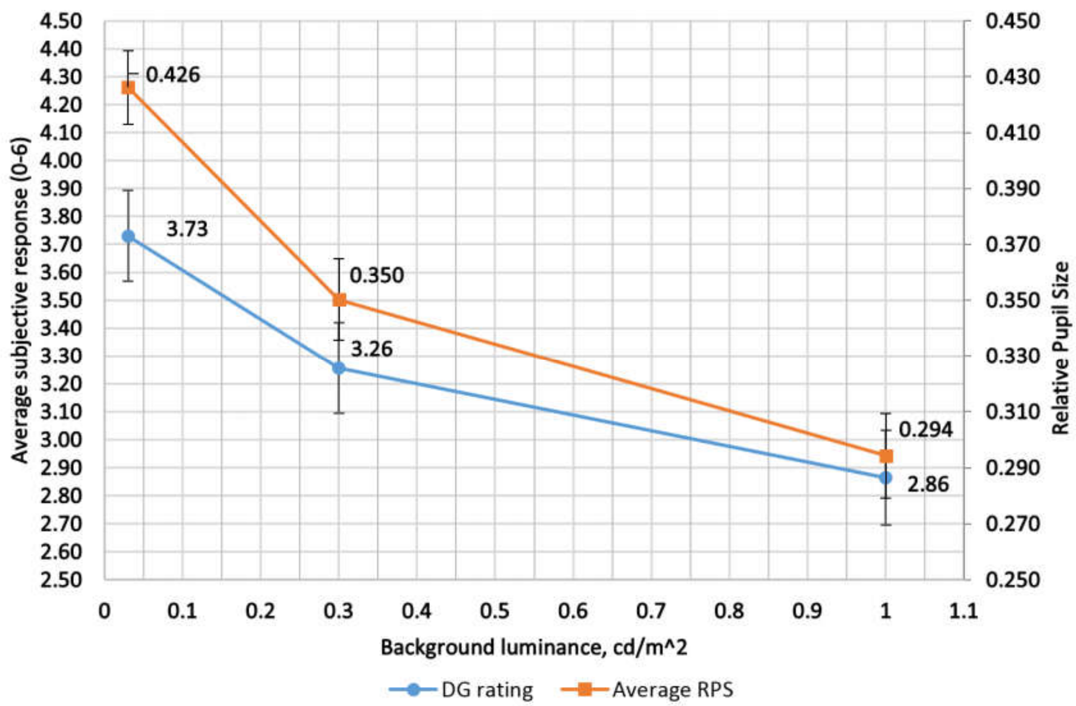


Figure 5-4. Average subjective rating and average relative pupil size for three background luminances used in this study

The difficulty in establishing a reliable and simple relationship between the pupil diameter and discomfort glare might be due to multiple physiological and psychological processes that govern pupil's size as well as its limited diameter range. After all, the pupil's size is also influenced by factors other than light, which include the age of the observer, the distance from the eyes to the object in focus, and emotions such as fear and excitement (Boyce 2014). The pupil size changes with accommodation; when the eye is focused on a near point, the pupil constricts (Rea 2013). Pupils also exhibit one of the associated reflexes - the psychical reflex (Rea 2013). This reflex occurs when patients show extreme emotion or fear, in which case they have dilated pupils. Conditions of increased attention or cognitive load can also dilate pupils (Sirois and Brisson 2014, Rosenbaum 1991). Drugs such as atropine can dilate the pupil as well, and drugs such as serine can constrict it (Rea 2013). In one study, a blind subject who lacked functional rods and cones, showed a pupil-constriction response, which peaked at a wavelength of 476 nm (Zaidi et al. 2007). The subject possessed pupillary constriction that was driven by short-wavelength photosensitive retinal ganglion cells (pRGC), which are responsible for nonvisual circadian and neuroendocrine responses to light. Watson and Yellott believe that the pupil is controlled by a complex mixture of rod, cone, and intrinsically pRGC sensitivities (2012).

Additionally, the pupil diameter's range is limited (the range for young adults is 2 - 8 mm (Boyce 2014)). If the adaptation luminance of 3,100 cd/m^2 is increased to approximately 1,000,000 cd/m^2, the light-adapted pupil of a young adult decreases by only 0.1 mm (DiLaura et al. 2011). This might indicate that the pupil has a limited reaction to the stimuli past a certain threshold. Therefore, other reactions in the body - looking away from the glare source, blinking more frequently, or closing the eyes to protect the vision - might indicate an uncomfortable state. Future research needs to address the pupil's reaction as part of this bigger picture.

5.2.4 EMG Data Discussion

The EMG data were not analyzed due to several issues with the data (Appendix W). The initial idea was to integrate the EMG recordings into the glare software, such that these data could be synchronized and compared (through the calculated MAC indices) with the subjective and pupil data.

Ideally, actual events such as human reactions to glare flashes would be clearly visible in the EMG recordings, which would allow one to synchronize all signals (in the eye tracking data one can identify different events such as flashes). The lack of third party support of the Focus EMG device made the integration of the EMG into the glare software not possible due to technical constraints. A more detailed knowledge of the EMG equipment and support by the manufacturer could confirm the correct application of all settings of the device. This would also clarify how to interpret the device's time stamps for the data it produced.

A full-scale pilot study would also help to identify issues with data collection at an earlier stage. For example, using a different data structure for storing data transmitted from the device to the host computer would have eliminated the missing data problem caused by the 'overwrite' issue. Given the time constraints, no further advanced analysis was done with the data.

5.2.5 Overall Discussion

One of the goals of this research was to simultaneously examine discomfort glare from multiple perspectives by studying the effects of a glare stimulus on the subjective, the pupil, and the facial muscle responses. Comparing results from multiple datasets could give a deeper understanding which mechanisms are involved in a response to the glare stimuli and to what extent.

Mechanisms such as blinking, frowning, apparent change in facial muscles, and others might be present when glare is shown to the subject (Hopkinson 1956, Lin et al. 2015). Stone believes that a response to discomfort glare is organized in the trigeminal nucleus (or nerve) (2009). The trigeminal nucleus (the fifth cranial nerve) is a nerve responsible for sensation in the face; it supplies sensory fibers to the eye, scalp, and orbital area (Fugate 1957). As an example, trigeminal nerve is involved in the corneal (blink) reflex, which acts as a protective mechanism against approaching objects. The sensory path detects the stimulus and initiates a motor response via the facial nerve (Rea 2014, Monkhouse 2005), which prompts the orbicularis oculi - the muscle responsible for closing the eyes. Blinking might also be involved in a response to a glare stimulus in a similar way.

As was mentioned previously (section 5.2.3), the relationship between pupil size and discomfort glare is not straightforward, because many factors influence the pupil size. However, this research found a significant correlation between the relative pupil size and discomfort glare. Therefore, the pupil's response might be an indicator of discomfort to some extent; its response should be interpreted together with the other mechanisms that might contribute to the sensation of discomfort. The ocular system might be examined together with the pupil response as being a small part of the system that responds to discomfort glare.

Additionally, a possible analogy can be made between the pupil's role in response to an uncomfortable stimulus and the pupil's role in the adaptation process. Among the three mechanisms that are known to take place during the adaptation process – the change of the pupil size, synaptic interactions, and pigment bleaching - "the change in pupil size in response to retinal illuminance can only account for a 1.2 log unit change in sensitivity to light" (DiLaura et al. 2011). This might mean that after a certain threshold is reached, the pupil's response is limited, and the role of other mechanisms becomes more apparent in the adaption. It is possible that similar processes happen during the exposure to glare.

Discomfort might occur due to a lack of ability to adapt to glare. Howarth and others assumed that discomfort can arise from light adaptation regulation mechanism (1993). If a part of the visual field is excessively bright, stress signals caused by the light overload could reach cortical pain centers. Since the retina has no pain receptors, other ocular structures have to be explored in order to find what is causing discomfort or pain (Stone 2009). For example, the cornea has no blood vessels, but is richly endowed with pain receptors to help protect the eyes (DiLaura et al. 2011). Also, the sclera, the iris, the choroid, and the ciliary body are supplied with sensory fibers of pain (Fugate 1957). Fugate hypothesized that discomfort is just a mild degree of pain. An uncomfortable sensation might be acting as protective mechanism preventing possible light damage from a glare source (Howarth et al. 1993).

Stone proposed that the neural processing tries to optimize the visual image in terms of clarity when glare or a high luminance contrast is present (2009). He assumes that the visual cortex system recruits the iris, lens, extraocular and facial muscles to resolve this strain put on the visual system. A frowning response that recruits the facial muscles, for example, results from the demand to reduce the luminance contrast (Stone 2009). To obtain a clear image in low light level situations the pupil dilates, and in high light levels, it constricts (Rea 2013). Stone argues that “a self-correcting ocular system under strain is the stimulus for the discomfort glare response” (2009).

One might argue that looking at multiple reactions would only complicate the problem. However, the author feels that if breaking down the problem into a simple relationship between variables cannot explain the phenomenon, one needs to examine a bigger picture. After all, as Boyce mentions, the visual system relies on the eye for image formation and the brain for image processing, rather than the eyes working in isolation (2014).

5.3 Future Research

Knowledge is of no value unless you put it into practice.
-Anton Chekhov

As was outlined in the introduction, in current lighting practices discomfort glare is rarely calculated, while it persists as an issue. This research investigated the influence of four variables on discomfort glare perception from small, high luminance light sources in outdoor nighttime environments. Among the four applicable discomfort glare metrics that were tested in this study, the UGR small source extension correlated best with human subject responses. The next step is to examine how to improve the UGR small source extension metric to achieve higher predictability of glare in outdoor nighttime environments. To encourage the use of discomfort glare metrics, after improving the predictability, the next necessary step is to incorporate this best performing metric into lighting software toolboxes. Modern technologies such as high dynamic range imaging (HDRI) can be used to measure bright LEDs and provide luminances of entire photographed scenes (Tyukhova and Waters 2014). Using HDRI technology for luminance data acquisition and software for glare analysis can potentially provide an excellent tool for discomfort glare measurements and calculations on site, and therefore, improve prediction and minimization of glare. Such analysis tools will allow researchers to investigate glare in real environments and designers to start using glare analysis in their every day practices.

Testing discomfort glare in real environments with the help of HDRI technology and lighting software with glare analysis capabilities might also provide researchers with a great tool to investigate glare in the context of a specific application. In the book “Human Factors in Lighting”, Boyce discussed the importance of the context in which glare is assessed (2014).

Glare is task dependent, meaning that ratings depend on whether the participant is reading, writing, or doing something else.

The UGR small source extension and Bullough's et al. combination of two metrics (2008, 2011) were the metrics that correlated best with human subjects' responses in this study (the UGR small source extension being significantly better). The combination of two metrics by Bullough et al. was used, because the authors made a distinction for sources below and above the visual angle threshold of 0.3°. For sources larger than 0.3°, in addition to illuminance, luminance is included in the equation as a significant predictor of discomfort glare. Since in the current research both source sizes were used, a combination of the two metrics had to be used to predict discomfort glare. Interestingly enough, both sets of metrics – the UGR and the UGR small source extension on the one hand, and Bullough's et al. 2008 and 2011 models on the other hand – indicate a threshold in the source size, after which some parameters of the metric's equation change (in case of the UGR metric, a threshold area is 0.005 m^2). One might wonder if there is a relation between these two distinctions in source size in both metrics. Therefore, another potential area for research is to define 'small' sources better.

Frequently, observers have multiple light sources in their field of view. For this reason, to further extend the applicability of this research to practical problems, research with multiple sources such as banks of light sources on a pole or a source with a grid of LEDs in one luminaire should be conducted. This research has shown that the constriction of the pupil can be explained if one takes into account adaptation by comparing the state before the glare was shown with the state after glare was introduced. One intriguing question is how adaptation changes, when several light sources are present in the field of view simultaneously and how discomfort glare perception would be affected in this case.

Relative pupil size correlated with discomfort glare in this study to some extent. However, as it was described in section 5.2.3, it is not easy to establish a simple relationship between pupil diameter and discomfort glare due to its physiological limit and other factors that influence the pupil's size. Future research on understanding to what extent the pupil reacts to discomfort glare along with other mechanisms such as extraocular muscle activity and eye movement might give a deeper insight into understanding the reactions that are involved in responding to discomfort glare. It might be beneficial to conduct interdisciplinary research investigating the combination of responses to glare with a team consisting of lighting specialists, ophthalmologists, visual scientists, neurologists, and potentially others.

Most certainly, understanding the true cause of discomfort and, therefore, having an objective measure(s) of discomfort glare, is highly desired. As has been described in section 2.4.2, many researchers have been looking at various measures of the physiological origin in the recent years. Yet no cause of discomfort has been established. Further investigation into this issue is warranted.

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Appendix A - HDRIs of background

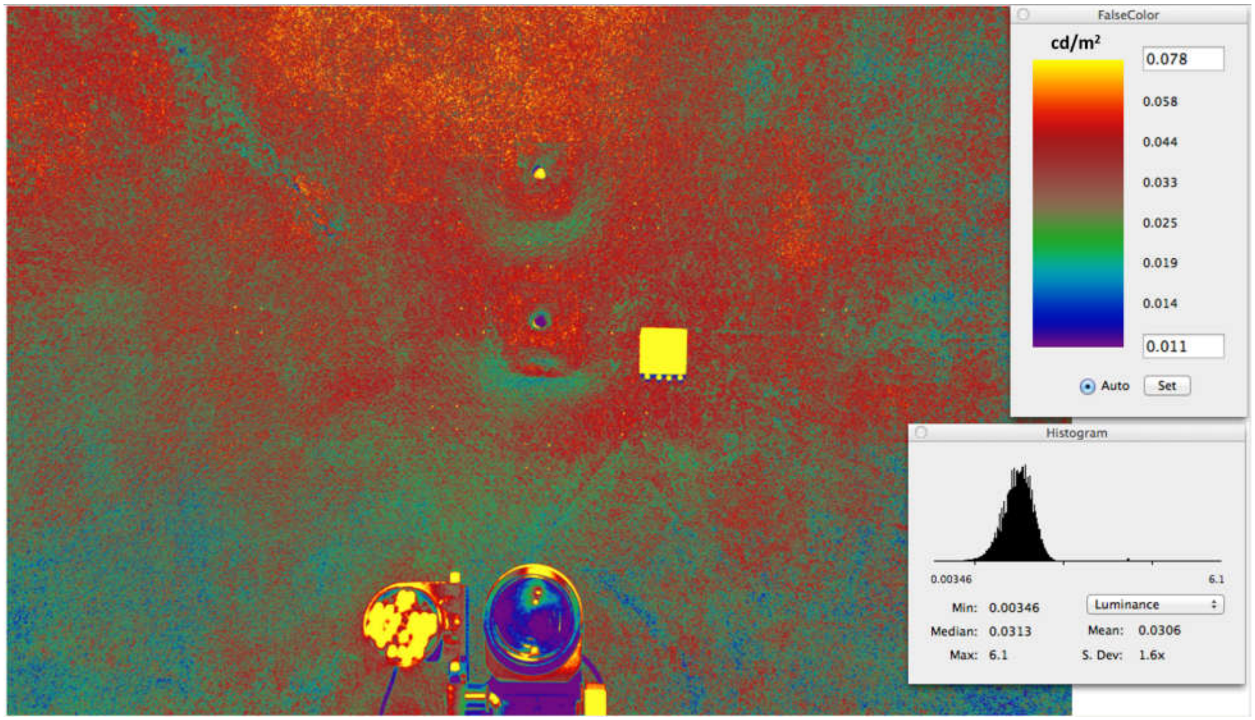

Figure A1. HDRI of the background luminance at level 0.03 cd/m^2

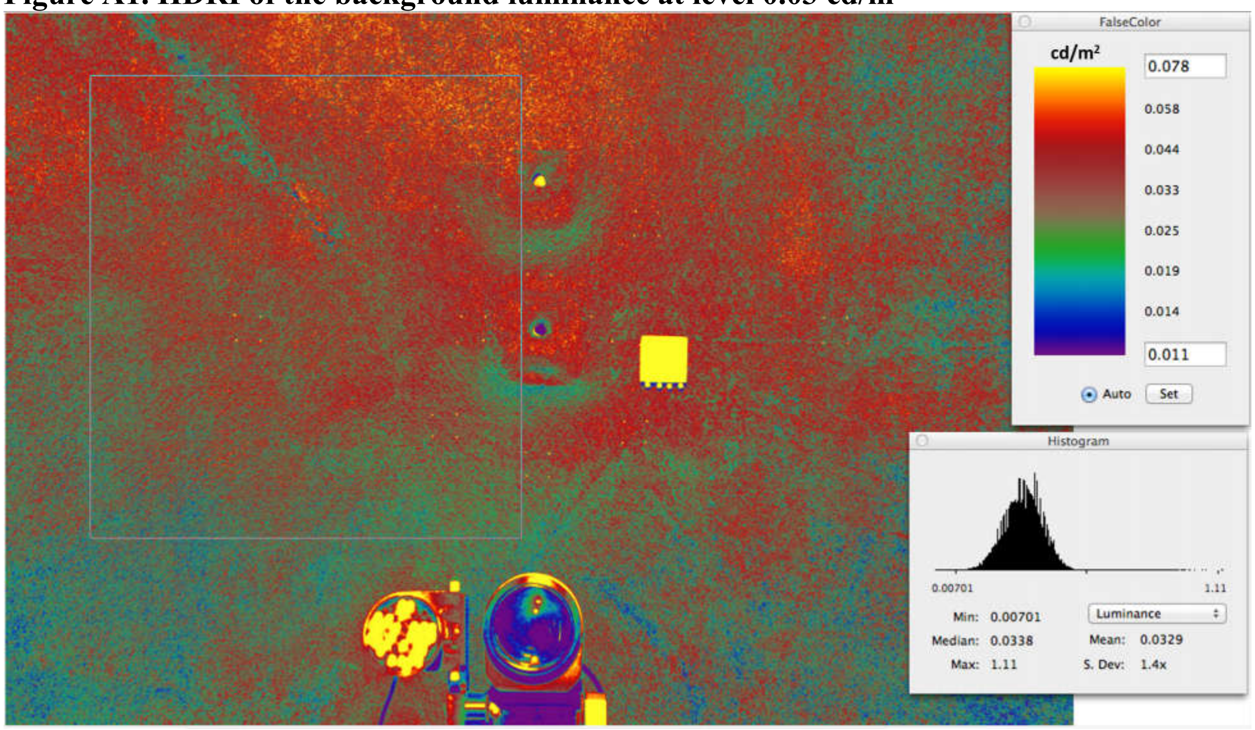

Figure A2. HDRI of the background luminance at level 0.03 cd/m^2 (left side of the field of view is highlighted, histogram shows data of the highlighted area)

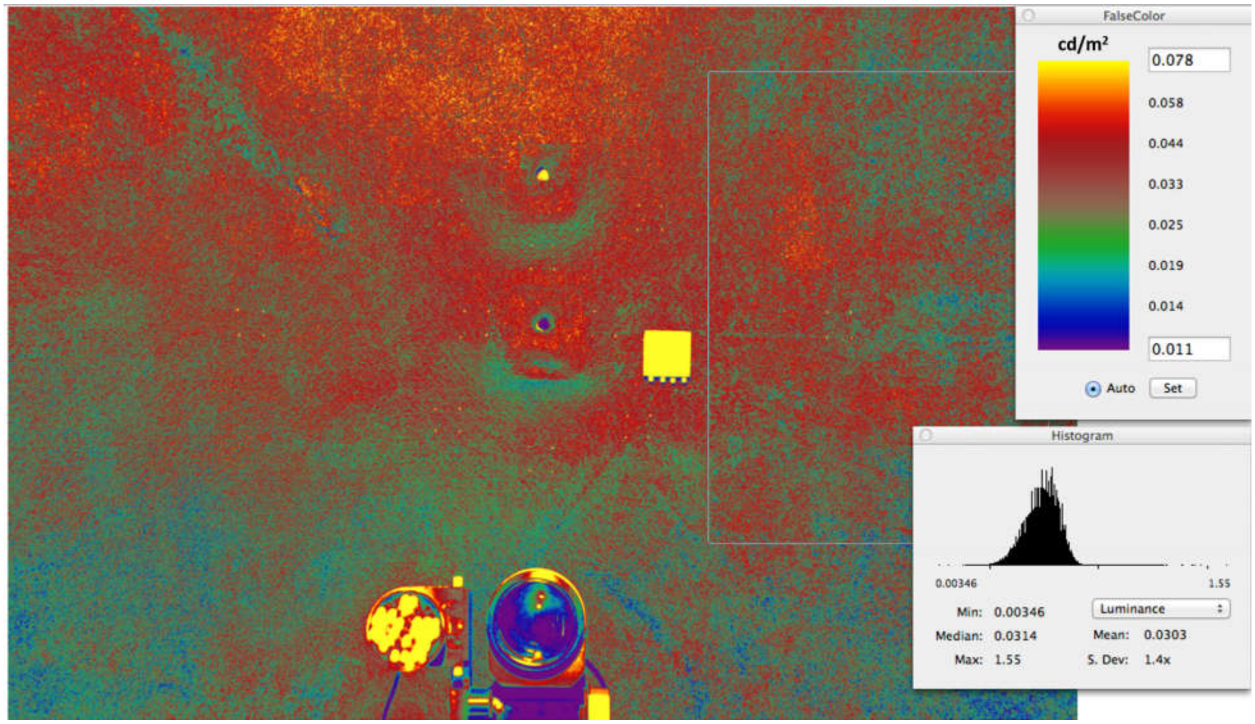

Figure A3. HDRI of the background luminance at level 0.03 cd/m^2 (right side of the field of view is highlighted, histogram shows data of the highlighted area)

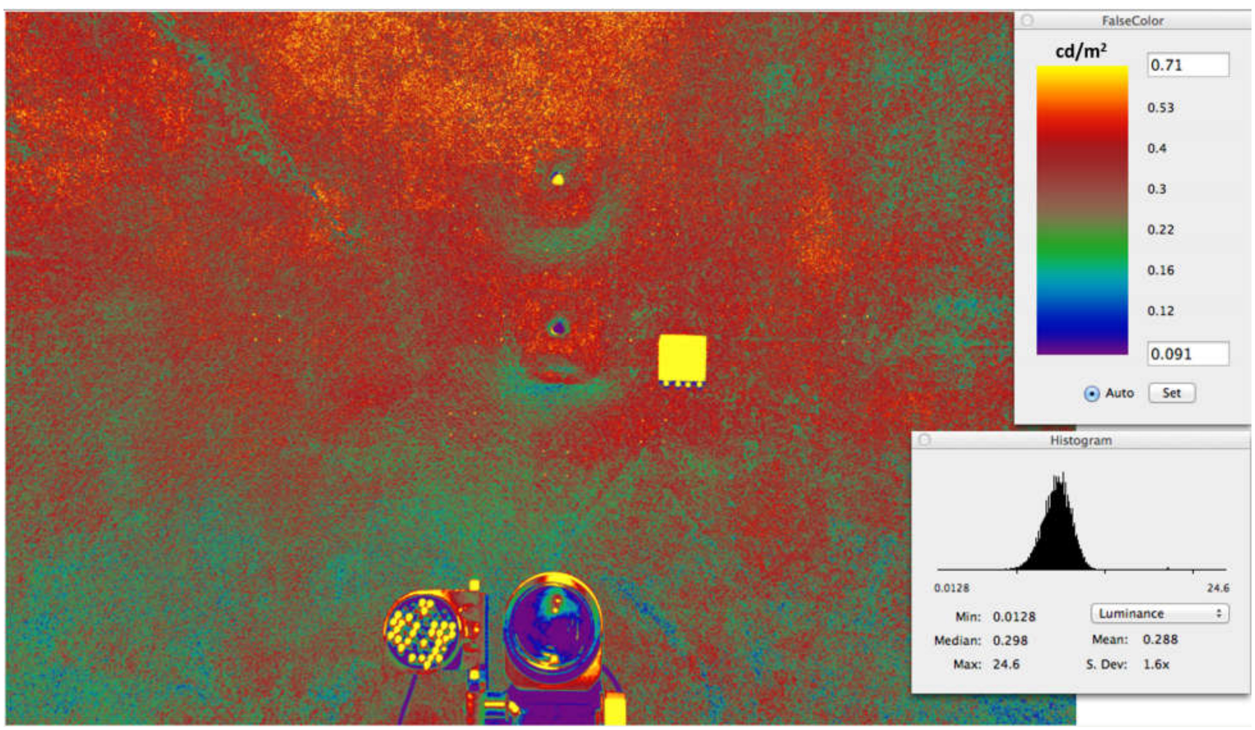

Figure A4. HDRI of the background luminance at level 0.3 cd/m^2

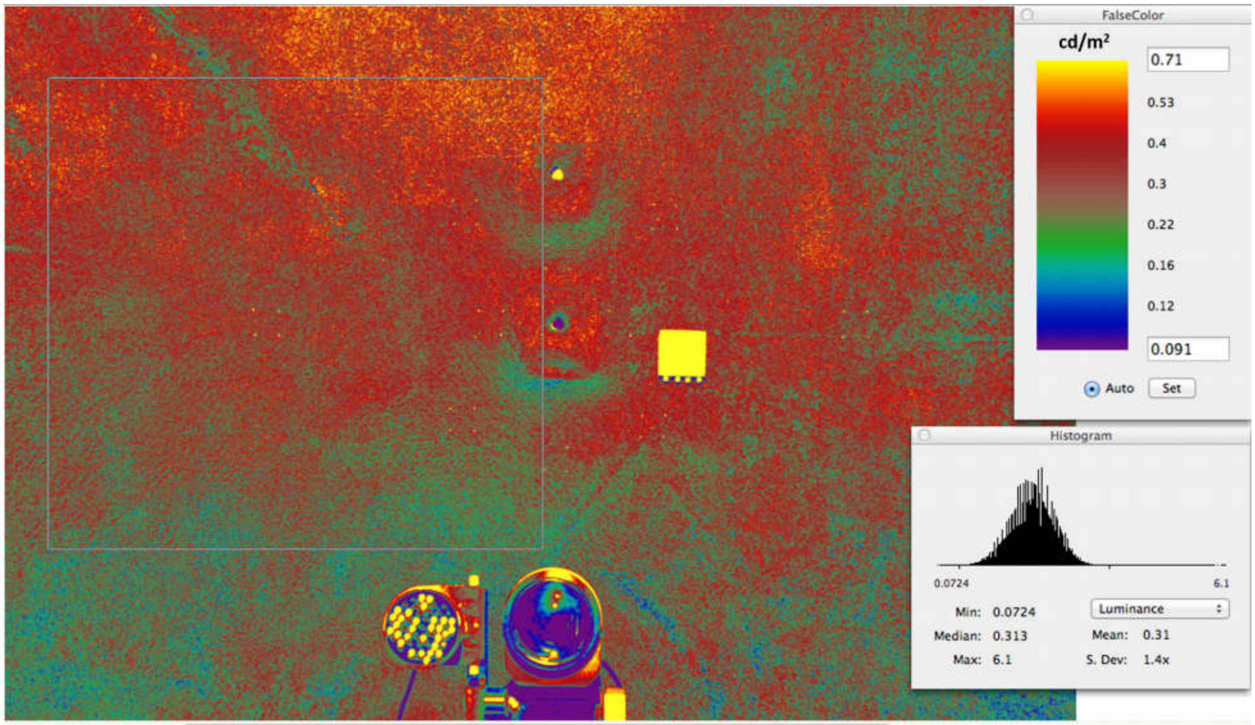

Figure A5. HDRI of the background luminance at level 0.3 cd/m^2 (left side of the field of view is highlighted, histogram shows data of the highlighted area)

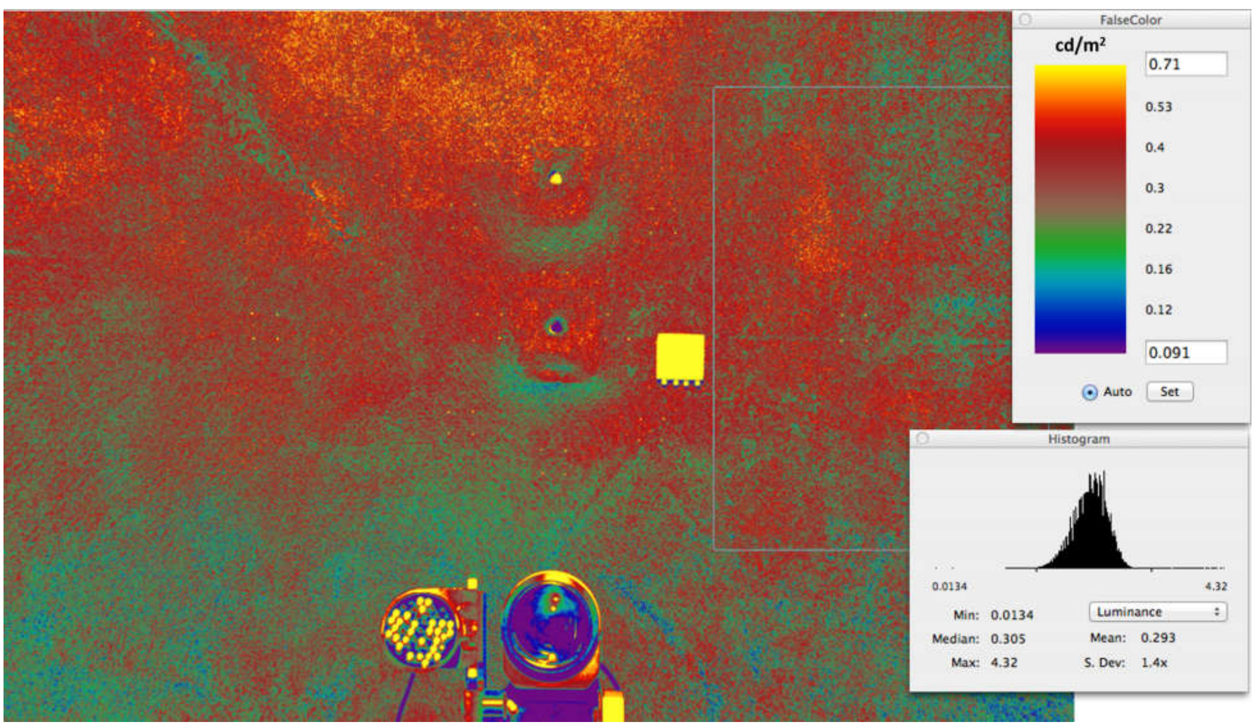

Figure A6. HDRI of the background luminance at level 0.3 cd/m^2 (right side of the field of view is highlighted, histogram shows data of the highlighted area)

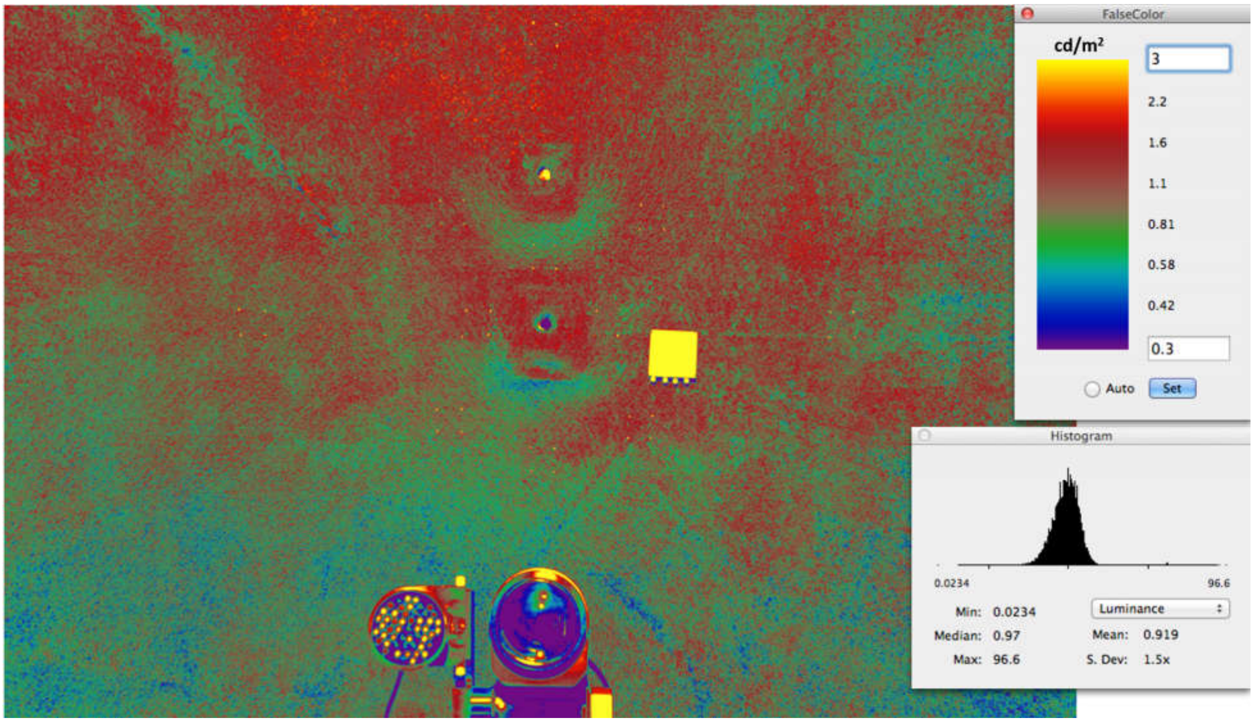

Figure A7. HDRI of the background luminance at level 1 cd/m^2

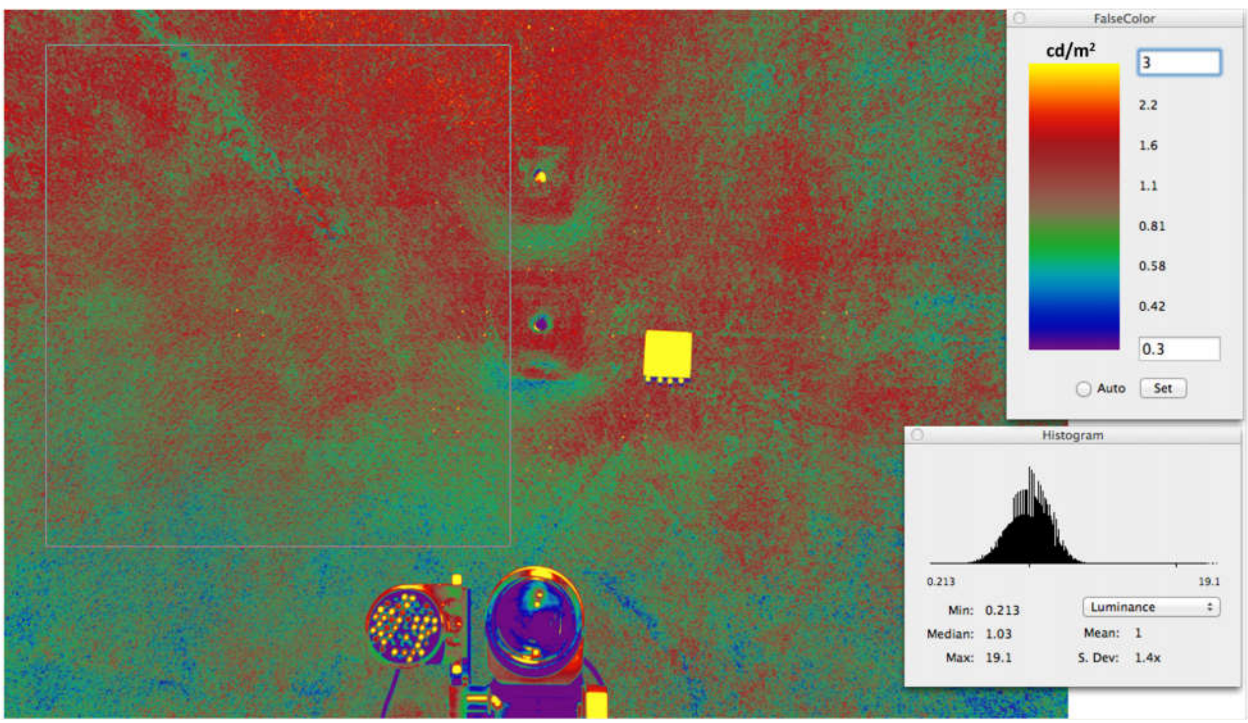

Figure A8. HDRI of the background luminance at level 1 cd/m^2 (left side of the field of view is highlighted, histogram shows data of the highlighted area)

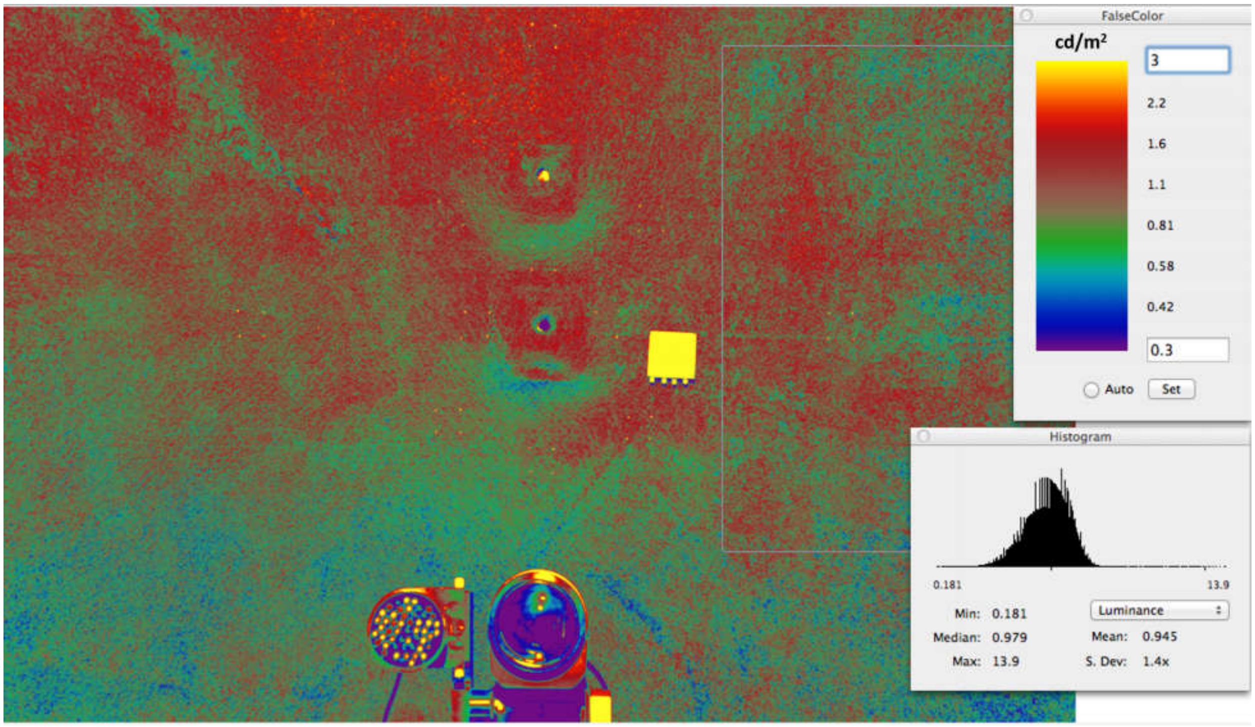

Figure A9. HDRI of the background luminance at level 1 cd/m² (right side of the field of view is highlighted, histogram shows data of the highlighted area)

Appendix B – Minimizing the spill light influence on the background luminance

Measured on **4/11/2015** with LS-110;
Background luminance 0.03 cd/m^2 (lowest level, worst condition);

Number of the point (refer to Figure 3-43)	**Background luminance without the glare source, cd/m^2**	**Background luminance with the glare source (750,000 cd/m^2,$\omega=10^{-4}$ sr, 0°), cd/m^2**
2	0.031	0.036
4	0.04	0.041
5	0.041	0.043
6	0.043	0.043
8	0.031	0.033
9	0.037	0.038
10	0.051	0.053
11	0.034	0.035
Number of the point	**Background luminance without the glare source, cd/m^2**	**Background luminance with the glare source (750,000 cd/m^2,$\omega=10^{-4}$ sr, 10°), cd/m^2**
4	0.042	0.039
5	0.042	0.041
6	0.044	0.041
8	0.033	0.031
9	0.037	0.037
10	0.051	0.047
11	0.035	0.033

Appendix C – Main settings of the devices for the 36 lighting conditions

The fixation point is a glare source at 0˚, set at 2 mA, 4000 in the aperture units.

#	LS @ 0º (fix, flash)	LS @ 10º	L_{backg}, scale (1-254)	Iris @ 0º, position	Iris @ 10º, position
1	Fix, on 12mA	Off	1	5, then 2	1
2	Fix, on 12mA	Off	90	5, then 2	1
3	Fix, on 12mA	Off	220	5, then 2	1
4	Fix, on 12mA	Off	1	5, then 3	1
5	Fix, on 12mA	Off	90	5, then 3	1
6	Fix, on 12mA	Off	220	5, then 3	1
7	Fix	On, 16 mA	1	5	2
8	Fix	On, 16 mA	90	5	2
9 (min)	Fix	On, 16 mA	220	5	2
10	Fix	On, 16 mA	1	5	3
11	Fix	On, 16 mA	90	5	3
12	Fix	On, 16 mA	220	5	3
13	Fix, on 110 mA	Off	1	5, then 2	1
14	Fix, on 110 mA	Off	90	5, then 2	1
15	Fix, on 110 mA	Off	220	5, then 2	1
16	Fix, on 110 mA	Off	1	5, then 3	1
17	Fix, on 110 mA	Off	90	5, then 3	1
18	Fix, on 110 mA	Off	220	5, then 3	1
19		On, 115 mA	1	5	2
20	Fix	On, 115 mA	90	5	2
21	Fix	On, 115 mA	220	5	2
22	Fix	On, 115 mA	1	5	3
23	Fix	On, 115 mA	90	5	3
24	Fix	On, 115 mA	220	5	3
25	Fix, on 410 mA	Off	1	5, then 2	1
26	Fix, on 410 mA	Off	90	5, then 2	1
27	Fix, on 410 mA	Off	220	5, then 2	1
28 (max)	Fix, on 410 mA	Off	1	5, then 3	1
29	Fix, on 410 mA	Off	90	5, then 3	1
30	Fix, on 410 mA	Off	220	5, then 3	1
31	Fix	On, 420 mA	1	5	2
32	Fix	On, 420 mA	90	5	2
33	Fix	On, 420 mA	220	5	2
34	Fix	On, 420 mA	1	5	3
35	Fix	On, 420 mA	90	5	3
36	Fix	On, 420 mA	220	5	3

Appendix D - Serial Ports

Controllable Device	Serial Port - USB
Glare source at position 0˚ (upper power supply)	COM 17
Glare source at position 10˚ (lower power supply)	COM 11
Background light source	COM 8
Aperture at position 0˚	COM 18
Aperture at position 10˚	COM 4
Illuminance meter	COM 7

Appendix E - Parameters file


```
<?xml version="1.0" encoding="utf-8" ?>
<!--Glare Study Test Initialization Parameters-->
<Parameters>
  <Source0>
    <voltsOn>72000</voltsOn>
    <voltsOff>55000</voltsOff>
    <current>0</current>
    <output>Off</output>
  </Source0>
  <Source10>
    <voltsOn>72000</voltsOn>
    <voltsOff>55000</voltsOff>
    <current>0</current>
    <output>Off</output>
  </Source10>
  <Fixation>
    <mAmps>2</mAmps>
  </Fixation>
  <backlight>
    <level>220</level>
  </backlight>
  <Aperture0>
    <initial>1</initial>
    <position1>0</position1>
    <position2>14000</position2>
    <position3>41000</position3>
    <position4>125000</position4>
    <position5>4000</position5>
    </Aperture0>
  <Aperture10>
    <initial>1</initial>
```

```
    <position1>0</position1>
    <position2>18000</position2>
    <position3>58000</position3>
    <position4>170000</position4>
    <position5>95000</position5>
  </Aperture10>
</Parameters>
```


Appendix F - Calibration tables

Table F1. Apertures

Position of the slider (manual mode)	Name of the position	Aperture diameter, mm (based on 1 m viewing distance)	Aperture at 0° (larger)	Aperture at 10° (smaller)
1	Closed	0	0	0
2	10^{-5} sr	3.6	14,000	18,000
3	10^{-4} sr	11.3	41,000	58,000
4	10^{-3} sr	35.7	125,000	170,000
5	Fixation point /$3*10^{-4}$ sr		4,000	95,000

Table F2. Light sources

Glare sources	Current, mA	Level, cd/m^2
At the 0°position	12	20,000
	110	205,000
	410	750,000
At the 10°position	16	20,000
	115	205,000
	420	750,000
Background source	**0-254 steps**	
	0	Switched off
	1	0.03
	90	0.3
	220	1

Appendix G - Example of a part of the pre-programmed Excel spreadsheet

Only 10 lighting conditions for one subject (ID 50) are shown due to the limited space. For display purposes the table was split into four parts.

Column meanings (Table G. Part 1 from left to right)

Date of recording
Time stamp was taken at the end of the condition
Test index order in which a lighting condition was shown
Scenario number is the number of the lighting condition
Time stamp off was taken when only the background source was on
Off - is the illuminance reflected off of the background (ambient)
Time stamp flash 1 was taken during flash 1
Power Supply glare source at 0° voltage
Power Supply glare source at 0° current
Power Supply glare source at 0° power
Power Supply glare source at 10° voltage
Power Supply glare source at 10° current
Power Supply glare source at 10° power

Column meanings (Table G. Part 2 from left to right)

Illuminance during flash 1
Time stamp was taken during flash 2
Power Supply glare source at 0° voltage
Power Supply glare source at 0° current
Power Supply glare source at 0° power
Power Supply glare source at 10° voltage
Power Supply glare source at 10° current
Power Supply glare source at 10° power
Illuminance during flash 2
Time stamp was taken during flash 3
Power Supply glare source at 0° voltage
Power Supply glare source at 0° current
Power Supply glare source at 0° power
Power Supply glare source at 10° voltage

Column meanings (Table G. Part 3 from left to right)

Power Supply glare source at 10° current
Power Supply glare source at 10° power
Illuminance during flash 3
Electrodes for the EMG (impedance test)
Does flash 1 meet the expected range of illuminance?
Does flash 2 meet the expected range of illuminance?
Does flash 3 meet the expected range of illuminance?
Does illuminance when glare source is off meet the expected range of illuminance?
Baseline illuminance for flash 1
Baseline illuminance for flash 2
Baseline illuminance for flash 3
Baseline illuminance for ambient illuminance
Allowed error ± **10%**

Column meanings (Table G. Part 4 from left to right)

Illuminance at the lower end of the baseline range for flashes (-10%)
Illuminance at the higher end of the baseline range for flashes (+10%)
Illuminance at the lower end of the baseline range for ambient illuminance (-10%)
Illuminance at the higher end of the baseline range for ambient illuminance (+10%)

Table G. Part 1

Date	Time	Test index	Scenario number	Subjective assessment (scale)	Time stamp off	Off, lx	Time stamp Flash 1	PS0, Voltage, mV	PS0, Current, mA	PS0, Power, *100 = W	PS10, Voltage, mV	PS10, Current, mA	PS10, Power, *100 = W
5/13/2015	13:51:30	14	1	**0**	51:00.4	**0.1**	51:18.3	61900	10	61	54900	0	0
5/13/2015	14:05:25	26	2	**0**	04:54.9	**1**	05:13.2	61900	10	61	54900	0	0
5/13/2015	14:15:52	35	3	**0**	15:21.9	**3.4**	15:40.1	61900	10	61	54900	0	0
5/13/2015	14:04:17	25	4	**4**	03:46.6	**0.1**	04:04.9	61900	10	61	54900	0	0
5/13/2015	14:13:34	33	5	**1**	13:03.8	**1**	13:22.2	61900	10	61	54900	0	0
5/13/2015	14:01:57	23	6	**0**	01:26.8	**3.3**	01:45.7	61900	10	61	54900	0	0
5/13/2015	14:11:17	31	7	**0**	10:46.4	**0.1**	11:04.7	60100	0	0	62000	20	124
5/13/2015	14:00:48	22	8	**0**	00:17.8	**1**	00:36.4	60100	0	0	62000	20	124
5/13/2015	14:06:34	27	9	**0**	06:03.5	**3.3**	06:21.8	60100	0	0	62000	20	124
5/13/2015	13:41:51	6	10	**1**	41:20.3	**0.1**	41:38.9	60100	0	0	62000	20	124

Table G. Part 2

Flash 1, lx	Time stamp Flash 2	PS0, Voltage, mV	PS0, Current, mA	PS0, Power, *100 = W	PS10, Voltage, mV	PS10, Current, mA	PS10, Power,*100 = W	Flash 2, lx	Time stamp Flash 3	PS0, Voltage, mV	PS0, Current, mA	PS0, Power, *100 = W	PS10, Voltage, mV
0.2	51:20.7	61900	10	61	54900	0	0	**0.2**	51:23.1	61900	10	61	54900
1.1	05:15.6	61900	10	61	54900	0	0	**1.1**	05:18.5	61900	10	61	54900
3.5	15:42.5	61900	10	61	54900	0	0	**3.5**	15:45.0	61900	10	61	54900
1.4	04:07.3	61900	10	61	54900	0	0	**1.4**	04:09.7	61900	10	61	54900
2.3	13:24.5	61900	10	61	54900	0	0	**2.3**	13:26.9	61900	10	61	54900
4.6	01:47.5	61900	10	61	54900	0	0	**4.6**	01:49.9	61900	10	61	54900
0.2	11:07.1	60100	0	0	62000	20	124	**0.2**	11:09.6	60100	0	0	62000
1.1	00:38.5	60200	0	0	62000	20	124	**1.1**	00:40.9	60200	0	0	62000
3.5	06:24.2	60100	0	0	62000	20	124	**3.5**	06:26.7	60100	0	0	62000
1.5	41:41.3	60100	0	0	62000	20	124	**1.5**	41:43.8	60100	0	0	62000

Table G. Part 3

PS10, Current, mA	PS10, Power, /*100 = W	Flash 3, lx	EMG (good/ bad)	Flash 1?	Flash 2?	Flash 3?	Off?	Flash 1	Flash 2	Flash 3	Off	Flashes ± 10%
0	0	0.2	Good EMG	Yes	Yes	Yes	Yes	**0.2**	**0.2**	**0.2**	**0.1**	0.02
0	0	1.1	Good EMG	Yes	Yes	Yes	Yes	**1.1**	**1.1**	**1.1**	**0.9**	0.11
0	0	3.5	Good EMG	Yes	Yes	Yes	Yes	**3.4**	**3.4**	**3.4**	**3.3**	0.34
0	0	1.4	Good EMG	No	No	No	Yes	**1.5**	**1.6**	**1.6**	**0.1**	0.16
0	0	2.2	Good EMG	Yes	Yes	Yes	Yes	**2.4**	**2.4**	**2.4**	**1**	0.24
0	0	4.6	Good EMG	Yes	Yes	Yes	Yes	**4.7**	**4.8**	**4.8**	**3.3**	0.48
20	124	0.2	Good EMG	Yes	Yes	Yes	Yes	**0.2**	**0.2**	**0.2**	**0.1**	0.02
20	124	1.1	Good EMG	Yes	Yes	Yes	Yes	**1.1**	**1.1**	**1.1**	**1**	0.11
20	124	3.5	Good EMG	Yes	Yes	Yes	Yes	**3.4**	**3.4**	**3.4**	**3.3**	0.34
20	124	1.6	Good EMG	Yes	Yes	No	Yes	**1.4**	**1.4**	**1.4**	**0.1**	0.14

Table G. Part 4

Expected range for the flashes		Expected range, off (no glare source)	
-10%	**10%**	**-10%**	**10%**
0.2	0.2	0.09	0.11
1.0	1.2	0.79	1.01
3.1	3.7	2.90	3.70
1.4	1.7	0.09	0.11
2.2	2.6	0.88	1.12
4.3	5.2	2.90	3.70
0.2	0.2	0.09	0.11
1.0	1.2	0.88	1.12
3.1	3.7	2.90	3.70
1.3	1.5	0.09	0.11

Appendix H - Part of the pupil data file

Below is a part of the pupil data file. First, a summary for all runs (conditions) for one subject is provided and, second, data for one second of one lighting condition are shown in Table H1.

ISCAN Tab-Delimited ASCII Data File
Version 4.00
ISCAN Data Recording
Runs Recorded: 36
Samps Recorded: 25920

RUN INFORMATION TABLE

Run #	*Date*	*Start Time*	*Samples*	*Samps/Sec*	*Run Secs*	*Image File*	*Description*
1	*2015/04/24*	*08:27:18*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
2	*2015/04/24*	*08:28:26*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
3	*2015/04/24*	*08:29:36*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
4	*2015/04/24*	*08:30:46*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
5	*2015/04/24*	*08:31:55*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
6	*2015/04/24*	*08:33:03*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
7	*2015/04/24*	*08:34:14*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
8	*2015/04/24*	*08:35:24*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
9	*2015/04/24*	*08:36:35*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
10	*2015/04/24*	*08:37:45*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
11	*2015/04/24*	*08:38:53*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
12	*2015/04/24*	*08:40:01*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
13	*2015/04/24*	*08:41:13*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
14	*2015/04/24*	*08:42:21*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
15	*2015/04/24*	*08:43:30*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
16	*2015/04/24*	*08:44:40*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
17	*2015/04/24*	*08:45:50*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
18	*2015/04/24*	*08:46:59*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
19	*2015/04/24*	*08:48:09*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
20	*2015/04/24*	*08:49:17*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
21	*2015/04/24*	*08:50:27*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
22	*2015/04/24*	*08:51:37*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
23	*2015/04/24*	*08:52:45*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
24	*2015/04/24*	*08:53:55*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
25	*2015/04/24*	*08:55:03*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
26	*2015/04/24*	*08:56:12*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
27	*2015/04/24*	*08:57:25*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
28	*2015/04/24*	*08:58:34*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
29	*2015/04/24*	*08:59:43*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
30	*2015/04/24*	*09:00:54*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
31	*2015/04/24*	*09:02:05*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
32	*2015/04/24*	*09:03:13*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
33	*2015/04/24*	*09:04:25*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
34	*2015/04/24*	*09:05:36*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
35	*2015/04/24*	*09:06:45*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*
36	*2015/04/24*	*09:07:54*	*720*	*60*	*12.00*	*default.igr*	*New Data Run*

Table H1. One second of one lighting condition for one subject (it was organized in a table for convenient viewing)

Run 1. Sample #	Pupil DMM1, mm	Run 1. Sample # (continued)	Pupil DMM1, mm (continued)
0	0	30	6
1	0	31	6
2	1.3	32	6
3	4.8	33	6.1
4	5.6	34	6
5	6	35	6
6	6	36	6.1
7	6.1	37	6
8	6.2	38	6
9	6.1	39	6
10	6.1	40	6
11	6.1	41	6.1
12	6.2	42	6
13	6.3	43	6
14	6.1	44	6
15	6	45	6
16	6.1	46	5.9
17	6.2	47	6
18	6.1	48	5.8
19	6.1	49	5.9
20	6.1	50	5.8
21	6	51	5.8
22	5.9	52	5.9
23	6	53	5.9
24	6	54	5.8
25	6	55	5.7
26	6.1	56	5.7
27	6.1	57	5.8
28	6	58	5.9
29	6	59	5.6

Appendix I - Sign-up questions via the website link

1. First and last name
2. Email address
3. Phone number
4. Gender a)female b)male
5. Age
6. Residence (city and state only)
7. Do you have normal vision (can be with glasses or contacts) a)yes b) no

   If no, what is the nature of the problem?
8. Are you a lighting professional? a)yes b)no

   If yes, what is your title, and role?
9. Are you a student? a) yes b) no
10. Are you a Musco Employee? a) yes b) no
11. Have you participated in a lighting research experiment before? a) yes b) no

    If yes, what kind of experiment?
12. Do you know anything about this study and/or helped in developing this study?

    a) yes b) no

    If yes, what do you know and/or how did you help?

Appendix J – Informed Adult Consent Form

University of Nebraska Lincoln

THE DURHAM SCHOOL of ARCHITECTURAL ENGINEERING and CONSTRUCTION

IRB# 20141114551EP
Date Approved: 03/23/2015
Valid Until: 11/25/2015

Offering Programs in Omaha and Lincoln
COLLEGE OF ENGINEERING

INFORMED ADULT CONSENT FORM

Project Title:
Discomfort glare in outdoor nighttime environments

Purpose:
This research project involves determining the degree of discomfort glare from a stimulus in outdoor nighttime environments, which will allow the experimenters to better understand the impact of the luminance of the background, the size of the stimulus, its position and luminance on our impression of discomfort glare in dark environments. You will be asked to complete one pre-screening session, which lasts approximately 10 minutes. If you meet the vision requirements, you will be included in the experiment. You will fill out a general information survey, and after that, you will begin your experimental session. If selected, the research will take place in one session lasting approximately 1.5 hours. This research is funded by Musco Sports Lighting, LLC. You must be 19 years of age or older to participate. You were selected to participate because you volunteered.

Procedures:
This research will take place in Musco Sports Lighting Facility, Oskaloosa, IA. At the start of the session, you will be given a brief training sheet to read and have the opportunity to ask any questions.

For the initial pre-screening you will take the Keystone Visual Skills Test to confirm you have normal vision. If your vision is acceptable for these experiments, you will be included in the study. Before the beginning of the study, the electromyographic (EMG) equipment is going to be attached to you; four electrodes are going to be placed below your eyes, and one on your forehead. In the study, you will sit in a chair with your head positioned in a head rest, focusing your gaze at a fixation point or a light source. A stimulus will be shown to you in your field of view and you will be asked to say on a scale from 0 to 6 how much discomfort it causes to you. Simultaneously the electrodes will be measuring the Muscle ACtivation (MAC) index, and the eye tracking device will record the movements of your eyes, pupil diameter, and blinks. The light source will be shown to you in the following sequence adaptation time – short time on – short time off – short time on – short time off- short time on- short time off. After this presentation, you have to make an assessment. You are expected to complete experimental session without breaks. This process will be repeated as the lighting conditions are changed.

Benefits:
There are no direct benefits to you as a research participant, but it may help to improve the methods of discomfort glare assessments in outdoor nighttime environments.

Risks and/or Discomforts:
There are no known risks associated with this research. You might feel discomfort when looking at the bright light sources. The highest presented luminance is in the range of 500,000 – 1,500,000 cd/m^2 (examples of typical luminances, moonless clear night sky 0.001 cd/m^2, scattered clouds 1000 cd/m^2, T5 High Output fluorescent lamp 31,000 cd/m^2, tungsten lamp filament 3,100,000 cd/m^2, sun at the horizon 10,000,000 cd/m^2, sun at midafternoon 100,000,000 cd/m^2 (DiLaura et al. 2011)). The Keystone Visual Skills test is a non-invasive screening test for vision. The EMG equipment is a non-invasive device measuring MAC index. In this study skin irritation is not expected due to the placement of the electrodes on the face.The radiation and thermal levels of the infrared LED illuminators used in the EyeTracking Laboratories fall well within Occupational Safety and Health Administration (OSHA) recommentaions. In the glare experiment, the luminance will be carefully monitored and controlled in a non-harmful range.

Confidentiality:
Any information obtained during this study, which could identify you, will be kept strictly confidential. The data will be stored in a locked cabinet in the investigator's office and will only be seen by the investigator and faculty advisor during the study and for 10 years after the study is complete. You will be asked to fill out a general information survey that includes demographic information such as gender, age, and city of residence, etc. Data from individual subjects may be reported, but in no case will you be personally connected to the data. The information obtained in this study may be published in scientific journals or presented at scientific meetings but the data will be reported as aggregated data.

Opportunity to ask questions:
You may ask any questions concerning this research and have those questions answered before agreeing to participate in or during the study. Or you may contact the investigator(s) at the phone numbers below. If you have any questions about your rights as a research participant that have not been answered by the investigator or to voice concerns about the research, you may contact the University of Nebraska-Lincoln Institutional Review Board at (402) 472-6965.

Participation is Voluntary:
Participation in this study is voluntary. You can refuse to participate or withdraw at any time without harming your relationship with the researchers of the

University of Nebraska-Lincoln. Your decision will not result in any loss of benefits to which you are otherwise entitled. If you are a Musco employee, your participation, non-participation or withdrawal from the research will have no effect on your employement with Musco Sports Lighting.

Consent, Right to Receive a Copy:
You are voluntarily making a decision whether or not to participate in this research study. Your signature certifies that you have decided to participate having read and understood the information presented. You will be given a copy of this consent form to keep.

Signature of Participant:

_________________________________ ____________________________
Signature of Research Participant Date

____
Printed Name

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Appendix K - Keystone Visual Skills Form

KEYSTONE VISUAL SKILLS PROFILE

For Use with Keystone Ophthalmic Telebinocular

Doctor's Cumulative Profile Form No. 3A

Order No. 5506

Name________________________ Age________ Date_______ Wearing Glasses: Yes_____ No_____

		Left Only	Right Only	Underconvergence Low Usable Vision	EXPECTED	Overconvergence High Usable Vision
Set at Far Point	Test 1 (DB-10A) Simultaneous Vision (Far Point)					
	Test 2 (DB-8C) Vertical Posture (Far Point)	only	only	3 2 1 0 1 2 3 / 3 2 1 0 1 2 3	3 2 1 0 1 2 3 / 3 2 1 0 1 2 3 / 3 2 1 0 1 2 3	3 2 1 0 1 2 3 / 3 2 1 0 1 2 3
	Test 3 (DB-9) Lateral Posture (Far Point)	only	15-14-13 · · 3-2-1 Numbers Only	15 14 13 12 11	10½ 10 9 8½ 8	7 6 5 4 3 2 1
	Test 4 (DB-4K) Fusion (Far Point)	only	only	Four, widely separated / Four, near each other	Four then three / Four, then three	Four, near each other / Four, widely separated
	Test 4½ (DB-1D) Usable Vision, Both Eyes (Far Point)			1 L 49% · 2 B 70% · 3 T 84% · 4 L 88% · 5 R 92% · 6 T 96%	7 L 98% · 8 B 100%	9 B 103% · 10 R 105%
	Test 5 (DB-3D) Usable Vision, Right Eye (Far Point)		No Dots Seen Unless Left Eye Is Occluded	1 T 49% · 2 R 70% · 3 L 84% · 4 T 88% · 5 B 92% · 6 B 96%	7 L 98% · 8 R 100%	9 T 103% · 10 R 105%
	Test 6 (DB-2D) Usable Vision, Left Eye (Far Point)	No Dots Seen Unless Right Eye Is Occluded		1 B 49% · 2 L 70% · 3 R 84% · 4 R 88% · 5 T 92% · 6 L 96%	7 B 98% · 8 L 100%	9 R 103% · 10 T 105%
	Test 7 (DB-6D) Stereopsis (Far Point)	+ only	only ●	1 + · 2 ○ · 3 ✳ · 4 ○ · 5 □ · 6 □ · 7 ♡ · 8 + · 9 ✳	10 + · 11 ♡ · 12 ○	
	Test 8 (DB-13A) Color Perception (Far Point)	32		79 · 23	ALL CORRECT	
	Test 9 (DB-14A) Color Perception (Far Point)	63		92 · 56	ALL CORRECT	
Move to Near Point	Test 10 (DB-9B) Lateral Posture (Near Point)	only	10-9 · · · · 4-3-2 Numbers Only	10 9 8 7	6½ 6 5 4½	4 3 2
	Test 11 (DB-5K) Fusion (Near Point)	only	only	Four, widely separated / Four, near each other	Four, then three / Four, then three	Four, near each other / Four, widely separated
	Test 12 (DB-15) Usable Vision, Both Eyes (Near Point)	1 D 10% · 2 L 20%	3 D 30% · 4 D 40%	5 L 50% · 6 D 50% · 7 D 60% · 8 L 60% · 9 D 70% · 10 D 70% · 11 G 80% · 12 L 80%	13 L 90% · 14 D 90% · 15 L 100% · 16 D 100% · 17 L 102% · 18 D 102%	19 G 103% · 20 D 103% · 21 D 105% · 22 L 105%
	Test 13 (DB-16) Usable Vision, Right Eye (Near Point)	1 D 10% · 2 D 20%	3 L 30% · 4 D 40%	5 L 50% · 6 D 50% · 7 D 60% · 8 L 60% · 9 D 70% · 10 L 70% · 11 D 80% · 12 G 80%	13 L 90% · 14 L 90% · 15 D 100% · 16 D 100% · 17 G 102% · 18 D 102%	19 L 103% · 20 D 103% · 21 D 105% · 22 L 105%
	Test 14 (DB-17) Usable Vision, Left Eye (Near Point)	1 L 10% · 2 D 20%	3 D 30% · 4 D 40%	5 L 50% · 6 D 50% · 7 L 60% · 8 D 60% · 9 D 70% · 10 D 70% · 11 L 80% · 12 L 80%	13 G 90% · 14 D 90% · 15 L 100% · 16 D 100% · 17 L 102% · 18 D 102%	19 L 103% · 20 G 103% · 21 D 105% · 22 L 105%

NOTES:

Phone (775) 324-2799 Fax (775) 324-5375 Email sales@keystoneview.com Printed in Costa Rica

735-272

Appendix L - Keystone Visual Skills Screening Test Subject Instructions

Experimenter: “This test will be done as a pre-screening for the main experiment. After you have completed the pre-screening, you will be informed whether you meet the requirements for the main experiment. At that time, you may choose to continue with the experiment or decline. This pre-screening test is to confirm you have normal vision. Now let’s begin the pre-screening.”

“Let’s adjust the apparatus. It is essential that you are comfortable when you do this test.”

(In case person does not wear glasses.)
“Are you wearing contacts?”
“Is it a new prescription or did you have them for a while?”

(In case subject wears glasses.)
“First, I need you to make sure your glasses are clean. You can use this spray to clean them. Also, please make sure the glasses sit well.”

“Are they bifocal?” *(If yes, the experimenter adjusts the Keystone apparatus accordingly.)*
“Are these glasses a new prescription or did you have them for a while?”

“I am going to show you different targets, and ask specific questions about them. Your goal is to simply report what you see. Do not pull back between the individual tests. Please always look at the targets with both eyes.”

(Experimenter runs the subject through the Keystone Visual Skills Test as directed in the manual. Questions are shown below.)

FAR-POINT

TARGET 1
“What do you see?” “Is the dog directly over the pig?”

TARGET 2
“Do you see a yellow line and the red figures?” (Pointing.) “What figure does the yellow line touch?”

TARGET 3
“To what number does the arrow point?”
If it swings between numbers, just tell me the range of the numbers.

TARGET 4
“How many circles do you see?” OR “Do you see two, three, or four circles?”
“Are they in vertical alignment?”

TARGETS 4 ½ , 5, 6
"You see some signboards. In No.1 *(pointing)* you see five white squares. And in one of these squares is a black dot. Is it in the right, left, top, or bottom square?" "Where is it in the other signs?" (Use pointer.) Continue until you can't see.

TARGET 7
"You see *(pointing to each figure in the top line)* a star, -square, -cross,-heart and ball. Does one of them seem to be closer to you than the rest (OR stand out)? Which one in the second line? etc. Continue until you can't see."

TARGET 8, 9
Read the number *(pointing)* in the top ball, in the lower left, and in the lower right.

"Ok, we've finished the pre-screening test."

"You meet the requirements for this test"
(If the subject responds within the expected range on the form or gray, for target 3 it is ok to partly be outside 11 or 8, it is ok to be one step out of the expected range)
OR
"You don't meet the requirements for this test."

Appendix M - General Information Survey

UNIVERSITY OF Nebraska Lincoln

THE DURHAM SCHOOL of ARCHITECTURAL ENGINEERING and CONSTRUCTION

Offering Programs in Omaha and Lincoln
COLLEGE OF ENGINEERING

For experimenter's use
Subject #: _________
Date: _____________

GENERAL INFORMATION SURVEY

Project Title:
Discomfort glare in outdoor nighttime environments

Your answers to the following questions will help us make a more adequate interpretation of the results of the research.

1. Gender a)female b)male
2. Age: __________________
3. What is your race? ____
4. What is your native language?____
5. Residence (city and state only) ____
6. Are you wearing: a) glasses b) contact lenses c)neither

   If you wear glasses or contact lenses, are they of any special type (tinted, aspheric, bifocal, polarized, etc.)?

   ____
7. What is your eye color: ______________________________
8. On a scale from 1 to 5 how sensitive are you to light?
   1-Not at all 2 3 4 5-Very sensitive
9. Is your profession mostly a) outdoor b)indoor c)both equally
10. Are you a lighting professional? a) yes b) no

If yes, what is your title, and role?

____

____

11. Are you a student? a)yes b)no

12. Are you a Musco Employee? a)yes b)no

13. Have you participated in a lighting research experiment before?
a) yes b) no

If yes, what kind of experiment?

____

____

____

____

14. Did you have caffeine today? a) yes b) no

Appendix N - Instructions for subjects

Nebraska UNIVERSITY OF Lincoln

THE DURHAM SCHOOL of ARCHITECTURAL ENGINEERING and CONSTRUCTION

Offering Programs in Omaha and Lincoln
COLLEGE OF ENGINEERING

Instructions for Discomfort Glare Experiments

Project Title:
Discomfort Glare in Outdoor Nighttime Environments

Identification of this Research:
This part of the experiment involves rating the level of discomfort of a single stimulus.

Instructions:
This experiment deals with your perception of discomfort glare. Discomfort glare is a sensation of annoyance or pain caused by high luminances in the field of view. Your task is to rate the level of discomfort caused by a single stimulus that flashes three times on a scale of 0 through 6. Your head will be held in a fixed position using a headrest, and I will ask that you always look directly at the fixation point or at a light source at 0˚ position (straight ahead). There will be times when the fixation point is NOT on, you may relax your eyes, and look around without moving your head. Once the fixation point is back on, keep your gaze at the fixation point at all times. This ensures that everyone views the same visual stimulus. When you have rated the level of discomfort, we will move to the next condition, and repeat until all conditions are completed.

The Charles W. Durham School of Architectural Engineering and Construction
The Peter Kiewit Institute / 1110 South 67th Street / Omaha, NE 68182-0816 / 402-554-2460 / www.durhamschool.unl.edu

Appendix O - Glare Rating Scale

0- No discomfort glare

1- Glare between non-existent and noticeable

2- Glare noticeable

3- Glare between noticeable and disagreeable

4- Glare disagreeable

5- Glare between disagreeable and intolerable

6- Glare intolerable

Appendix P - Experiment Instructions (read by experimenter)

(The sources are at 110mA (GS0) & 115mA (GS10), background at 220 during the instructions)

1. **Consent form**

"I will email your consent form to you."

2. **Keystone Test (separate instructions)**

3. **General introduction**

(MANUAL
Background source is on at 220;
The fixation point is on IRIS0 @ position 5, GS0 @ 2mA)

Experimenter: "The research you will be participating in today involves assessing discomfort glare from small bright light sources in dark environments. In the study I will show you a stimulus that flashes three times, your task is to rate how much discomfort is caused by this stimulus."

"First, I will explain the apparatus to you. Next, I will explain the experimental procedures. Then I will attach the electrodes to your face. I will show you the range of possible conditions, we will do a few practice trials to get a feeling for the procedure, and then we will start the main experiment."

"Would you please leave your cell phone here, so you are not disturbed during the experiment?"

4. **The apparatus introduction**

"First, I will introduce this apparatus to you. This is a sphere where you will make the assessments of different lighting conditions presented to you."

(The experimenter goes inside of the sphere, and the participant sits on a chair in front of it)

"When you are doing the experiments, you will sit in the chair and put your chin on the chinrest and your forehead against the forehead rest. It is important that your eyes are positioned in line with this 0 degree opening. I will make sure that the eye level matches the mark on the chinrest. It is critical. We will adjust the chair so that you are at a comfortable position."

(The experimenter points to the two positions of the targets.)

"The stimuli will be presented to you from one of the two openings – the 0˚ position, and the one above it. During the presentation, you must ALWAYS look straight ahead (at 0-degree position). This straight-ahead position is multifunctional. Sometimes you will see the fixation point there, just like right now. There will be times when no fixation point is going to be on, you can move your eyes without moving your head. Once the fixation point is on, you must always look at it. Sometimes instead of the fixation point at 0 degrees you will see a stimulus flashing three times, you must look at this stimulus."

"Do not pull back your head after I show you the stimulus. Please always keep your head in the chinrest."

"If you have any questions feel free to ask me at any time."

"Now I will let you adjust the chair. I will make sure your eye level is in line with the mark on the chinrest. When you pull your chair, watch out for the caster cups attached to the floor. And I will adjust the eye-tracking device, so that it tracks your pupil correctly."

"Are you comfortable?"

"Ok, the eye-tracking device tracks your pupil correctly."

(If subject answers yes, move on. If subject answers no, readjust. Repeat as needed.)

(Adjust the eye-tracking device, so it tracks the eye correctly)

5. Instructions for the experimental procedures

(Give out a "Rating scale subject instructions" paper sheet to the subject.)

"Would you please turn around for more instructions?"

"I will read the experiment instructions with you."

(Read the instructions with the subject)

"In total there will be 36 trials. After you finish all the trials, the experimental session will be complete."

"Here is the scale I want you to use."

(Give the subject a copy of the rating scale, and read the scale with the subject.)

"I will remind you the scale a few times during the experiment, but feel free to ask at any time."

"Any questions at this stage?"

"Now let's attach the electrodes. They might feel a little unusual, but nothing is going to hurt. The electrodes just record the muscle activity around your eyes.

Let me clean the areas on your face with Alcohol Swab. I put some gel on the electrodes. And now, let us place them on the appropriate areas. We need to make sure they are attached well, so we'll apply some tape."
(Attach the electrodes, have plus and minus go around the ears, tie the electrodes behind the subject.)
"Let me clip them together behind your head".

6. Range of the conditions

(MANUAL part of the software;
Lowest – GS0 2mA, position 5; GS10 16mA; background 220, IRIS10 position 2;
Highest – GS0 410 mA, background 1, IRIS 0 position 3)

"Now I will show you the range of possible conditions, so you know what to expect."

(Switch on a condition that creates no sensation of discomfort glare)

"Keep looking at the fixation point. Most people would say that this condition creates no discomfort glare. It is 0 on the glare rating scale."

(Change the lighting condition to the one that creates very high discomfort glare)

"Keep on looking straight ahead. Most people would say that this level of light is intolerably glaring. It is 6 on the glare rating scale."

"In the main experiment you will see different lighting conditions in a random order. They will create various levels of discomfort that you're going to rate on a scale of 0 through 6."

"Now let us do a few practice trials."

7. Practice trials

(Load scenarios file (in the input part of the AUTO test) just like in the main experiment, randomize)

"I will remind you of the procedures step-by-step."

"When there's no fixation point, you may look around without moving your head. It gives an opportunity to relax your eyes a little. Once the fixation point is on, you must look at it at all times. Now, please rate the level of discomfort on a scale of 0 through 6."

(Wait for the subject to tell the level of discomfort)
(Change the lighting condition to another one. Repeat a few more times (at least 3).)

"Let us do one more practice trial, and if you are comfortable with the procedure, we can continue with the main experiment."

"Are you ready to proceed?"
(The experimenter repeats a practice trial as needed)

8. The main experiment
"Let me close the curtain, so no light from outside can enter the sphere."

"Ok. Let us start."

(The software runs the lighting conditions in a random order (it changes the luminance of the light source, its size, its position, and/or background luminance.)

On the 39th increment (1 increment = 1.2 seconds in duration) of the each lighting condition manually click record the eye-tracking data (720 data points = 12 seconds).

Repeat the scale wording every 10 conditions (3 times total).

"Please rate the level of discomfort."

(When a subject completes all 36 trials, the session is over.)

"This completes the study. I will ask you to answer a one-question survey before you leave."

(*Save all the files with the subject's recordings including the eye-tracking data.)*

'Thank you."

Appendix Q - Survey on the Experiment

University of Nebraska Lincoln

THE DURHAM SCHOOL of ARCHITECTURAL ENGINEERING and CONSTRUCTION

Offering Programs in Omaha and Lincoln
COLLEGE OF ENGINEERING

For experimenter's use
Subject #: _________
Date: _____________

SURVEY ON THE EXPERIMENT

Project Title:
Discomfort glare in outdoor nighttime environments

Your answer to the following question will help us make a more adequate interpretation of the results of the research.

1. Do you have any comments and/or concerns related to the experiment that may have impacted your response?
   ____
   ____
   ____
   ____
   ____
   ____
   ____

The Charles W. Durham School of Architectural Engineering and Construction
The Peter Kiewit Institute / 1110 South 67th Street / Omaha, NE 68182-0816 / 402-554-2460 / www.durhamschool.unl.edu

Appendix R - SAS Command File for Subjective Responses Analysis

The output file is not printed here due to its large size.

```
data MAIN;
Input subjid a1-a36 age;

/*EXCLUDED 9 subjects (problematic eye tracking data);
Levels:
lumin1 = 20,000         lumin2 = 205,000  lumin3 = 750,000
posit1 = 0              posit2 = 10
backs1= 0.03            backs2 = 0.3            backs3 = 1
solid1 = 10^(-5)  solid2 = 10^(-4)
*/

/*Computation of means*/
lumin1 = mean (of a1-a12); /*computes mean of all conditions with luminance 1
(20,000)*/
lumin2 = mean (of a13-a24); /*computes mean of all conditions with luminance
2 (205,000)*/
lumin3 = mean (of a25-a36); /*computes mean of all conditions with luminance
3 (750,000)*/

posit1 = mean (a1, a2, a3, a4,a5, a6,a13, a14, a15, a16, a17, a18, a25, a26,
a27, a28,a29, a30);
/*computes mean of all conditions with position 1 (0)*/
posit2 = mean (a7, a8, a9, a10, a11, a12, a19, a20, a21, a22, a23, a24, a31,
a32, a33, a34, a35, a36);
/*computes mean of all conditions with position 2 (10)*/

solid1 = mean (a1, a2, a3,a7, a8, a9, a13, a14, a15, a19, a20, a21, a25, a26,
a27, a31, a32, a33);
/*computes mean of all conditions with solid angle 1 (10^-5 sr)*/
solid2 = mean (a4, a5, a6,a10, a11, a12, a16, a17, a18, a22, a23, a24, a28,
a29, a30, a34, a35, a36);
/*computes mean of all conditions with solid angle 2 (10^-4 sr)*/

backs1 = mean (a1, a4, a7, a10, a13, a16, a19, a22, a25, a28, a31, a34);
/*computes mean of all conditions with background luminance 1 (0.03)*/
backs2 = mean (a2, a5, a8, a11, a14, a17, a20, a23, a26, a29, a32, a35);
/*computes mean of all conditions with background luminance 2 (0.3)*/
backs3 = mean (a3, a6, a9, a12, a15, a18, a21, a24, a27, a30, a33, a36);
/*computes mean of all conditions with background luminance 3 (1)*/

lumin1pos1 = mean(a1, a2, a3, a4, a5, a6); /*computes mean of all conditions
with luminance 1 & position1*/
lumin1pos2 = mean(a7, a8, a9, a10, a11, a12);
lumin2pos1 = mean(a13, a14, a15, a16, a17, a18);
lumin2pos2 = mean(a19, a20, a21, a22, a23, a24);
lumin3pos1 = mean(a25, a26, a27, a28, a29, a30);
lumin3pos2 = mean(a31, a32, a33, a34, a35, a36);

lumin1sol1 = mean (a1, a2, a3, a7, a8, a9);
lumin1sol2 = mean (a4, a5, a6, a10, a11, a12);
lumin2sol1 = mean (a13, a14, a15, a19, a20, a21);
lumin2sol2 = mean (a16, a17, a18, a22, a23, a24);
lumin3sol1 = mean (a25, a26, a27, a31, a32, a33);
```

```
lumin3sol2 = mean (a28, a29, a30, a34, a35, a36);

lumin1backs1 = mean (a1, a4, a7, a10);
lumin1backs2 = mean (a2, a5,a8, a11);
lumin1backs3 = mean (a3, a6, a9, a12);
lumin2backs1 = mean (a13, a16, a19, a22);
lumin2backs2 = mean (a14, a17, a20, a23);
lumin2backs3 = mean (a15, a18, a21, a24);
lumin3backs1 = mean (a25, a28, a31, a34);
lumin3backs2 = mean (a26, a29, a32, a35);
lumin3backs3 = mean (a27, a30, a33, a36);

pos1sol1 = mean (a1, a2, a3, a13, a14, a15, a25, a26, a27);
pos1sol2 = mean (a4, a5, a6, a16, a17, a18, a28, a29, a30);
pos2sol1 = mean (a7, a8, a9, a19, a20, a21, a31, a32, a33);
pos2sol2 = mean (a10, a11, a12, a22, a23, a24, a34, a35, a36);

pos1backs1 = mean (a1, a4, a13, a16, a25, a28);
pos1backs2 = mean (a2, a5, a14, a17, a26, a29);
pos1backs3 = mean (a3, a6, a15, a18, a27, a30);
pos2backs1 = mean (a7, a10, a19, a22, a31,a34);
pos2backs2 = mean (a8, a11, a20, a23, a32, a35);
pos2backs3 = mean (a9, a12, a21, a24, a33, a36);

sol1backs1 = mean (a1, a7, a13, a19, a25, a31);
sol1backs2 = mean (a2, a8, a14, a20, a26, a32);
sol1backs3 = mean (a3, a9, a15, a21, a27, a33);
sol2backs1 = mean (a4, a10, a16, a22, a28, a34);
sol2backs2 = mean (a5, a11, a17, a23, a29, a35);
sol2backs3 = mean (a6, a12, a18, a24, a30, a36);

Cards;
1    1    1    0    5    4    5    1    1    0    2    5    2
     4    4    3    6    6    6    4    3    0    5    3    4
     5    4    4    6    6    6    2    3    2    6    6    5
     44
2    1    0    1    3    4    3    2    2    1    2    3    2
     4    3    4    6    6    5    3    3    2    5    4    3
     4    4    4    6    6    5    4    3    3    6    5    4
     32
3    1    1    0    5    3    3    1    2    0    3    2    1
     2    3    1    6    6    5    2    2    3    5    4    4
     5    3    3    6    6    6    4    4    2    5    6    4
     34
4    2    1    2    3    3    3    1    0    1    2    2    2
     1    3    4    5    5    4    2    2    2    4    3    3
     4    4    4    6    6    6    3    2    3    5    5    4
     28
5    1    0    1    3    2    1    0    0    0    1    2    2
     3    4    3    6    5    5    2    2    2    4    4    4
     4    3    5    6    6    6    3    3    2    6    6    5
     40
6    1    1    1    3    2    2    1    1    1    3    3    3
     3    3    2    4    5    4    2    2    1    3    2    3
     3    4    2    6    5    6    2    2    2    4    4    4
     48
```

7	0	0	1	3	4	2	1	0	0	4	2	0
	1	2	0	6	5	6	2	1	0	5	4	4
	5	2	2	6	6	5	2	5	3	6	6	6
	22											
8	1	1	1	3	4	3	3	3	1	4	2	2
	1	3	1	6	5	4	4	2	2	5	3	4
	2	2	2	6	5	4	5	4	4	6	6	5
	24											
9	0	1	0	3	2	3	2	1	1	5	3	2
	4	4	2	6	5	5	3	3	0	6	4	2
	5	4	0	5	6	6	4	2	2	6	6	4
	24											
10	0	0	0	3	0	0	0	0	0	1	0	0
	0	0	0	4	4	2	0	0	0	4	4	2
	4	2	0	6	4	5	4	3	2	6	6	6
	26											
11	1	0	2	2	2	1	1	1	0	3	3	3
	4	2	3	5	6	4	3	2	1	4	5	3
	5	5	3	6	6	5	4	5	4	6	6	5
	44											
12	2	0	1	4	3	4	2	0	0	3	2	0
	4	3	1	6	5	6	3	2	3	5	3	4
	6	5	3	6	6	6	4	2	2	6	5	5
	20											
13	1	0	2	3	2	2	1	0	0	3	3	1
	2	2	3	6	4	5	2	3	3	5	4	4
	4	4	4	6	6	6	4	4	4	5	6	6
	42											
14	1	0	1	3	3	4	1	0	0	3	3	2
	3	1	0	5	5	4	5	2	2	6	6	5
	5	3	3	6	6	6	4	3	2	6	6	6
	59											
15	1	1	1	3	3	2	1	1	1	2	2	1
	2	3	1	6	4	4	4	2	2	4	3	3
	3	3	3	6	6	6	3	5	2	5	5	5
	42											
16	3	3	2	5	3	3	2	2	2	4	4	3
	4	4	3	5	5	4	3	4	2	5	4	4
	5	5	5	6	5	5	5	4	4	6	5	5
	51											
17	3	1	1	6	4	3	2	1	1	3	2	1
	5	5	2	6	6	5	4	1	1	5	5	4
	6	2	4	6	6	5	4	2	2	5	6	5
	41											
18	1	1	0	5	3	2	1	2	1	2	2	3
	3	2	3	6	6	6	3	2	0	5	4	4
	5	3	4	6	5	5	4	4	4	4	5	6
	37											
19	2	1	0	5	3	3	4	2	1	5	4	1
	4	4	5	6	5	5	5	3	3	6	6	4
	5	5	5	6	6	6	5	5	4	6	6	6
	23											
20	2	2	1	4	3	4	2	2	2	3	4	2
	4	3	2	6	6	6	3	1	3	5	5	4
	4	5	3	6	6	6	4	4	4	6	6	5
	43											

21	0	0	0	3	2	2	0	0	0	2	2	1
	2	3	1	5	4	4	2	2	1	5	4	4
	4	2	2	6	6	6	4	3	3	5	5	4
	52											
22	1	1	0	3	2	2	3	2	1	3	4	4
	3	3	2	6	6	4	3	4	1	5	5	4
	3	2	2	6	6	6	5	5	4	6	6	5
	40											
23	1	1	1	4	3	2	1	1	0	1	1	1
	3	2	2	5	5	5	1	1	1	2	2	2
	4	3	3	6	6	5	2	1	1	4	4	4
	55											
24	1	1	0	4	3	2	1	0	1	2	3	1
	3	2	2	6	4	5	4	2	0	4	5	3
	4	3	1	6	6	5	4	4	2	4	4	4
	34											
25	2	0	0	3	4	5	2	2	1	4	3	2
	5	3	2	6	5	5	5	4	1	6	5	4
	5	4	4	6	6	6	5	3	3	6	6	5
	55											
26	2	1	1	3	2	2	1	0	0	3	2	1
	1	1	1	5	3	5	4	2	2	3	5	4
	4	3	2	6	6	5	4	2	2	5	4	4
	43											
27	1	2	2	4	3	4	3	1	2	4	3	3
	4	3	2	5	6	6	2	3	3	5	5	5
	5	5	5	6	6	6	3	4	3	5	5	5
	32											
28	0	0	0	3	0	0	0	0	0	0	0	0
	2	0	0	6	4	3	1	1	0	6	5	4
	2	5	2	6	6	5	4	4	1	6	6	6
	28											
29	2	2	2	3	3	3	3	3	2	3	3	3
	3	3	3	5	5	4	4	3	3	5	4	5
	5	4	3	6	6	6	4	4	3	6	5	5
	28											
30	1	0	0	2	1	1	0	0	0	1	1	0
	3	1	3	6	5	5	0	2	0	5	3	4
	2	3	4	6	6	5	3	2	1	6	5	5
	38											
31	2	2	1	3	3	2	2	2	0	3	1	3
	4	3	3	6	6	6	4	3	4	4	5	3
	6	5	4	6	6	6	5	4	2	6	6	5
	60											
32	2	2	2	4	4	3	2	3	2	4	3	3
	4	4	3	6	6	5	3	3	3	5	5	4
	6	4	4	6	6	6	6	4	4	6	6	5
	30											
33	2	0	0	5	2	2	0	1	0	5	4	2
	6	3	2	6	6	4	3	0	0	6	6	5
	5	4	4	6	6	6	4	4	4	6	5	5
	24											
34	1	1	1	4	3	4	1	1	1	2	1	2
	2	2	1	5	5	5	2	1	2	4	4	4
	3	4	2	6	6	6	3	3	2	5	4	5
	48											

```
35      2       2       1       3       2       2       2       1       1       3       3       2
        4       2       2       6       5       4       3       3       2       5       4       4
        4       4       3       6       6       6       4       3       3       6       5       4
        43
36      1       2       1       4       3       4       2       2       1       3       3       3
        3       2       2       6       6       5       5       3       3       6       5       5
        3       4       4       6       6       6       4       4       4       6       5       6
        28
37      1       0       3       4       3       3       1       1       0       2       2       1
        4       2       2       6       5       5       1       2       3       4       2       2
        5       5       4       6       6       6       3       4       3       6       5       5
        45
38      2       1       1       3       2       2       2       1       1       3       3       2
        4       2       3       5       4       5       2       2       2       4       3       3
        4       4       5       6       6       6       4       2       3       6       6       4
        38
39      3       2       3       4       5       4       3       3       2       4       5       4
        5       3       4       6       6       6       5       3       3       6       6       5
        5       5       6       6       6       6       5       6       5       6       6       6
        76
40      0       1       0       3       2       2       2       1       0       3       3       2
        2       1       1       5       5       3       2       3       2       5       4       3
        4       3       3       6       6       5       3       2       3       6       5       4
        60
41      0       1       1       4       3       2       1       2       2       3       3       3
        1       2       1       4       4       4       2       3       2       4       4       4
        4       2       3       6       6       5       3       3       3       5       5       4
        20
42      0       0       0       4       1       0       0       0       0       1       0       1
        0       0       0       5       2       2       3       1       1       5       3       3
        3       3       0       6       6       5       3       1       2       6       6       5
        61
43      3       0       1       3       3       2       0       0       1       3       3       2
        0       2       3       6       4       4       3       0       0       1       3       4
        5       0       3       6       6       4       3       1       2       5       5       0
        57
44      2       2       2       1       1       1       2       1       1       3       2       2
        4       3       2       4       6       5       2       3       2       3       4       4
        5       4       2       5       6       6       3       3       2       5       5       4
        41
45      2       1       1       3       1       1       2       1       0       4       3       2
        3       3       3       6       5       3       4       2       3       5       5       3
        4       4       3       6       5       6       5       4       3       6       5       5
        30
46      3       1       2       3       2       2       2       1       1       3       2       2
        4       4       4       5       5       5       4       3       3       6       3       4
        6       5       4       6       5       6       5       4       3       6       5       5
        33
47      1       0       0       1       1       1       1       1       0       3       2       2
        2       3       1       6       5       5       3       3       2       5       4       5
        3       4       3       6       6       6       4       3       2       6       6       5
        22
;;

proc print data=MAIN;
run;
```

```
proc means data = MAIN var;
var a1-a36;
run;

proc means data = MAIN;
var age
lumin1 lumin2 lumin3
posit1 posit2
solid1 solid2
backs1 backs2 backs3
lumin1pos1 lumin1pos2 lumin2pos1 lumin2pos2 lumin3pos1 lumin3pos2
lumin1sol1 lumin1sol2 lumin2sol1 lumin2sol2 lumin3sol1 lumin3sol2
lumin1backs1 lumin1backs2 lumin1backs3
lumin2backs1 lumin2backs2 lumin2backs3
lumin3backs1 lumin3backs2 lumin3backs3
pos1sol1 pos1sol2 pos2sol1 pos2sol2
pos1backs1 pos1backs2 pos1backs3 pos2backs1 pos2backs2 pos2backs3
sol1backs1 sol1backs2 sol1backs3 sol2backs1 sol2backs2 sol2backs3;
run;

/*It allows to check confidence interval - standard error*1.96 = margin of
error */
proc surveymeans data = MAIN;
var a1-a36;
run;
proc surveymeans data = MAIN;
var age
lumin1 lumin2 lumin3
posit1 posit2
solid1 solid2
backs1 backs2 backs3;
run;

proc glm data=MAIN;
model a1-a36 = /nouni;
repeated luminance 3 polynomial, position 2 polynomial, solidangle 2
polynomial, backgroundlum 3 polynomial/nom summary;
run;
```

Appendix S - Step-by-step calculations of discomfort glare for the 36 lighting conditions using the applicable metrics

Table S1. Metric 1 - Outdoor sports and area lighting metric (CIE 112-1994)

Equation	**Glare rating (GR)** $GR = 27 + 24\log(\frac{L_{vl}}{L_{ve}^{0.9}})$
Components of the equation	$L_{vl} = 10\sum_{i=1}^{n}\frac{E_{glare,i}}{\theta_i^2}$ L_{vl} is the equivalent veiling luminance produced by the luminaires, in cd/m^2; E_{glare} is the illuminance at the observer's eyes in a plane perpendicular to the line of sight, produced by the i-th glare source, in lx; θ is the angle of displacement of the glare source from the observer's line of sight, in degrees; n is the total number of glare sources. $L_{ve} = 0.035 \times L_{f,av}$ L_{ve} is the equivalent veiling luminance from the environment, in cd/m^2; $L_{f,av}$ is the average field luminance, in cd/m^2;
Subjective scale	90 unbearable 80 70 disturbing 60 50 just admissible 40 30 noticeable 20 10 unnoticeable
Validity/limitations	Restricted to viewing directions below eye level (CIE 112-1994). The angular displacement is limited to 1.5˚ <θ < 60˚ (CIE 112-1994). L_{ve} = (0.02-5) cd/m^2 (Tekelenburg 1982, Van Bommel et al. 1983). L_{vl} = (0.02-20) cd/m^2 (Tekelenburg 1982, Van Bommel et al. 1983). Viewing directions from the luminaire position were within 10˚ - 90˚ in the studies that lead to the CIE standard development (Tekelenburg 1982, Van Bommel et al. 1983).

The first row in tables S2, S4, S6, and S8 in Appendix S show the validity range/limitations of the metric discussed. The second row of the table shows the parameters of the discomfort glare equation.

Equation parameters and calculations in table S2

E_{glare}, lx is the measured direct component of illuminance from the glare source at the center of the chinrest (between the eyes). It was averaged for the measurements taken during 4/26/2015-5/16/2015.

θ, degrees is the angle between the fixation point and the glare source.

L_b, cd/m^2 is the measured background luminance created by the source above the subject's head. It was averaged for the measurements taken during 4/11/2015-5/16/2015.

GR becomes infinitely large, when θ=0˚ is used. This value was substituted with 1'=0.017˚ for calculation of GR, as shown in the "SUBSTITUTED θ, degrees" column.

Some values in L_{ve} and L_{vl} columns fall outside of the validity ranges as specified by the studies that led to the metric development (Tekelenburg 1982, Bommel et al. 1983). They are shown in *cursive*.

The GR calculated for each lighting condition is shown in the last column of the table.

Table S2. Calculations of GR and its parameters as defined by CIE 112-1994

Validity range/ limitations		Viewing directions below eye level; (1.5-60) degrees			(0.02-5) cd/m^2	(0.02-20) cd/m^2	(10 - 90)
Condition (scenario) #	**E_{glare}, lx**	**θ, degrees**	**L_b, cd/m^2**	**SUBSTITUTED θ, degrees**	**L_{ve}, cd/m^2**	**L_{vl}, cd/m^2**	**GR**
1	0.16	0	0.037	0.017	*0.001*	*5449.83*	***179***
2	0.16	0	0.344	0.017	*0.012*	*5449.83*	***158***
3	0.16	0	1.156	0.017	0.040	*5449.83*	***147***
4	1.97	0	0.037	0.017	*0.001*	*68166.09*	***205***
5	1.97	0	0.344	0.017	*0.012*	*68166.09*	***184***
6	1.97	0	1.156	0.017	0.040	*68166.09*	***173***
7	0.21	10	0.037		*0.001*	0.02	**49**
8	0.21	10	0.344		*0.012*	0.02	**28**

9	0.21	10	1.156		0.040	0.02	**17**
10	2.40	10	0.037		*0.001*	0.24	**74**
11	2.40	10	0.344		*0.012*	0.24	**54**
12	2.40	10	1.156		0.040	0.24	**42**
13	1.89	0	0.037	0.017	*0.001*	*65397.92*	***205***
14	1.89	0	0.344	0.017	*0.012*	*65397.92*	***184***
15	1.89	0	1.156	0.017	0.040	*65397.92*	***173***
16	22.62	0	0.037	0.017	*0.001*	*782525.95*	***231***
17	22.62	0	0.344	0.017	*0.012*	*782525.95*	***210***
18	22.62	0	1.156	0.017	0.040	*782525.95*	***199***
19	1.92	10	0.037		*0.001*	0.19	**72**
20	1.92	10	0.344		*0.012*	0.19	**51**
21	1.92	10	1.156		0.040	0.19	**40**
22	22.31	10	0.037		*0.001*	2.23	***98***
23	22.31	10	0.344		*0.012*	2.23	**77**
24	22.31	10	1.156		0.040	2.23	**65**
25	6.86	0	0.037	0.017	*0.001*	*237283.74*	***218***
26	6.86	0	0.344	0.017	*0.012*	*237283.74*	***197***
27	6.86	0	1.156	0.017	0.040	*237283.74*	***186***
28	81.48	0	0.037	0.017	*0.001*	*2819204.15*	***244***
29	81.48	0	0.344	0.017	*0.012*	*2819204.15*	***223***
30	81.48	0	1.156	0.017	0.040	*2819204.15*	***212***
31	6.67	10	0.037		*0.001*	0.67	**85**
32	6.67	10	0.344		*0.012*	0.67	**64**
33	6.67	10	1.156		0.040	0.67	**53**
34	77.45	10	0.037		*0.001*	7.75	***111***
35	77.45	10	0.344		*0.012*	7.75	**90**
36	77.45	10	1.156		0.040	7.75	**78**

Table S3. Metric 2 - Motor vehicle lighting (Schmidt-Clausen and Bindels 1974)

Equation	**Discomfort glare rating (W)** $W = 5 - 2log \frac{E_{glare}}{0.003\left[1+\sqrt{\frac{L_{adap}}{0.04}}\right]\cdot\theta^{0.46}}$
Components of the equation	W is the discomfort glare rating on a 9-point scale (smaller numbers mean more discomfort); E_{glare} is the glare illuminance at the eyes, in lx; L_{adap} is the adaptation luminance, in cd/m^2; θ is the angle between the direction of viewing and the direction of the glare source, in min. arc;
Subjective scale	**ORIGINAL** / **INVERTED** Unbearable 1 / Noticeable 1 2 / 2 Disturbing 3 / Acceptable 3 4 / 4 Just admissible 5 / Just admissible 5 6 / 6 Acceptable 7 / Disturbing 7 8 / 8 Noticeable 9 / Unbearable 9
Validity/limitations	The authors investigated discomfort glare in the following ranges. E_{glare} = 0.0025-6.9 lx, L_{adap}=0.0015-2 cd/m^2, θ = 10'-90˚. The glare source subtended an angle of 8' at the observer's eyes (equivalent to the diameter of 24 cm at the distance of 100 m). The sky was considered to be black.

Equation parameters and calculations in table S4

E_{glare}, lx is the measured direct component of illuminance from the glare source at the center of the chinrest (between the eyes). It was averaged for the measurements taken during 4/26/2015-5/16/2015.

L_{adap}, cd/m^2 is the measured background luminance created by the source above the subject's head. It was averaged for the measurements taken during 4/11/2015-5/16/2015.

θ, minutes of arc is the angle between the fixation point and the glare source.

Discomfort glare rating (W) becomes infinitely large, when θ=0’ is used. This value was substituted with 1’ for the calculation of W, as shown in the “SUBSTITUTED θ, min” column.

Some values in the E_{glare} column fall outside of the ranges used in the experiment for developing this metric. They are shown in *cursive*.

The calculated W for each lighting condition is shown in the second to last column in the table. Values smaller than 1 fall outside of the predefined subjective scale range for this metric (1-9) and are shown *in cursive*.

The calculated W has an inverted scale as compared to the subjective scale used in the current study (lower number means more glare in this W metric). For the ease of the comparison, the scale W was inverted by subtracting the resulting number as calculated by this metric from the number 10. Now, higher ratings for both W and subjective responses in this study mean more glare.

Table S4. Calculations of W and its components as defined by Schmidt-Clausen and Bindels 1974

Validity range/ limitations	0.0025-6.9 lx	0.0015-2 cd/m^2		10'-90˚	(1(max glare) - 9)	(1 – 9(max glare))
Condition (scenario) #	**E_{glare}, lx**	**L_{adap}, cd/m^2**	**θ, min**	**SUBSTITUTE D θ, min**	**W**	**W inverted scale**
1	0.16	0.037	0	1	2.1	**7.9**
2	0.16	0.344	0	1	2.7	**7.3**
3	0.16	1.156	0	1	3.2	**6.8**
4	1.97	0.037	0	1	*0.0*	***10.0***
5	1.97	0.344	0	1	*0.6*	***9.4***
6	1.97	1.156	0	1	1.0	**9.0**
7	0.21	0.037	600		4.5	**5.5**
8	0.21	0.344	600		5.1	**4.9**
9	0.21	1.156	600		5.5	**4.5**
10	2.40	0.037	600		2.3	**7.7**
11	2.40	0.344	600		2.9	**7.1**
12	2.40	1.156	600		3.4	**6.6**
13	1.89	0.037	0	1	*0.0*	***10.0***

14	1.89	0.344	0	1	*0.6*	***9.4***
15	1.89	1.156	0	1	1.0	**9.0**
16	*22.62*	0.037	0	1	*-2.2*	***12.2***
17	*22.62*	0.344	0	1	*-1.6*	***11.6***
18	*22.62*	1.156	0	1	*-1.1*	***11.1***
19	1.92	0.037	600		2.5	**7.5**
20	1.92	0.344	600		3.1	**6.9**
21	1.92	1.156	600		3.6	**6.4**
22	*22.31*	0.037	600		*0.4*	***9.6***
23	*22.31*	0.344	600		1.0	**9.0**
24	*22.31*	1.156	600		1.4	**8.6**
25	6.86	0.037	0	1	*-1.1*	***11.1***
26	6.86	0.344	0	1	*-0.5*	***10.5***
27	6.86	1.156	0	1	*-0.1*	***10.1***
28	*81.48*	0.037	0	1	*-3.3*	***13.3***
29	*81.48*	0.344	0	1	*-2.7*	***12.7***
30	*81.48*	1.156	0	1	*-2.3*	***12.3***
31	6.67	0.037	600		1.5	**8.5**
32	6.67	0.344	600		2.1	**7.9**
33	6.67	1.156	600		2.5	**7.5**
34	*77.45*	0.037	600		*-0.7*	***10.7***
35	*77.45*	0.344	600		*-0.1*	***10.1***
36	*77.45*	1.156	600		*0.3*	***9.7***

Table S5. Metric 3 – Bullough's et al. formulas (2008, 2011). Combination of two formulas

Equation	**De Boer rating (DB)** $\mathbf{DB = 6.6 - 6.4logDG}$ **(2008)** For GS of the angular size of 0.3º or more: **DB=6.6-6.4logDG+1.4log(50,000/L_L) (2011)**
Components of the equation	DB – the De Boer discomfort glare rating (smaller numbers mean more discomfort). $\mathbf{DG = log(E_l + E_s) + 0.6\,log\left(\frac{E_l}{E_s}\right) - 0.5log(E_a)}$ E_a is the ambient illuminance, in lx, it is a vertical illuminance at the subject's viewing location (light source switched off); E_l is the vertical illuminance from the light source at the subject's viewing location, in lx (h=1.5m) (direct illuminance from the light source); E_s is the surround illuminance, in lx (the total illuminance at the subjects' eyes minus E_l and E_a, i.e. illuminance at the eyes received from a light source after being reflected or scattered).
Subjective scale	**ORIGINAL** / **INVERTED** Unbearable 1 / Just noticeable 1 2 / 2 Disturbing 3 / Satisfactory 3 4 / 4 Just permissible 5 / Just permissible 5 6 / 6 Satisfactory 7 / Disturbing 7 8 / 8 Just noticeable 9 / Unbearable 9
Validity/limitations	The authors developed the metric in the following ranges of variables. E_l=0.1-113.3 lx, E_s = 0.01-0.4 lx, E_a=0.01-1.6, L_l=5,300-196,000 cd/m^2, viewing distance 3-20 m.

Equation parameters and calculations in table S6 parts 1 and 2

E_l, lx is the measured direct component of illuminance from the glare source at the center of the chinrest (between the eyes). It was averaged for the measurements taken during 4/26/2015-5/16/2015. It is the same as E_{glare} in the previous two DG models – outdoor sports and area lighting and motor vehicle lighting models.

E_s, lx is the surround illuminance, the illuminance at the eyes received from a light source after being reflected. There are two columns with E_s in the table S6 part 1, one has the calculated value (E_s=E_{total}-E_a-E_l), and the other one has the measured value that was averaged for 4/26/2015-5/16/2015. E_s - calculated resulted in the negative numbers for certain scenarios due to a potential aggregated measuring error of its components (shown in *cursive*). Therefore, E_s - measured was used for the final calculation of the discomfort glare prediction.

E_a, lx is the measured ambient illuminance and averaged for the measurements taken during 4/26/2015-5/16/2015. It was created with the source above the subject's head. Some values fall outside of the validity ranges, shown in *cursive*.

L_l, cd/m^2 is the measured luminance of the glare source at both positions 0˚ and 10˚. It was averaged for the measurements taken during 4/11/2015-5/16/2015. Some values fall outside of the validity ranges, shown in *cursive*.

E_{total}, lx is the measured total illuminance at the center of the chinrest (between the subject's eyes). It was averaged for the measurements taken during 4/26/2015-5/16/2015.

The intermediate step of discomfort glare calculation resulted in the negative numbers for the DG component (numbers in *cursive* in the DG (with measured E_s) column). This means that for those lighting conditions it is impossible to calculate glare, because logarithm - which is used in the calculation of DB - of a negative number is not defined. What would be a meaningful substitution in this case? All numbers should be transformed into a new set of numbers by performing the same mathematical operation in order to maintain the relative nature between the amount of discomfort glare experienced. The subjective scales are arbitrary. What is important is to preserve the relative nature between the assessments. Even in the CIE 112 (1994) technical report, it is indicated that the scale's purpose is not to specify the glare restriction limits, but to offer insight into the practical meaning of differences in glare ratings for evaluation purposes. It makes it possible to find out how much more or less glare one lighting condition creates as compared to the other. Therefore, the investigator decided to add a constant to all values to make them positive (DG (with measured Es)+(const=1) column).

Bullough found out that for a light source of the angular size of 0.3º or more the glare model includes luminance of the light source (L_L) in its equation (version 2011). Since in this discomfort glare study light source has two levels of the solid angle 10^{-4} sr = 0.64˚ and 10^{-5}sr = 0.2˚, therefore, two versions of the equations were used to predict discomfort glare from RPI's equations. Discomfort glare for lighting conditions where glare sources had a solid angle of 10^{-5} sr was calculated using 2008 equation, for glare sources of 10^{-4} sr 2011 equation was used. The columns 2 and 3 of the table S6 part 2 show calculations of DG by RPI's 2008 and 2011 metrics respectively. The numbers that are valid for this study are shown in bold in those columns.

The second to last column in table S6 part 2 shows the combination of calculations by both equations, and the last column shows the final inverted scale of DB.

Table S6. Part 1. Calculations of DB and its components as defined by Bullough et al. 2008&2011

Validity range/ limitations	0.1 to 113.3 lx	0.01-0.4 lx	0.01-0.4 lx	0.01-1.6 lx	5,300-196,000	Viewing distance 3 - 20, m		
Condition (scenario) #	**El, lx**	**E_s (calculated), lx**	**E_s (measured), lx**	**E_a, lx**	**L_l, cd/m^2**	**E_{total}, lx**	**DG (with measured E_s)**	**DG (with measured E_s) + (const=1)**
1	0.16	0.02	0.02	0.11	20,477	0.29	0.27	1.27
2	0.16	0.05	0.02	1.00	20,477	1.22	*-0.21*	0.79
3	0.16	0.21	0.02	*3.58*	20,477	3.95	*-0.49*	0.51
4	1.97	0.05	0.02	0.11	20,477	2.13	1.97	2.97
5	1.97	0.12	0.02	1.00	20,477	3.10	1.49	2.49
6	1.97	0.24	0.02	*3.58*	20,477	5.79	1.22	2.22
7	0.21	0.02	0.02	0.11	23,460	0.34	0.44	1.44
8	0.21	0.09	0.02	1.00	23,460	1.30	*-0.04*	0.96
9	0.21	0.20	0.02	*3.58*	23,460	3.98	*-0.32*	0.68
10	2.40	0.03	0.02	0.11	23,460	2.54	2.11	3.11
11	2.40	0.10	0.02	1.00	23,460	3.50	1.63	2.63
12	2.40	0.21	0.02	*3.58*	23,460	6.19	1.35	2.35
13	1.89	0.02	0.02	0.11	*213,417*	2.02	1.95	2.95
14	1.89	0.10	0.02	1.00	*213,417*	2.99	1.47	2.47
15	1.89	0.20	0.02	*3.58*	*213,417*	5.67	1.19	2.19
16	22.62	0.19	0.03	0.11	*213,417*	22.92	3.56	4.56
17	22.62	0.26	0.03	1.00	*213,417*	23.88	3.08	4.08

18	22.62	0.37	0.03	*3.58*	*213,417*	26.56	2.80	3.80
19	1.92	0.01	0.02	0.11	*221,580*	2.05	1.96	2.96
20	1.92	0.07	0.02	1.00	*221,580*	3.00	1.48	2.48
21	1.92	0.19	0.02	*3.58*	*221,580*	5.69	1.20	2.20
22	22.31	*-0.05*	0.02	0.11	*221,580*	22.38	3.66	4.66
23	22.31	0.02	0.02	1.00	*221,580*	23.34	3.18	4.18
24	22.31	0.13	0.02	*3.58*	*221,580*	26.02	2.90	3.90
25	6.86	0.03	0.02	0.11	*760,733*	7.00	2.84	3.84
26	6.86	0.06	0.02	1.00	*760,733*	7.92	2.36	3.36
27	6.86	0.15	0.02	*3.58*	*760,733*	10.58	2.08	3.08
28	81.48	*-0.14*	0.06	0.11	*760,733*	81.45	4.29	5.29
29	81.48	*-0.15*	0.06	1.00	*760,733*	82.33	3.81	4.81
30	81.48	*-0.10*	0.06	*3.58*	*760,733*	84.95	3.54	4.54
31	6.67	0.00	0.02	0.11	*766,440*	6.78	2.82	3.82
32	6.67	0.03	0.02	1.00	*766,440*	7.70	2.34	3.34
33	6.67	0.11	0.02	*3.58*	*766,440*	10.35	2.06	3.06
34	77.45	*-0.09*	0.03	0.11	*766,440*	77.48	4.39	5.39
35	77.45	*-0.13*	0.03	1.00	*766,440*	78.33	3.91	4.91
36	77.45	*-0.03*	0.03	*3.58*	*766,440*	81.00	3.64	4.64

Table S6. Part 2. Calculations of DB and its components as defined by Bullough et al. 2008&2011

Validity range/ limitations	Only conditions that had GS of 10^-5 sr are valid from this column	Only conditions that had GS of 10^-4 sr are valid from this column	(1(max glare)-9)	(1-9(max glare))
Condition (scenario) #	**DB (2008) (from DG E_s meas. + (const=1))**	**DB (2011) (from DG E_s meas. + (const=1))**	**DB (combination of 2008 & 2011)**	**DB, inverted scale**
1	**5.94**	6.49	5.94	**4.06**
2	**7.27**	7.81	7.27	**2.73**

3	**8.47**	9.01	8.47	**1.53**
4	3.57	**4.11**	4.11	**5.89**
5	4.06	**4.60**	4.60	**5.40**
6	4.39	**4.93**	4.93	**5.07**
7	**5.59**	6.05	5.59	**4.41**
8	**6.72**	7.18	6.72	**3.28**
9	**7.66**	8.12	7.66	**2.34**
10	3.45	**3.91**	3.91	**6.09**
11	3.91	**4.37**	4.37	**5.63**
12	4.22	**4.68**	4.68	**5.32**
13	**3.60**	2.71	3.60	**6.40**
14	**4.09**	3.21	4.09	**5.91**
15	**4.42**	3.54	4.42	**5.58**
16	2.38	**1.50**	1.50	**8.50**
17	2.69	**1.81**	1.81	**8.19**
18	2.89	**2.00**	2.00	**8.00**
19	**3.59**	2.68	3.59	**6.41**
20	**4.08**	3.17	4.08	**5.92**
21	**4.41**	3.50	4.41	**5.59**
22	2.32	**1.42**	1.42	**8.58**
23	2.63	**1.72**	1.72	**8.28**
24	2.82	**1.91**	1.91	**8.09**
25	**2.86**	1.21	2.86	**7.14**
26	**3.23**	1.58	3.23	**6.77**
27	**3.47**	1.82	3.47	**6.53**
28	1.97	**0.31**	*0.31*	***9.69***
29	2.23	**0.58**	*0.58*	***9.42***
30	2.40	**0.74**	*0.74*	***9.26***
31	**2.88**	1.22	2.88	**7.12**

32	**3.25**	1.59	3.25	**6.75**
33	**3.49**	1.83	3.49	**6.51**
34	1.92	**0.26**	*0.26*	***9.74***
35	2.17	**0.51**	*0.51*	***9.49***
36	2.34	**0.68**	*0.68*	***9.32***

Table S7. Metric 4 - UGR extension for small sources (CIE146-147 2002)

Equation	**Unified Glare Rating (UGRs) small source extension** $\mathbf{UGRs = 8log \cdot [\frac{0.25}{L_b} \cdot \sum \frac{200 \cdot I^2}{R^2 p^2}]}$
Components of the equation	L_b is the background luminance, in cd/m2; I is the luminous intensity, in cd; p is the Guth position index for each luminaire (displacement from the line of sight); r is the distance from the observer to the center of the luminous parts of the luminaire, in m.
Subjective scale	(Mistrick and Choi 1999) 10 – imperceptible 16 – perceptible 19 – just acceptable 22 – unacceptable 25 – just uncomfortable 28 – uncomfortable 31 – just intolerable
Validity/limitations	Restricted to sources more than 5 degrees off the line of sight, at interior lighting distances. For the UGR small extension – projected area of 0.005 m^2 is accepted. Glare from small sources is determined by their intensity (I) towards the eye.

Equation parameters and calculations in table S8

L_b, cd/m^2 is the measured background luminance created by the source above the subject's head. It was averaged for the measurements taken during 4/11/2015-5/16/2015.

R, m is the measured distance between the glare source and the subject's eyes.

A, m^2 is the area of the glare source that was calculated from the measured diameter.

L_l, cd/m^2 is the measured luminance of the glare source at both positions 0˚ and 10˚. It was averaged for the measurements taken during 4/11/2015-5/16/2015.

I, cd is the calculated luminous intensity of the glare source towards the eyes based on the actual luminance and area.

P is the position index acquired from the CIE 117-1995 technical report. It was interpolated for the glare source position of 10˚.

UGRs is the calculated discomfort glare as predicted by the UGR small extension equation. Some values exceed predefined maximum of the scale (30).

Table S8. Calculations of discomfort glare using the UGR small source extension

Condition (scenario) #	L_b, cd/m^2	R, m	A, m^2	L_{ls}, cd/m^2	I (calculated), cd	Position index	UGRs
1	0.037	0.997	0.000010	20,477	0.20	1	**14.0**
2	0.344	0.997	0.000010	20,477	0.20	1	**6.3**
3	1.156	0.997	0.000010	20,477	0.20	1	**2.1**
4	0.037	0.997	0.000100	20,477	2.05	1	**30.0**
5	0.344	0.997	0.000100	20,477	2.05	1	**22.3**
6	1.156	0.997	0.000100	20,477	2.05	1	**18.1**
7	0.037	0.997	0.000010	23,460	0.23	1.467	**12.3**
8	0.344	0.997	0.000010	23,460	0.23	1.467	**4.6**
9	1.156	0.997	0.000010	23,460	0.23	1.467	**0.4**
10	0.037	0.997	0.000100	23,460	2.35	1.467	**28.3**
11	0.344	0.997	0.000100	23,460	2.35	1.467	**20.6**
12	1.156	0.997	0.000100	23,460	2.35	1.467	**16.4**
13	0.037	0.997	0.000010	213,417	2.14	1	***30.3***
14	0.344	0.997	0.000010	213,417	2.14	1	**22.6**
15	1.156	0.997	0.000010	213,417	2.14	1	**18.4**
16	0.037	0.997	0.000100	213,417	21.37	1	***46.3***
17	0.344	0.997	0.000100	213,417	21.37	1	***38.6***
18	1.156	0.997	0.000100	213,417	21.37	1	***34.4***
19	0.037	0.997	0.000010	221,580	2.22	1.467	**27.9**
20	0.344	0.997	0.000010	221,580	2.22	1.467	**20.2**
21	1.156	0.997	0.000010	221,580	2.22	1.467	**16.0**
22	0.037	0.997	0.000100	221,580	22.18	1.467	***43.9***
23	0.344	0.997	0.000100	221,580	22.18	1.467	***36.2***
24	1.156	0.997	0.000100	221,580	22.18	1.467	***32.0***
25	0.037	0.997	0.000010	760,733	7.61	1	***39.1***

26	0.344	0.997	0.000010	760,733	7.61	1	***31.4***
27	1.156	0.997	0.000010	760,733	7.61	1	**27.2**
28	0.037	0.997	0.000100	760,733	76.16	1	***55.1***
29	0.344	0.997	0.000100	760,733	76.16	1	***47.4***
30	1.156	0.997	0.000100	760,733	76.16	1	***43.2***
31	0.037	0.997	0.000010	766,440	7.67	1.467	***36.5***
32	0.344	0.997	0.000010	766,440	7.67	1.467	**28.8**
33	1.156	0.997	0.000010	766,440	7.67	1.467	**24.6**
34	0.037	0.997	0.000100	766,440	76.73	1.467	***52.5***
35	0.344	0.997	0.000100	766,440	76.73	1.467	***44.8***
36	1.156	0.997	0.000100	766,440	76.73	1.467	***40.6***

Appendix T - SAS Command File for the Correlation analysis of four applicable metrics with Subjective Responses collected in this study

The output file is not printed here due to its large size.

```
data BESTm;
Input condition subj1-subj47 metric1 metric2 metric3 metric4;
/*EXCLUDED 9 subjects (problematic eye tracking data)

  metric 1 - the outdoor sports and area lighting 10-90;
  metric 2 - the motor vehicle lighting INVERTED 1(min)-9(max);
  metric 3 - Bullough's et al. combo of 2008&2011 INVERTED 1(min)-9(max) ;
  metric 4 - the UGR small source extension 10-30*/
Cards;
1     1     1     1     2     1     1     0     1     0     0     1     2
      1     1     1     3     3     1     2     2     0     1     1     1
      2     2     1     0     2     1     2     2     2     1     2     1
      1     2     3     0     0     0     3     2     2     3     1     179
      7.9   4.1   14.0
2     1     0     1     1     0     1     0     1     1     0     0     0
      0     0     1     3     1     1     1     2     0     1     1     1
      0     1     2     0     2     0     2     2     0     1     2     2
      0     1     2     1     1     0     0     2     1     1     0     158
      7.3   2.7   6.3
3     0     1     0     2     1     1     1     1     0     0     2     1
      2     1     1     2     1     0     0     1     0     0     1     0
      0     1     2     0     2     0     1     2     0     1     1     1
      3     1     3     0     1     0     1     2     1     2     0     147
      6.8   1.5   2.1
4     5     3     5     3     3     3     3     3     3     3     2     4
      3     3     3     5     6     5     5     4     3     3     4     4
      3     3     4     3     3     2     3     4     5     4     3     4
      4     3     4     3     4     4     3     1     3     3     1     205
      10.0  5.9   30.0
5     4     4     3     3     2     2     4     4     2     0     2     3
      2     3     3     3     4     3     3     3     2     2     3     3
      4     2     3     0     3     1     3     4     2     3     2     3
      3     2     5     2     3     1     3     1     1     2     1     184
      9.4   5.4   22.3
6     5     3     3     3     1     2     2     3     3     0     1     4
      2     4     2     3     3     2     3     4     2     2     2     2
      5     2     4     0     3     1     2     3     2     4     2     4
      3     2     4     2     2     0     2     1     1     2     1     173
      9.0   5.1   18.1
7     1     2     1     1     0     1     1     3     2     0     1     2
      1     1     1     2     2     1     4     2     0     3     1     1
      2     1     3     0     3     0     2     2     0     1     2     2
      1     2     3     2     1     0     0     2     2     2     1     49
      5.5   4.4   12.3
8     1     2     2     0     0     1     0     3     1     0     1     0
      0     0     1     2     1     2     2     2     0     2     1     0
      2     0     1     0     3     0     2     3     1     1     1     2
      1     1     3     1     2     0     0     1     1     1     1     28
      4.9   3.3   4.6
9     0     1     0     1     0     1     0     1     1     0     0     0
      0     0     1     2     1     1     1     2     0     1     0     1
```

	1	0	2	0	2	0	0	2	0	1	1	1
	0	1	2	0	2	0	1	1	0	1	0	17
	4.5	2.3	0.4									
10	2	2	3	2	1	3	4	4	5	1	3	3
	3	3	2	4	3	2	5	3	2	3	1	2
	4	3	4	0	3	1	3	4	5	2	3	3
	2	3	4	3	3	1	3	3	4	3	3	74
	7.7	6.1	28.3									
11	5	3	2	2	2	3	2	2	3	0	3	2
	3	3	2	4	2	2	4	4	2	4	1	3
	3	2	3	0	3	1	1	3	4	1	3	3
	2	3	5	3	3	0	3	2	3	2	2	54
	7.1	5.6	20.6									
12	2	2	1	2	2	3	0	2	2	0	3	0
	1	2	1	3	1	3	1	2	1	4	1	1
	2	1	3	0	3	0	3	3	2	2	2	3
	1	2	4	2	3	1	2	2	2	2	2	42
	6.6	5.3	16.4									
13	4	4	2	1	3	3	1	1	4	0	4	4
	2	3	2	4	5	3	4	4	2	3	3	3
	5	1	4	2	3	3	4	4	6	2	4	3
	4	4	5	2	1	0	0	4	3	4	2	205
	10.0	6.4	30.3									
14	4	3	3	3	4	3	2	3	4	0	2	3
	2	1	3	4	5	2	4	3	3	3	2	2
	3	1	3	0	3	1	3	4	3	2	2	2
	2	2	3	1	2	0	2	3	3	4	3	184
	9.4	5.9	22.6									
15	3	4	1	4	3	2	0	1	2	0	3	1
	3	0	1	3	2	3	5	2	1	2	2	2
	2	1	2	0	3	3	3	3	2	1	2	2
	2	3	4	1	1	0	3	2	3	4	1	173
	9.0	5.6	18.4									
16	6	6	6	5	6	4	6	6	6	4	5	6
	6	5	6	5	6	6	6	6	5	6	5	6
	6	5	5	6	5	6	6	6	6	5	6	6
	6	5	6	5	4	5	6	4	6	5	6	231
	12.2	8.5	46.3									
17	6	6	6	5	5	5	5	5	5	4	6	5
	4	5	4	5	6	6	5	6	4	6	5	4
	5	3	6	4	5	5	6	6	6	5	5	6
	5	4	6	5	4	2	4	6	5	5	5	210
	11.6	8.2	38.6									
18	6	5	5	4	5	4	6	4	5	2	4	6
	5	4	4	4	5	6	5	6	4	4	5	5
	5	5	6	3	4	5	6	5	4	5	4	5
	5	5	6	3	4	2	4	5	3	5	5	199
	11.1	8.0	34.4									
19	4	3	2	2	2	2	2	4	3	0	3	3
	2	5	4	3	4	3	5	3	2	3	1	4
	5	4	2	1	4	0	4	3	3	2	3	5
	1	2	5	2	2	3	3	2	4	4	3	72
	7.5	6.4	27.9									
20	3	3	2	2	2	2	1	2	3	0	2	2
	3	2	2	4	1	2	3	1	2	4	1	2
	4	2	3	1	3	2	3	3	0	1	3	3

	2	2	3	3	3	1	0	3	2	3	3	51
	6.9	5.9	20.2									
21	0	2	3	2	2	1	0	2	0	0	1	3
	3	2	2	2	1	0	3	3	1	1	1	0
	1	2	3	0	3	0	4	3	0	2	2	3
	3	2	3	2	2	1	0	2	3	3	2	40
	6.4	5.6	16.0									
22	5	5	5	4	4	3	5	5	6	4	4	5
	5	6	4	5	5	5	6	5	5	5	2	4
	6	3	5	6	5	5	4	5	6	4	5	6
	4	4	6	5	4	5	1	3	5	6	5	98
	9.6	8.6	43.9									
23	3	4	4	3	4	2	4	3	4	4	5	3
	4	6	3	4	5	4	6	5	4	5	2	5
	5	5	5	5	4	3	5	5	6	4	4	5
	2	3	6	4	4	3	3	4	5	3	4	77
	9.0	8.3	36.2									
24	4	3	4	3	4	3	4	4	2	2	3	4
	4	5	3	4	4	4	4	4	4	4	2	3
	4	4	5	4	5	4	3	4	5	4	4	5
	2	3	5	3	4	3	4	4	3	4	5	65
	8.6	8.1	32.0									
25	5	4	5	4	4	3	5	2	5	4	5	6
	4	5	3	5	6	5	5	4	4	3	4	4
	5	4	5	2	5	2	6	6	5	3	4	3
	5	4	5	4	4	3	5	5	4	6	3	218
	11.1	7.1	39.1									
26	4	4	3	4	3	4	2	2	4	2	5	5
	4	3	3	5	2	3	5	5	2	2	3	3
	4	3	5	5	4	3	5	4	4	4	4	4
	5	4	5	3	2	3	0	4	4	5	4	197
	10.5	6.8	31.4									
27	4	4	3	4	5	2	2	2	0	0	3	3
	4	3	3	5	4	4	5	3	2	2	3	1
	4	2	5	2	3	4	4	4	4	2	3	4
	4	5	6	3	3	0	3	2	3	4	3	186
	10.1	6.5	27.2									
28	6	6	6	6	6	6	6	6	5	6	6	6
	6	6	6	6	6	6	6	6	6	6	6	6
	6	6	6	6	6	6	6	6	6	6	6	6
	6	6	6	6	6	6	6	5	6	6	6	244
	13.3	9.7	55.1									
29	6	6	6	6	6	5	6	5	6	4	6	6
	6	6	6	5	6	5	6	6	6	6	6	6
	6	6	6	6	6	6	6	6	6	6	6	6
	6	6	6	6	6	6	6	6	5	5	6	223
	12.7	9.4	47.4									
30	6	5	6	6	6	6	5	4	6	5	5	6
	6	6	6	5	5	5	6	6	6	6	5	5
	6	5	6	5	6	5	6	6	6	6	6	6
	6	6	6	5	5	5	4	6	6	6	6	212
	12.3	9.3	43.2									
31	2	4	4	3	3	2	2	5	4	4	4	4
	4	4	3	5	4	4	5	4	4	5	2	4
	5	4	3	4	4	3	5	6	4	3	4	4
	3	4	5	3	3	3	3	3	5	5	4	85
	8.5	7.1	36.5									

```
32      3      3      4      2      3      2      5      4      2      3      5      2
        4      3      5      4      2      4      5      4      3      5      1      4
        3      2      4      4      4      2      4      4      4      3      3      4
        4      2      6      2      3      1      1      3      4      4      3      64
        7.9    6.8    28.8
33      2      3      2      3      2      2      3      4      2      2      4      2
        4      2      2      4      2      4      4      4      3      4      1      2
        3      2      3      1      3      1      2      4      4      2      3      4
        3      3      5      3      3      2      2      2      3      3      2      53
        7.5    6.5    24.6
34      6      6      5      5      6      4      6      6      6      6      6      6
        5      6      5      6      5      4      6      6      5      6      4      4
        6      5      5      6      6      6      6      6      6      5      6      6
        6      6      6      6      5      6      5      5      6      6      6      111
        10.7   9.7    52.5
35      6      5      6      5      6      4      6      6      6      6      6      5
        6      6      5      5      6      5      6      6      5      6      4      4
        6      4      5      6      5      5      6      6      5      4      5      5
        5      6      6      5      5      6      5      5      5      5      6      90
        10.1   9.5    44.8
36      5      4      4      4      5      4      6      5      4      6      5      5
        6      6      5      5      5      6      6      5      4      5      4      4
        5      4      5      6      5      5      5      5      5      5      4      6
        5      4      6      4      4      5      0      4      5      5      5      78
        9.7    9.3    40.6
;;
proc print data=BESTm;
run;

/*This computes Pearson correlation coefficients and z-transformed
correlation coefficients (so that the coefficients
are not skewed)."*/

proc corr data=BESTm outp = newdataset Fisher(biasadj=no);
var subj1-subj47;
with metric1 metric2 metric3 metric4;
run;

proc print data=newdataset;
run;

/*This procedure gives names to the columns without names in the new
dataset.*/
data temp;
set newdataset;
if _TYPE_ = 'MEAN' then _NAME_ = 'mean';
if _TYPE_ = 'STD' then _NAME_ = 'STD';
if _TYPE_ = 'N' then _NAME_ = 'n';
run;

/*It transposes the data*/
proc transpose data=temp out=transpose;
run;

/*It calculates the Fisher's z transformation.*/
data transpose;
set transpose;
```

```
metricz1 = .5*log((1+metric1)/(1-metric1));
metricz2 = .5*log((1+metric2)/(1-metric2));
metricz3 = .5*log((1+metric3)/(1-metric3));
metricz4 = .5*log((1+metric4)/(1-metric4));
run;
proc print data=transpose;
run;


/*Now the correlation coefficients can be analyzed just like in the repeated-
measures design. The means between the metrics can be compared, it can be
determined whether they are significantly different from each other. One can
do glm, univariate, or compute all possible differences to see if any of the
differences are statistically significant from 0.*/

proc glm data=transpose;
model metricz1 metricz2 metricz3 metricz4 = /nouni;
repeated metric 4 polynomial/nom summary;
run;

/*Diffirences (diff) just like w, that is why they are divided by the sqrt of
2. */
data transpose;
set transpose;
diff12=(metricz1-metricz2)/2**.5;
diff23=(metricz2-metricz3)/2**.5;
diff31=(metricz3-metricz1)/2**.5;
diff41=(metricz4-metricz1)/2**.5;
diff42=(metricz4-metricz2)/2**.5;
diff43=(metricz4-metricz3)/2**.5;
run;
proc univariate data=transpose;
var diff12 diff23 diff31 diff41 diff42 diff43;
run;

proc print data=transpose;
run;

proc glm data=transpose;
model metricz1 metricz2 metricz3 metricz4= /nouni;
repeated metric 4 polynomial/nom summary;
run;
proc univariate data=transpose;
var diff12 diff23 diff31 diff41 diff42 diff43;
run;
proc means data=transpose;
var metricz1 metricz2 metricz3 metricz4;
output out=means;
run;
/*Conversion back to the original metrics*/
data means;
set means;
if _STAT_ = 'MEAN';
orig1 = ((exp(1)**(metricz1*2)-1)/(exp(1)**(metricz1*2)+1));
orig2 = ((exp(1)**(metricz2*2)-1)/(exp(1)**(metricz2*2)+1));
orig3 = ((exp(1)**(metricz3*2)-1)/(exp(1)**(metricz3*2)+1));
orig4 = ((exp(1)**(metricz4*2)-1)/(exp(1)**(metricz4*2)+1));
```

```
run;

proc print data=means;
run;

/*It transposes the data*/
proc transpose data=means out=meanstranspose;
run;

proc print data=meanstranspose;
run;
```

Appendix U - SAS Command File for Relative Pupil Size Analysis

The output file is not printed here due to its large size.

```
/*This file calculates the repeated-measures ANOVA on the relative pupil
size.*/

data MAIN;
Input newsubjid a1-a36;
/*newsubjid is the new assigned ID as if there were no excluded subjects, one
line for one subject
a1-a36 are the relative pupil diameters for conditions 1-36*/
/*EXCLUDED 9 subjects (problematic eye tracking data)*/

lumin1 = mean (of a1-a12); /*computes mean of all conditions with luminance 1
(20,000)*/
lumin2 = mean (of a13-a24); /*computes mean of all conditions with luminance
2 (205,000)*/
lumin3 = mean (of a25-a36); /*computes mean of all conditions with luminance
3 (750,000)*/

posit1 = mean (a1, a2, a3, a4,a5, a6,a13, a14, a15, a16, a17, a18, a25, a26,
a27, a28,a29, a30);
/*computes mean of all conditions with position 1 (0)*/
posit2 = mean (a7, a8, a9, a10, a11, a12, a19, a20, a21, a22, a23, a24, a31,
a32, a33, a34, a35, a36);
/*computes mean of all conditions with position 2 (10)*/

solid1 = mean (a1, a2, a3,a7, a8, a9, a13, a14, a15, a19, a20, a21, a25, a26,
a27, a31, a32, a33);
/*computes mean of all conditions with solid 1 (10^-5 sr)*/
solid2 = mean (a4, a5, a6,a10, a11, a12, a16, a17, a18, a22, a23, a24, a28,
a29, a30, a34, a35, a36);
/*computes mean of all conditions with solid 2 (10^-4 sr)*/

backs1 = mean (a1, a4, a7, a10, a13, a16, a19, a22, a25, a28, a31, a34);
/*computes mean of all conditions with background luminance 1 (0.03)*/
backs2 = mean (a2, a5, a8, a11, a14, a17, a20, a23, a26, a29, a32, a35);
/*computes mean of all conditions with background luminance 2 (0.3)*/
backs3 = mean (a3, a6, a9, a12, a15, a18, a21, a24, a27, a30, a33, a36);
/*computes mean of all conditions with background luminance 3 (1)*/

lumin1pos1 = mean(a1, a2, a3, a4, a5, a6); /*computes mean of all conditions
with luminance 1 & position1*/
lumin1pos2 = mean(a7, a8, a9, a10, a11, a12);
lumin2pos1 = mean(a13, a14, a15, a16, a17, a18);
lumin2pos2 = mean(a19, a20, a21, a22, a23, a24);
lumin3pos1 = mean(a25, a26, a27, a28, a29, a30);
lumin3pos2 = mean(a31, a32, a33, a34, a35, a36);

lumin1sol1 = mean (a1, a2, a3, a7, a8, a9);
lumin1sol2 = mean (a4, a5, a6, a10, a11, a12);
lumin2sol1 = mean (a13, a14, a15, a19, a20, a21);
lumin2sol2 = mean (a16, a17, a18, a22, a23, a24);
lumin3sol1 = mean (a25, a26, a27, a31, a32, a33);
lumin3sol2 = mean (a28, a29, a30, a34, a35, a36);
```

```
lumin1backs1 = mean (a1, a4, a7, a10);
lumin1backs2 = mean (a2, a5,a8, a11);
lumin1backs3 = mean (a3, a6, a9, a12);
lumin2backs1 = mean (a13, a16, a19, a22);
lumin2backs2 = mean (a14, a17, a20, a23);
lumin2backs3 = mean (a15, a18, a21, a24);
lumin3backs1 = mean (a25, a28, a31, a34);
lumin3backs2 = mean (a26, a29, a32, a35);
lumin3backs3 = mean (a27, a30, a33, a36);

pos1sol1 = mean (a1, a2, a3, a13, a14, a15, a25, a26, a27);
pos1sol2 = mean (a4, a5, a6, a16, a17, a18, a28, a29, a30);
pos2sol1 = mean (a7, a8, a9, a19, a20, a21, a31, a32, a33);
pos2sol2 = mean (a10, a11, a12, a22, a23, a24, a34, a35, a36);

pos1backs1 = mean (a1, a4, a13, a16, a25, a28);
pos1backs2 = mean (a2, a5, a14, a17, a26, a29);
pos1backs3 = mean (a3, a6, a15, a18, a27, a30);
pos2backs1 = mean (a7, a10, a19, a22, a31,a34);
pos2backs2 = mean (a8, a11, a20, a23, a32, a35);
pos2backs3 = mean (a9, a12, a21, a24, a33, a36);

sol1backs1 = mean (a1, a7, a13, a19, a25, a31);
sol1backs2 = mean (a2, a8, a14, a20, a26, a32);
sol1backs3 = mean (a3, a9, a15, a21, a27, a33);
sol2backs1 = mean (a4, a10, a16, a22, a28, a34);
sol2backs2 = mean (a5, a11, a17, a23, a29, a35);
sol2backs3 = mean (a6, a12, a18, a24, a30, a36);

Cards;
1      0.273 0.255 0.280 0.336 0.237 0.350 0.228 0.172 0.117 0.397 0.302 0.295
       0.477 0.453 0.379 0.439 0.346 0.464 0.393 0.262 0.234 0.315 0.424 0.357
       0.387 0.447 0.436 0.493 0.477 0.489 0.436 0.358 0.252 0.488 0.352 0.442
2      0.374 0.301 0.290 0.477 0.423 0.360 0.285 0.283 0.173 0.425 0.347 0.275
       0.414 0.392 0.330 0.506 0.463 0.437 0.402 0.330 0.320 0.496 0.469 0.402
       0.475 0.412 0.380 0.509 0.467 0.444 0.496 0.431 0.305 0.554 0.446 0.472
3      0.360 0.194 0.217 0.529 0.408 0.259 0.318 0.200 0.096 0.480 0.290 0.239
       0.508 0.400 0.328 0.558 0.387 0.385 0.421 0.374 0.305 0.483 0.375 0.393
       0.529 0.400 0.277 0.559 0.451 0.389 0.508 0.397 0.375 0.542 0.505 0.368
4      0.267 0.253 0.113 0.421 0.248 0.251 0.198 0.052 0.061 0.330 0.206 0.155
       0.403 0.266 0.219 0.475 0.378 0.299 0.303 0.213 0.149 0.450 0.336 0.256
       0.419 0.354 0.303 0.477 0.417 0.390 0.365 0.298 0.169 0.518 0.442 0.355
5      0.311 0.210 0.201 0.388 0.343 0.227 0.180 0.092 0.073 0.355 0.221 0.148
       0.378 0.276 0.205 0.441 0.399 0.322 0.357 0.304 0.140 0.488 0.328 0.330
       0.489 0.337 0.277 0.478 0.447 0.316 0.439 0.277 0.252 0.456 0.435 0.372
6      0.208 0.300 0.103 0.396 0.365 0.236 0.233 0.062 -0.544      0.356 0.179
       0.210 0.413 0.292 0.284 0.505 0.492 0.401 0.333 0.261 0.223 0.364 0.467
       0.306 0.513 0.347 0.367 0.616 0.413 0.454 0.372 0.240 0.107 0.479 0.288
       0.399
7      0.350 0.173 0.282 0.468 0.393 0.264 0.332 0.156 0.059 0.460 0.315 0.220
       0.478 0.403 0.143 0.461 0.457 0.341 0.380 0.213 0.143 0.527 0.431 0.401
       0.503 0.318 0.364 0.539 0.526 0.395 0.430 0.216 0.221 0.533 0.417 0.313
8      0.273 0.290 0.263 0.411 0.397 0.285 0.211 0.181 0.130 0.358 0.300 0.294
       0.458 0.347 0.359 0.540 0.449 0.331 0.411 0.246 0.206 0.509 0.384 0.450
       0.475 0.392 0.313 0.560 0.471 0.404 0.460 0.387 0.336 0.548 0.476 0.405
```

9	0.424	0.284	0.237	0.446	0.393	0.306	0.262	0.160	0.128	0.446	0.286	0.312
	0.377	0.398	0.273	0.572	0.453	0.301	0.381	0.304	0.361	0.489	0.376	0.333
	0.507	0.400	0.357	0.456	0.361	0.364	0.504	0.365	0.295	0.442	0.452	0.387
10	0.368	0.297	0.307	0.399	0.307	0.224	0.171	0.160	0.148	0.320	0.370	0.283
	0.440	0.368	0.305	0.373	0.289	0.308	0.338	0.296	0.201	0.386	0.364	0.258
	0.402	0.213	0.267	0.535	0.300	0.264	0.442	0.208	0.054	0.491	0.438	0.339
11	0.369	0.254	0.174	0.547	0.442	0.306	0.175	0.064	0.057	0.479	0.300	0.175
	0.474	0.255	0.322	0.593	0.444	0.409	0.395	0.176	0.193	0.516	0.441	0.212
	0.447	0.453	0.306	0.484	0.540	0.452	0.478	0.364	0.362	0.590	0.468	0.235
12	0.409	0.365	0.283	0.487	0.414	0.269	0.273	0.073	0.112	0.502	0.311	0.270
	0.490	0.459	0.250	0.571	0.511	0.403	0.487	0.372	0.282	0.546	0.411	0.432
	0.536	0.450	0.391	0.544	0.538	0.397	0.433	0.393	0.199	0.562	0.500	0.489
13	0.513	0.449	0.330	0.542	0.479	0.294	0.423	0.149	0.204	0.486	0.313	0.208
	0.467	0.479	0.277	0.594	0.456	0.466	0.467	0.463	0.292	0.564	0.511	0.382
	0.533	0.488	0.369	0.568	0.434	0.488	0.534	0.321	0.443	0.491	0.535	0.289
14	0.385	0.282	0.229	0.392	0.316	0.259	0.301	0.169	0.252	0.434	0.185	0.214
	0.507	0.318	0.240	0.562	0.562	0.330	0.398	0.357	0.344	0.550	0.420	0.342
	0.526	0.381	0.449	0.564	0.590	0.435	0.466	0.425	0.306	0.561	0.523	0.437
15	0.374	0.276	0.149	0.450	0.365	0.260	0.259	0.225	0.086	0.354	0.331	0.196
	0.456	0.340	0.341	0.484	0.462	0.400	0.330	0.354	0.255	0.475	0.431	0.356
	0.476	0.379	0.337	0.492	0.436	0.450	0.432	0.304	0.310	0.515	0.430	0.393
16	0.481	0.354	0.292	0.459	0.469	0.349	0.294	0.195	0.194	0.467	0.215	0.320
	0.439	0.306	0.272	0.549	0.443	0.455	0.442	0.351	0.203	0.523	0.264	0.252
	0.565	0.438	0.350	0.508	0.398	0.430	0.456	0.306	0.347	0.478	0.433	0.409
17	0.317	0.211	0.230	0.403	0.327	0.287	0.257	0.141	0.181	0.438	0.205	0.181
	0.386	0.348	0.164	0.455	0.384	0.277	0.327	0.277	0.136	0.409	0.393	0.235
	0.396	0.378	0.275	0.438	0.344	0.356	0.450	0.236	0.307	0.551	0.358	0.266
18	0.373	0.261	0.200	0.459	0.381	0.272	0.250	0.149	0.155	0.365	0.219	0.195
	0.453	0.316	0.181	0.517	0.401	0.361	0.328	0.389	0.178	0.442	0.314	0.316
	0.511	0.382	0.387	0.509	0.453	0.357	0.373	0.273	0.248	0.465	0.347	0.302
19	0.472	0.447	0.452	0.512	0.532	0.464	0.158	0.307	0.234	0.417	0.278	0.174
	0.496	0.544	0.477	0.550	0.551	0.419	0.424	0.408	0.324	0.530	0.537	0.457
	0.579	0.553	0.558	0.576	0.508	0.568	0.505	0.362	0.189	0.540	0.564	0.371
20	0.464	0.385	0.271	0.418	0.440	0.326	0.400	0.196	0.141	0.466	0.231	0.181
	0.455	0.333	0.258	0.480	0.446	0.416	0.425	0.318	0.257	0.523	0.411	0.347
	0.522	0.412	0.303	0.519	0.395	0.374	0.438	0.388	0.280	0.552	0.454	0.399
21	0.446	0.360	0.300	0.511	0.355	0.250	0.382	0.158	0.066	0.417	0.390	0.338
	0.444	0.471	0.296	0.505	0.374	0.396	0.390	0.338	0.286	0.428	0.369	0.312
	0.478	0.358	0.343	0.488	0.483	0.413	0.512	0.337	0.302	0.437	0.450	0.449
22	0.362	0.238	0.269	0.533	0.378	0.404	0.245	0.207	0.019	0.298	0.228	0.294
	0.507	0.484	0.314	0.563	0.549	0.504	0.430	0.315	0.192	0.529	0.475	0.362
	0.534	0.469	0.324	0.586	0.459	0.492	0.513	0.350	0.172	0.569	0.465	0.443
23	0.306	0.249	0.231	0.372	0.308	0.306	0.257	0.073	0.089	0.393	0.323	0.207
	0.446	0.392	0.303	0.531	0.377	0.337	0.371	0.213	0.229	0.477	0.322	0.309
	0.437	0.346	0.377	0.455	0.335	0.367	0.341	0.255	0.284	0.447	0.413	0.335
24	0.265	0.132	0.207	0.303	0.290	0.273	0.174	0.049	0.052	0.348	0.217	0.170
	0.414	0.299	0.194	0.432	0.395	0.327	0.351	0.194	0.184	0.472	0.351	0.253
	0.421	0.237	0.299	0.445	0.378	0.344	0.376	0.299	0.115	0.491	0.411	0.336
25	0.328	0.263	0.192	0.425	0.335	0.341	0.262	0.155	0.209	0.396	0.325	0.217
	0.427	0.349	0.275	0.451	0.368	0.310	0.379	0.335	0.267	0.480	0.265	0.381
	0.458	0.390	0.330	0.487	0.433	0.366	0.423	0.373	0.286	0.478	0.394	0.333
26	0.444	0.381	0.255	0.451	0.350	0.335	0.268	0.090	0.152	0.423	0.431	0.330
	0.546	0.455	0.384	0.547	0.465	0.417	0.348	0.267	0.273	0.545	0.545	0.420
	0.555	0.493	0.479	0.508	0.439	0.458	0.513	0.406	0.363	0.541	0.489	0.531
27	0.328	0.282	0.266	0.340	0.359	0.283	0.223	0.133	0.124	0.321	0.217	0.155
	0.372	0.257	0.276	0.397	0.396	0.328	0.282	0.167	0.189	0.382	0.340	0.294
	0.387	0.329	0.317	0.454	0.427	0.321	0.380	0.285	0.222	0.447	0.423	0.309

28	0.389	0.381	0.356	0.516	0.481	0.262	0.275	0.280	0.239	0.412	0.392	0.285
	0.466	0.436	0.344	0.511	0.505	0.481	0.423	0.398	0.325	0.451	0.481	0.340
	0.554	0.436	0.393	0.532	0.531	0.513	0.444	0.411	0.306	0.507	0.471	0.378
29	0.357	0.250	0.277	0.472	0.392	0.310	0.254	0.219	0.144	0.362	0.326	0.204
	0.455	0.333	0.278	0.464	0.393	0.317	0.399	0.313	0.241	0.468	0.393	0.358
	0.449	0.443	0.290	0.514	0.472	0.425	0.472	0.378	0.310	0.453	0.422	0.306
30	0.244	0.167	0.155	0.386	0.240	0.037	0.465	0.433	0.216	0.267	0.441	0.147
	0.327	0.279	0.231	0.430	0.357	0.360	0.322	0.145	0.340	0.285	0.328	0.472
	0.388	0.387	0.279	0.221	0.187	0.235	0.200	0.090	0.418	0.229	0.112	0.133
31	0.425	0.391	0.329	0.517	0.499	0.387	0.292	0.226	0.112	0.411	0.331	0.274
	0.479	0.387	0.397	0.538	0.489	0.487	0.451	0.318	0.249	0.540	0.452	0.368
	0.487	0.424	0.484	0.562	0.492	0.463	0.450	0.336	0.280	0.547	0.427	0.448
32	0.329	0.285	0.179	0.451	0.402	0.286	0.229	0.137	0.080	0.359	0.279	0.253
	0.430	0.356	0.329	0.508	0.474	0.425	0.359	0.289	0.227	0.485	0.409	0.314
	0.470	0.420	0.360	0.514	0.501	0.452	0.417	0.393	0.309	0.548	0.494	0.444
33	0.387	0.383	0.267	0.453	0.419	0.376	0.318	0.263	0.268	0.390	0.199	0.239
	0.335	0.416	0.228	0.519	0.422	0.388	0.433	0.259	0.264	0.475	0.419	0.283
	0.454	0.418	0.242	0.509	0.395	0.487	0.492	0.274	0.329	0.477	0.456	0.484
34	0.311	0.199	0.161	0.356	0.279	0.302	0.188	0.080	0.078	0.316	0.230	0.147
	0.364	0.320	0.233	0.399	0.367	0.277	0.290	0.214	0.151	0.409	0.315	0.273
	0.351	0.328	0.237	0.438	0.382	0.333	0.352	0.237	0.206	0.451	0.367	0.347
35	0.352	0.235	-0.035		0.380	0.320	0.135	0.304	0.163	0.061	0.391	0.221
	0.137	0.387	0.380	0.298	0.415	0.393	0.397	0.488	0.401	0.145	0.440	0.351
	0.293	0.514	0.464	0.319	0.489	0.475	0.383	0.406	0.320	0.181	0.497	0.369
	0.427											
36	0.381	0.325	0.239	0.489	0.386	0.346	0.242	0.211	0.174	0.394	0.263	0.276
	0.457	0.361	0.333	0.524	0.491	0.473	0.442	0.235	0.289	0.505	0.446	0.279
	0.521	0.435	0.360	0.556	0.484	0.508	0.446	0.420	0.267	0.506	0.474	0.389
37	0.366	0.480	0.356	0.385	0.455	0.525	0.410	0.242	0.279	0.343	0.370	0.321
	0.436	0.475	0.324	0.354	0.522	0.503	0.413	0.329	0.292	0.516	0.467	0.513
	0.436	0.482	0.457	0.404	0.429	0.437	0.470	0.419	0.337	0.449	0.500	0.512
38	0.317	0.189	0.150	0.430	0.197	0.207	-0.031		0.168	-0.049		0.320
	0.230	0.090	0.410	0.245	0.164	0.550	0.358	0.147	0.299	0.165	0.151	0.512
	0.250	0.202	0.442	0.377	0.318	0.368	0.499	0.443	0.389	0.244	0.020	0.508
	0.337	0.236										
39	0.246	0.176	0.068	0.353	0.287	0.181	0.178	0.069	0.022	0.285	0.170	0.132
	0.283	0.295	0.216	0.254	0.242	0.225	0.220	0.189	0.118	0.278	0.268	0.269
	0.272	0.244	0.228	0.286	0.397	0.262	0.353	0.263	0.265	0.316	0.224	0.255
40	0.439	0.329	0.273	0.465	0.387	0.333	0.311	0.091	0.079	0.404	0.291	0.234
	0.482	0.453	0.365	0.485	0.479	0.479	0.416	0.302	0.291	0.515	0.347	0.300
	0.517	0.429	0.355	0.498	0.429	0.515	0.443	0.440	0.143	0.484	0.535	0.470
41	0.356	0.290	0.258	0.394	0.296	0.391	0.273	0.177	0.082	0.342	0.259	0.264
	0.372	0.289	0.233	0.493	0.379	0.432	0.357	0.267	0.082	0.475	0.391	0.324
	0.463	0.328	0.316	0.551	0.475	0.359	0.375	0.230	0.286	0.472	0.462	0.308
42	0.378	0.280	0.203	0.440	0.308	0.316	0.262	0.185	0.131	0.396	0.271	0.223
	0.472	0.384	0.329	0.510	0.449	0.409	0.372	0.317	0.249	0.486	0.370	0.317
	0.502	0.421	0.375	0.540	0.408	0.438	0.430	0.352	0.227	0.469	0.415	0.362
43	0.470	0.392	0.422	0.527	0.512	0.450	0.310	0.272	0.203	0.496	0.429	0.322
	0.514	0.465	0.393	0.528	0.521	0.480	0.481	0.414	0.325	0.540	0.472	0.396
	0.550	0.528	0.442	0.523	0.468	0.485	0.502	0.461	0.446	0.520	0.492	0.481
44	0.316	0.227	0.205	0.427	0.306	0.223	0.275	0.212	0.107	0.388	0.300	0.228
	0.467	0.352	0.292	0.488	0.389	0.368	0.416	0.297	0.191	0.472	0.376	0.342
	0.486	0.375	0.350	0.558	0.460	0.358	0.411	0.389	0.247	0.505	0.437	0.395
45	0.243	0.214	0.165	0.363	0.268	0.245	0.185	0.175	0.118	0.293	0.220	0.183
	0.349	0.317	0.267	0.483	0.414	0.349	0.318	0.208	0.132	0.426	0.368	0.232
	0.411	0.350	0.309	0.506	0.461	0.408	0.364	0.309	0.265	0.500	0.458	0.384

```
46    0.458 0.328 0.414 0.535 0.553 0.349 0.253 0.343 0.372 0.386 0.430 0.385
      0.443 0.387 0.373 0.458 0.548 0.389 0.432 0.475 0.326 0.437 0.435 0.507
      0.515 0.455 0.384 0.528 0.454 0.493 0.360 0.522 0.322 0.403 0.409 0.574
47    0.349 0.169 0.317 0.423 0.345 0.345 0.371 0.216 0.026 0.278 0.311 0.342
      0.353 0.325 0.320 0.476 0.480 0.356 0.375 0.307 0.210 0.398 0.327 0.313
      0.316 0.349 0.272 0.438 0.362 0.342 0.336 0.275 0.134 0.508 0.328 0.271
;;

proc print data=MAIN;
run;
proc means data = MAIN;
var a1-a36;
run;
proc means data = MAIN;
var
lumin1 lumin2 lumin3
posit1 posit2
solid1 solid2
backs1 backs2 backs3

lumin1backs1 lumin2backs1 lumin3backs1
lumin1backs2 lumin2backs2 lumin3backs2
lumin1backs3 lumin2backs3 lumin3backs3

lumin1pos1 lumin2pos1 lumin3pos1 lumin1pos2 lumin2pos2 lumin3pos2

lumin1sol1 lumin1sol2 lumin2sol1 lumin2sol2 lumin3sol1 lumin3sol2

pos1sol1 pos1sol2 pos2sol1 pos2sol2

pos1backs1 pos1backs2 pos1backs3 pos2backs1 pos2backs2 pos2backs3

sol1backs1 sol1backs2 sol1backs3 sol2backs1 sol2backs2 sol2backs3;
run;

/*It allows to check confidence interval - standard error*1.96=margin of
error */
proc surveymeans data = MAIN;
VAR
lumin1 lumin2 lumin3
posit1 posit2
solid1 solid2
backs1 backs2 backs3;
run;

/*If there are missing data, glm ignores the whole subject*/
proc glm data=MAIN;
repeated luminance 3 polynomial, position 2 polynomial, solidangle 2
polynomial, backgroundlum 3 polynomial/nom summary;
run;
```

Appendix V - SAS Command File for Correlation Analysis between Subjective Responses and Relative Pupil Size

The output file is not printed here due to its large size.

```
/*Correlation between subjective data and RPS
widePUPIL - wide dataset
longPUPIl - long dataset*/

data widePUPIL;
Input subjectID scale1-scale36 r1-r36;
/*EACH line - for one subject;
First line:
Scale 1-36 subjective scale response of subject 1 for 36 conditions, rps 1-36
relative pupil size for subject 1
for 36 conditions*/
/*EXCLUDED 9 subjects*/
Cards;
1      1     1     0     5     4     5     1     1     0     2     5     2
       4     4     3     6     6     6     4     3     0     5     3     4
       5     4     4     6     6     6     2     3     2     6     6     5
       0.273 0.255 0.280 0.336 0.237 0.350 0.228 0.172 0.117 0.397 0.302 0.295
       0.477 0.453 0.379 0.439 0.346 0.464 0.393 0.262 0.234 0.315 0.424 0.357
       0.387 0.447 0.436 0.493 0.477 0.489 0.436 0.358 0.252 0.488 0.352 0.442
2      1     0     1     3     4     3     2     2     1     2     3     2
       4     3     4     6     6     5     3     3     2     5     4     3
       4     4     4     6     6     5     4     3     3     6     5     4
       0.374 0.301 0.290 0.477 0.423 0.360 0.285 0.283 0.173 0.425 0.347 0.275
       0.414 0.392 0.330 0.506 0.463 0.437 0.402 0.330 0.320 0.496 0.469 0.402
       0.475 0.412 0.380 0.509 0.467 0.444 0.496 0.431 0.305 0.554 0.446 0.472
3      1     1     0     5     3     3     1     2     0     3     2     1
       2     3     1     6     6     5     2     2     3     5     4     4
       5     3     3     6     6     6     4     4     2     5     6     4
       0.360 0.194 0.217 0.529 0.408 0.259 0.318 0.200 0.096 0.480 0.290 0.239
       0.508 0.400 0.328 0.558 0.387 0.385 0.421 0.374 0.305 0.483 0.375 0.393
       0.529 0.400 0.277 0.559 0.451 0.389 0.508 0.397 0.375 0.542 0.505 0.368
4      2     1     2     3     3     3     1     0     1     2     2     2
       1     3     4     5     5     4     2     2     2     4     3     3
       4     4     4     6     6     6     3     2     3     5     5     4
       0.267 0.253 0.113 0.421 0.248 0.251 0.198 0.052 0.061 0.330 0.206 0.155
       0.403 0.266 0.219 0.475 0.378 0.299 0.303 0.213 0.149 0.450 0.336 0.256
       0.419 0.354 0.303 0.477 0.417 0.390 0.365 0.298 0.169 0.518 0.442 0.355
5      1     0     1     3     2     1     0     0     0     1     2     2
       3     4     3     6     5     5     2     2     2     4     4     4
       4     3     5     6     6     6     3     3     2     6     6     5
       0.311 0.210 0.201 0.388 0.343 0.227 0.180 0.092 0.073 0.355 0.221 0.148
       0.378 0.276 0.205 0.441 0.399 0.322 0.357 0.304 0.140 0.488 0.328 0.330
       0.489 0.337 0.277 0.478 0.447 0.316 0.439 0.277 0.252 0.456 0.435 0.372
6      1     1     1     3     2     2     1     1     1     3     3     3
       3     3     2     4     5     4     2     2     1     3     2     3
       3     4     2     6     5     6     2     2     2     4     4     4
       0.208 0.300 0.103 0.396 0.365 0.236 0.233 0.062 -0.544      0.356 0.179
       0.210 0.413 0.292 0.284 0.505 0.492 0.401 0.333 0.261 0.223 0.364 0.467
       0.306 0.513 0.347 0.367 0.616 0.413 0.454 0.372 0.240 0.107 0.479 0.288
       0.399
7      0     0     1     3     4     2     1     0     0     4     2     0
       1     2     0     6     5     6     2     1     0     5     4     4
```

	5	2	2	6	6	5	2	5	3	6	6	6
	0.350	0.173	0.282	0.468	0.393	0.264	0.332	0.156	0.059	0.460	0.315	0.220
	0.478	0.403	0.143	0.461	0.457	0.341	0.380	0.213	0.143	0.527	0.431	0.401
	0.503	0.318	0.364	0.539	0.526	0.395	0.430	0.216	0.221	0.533	0.417	0.313
8	1	1	1	3	4	3	3	3	1	4	2	2
	1	3	1	6	5	4	4	2	2	5	3	4
	2	2	2	6	5	4	5	4	4	6	6	5
	0.273	0.290	0.263	0.411	0.397	0.285	0.211	0.181	0.130	0.358	0.300	0.294
	0.458	0.347	0.359	0.540	0.449	0.331	0.411	0.246	0.206	0.509	0.384	0.450
	0.475	0.392	0.313	0.560	0.471	0.404	0.460	0.387	0.336	0.548	0.476	0.405
9	0	1	0	3	2	3	2	1	1	5	3	2
	4	4	2	6	5	5	3	3	0	6	4	2
	5	4	0	5	6	6	4	2	2	6	6	4
	0.424	0.284	0.237	0.446	0.393	0.306	0.262	0.160	0.128	0.446	0.286	0.312
	0.377	0.398	0.273	0.572	0.453	0.301	0.381	0.304	0.361	0.489	0.376	0.333
	0.507	0.400	0.357	0.456	0.361	0.364	0.504	0.365	0.295	0.442	0.452	0.387
10	0	0	0	3	0	0	0	0	0	1	0	0
	0	0	0	4	4	2	0	0	0	4	4	2
	4	2	0	6	4	5	4	3	2	6	6	6
	0.368	0.297	0.307	0.399	0.307	0.224	0.171	0.160	0.148	0.320	0.370	0.283
	0.440	0.368	0.305	0.373	0.289	0.308	0.338	0.296	0.201	0.386	0.364	0.258
	0.402	0.213	0.267	0.535	0.300	0.264	0.442	0.208	0.054	0.491	0.438	0.339
11	1	0	2	2	2	1	1	1	0	3	3	3
	4	2	3	5	6	4	3	2	1	4	5	3
	5	5	3	6	6	5	4	5	4	6	6	5
	0.369	0.254	0.174	0.547	0.442	0.306	0.175	0.064	0.057	0.479	0.300	0.175
	0.474	0.255	0.322	0.593	0.444	0.409	0.395	0.176	0.193	0.516	0.441	0.212
	0.447	0.453	0.306	0.484	0.540	0.452	0.478	0.364	0.362	0.590	0.468	0.235
12	2	0	1	4	3	4	2	0	0	3	2	0
	4	3	1	6	5	6	3	2	3	5	3	4
	6	5	3	6	6	6	4	2	2	6	5	5
	0.409	0.365	0.283	0.487	0.414	0.269	0.273	0.073	0.112	0.502	0.311	0.270
	0.490	0.459	0.250	0.571	0.511	0.403	0.487	0.372	0.282	0.546	0.411	0.432
	0.536	0.450	0.391	0.544	0.538	0.397	0.433	0.393	0.199	0.562	0.500	0.489
13	1	0	2	3	2	2	1	0	0	3	3	1
	2	2	3	6	4	5	2	3	3	5	4	4
	4	4	4	6	6	6	4	4	4	5	6	6
	0.513	0.449	0.330	0.542	0.479	0.294	0.423	0.149	0.204	0.486	0.313	0.208
	0.467	0.479	0.277	0.594	0.456	0.466	0.467	0.463	0.292	0.564	0.511	0.382
	0.533	0.488	0.369	0.568	0.434	0.488	0.534	0.321	0.443	0.491	0.535	0.289
14	1	0	1	3	3	4	1	0	0	3	3	2
	3	1	0	5	5	4	5	2	2	6	6	5
	5	3	3	6	6	6	4	3	2	6	6	6
	0.385	0.282	0.229	0.392	0.316	0.259	0.301	0.169	0.252	0.434	0.185	0.214
	0.507	0.318	0.240	0.562	0.562	0.330	0.398	0.357	0.344	0.550	0.420	0.342
	0.526	0.381	0.449	0.564	0.590	0.435	0.466	0.425	0.306	0.561	0.523	0.437
15	1	1	1	3	3	2	1	1	1	2	2	1
	2	3	1	6	4	4	4	2	2	4	3	3
	3	3	3	6	6	6	3	5	2	5	5	5
	0.374	0.276	0.149	0.450	0.365	0.260	0.259	0.225	0.086	0.354	0.331	0.196
	0.456	0.340	0.341	0.484	0.462	0.400	0.330	0.354	0.255	0.475	0.431	0.356
	0.476	0.379	0.337	0.492	0.436	0.450	0.432	0.304	0.310	0.515	0.430	0.393
16	3	3	2	5	3	3	2	2	2	4	4	3
	4	4	3	5	5	4	3	4	2	5	4	4
	5	5	5	6	5	5	5	4	4	6	5	5
	0.481	0.354	0.292	0.459	0.469	0.349	0.294	0.195	0.194	0.467	0.215	0.320

	0.439	0.306	0.272	0.549	0.443	0.455	0.442	0.351	0.203	0.523	0.264	0.252
	0.565	0.438	0.350	0.508	0.398	0.430	0.456	0.306	0.347	0.478	0.433	0.409
17	3	1	1	6	4	3	2	1	1	3	2	1
	5	5	2	6	6	5	4	1	1	5	5	4
	6	2	4	6	6	5	4	2	2	5	6	5
	0.317	0.211	0.230	0.403	0.327	0.287	0.257	0.141	0.181	0.438	0.205	0.181
	0.386	0.348	0.164	0.455	0.384	0.277	0.327	0.277	0.136	0.409	0.393	0.235
	0.396	0.378	0.275	0.438	0.344	0.356	0.450	0.236	0.307	0.551	0.358	0.266
18	1	1	0	5	3	2	1	2	1	2	2	3
	3	2	3	6	6	6	3	2	0	5	4	4
	5	3	4	6	5	5	4	4	4	4	5	6
	0.373	0.261	0.200	0.459	0.381	0.272	0.250	0.149	0.155	0.365	0.219	0.195
	0.453	0.316	0.181	0.517	0.401	0.361	0.328	0.389	0.178	0.442	0.314	0.316
	0.511	0.382	0.387	0.509	0.453	0.357	0.373	0.273	0.248	0.465	0.347	0.302
19	2	1	0	5	3	3	4	2	1	5	4	1
	4	4	5	6	5	5	5	3	3	6	6	4
	5	5	5	6	6	6	5	5	4	6	6	6
	0.472	0.447	0.452	0.512	0.532	0.464	0.158	0.307	0.234	0.417	0.278	0.174
	0.496	0.544	0.477	0.550	0.551	0.419	0.424	0.408	0.324	0.530	0.537	0.457
	0.579	0.553	0.558	0.576	0.508	0.568	0.505	0.362	0.189	0.540	0.564	0.371
20	2	2	1	4	3	4	2	2	2	3	4	2
	4	3	2	6	6	6	3	1	3	5	5	4
	4	5	3	6	6	6	4	4	4	6	6	5
	0.464	0.385	0.271	0.418	0.440	0.326	0.400	0.196	0.141	0.466	0.231	0.181
	0.455	0.333	0.258	0.480	0.446	0.416	0.425	0.318	0.257	0.523	0.411	0.347
	0.522	0.412	0.303	0.519	0.395	0.374	0.438	0.388	0.280	0.552	0.454	0.399
21	0	0	0	3	2	2	0	0	0	2	2	1
	2	3	1	5	4	4	2	2	1	5	4	4
	4	2	2	6	6	6	4	3	3	5	5	4
	0.446	0.360	0.300	0.511	0.355	0.250	0.382	0.158	0.066	0.417	0.390	0.338
	0.444	0.471	0.296	0.505	0.374	0.396	0.390	0.338	0.286	0.428	0.369	0.312
	0.478	0.358	0.343	0.488	0.483	0.413	0.512	0.337	0.302	0.437	0.450	0.449
22	1	1	0	3	2	2	3	2	1	3	4	4
	3	3	2	6	6	4	3	4	1	5	5	4
	3	2	2	6	6	6	5	5	4	6	6	5
	0.362	0.238	0.269	0.533	0.378	0.404	0.245	0.207	0.019	0.298	0.228	0.294
	0.507	0.484	0.314	0.563	0.549	0.504	0.430	0.315	0.192	0.529	0.475	0.362
	0.534	0.469	0.324	0.586	0.459	0.492	0.513	0.350	0.172	0.569	0.465	0.443
23	1	1	1	4	3	2	1	1	0	1	1	1
	3	2	2	5	5	5	1	1	1	2	2	2
	4	3	3	6	6	5	2	1	1	4	4	4
	0.306	0.249	0.231	0.372	0.308	0.306	0.257	0.073	0.089	0.393	0.323	0.207
	0.446	0.392	0.303	0.531	0.377	0.337	0.371	0.213	0.229	0.477	0.322	0.309
	0.437	0.346	0.377	0.455	0.335	0.367	0.341	0.255	0.284	0.447	0.413	0.335
24	1	1	0	4	3	2	1	0	1	2	3	1
	3	2	2	6	4	5	4	2	0	4	5	3
	4	3	1	6	6	5	4	4	2	4	4	4
	0.265	0.132	0.207	0.303	0.290	0.273	0.174	0.049	0.052	0.348	0.217	0.170
	0.414	0.299	0.194	0.432	0.395	0.327	0.351	0.194	0.184	0.472	0.351	0.253
	0.421	0.237	0.299	0.445	0.378	0.344	0.376	0.299	0.115	0.491	0.411	0.336
25	2	0	0	3	4	5	2	2	1	4	3	2
	5	3	2	6	5	5	5	4	1	6	5	4
	5	4	4	6	6	6	5	3	3	6	6	5
	0.328	0.263	0.192	0.425	0.335	0.341	0.262	0.155	0.209	0.396	0.325	0.217
	0.427	0.349	0.275	0.451	0.368	0.310	0.379	0.335	0.267	0.480	0.265	0.381
	0.458	0.390	0.330	0.487	0.433	0.366	0.423	0.373	0.286	0.478	0.394	0.333

26	2	1	1	3	2	2	1	0	0	3	2	1
	1	1	1	5	3	5	4	2	2	3	5	4
	4	3	2	6	6	5	4	2	2	5	4	4
	0.444	0.381	0.255	0.451	0.350	0.335	0.268	0.090	0.152	0.423	0.431	0.330
	0.546	0.455	0.384	0.547	0.465	0.417	0.348	0.267	0.273	0.545	0.545	0.420
	0.555	0.493	0.479	0.508	0.439	0.458	0.513	0.406	0.363	0.541	0.489	0.531
27	1	2	2	4	3	4	3	1	2	4	3	3
	4	3	2	5	6	6	2	3	3	5	5	5
	5	5	5	6	6	6	3	4	3	5	5	5
	0.328	0.282	0.266	0.340	0.359	0.283	0.223	0.133	0.124	0.321	0.217	0.155
	0.372	0.257	0.276	0.397	0.396	0.328	0.282	0.167	0.189	0.382	0.340	0.294
	0.387	0.329	0.317	0.454	0.427	0.321	0.380	0.285	0.222	0.447	0.423	0.309
28	0	0	0	3	0	0	0	0	0	0	0	0
	2	0	0	6	4	3	1	1	0	6	5	4
	2	5	2	6	6	5	4	4	1	6	6	6
	0.389	0.381	0.356	0.516	0.481	0.262	0.275	0.280	0.239	0.412	0.392	0.285
	0.466	0.436	0.344	0.511	0.505	0.481	0.423	0.398	0.325	0.451	0.481	0.340
	0.554	0.436	0.393	0.532	0.531	0.513	0.444	0.411	0.306	0.507	0.471	0.378
29	2	2	2	3	3	3	3	3	2	3	3	3
	3	3	3	5	5	4	4	3	3	5	4	5
	5	4	3	6	6	6	4	4	3	6	5	5
	0.357	0.250	0.277	0.472	0.392	0.310	0.254	0.219	0.144	0.362	0.326	0.204
	0.455	0.333	0.278	0.464	0.393	0.317	0.399	0.313	0.241	0.468	0.393	0.358
	0.449	0.443	0.290	0.514	0.472	0.425	0.472	0.378	0.310	0.453	0.422	0.306
30	1	0	0	2	1	1	0	0	0	1	1	0
	3	1	3	6	5	5	0	2	0	5	3	4
	2	3	4	6	6	5	3	2	1	6	5	5
	0.244	0.167	0.155	0.386	0.240	0.037	0.465	0.433	0.216	0.267	0.441	0.147
	0.327	0.279	0.231	0.430	0.357	0.360	0.322	0.145	0.340	0.285	0.328	0.472
	0.388	0.387	0.279	0.221	0.187	0.235	0.200	0.090	0.418	0.229	0.112	0.133
31	2	2	1	3	3	2	2	2	0	3	1	3
	4	3	3	6	6	6	4	3	4	4	5	3
	6	5	4	6	6	6	5	4	2	6	6	5
	0.425	0.391	0.329	0.517	0.499	0.387	0.292	0.226	0.112	0.411	0.331	0.274
	0.479	0.387	0.397	0.538	0.489	0.487	0.451	0.318	0.249	0.540	0.452	0.368
	0.487	0.424	0.484	0.562	0.492	0.463	0.450	0.336	0.280	0.547	0.427	0.448
32	2	2	2	4	4	3	2	3	2	4	3	3
	4	4	3	6	6	5	3	3	3	5	5	4
	6	4	4	6	6	6	6	4	4	6	6	5
	0.329	0.285	0.179	0.451	0.402	0.286	0.229	0.137	0.080	0.359	0.279	0.253
	0.430	0.356	0.329	0.508	0.474	0.425	0.359	0.289	0.227	0.485	0.409	0.314
	0.470	0.420	0.360	0.514	0.501	0.452	0.417	0.393	0.309	0.548	0.494	0.444
33	2	0	0	5	2	2	0	1	0	5	4	2
	6	3	2	6	6	4	3	0	0	6	6	5
	5	4	4	6	6	6	4	4	4	6	5	5
	0.387	0.383	0.267	0.453	0.419	0.376	0.318	0.263	0.268	0.390	0.199	0.239
	0.335	0.416	0.228	0.519	0.422	0.388	0.433	0.259	0.264	0.475	0.419	0.283
	0.454	0.418	0.242	0.509	0.395	0.487	0.492	0.274	0.329	0.477	0.456	0.484
34	1	1	1	4	3	4	1	1	1	2	1	2
	2	2	1	5	5	5	2	1	2	4	4	4
	3	4	2	6	6	6	3	3	2	5	4	5
	0.311	0.199	0.161	0.356	0.279	0.302	0.188	0.080	0.078	0.316	0.230	0.147
	0.364	0.320	0.233	0.399	0.367	0.277	0.290	0.214	0.151	0.409	0.315	0.273
	0.351	0.328	0.237	0.438	0.382	0.333	0.352	0.237	0.206	0.451	0.367	0.347
35	2	2	1	3	2	2	2	1	1	3	3	2
	4	2	2	6	5	4	3	3	2	5	4	4
	4	4	3	6	6	6	4	3	3	6	5	4

	0.352	0.235	-0.035		0.380	0.320	0.135	0.304	0.163	0.061	0.391	0.221
	0.137	0.387	0.380	0.298	0.415	0.393	0.397	0.488	0.401	0.145	0.440	0.351
	0.293	0.514	0.464	0.319	0.489	0.475	0.383	0.406	0.320	0.181	0.497	0.369
	0.427											
36	1	2	1	4	3	4	2	2	1	3	3	3
	3	2	2	6	6	5	5	3	3	6	5	5
	3	4	4	6	6	6	4	4	4	6	5	6
	0.381	0.325	0.239	0.489	0.386	0.346	0.242	0.211	0.174	0.394	0.263	0.276
	0.457	0.361	0.333	0.524	0.491	0.473	0.442	0.235	0.289	0.505	0.446	0.279
	0.521	0.435	0.360	0.556	0.484	0.508	0.446	0.420	0.267	0.506	0.474	0.389
37	1	0	3	4	3	3	1	1	0	2	2	1
	4	2	2	6	5	5	1	2	3	4	2	2
	5	5	4	6	6	6	3	4	3	6	5	5
	0.366	0.480	0.356	0.385	0.455	0.525	0.410	0.242	0.279	0.343	0.370	0.321
	0.436	0.475	0.324	0.354	0.522	0.503	0.413	0.329	0.292	0.516	0.467	0.513
	0.436	0.482	0.457	0.404	0.429	0.437	0.470	0.419	0.337	0.449	0.500	0.512
38	2	1	1	3	2	2	2	1	1	3	3	2
	4	2	3	5	4	5	2	2	2	4	3	3
	4	4	5	6	6	6	4	2	3	6	6	4
	0.317	0.189	0.150	0.430	0.197	0.207	-0.031		0.168	-0.049		0.320
	0.230	0.090	0.410	0.245	0.164	0.550	0.358	0.147	0.299	0.165	0.151	0.512
	0.250	0.202	0.442	0.377	0.318	0.368	0.499	0.443	0.389	0.244	0.020	0.508
	0.337	0.236										
39	3	2	3	4	5	4	3	3	2	4	5	4
	5	3	4	6	6	6	5	3	3	6	6	5
	5	5	6	6	6	6	5	6	5	6	6	6
	0.246	0.176	0.068	0.353	0.287	0.181	0.178	0.069	0.022	0.285	0.170	0.132
	0.283	0.295	0.216	0.254	0.242	0.225	0.220	0.189	0.118	0.278	0.268	0.269
	0.272	0.244	0.228	0.286	0.397	0.262	0.353	0.263	0.265	0.316	0.224	0.255
40	0	1	0	3	2	2	2	1	0	3	3	2
	2	1	1	5	5	3	2	3	2	5	4	3
	4	3	3	6	6	5	3	2	3	6	5	4
	0.439	0.329	0.273	0.465	0.387	0.333	0.311	0.091	0.079	0.404	0.291	0.234
	0.482	0.453	0.365	0.485	0.479	0.479	0.416	0.302	0.291	0.515	0.347	0.300
	0.517	0.429	0.355	0.498	0.429	0.515	0.443	0.440	0.143	0.484	0.535	0.470
41	0	1	1	4	3	2	1	2	2	3	3	3
	1	2	1	4	4	4	2	3	2	4	4	4
	4	2	3	6	6	5	3	3	3	5	5	4
	0.356	0.290	0.258	0.394	0.296	0.391	0.273	0.177	0.082	0.342	0.259	0.264
	0.372	0.289	0.233	0.493	0.379	0.432	0.357	0.267	0.082	0.475	0.391	0.324
	0.463	0.328	0.316	0.551	0.475	0.359	0.375	0.230	0.286	0.472	0.462	0.308
42	0	0	0	4	1	0	0	0	0	1	0	1
	0	0	0	5	2	2	3	1	1	5	3	3
	3	3	0	6	6	5	3	1	2	6	6	5
	0.378	0.280	0.203	0.440	0.308	0.316	0.262	0.185	0.131	0.396	0.271	0.223
	0.472	0.384	0.329	0.510	0.449	0.409	0.372	0.317	0.249	0.486	0.370	0.317
	0.502	0.421	0.375	0.540	0.408	0.438	0.430	0.352	0.227	0.469	0.415	0.362
43	3	0	1	3	3	2	0	0	1	3	3	2
	0	2	3	6	4	4	3	0	0	1	3	4
	5	0	3	6	6	4	3	1	2	5	5	0
	0.470	0.392	0.422	0.527	0.512	0.450	0.310	0.272	0.203	0.496	0.429	0.322
	0.514	0.465	0.393	0.528	0.521	0.480	0.481	0.414	0.325	0.540	0.472	0.396
	0.550	0.528	0.442	0.523	0.468	0.485	0.502	0.461	0.446	0.520	0.492	0.481
44	2	2	2	1	1	1	2	1	1	3	2	2
	4	3	2	4	6	5	2	3	2	3	4	4
	5	4	2	5	6	6	3	3	2	5	5	4
	0.316	0.227	0.205	0.427	0.306	0.223	0.275	0.212	0.107	0.388	0.300	0.228

```
      0.467 0.352 0.292 0.488 0.389 0.368 0.416 0.297 0.191 0.472 0.376 0.342
      0.486 0.375 0.350 0.558 0.460 0.358 0.411 0.389 0.247 0.505 0.437 0.395
45    2     1     1     3     1     1     2     1     0     4     3     2
      3     3     3     6     5     3     4     2     3     5     5     3
      4     4     3     6     5     6     5     4     3     6     5     5
      0.243 0.214 0.165 0.363 0.268 0.245 0.185 0.175 0.118 0.293 0.220 0.183
      0.349 0.317 0.267 0.483 0.414 0.349 0.318 0.208 0.132 0.426 0.368 0.232
      0.411 0.350 0.309 0.506 0.461 0.408 0.364 0.309 0.265 0.500 0.458 0.384
46    3     1     2     3     2     2     2     1     1     3     2     2
      4     4     4     5     5     5     4     3     3     6     3     4
      6     5     4     6     5     6     5     4     3     6     5     5
      0.458 0.328 0.414 0.535 0.553 0.349 0.253 0.343 0.372 0.386 0.430 0.385
      0.443 0.387 0.373 0.458 0.548 0.389 0.432 0.475 0.326 0.437 0.435 0.507
      0.515 0.455 0.384 0.528 0.454 0.493 0.360 0.522 0.322 0.403 0.409 0.574
47    1     0     0     1     1     1     1     1     0     3     2     2
      2     3     1     6     5     5     3     3     2     5     4     5
      3     4     3     6     6     6     4     3     2     6     6     5
      0.349 0.169 0.317 0.423 0.345 0.345 0.371 0.216 0.026 0.278 0.311 0.342
      0.353 0.325 0.320 0.476 0.480 0.356 0.375 0.307 0.210 0.398 0.327 0.313
      0.316 0.349 0.272 0.438 0.362 0.342 0.336 0.275 0.134 0.508 0.328 0.271
;;

proc print data=widePUPIL;
run;
/*It restructures a wide dataset to a long dataset*/
DATA longPUPIL;
  SET widePUPIL;
  ARRAY ascale(1:36) scale1 - scale36 ;
  ARRAY ar(1:36) r1-r36;
  DO condition = 1 to 36 ;
    scale = ascale(condition);
      r = ar(condition);
    OUTPUT;
  END;
  Drop scale1-scale36;
  DROP r1 - r36 ;
RUN;
PROC PRINT DATA=longPUPIL ;
RUN ;

/*One needs to do the z transformation, if the variables are correlations.
In this case, the variables are correlations. The correlations between the
subjective responses and pupil for EACH subject are computed, and analyzed.*/

/*This computes Pearson correlation coefficients and z-transformed
correlation coefficients (so that the coefficients are not skewed).One wants
to know only the correlation between the subjective response (scale) and the
change in pupil diameter(delta). */

proc corr data=longPUPIL outp = newdataset Fisher(biasadj=no);
var r;
with scale;
by subjectID;
run;

proc print data=newdataset;
run;
```

```
proc plot data= longPupil;
plot r * scale = '+';
run;

data temp;
set newdataset;
if _TYPE_ = 'MEAN' then _NAME_ = 'mean';
if _TYPE_ = 'STD' then _NAME_ = 'STD';
if _TYPE_ = 'N' then _NAME_ = 'n';
run;

proc print data=temp;
run;
proc sort data=temp;
by _NAME_;
run;

/*One wants to output correlation coefficients between scale and delta only*/
data temp2;
set temp;
if _NAME_ = 'scale';
output;
run;
proc print data=temp2;
run;
/* "To compute the correlation for each subject, z transform them, compute
and test the mean, and convert the mean back to the original metric." */
/*It computes the Fisher's z-transformation "manually" */
data temp2;
set temp2;
rz = .5*log((1+r)/(1-r));
run;
proc print data=temp2;
run;

/*This finds the mean correlation coefficient*/
proc means data=temp2;
var rz;
output out=means;
run;
/*This checks whether it is significantly different from 0. A simple t-test*/
proc univariate data=temp2;
var rz;
run;

/*This is a conversion back to the original metric*/
data means;
set means;
if _STAT_ = 'MEAN';
orig1 = ((exp(1)**(rz*2)-1)/(exp(1)**(rz*2)+1));
run;

proc print data=means;
run;
```

Appendix W – EMG data problems discussion

For each subject 36 files (12 seconds each) were recorded – one for each experimental condition. Each collected EMG file consisted of four columns of data: the elapsed time, the sync value, the voltage on channel 1 (right eye data), and the voltage on channel 2 (left eye data).

The elapsed time indicated the time between the start of the EMG recording and receiving the data from the Focus EMG Machine measured on the computer that ran the controls software. Note that the elapsed time was not the device's time. Every time the laptop received 600 data points from the EMG Machine, it recorded the elapsed time. Since data were transmitted in blocks, multiple data points had the same elapsed time, which to the data recording module on the host computer appeared like simultaneous data points. Therefore, elapsed time did not constitute a unique time stamp that could be used to align EMG data with other data signals.

The sync value was read directly from the EMG device and appeared to be a count of recorded data points. Once the sync value reached its maximum value of 2047, it was reset to zero (figure W1). In addition, since the constant sampling rate of 20 KHz was known, the sync value was equivalent to the device's time.

The main idea was to acquire and analyze the MAC indices (equation (3-2)) for glare and no-glare states (section 3.9). Unlike in the eye tracking data, in the EMG data the presence of physiological responses was not easily identifiable. After an initial examination, it was unclear which parts of the EMG signal actually represented the occurrence of glare source flashes.

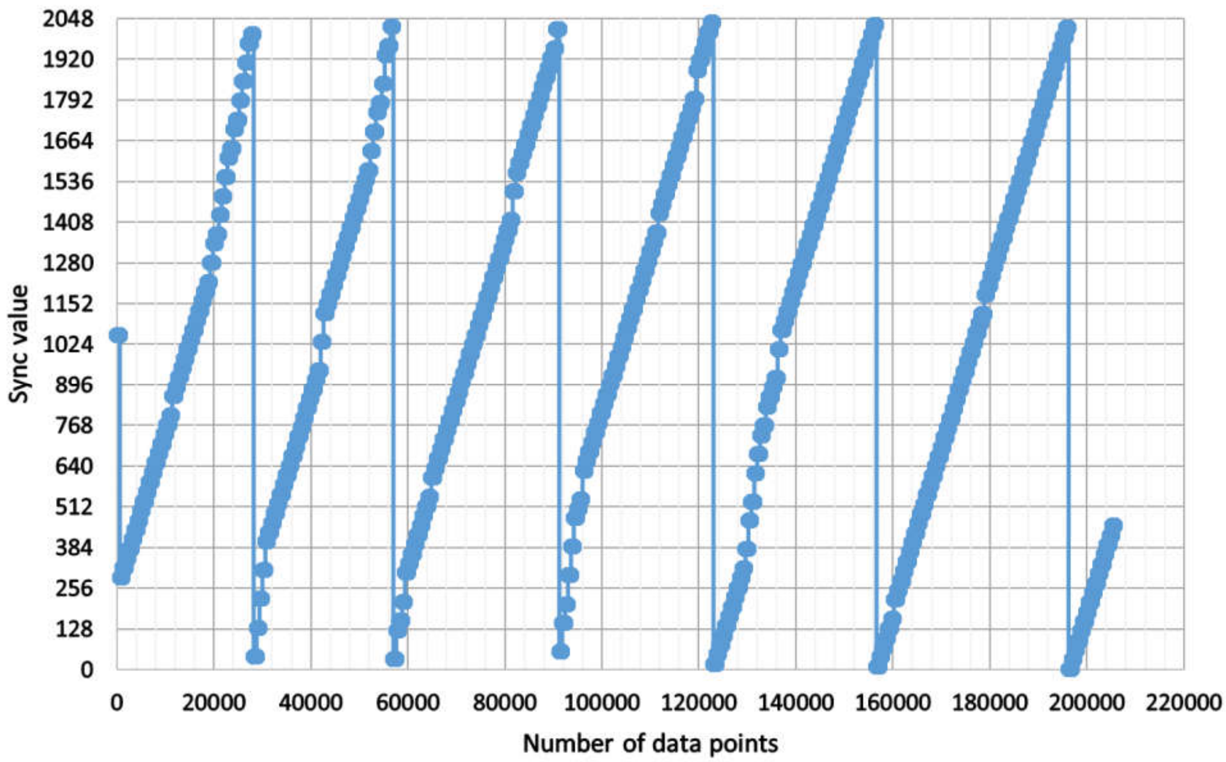


Figure W1. Sync values for one subject for one condition (Subject ID13, condition 6)

The EMG recording was programmed to start at 46.8 seconds (the 39th time step) (Figure 3-34), and stop at 58.8 seconds (the 49th time step) (12 seconds). This accurate timing should have allowed the alignment of all data signals, and thus, the computation of the MAC indices for the correct portion of the signal, i.e. during both no-glare and glare states. In Figure W2, the expected timing of the events is shown. Since a time step of 1.2 seconds was used, flashes were expected at 2.4-3.6 seconds, 4.8-6 seconds, and 7.2-8.4 seconds. In other words, since the EMG sampling rate was 20 KHz, flashes were expected during the following data point ranges: 48K-72K, 96K-120K, and 144K-168K. However, the files were inconsistent in the number of data points recorded, in other words, in the duration of the recordings (for example, Figure W3 and W4 – approximately 250,000 data points versus 215,000).

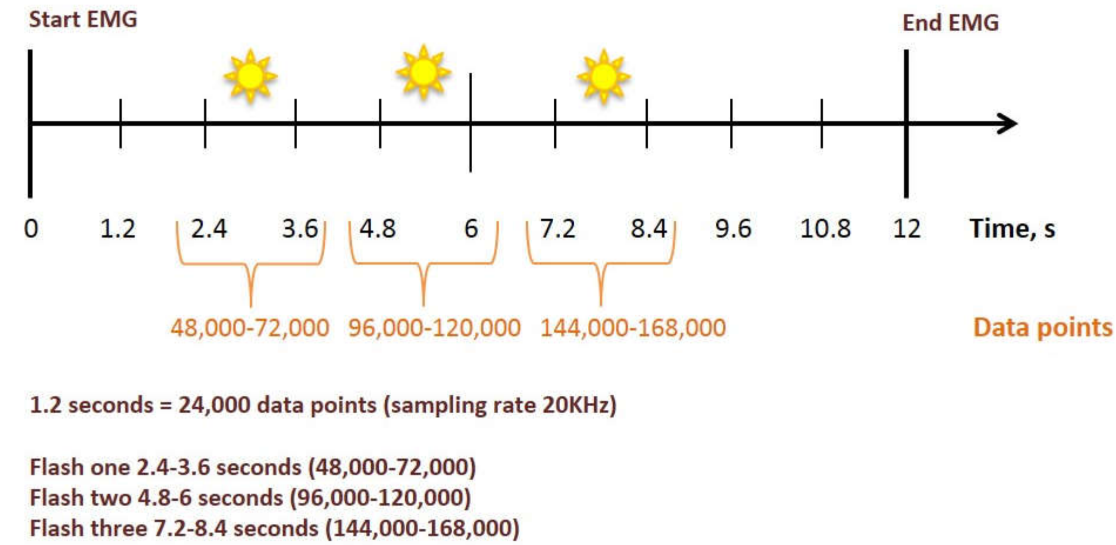


Figure W2. Expected timing of the EMG recording during one lighting condition

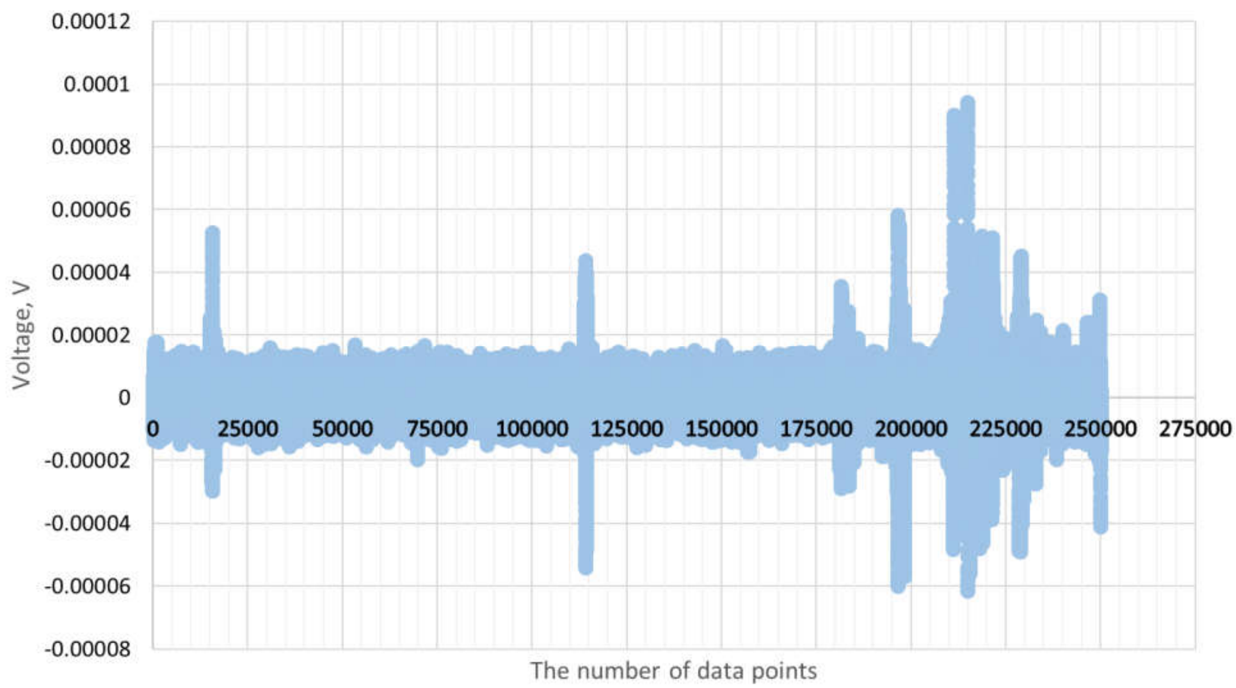


Figure W3. Number of data points in the EMG file for Subject ID5 condition 11

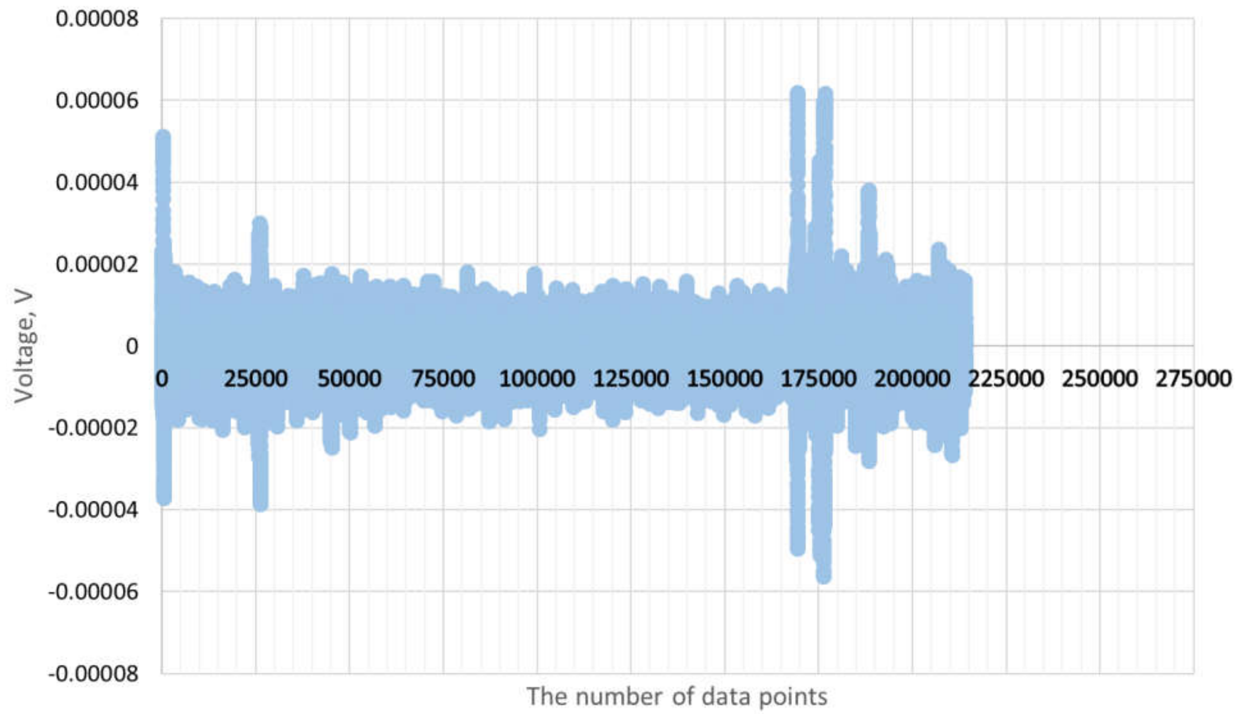
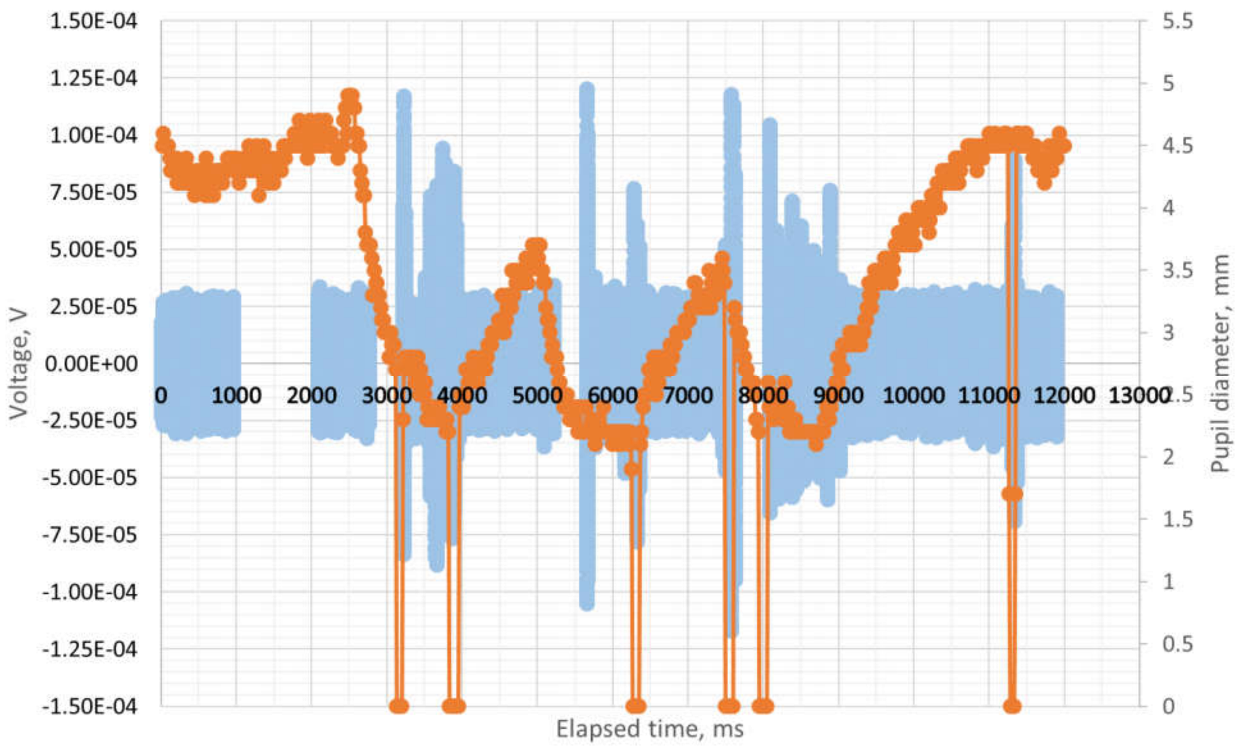


Figure W4. Number of data points in the EMG file for Subject ID18 condition 11

One reason for the variable number of sample points was missing data due to dropped data packages (see discussion below). The other reason was that delays could be introduced by aperture adjustments and inconsistent communication speed between the devices and the software. Even if the recording duration of the files were consistent, an error when compared to the expected timing would still occur. Each EMG file was recorded for 12 seconds. However, this did not mean that the first flash actually happened at precisely 2.4 seconds, because the aperture had to be adjusted to the setting specified for the condition under test. A large movement of the iris (fixation point to 10^{-4} sr solid angle state) takes more time to complete, and the introduced delay had the potential of shifting the location of the flash to a later point in time. The controls software's program flow did not specifically account for such hardware delays and executed all events strictly sequentially. Until the aperture adjustment was completed, the glare source would not flash, and, therefore, the flash could be shifted in time. This brought into question the exact timing of the stimuli. If one wants to calculate the MAC index during the first flash, the timing of when the flash actually occurred was crucial to know, which was not clear because of this timing issue.

A way to match the EMG signal with the flashes was attempted using the available eye tracking data. Despite the fact that the eye tracking files were manually recorded and were not accurately synchronized with the discomfort glare software due to human error, one could infer the occurrence of the flashes. In the eye tracking data flashes were clearly visible, which could be identified as a decrease in pupil diameter after accounting for the constriction latency of the pupil.

Eye tracking data were consistent in the number of total data points (720) across all files. If one could measure a number of points between the actual flashes, one could map them to time (1.2 seconds = 72 data points) (Figure 3-69). A translation of the number of data points into seconds allowed the creation of overlays of the eye tracking data over the EMG data as shown in Figure W5. Note, however, that the shown signals were not synchronized in time, which would have to be aligned in the next step. One might consider identifying and aligning the blinks. However, after an initial inspection of multiple EMG files, it was found that not all files exhibit easily identifiable blinks. In addition, missing data caused another problem with alignment, which leads to the second issue explained below.



FigureW5. Pupil data file overlaid on the EMG data (not synchronized in time) (subject ID 4, condition 28)

Unexpected pauses in the processing thread of the controls software affected the EMG data (Figure W6). It resulted in data loss between 10% and 20% because the chosen data structure for storing the EMG recordings caused data to be overwritten (in this case a hash data structure was used with the time stamp as hash key). Because the used hash key (the data's time stamps in this case) was not unique, data was overwritten when multiple data packages were received with the same time stamp. For example, if a data package was recorded at 12 milliseconds, then it would be stored at a location in the hash corresponding to 12 milliseconds. If another data package arrived at 12 milliseconds, it would overwrite previously stored data. The fact that there were randomly missing values meant that the use of MAC indices, which sum up a fixed number of values, would not produce reliable results since it is not a robust measure with respect to missing data points. In other words, the MAC index computed over 24,000 data points (1.2 seconds) was not guaranteed to capture the entire duration of the flash.

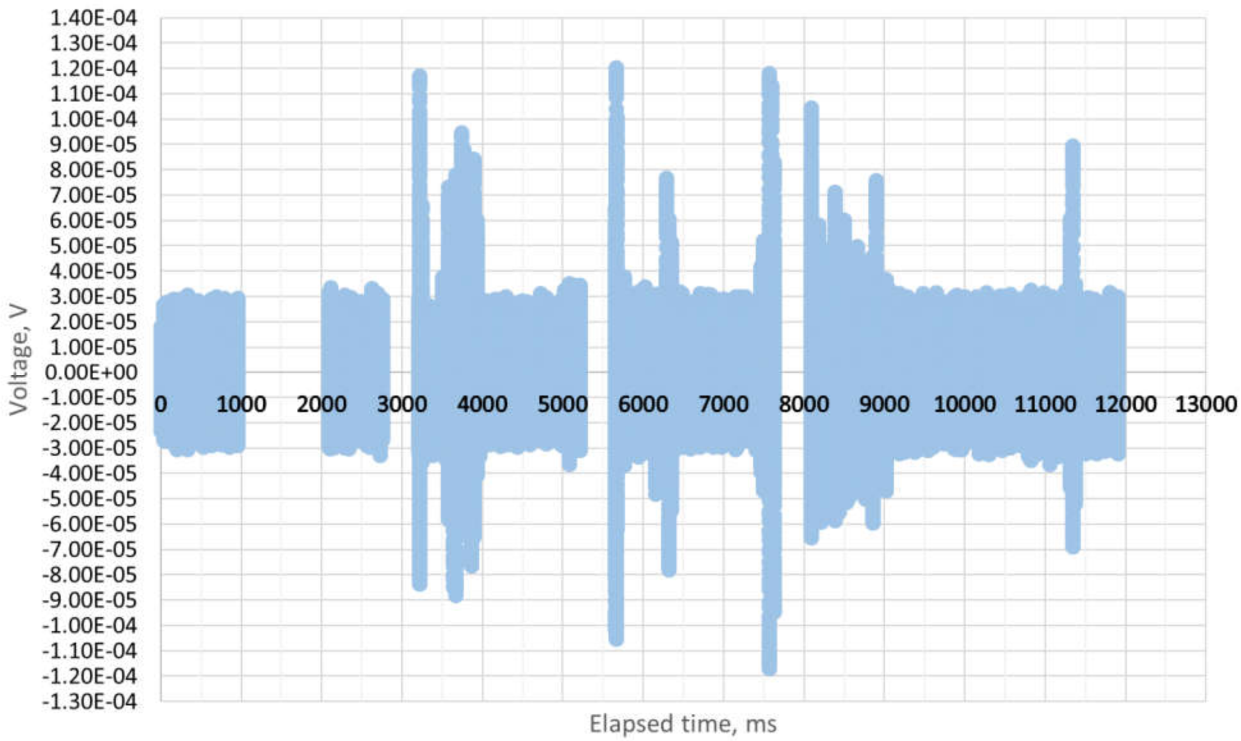


Figure W6. Example of the acquired EMG data plotted over elapsed time (Subject ID4 condition 28)

The final issue with the data was the uncertainty of whether the data were indeed raw, whether the desired processing on the device (such as filtering out 60 Hz components) was applied before transmitting data to the controls software, or whether an unknown processing step was performed on the device. Moreover, since third party development was not supported, the quality of the EMG data was unknown.

Berman and others indicated the importance of filtering out 60 Hz power line artifacts and frequencies lower than 10 Hz, because they contribute to a confounding response (1994). For the final recordings, low/high pass and notch filter settings were applied to the EMG data before data were transmitted and recorded. These filters are typically applied in the original EMG software that was shipped with the device. However, the question of whether the filters were actually applied was raised, when the following examination of the data was done. An FFT transform, which breaks down the signal into its sinusoidal temporal frequency components, was applied to the recorded signal in Matlab (Figure W7). As one can see from the figure, there was a dominant 60 Hz component in a supposedly processed file – the notch filter which filters out the 60 Hz component was clearly not applied to the signal on the device. Therefore, it is not clear which, if any, filters were applied prior to the transmission of data to the controls software.

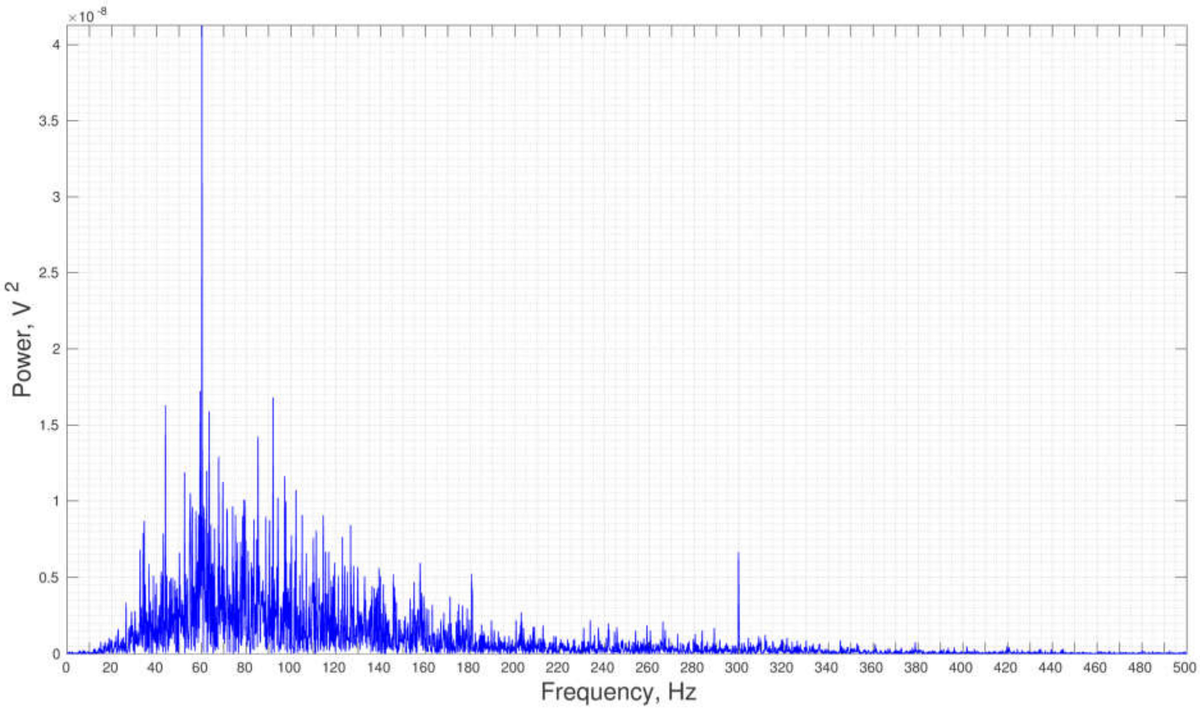


Figure W7. EMG file for one condition displayed as a frequency power spectrum

The initial idea was to integrate the EMG recordings into the glare software, such that these collected data could be compared to the subjective responses as well as the pupil data. Because of the uncertainty in the quality of the recorded EMG data, these data were not used in this research.