Lighting for Work: A Study of the Relationships among Discomfort Glare, Physiological Responses and Visual Performance

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Abstract

Objective measures of visual discomfort have the potential to quantify the individual's sensations under discomfort glare conditions although such measures have yet to be circumscribed. The present study aimed to examine the extent to which visual discomfort sensation can be both operationalised and measured, utilising many light-induced physiological measures. These measurements were coupled with visual performance evaluations, in combination with conventional measures of photometric measurements and subjective evaluations. The variables measured were mean Pupil Diameter, Pupillary Unrest Index, Blink Rate, Blink Amplitude, number of fixational eye movements during reading (Fixation Rate), and average Fixation Duration, as well as Combined Visual Performance. The results of this study indicate that most of these parameters show significant differences between high and low lighting conditions. In particular, participants in high discomfort conditions exhibited a higher Fixation Rate, lower Blink Rate, higher Blink Amplitude and a smaller Pupil Diameter than those in both low and medium discomfort conditions. In other words, the studied physiological measures can be used as an index of high levels of glare or visual discomfort. In addition, regarding subjective evaluations, the results of correlation analysis suggest that visual comfort level ratings may provide a more reliable indicator of visual discomfort sensation.

Keywords: Daylighting, Visual discomfort, Ocular behaviour, Objective assessment.

1 Introduction

Exposure to appropriate amounts of natural light elevates occupant mood, alertness [1, 2] and overall health, and reinforces synchronising of our circadian rhythms to day and night [3, 4]. The existing building practice represents a trend towards direct sunlight avoidance in order to ensure energy-saving and visual comfort. In contrast, more recent standards with a greater focus on occupant health and wellbeing, that is, the WELL Building Standard [5] and the new European standard (EN 17037) [6], require a minimum amount of exposure time to natural light in order to fortify occupant physical and psychological health. However, excessive sunlight remains problematic in terms of glare and undesirable visual discomfort.

In daylit workplaces, visual discomfort can occur due to glare, veiling reflections, shadows or too much non-uniformity in the created visual field [7]. Avoiding glare is considered as one of the key features in addressing visual discomfort in office buildings with high daylight availability and clear skies. This phenomenon can occur due to either high luminance contrast or an unsuitable range or distribution of luminance, leading to discomfort sensation in or around the eyes without necessarily impairing the vision [8, 9]. Hopkinson [10] proposed the first model to assess the perceived discomfort glare from windows by using the Cornell equation [10], which was later modified by Chauvel [11] and introduced as Daylight Glare Index (DGI):

$$DGI = 10 \times \log_{10} \left[0.478 \sum_{i=1}^n \left(\frac{L_{si}^{1.6} \cdot \omega_{si}^{0.8}}{L_b + 0.07 \omega^{0.5} \cdot L_{win} \cdot P_i^{1.6}} \right) \right] \quad (1)$$

L_{si} indicates the luminance of the glare source(s) (cd/m²); ω_{si} shows the solid angle subtending each source from the viewer's line of sight, and the position index of each luminaire (P_i); L_b is the luminance of the background (cd/m²); ω represents the solid angle of the window; and L_{win} is considered as the luminance of the window (cd/m²). This index is not related well with direct sunlight or interior specular reflection. In addition, it fails to perform well when the glare source fills almost the entire field of view or when the background luminance equals to the source luminance due to the focus on window luminance as a part of background luminance.

To account for DGI limitations, Wienold and Christoffersen [12] incorporated vertical eye illuminance (E_v) as an adaptation level into their equation and proposed the Daylight Glare Probability (DGP) index:

$$DGP = 5.87 \times 10^{-5} \cdot E_v + 9.18 \times 10^{-2} \cdot \log_{10} \left[1 + \sum_{i=1}^n \left(\frac{L_{si}^2 \cdot \omega_{si}}{E_v^{1.87} \cdot P_i^2} \right) \right] + 0.16 \quad (4)$$

Where E_v represents the vertical eye illuminance received from the light source (lux); P_i represents the position index with respect to the glare source; L_{si} indicates for the luminance of the source [cd/m²]; ω_{si} shows the solid angle of the source seen by an observer. DGP values ranging from 0.3 to 0.45 indicate the progression of glare evaluations from imperceptible glare to intolerable glare respectively. In addition, it can be interpreted as the percentage of people perceiving discomfort in a lighting situation [12].

Quantifying visual discomfort has been considered as a controversial and much-disputed subject within the field of lighting research [13, 14] despite myriad studies conducted on glare and visual discomfort [13, 15-19]. That is, in all existing models, the physical quantities of the luminous environment are attributed to discomfort sensation through psychophysical procedures such as subjective rating scales [20, 21]. Although subjective evaluations facilitate broadening research understanding of the topic, there is always a degree of uncertainty and bias associated with these subjective measures [22]. Further, the subjective perception of lighting environment has been argued to be inextricably interwoven with the subject's preferences, background, culture, and physiological differences, and is consequently susceptible to individuals' to [7, 23]. The inconsistency indicated by a number of validation studies [13, 14] has emphasised this deficiency. Thus, pairing subjective assessments with objective measures is suggested as the more promising research method [24-26] in order to quantify the individual's sensation under discomfort glare conditions and compensate for the subjectivity of glare perception.

Although the human visual system responses have been shown to be sensitive to the lit environment and could be considered as objective measures, to date, physiological measurement has received scant attention in the lighting research literature. Hamedani et al. [25] conducted a thorough review of physiological responses studied in lighting research as an objective measure of visual discomfort sensation. According to this literature review, measures of pupil size [27-35], eye movement [27, 36], eye blink [37] and degree of eye-opening [34, 38] have been investigated previously. Pupil size was shown to be sensitive to the overall background luminance and illuminance at eye level; however, relative measures of pupil size characterising pupil oscillation (fluctuations in pupil size) indicated a better correlation with subjective evaluations and glare indices. Further, they identified eye movements and spontaneous blink rate as potential indicators of visual discomfort; however,

more research was recommended in this regard. Finally, a holistic approach that includes two main objective measures, coupled with common methods in lighting research, light-induced physiological responses and visual performance, was suggested to overcome the limitations associated with the subjectivity and individuality aspects of visual discomfort evaluations [25]. Thus, in this research, this approach was undertaken in order to objectify the individual's visual discomfort sensation, which may provide a higher predictive reliability.

Visual performance has been defined as the speed and accuracy of performing a visual task. Speed and accuracy are considered primary requirements for worker productivity as they engage visual and motor factors of task performance [39]. To this end, Boyce et al. [40] utilised a timed vision test and recorded the accuracy and speed of performing the test as quantitative measures in their analyses. Despite the objective nature of task performance, to the best of our knowledge, no study has incorporated visual performance measures into physiological research.

To date, little experimental evidence has been reported on the full range of known light-induced physiological responses. The present study coupled a wide range of physiological measures and visual performance evaluations with the common lighting research method concerning photometric measurements and subjective evaluations. In particular, the present study focused on examining mean Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), number of fixational eye movements during reading (Fixation Rate) (FR), and average Fixation Duration (FD), as well as Combined Visual Performance (CVP). Therefore, this study is the first to bring together a wide range of objective, subjective and photometric measures. This holistic approach offers new insight into the application of objective measures in the assessment and prediction of visual discomfort, by advancing knowledge on various involuntary physiological responses and identifying the most sensitive indicators. Further, these indicators can create more definitive glare markers, which can in turn lead to the development of efficient predictive models and responsive lighting solutions.

2 Methodology

2.1 Experimental design

The present study sought to evaluate the effect of luminous conditions on involuntary physiological responses and performance among the participants. With this aim, a between-subjects experimental design was implemented, which included lighting conditions as between-subject factors at three levels. Each participant experienced one lighting condition, with either low, medium or high visual discomfort level. Repeatable lighting conditions under daylight were desirable for the experiment in order to select the best time of day and schedule data collections. However, actual lighting conditions were determined based on field measurements, not simulations. Three main daylight conditions were identified through a parametric lighting simulation for the estimated duration of data collection throughout the 8am-5pm working hours at 15-minute intervals. The simulations were performed using DIVA 4.0 for grasshopper, in Rhino. Three main repeatable lighting conditions were identified in these simulations, based on DGP as well as the adaptive levels introduced by the average luminance in the visual field (L_m) and the vertical illuminance at eye level (E_v). However, the experienced lighting conditions by each participant were finally identified based on field measurements and if there were observable changes in lighting conditions during the session, or if the measurements at the beginning and end of each session differed by more than 10%, those participants' data were excluded from the dataset. Lighting condition characteristics of the experiment based on the actual field measurements are listed in [Table 1](#). To avoid introducing confounds, the order of stimuli and the number of each gender allocated to experimental conditions were counterbalanced.

Table 1 Three main lighting condition characteristics

Lighting Condition	DGP	Average L_m [cd/m ²]	Average E_v [lux]
Low	<35	560	2100
Medium	35<DGP<40	810	3400
High	>45	1100	4800

The data were collected during the winter solstice (June in the Southern Hemisphere) (n=61), and summer solstice (December in the Southern Hemisphere) (n=37) with the sun in its lowest and highest elevations in the sky, respectively (see [Figure 1](#)).

Figure 1 Sun paths during the course of the experiments

2.2 Participants

Participants in this study were recruited from students and staff members of Griffith University, Australia. Primary inclusion criteria for the participants were age, vision health, and native language. To avoid age-related vision impairment, eligible participants were younger than 40 years and did not require corrective lenses. All participants were English native speakers to avoid biases associated with any lack of linguistic comprehension[41]. The Griffith University Human Research Ethics committee approved the experimental protocol, and volunteers were required to sign an informed consent form before starting the experimental session. A sample of 48 males and 50 females (total $n=98$) ranging from 18 to 36 years of age ($M=23.56$ years; $SD=4.81$ years) was recruited. Participants were randomly allocated to different lighting conditions.

2.3 Experimental setting

The experiment was conducted in an office with a north-west orientation, Gold Coast, Australia (latitude S $27^{\circ} 57' 47.3463''$; longitude E $153^{\circ} 23' 2.5444''$). The office (dimensions, L: $3.89 \times$ W: $5.16 \times$ H: 2.70 m) had a high window to wall ratio ($WWR = 0.24$) and two adjacent sides with glazing. The window contained a 6 mm single tinted glass pane with visible transmittance (VT) of 46%. The white wall and ceiling (80% reflectance) and dark grey carpet flooring representing typical material utilized in offices in Australia. The only

light source in the space was daylight coming through 1.66 m high windows. The location of the office on the third floor and the low-density built area setting removed any impediment to maximising access to sunlight. Participants performed the required tasks using a DELL all-in-one PC with a 23.8" display. The workstation was located next to the window, and the user was seated facing the window at a distance of 1.2 m. The office layout was unchanged for the duration of the experiment (see [Figure 3 \(b\)](#)).

2.4 Measurements

2.4.1 Photometric measurements

Luminance values were captured at the beginning and end of each experimental session, using high dynamic range (HDR) imaging by means of a Canon EOS 5D MARK III digital camera with a full-frame CMOS (36.0x24.0) sensor, and the EF 8-15mm f/4L fisheye USM lens. The fisheye lens is an L-type fisheye zoom lens producing circular and full-frame images with 180° diagonal angle of view and equisolid-angle projection type. In obtaining luminance maps, a sequence of 15 multiple exposure low dynamic range (LDR) images was captured at one exposure value (EV) intervals (ranging from 1/1000s - 5s). Simultaneously, the luminance of the target (measured at 1°) and vertical illuminance at camera lens level (the camera height was levelled with the height of the participant's eye after they adjusted their seat behind the desk) were recorded at the beginning and end of each sequence. To this end, a Konica Minolta spot luminance meter LS-100 (accuracy: $\pm 2\%$ at 1°), and Konica Minolta illuminance meter T-10MA (linearity: $\pm 2\%$) which were fitted with automatic calibration and auto range function were employed. In addition, a mid-range aperture size of F/11 was kept constant for all images in order to address the issues associated with small and large aperture sizes [42-44].

The calibration process included capturing multiple exposure images and selecting appropriate images, deriving camera response curve, generating HDR image, adjusting calibration by measuring luminance, correcting vignetting effect, and geometrical re-projection [44]. In the next procedure, glare assessments were performed using *Evalglare*, a Radiance-based command-line program, and validated for research purposes [45]. Since average task-zone luminance is recommended as a threshold luminance for VDT (visual display terminal) tasks [12], a target task-zone with an opening angle of approximately 0.55sr was employed to address the majority of the computer screen area. Also, the glare source was

identified as pixels with a luminance value four times higher than the average task-zone luminance.

Furthermore, the vertical illuminance values were utilised to confirm the calculated metrics using calibrated HDR images. It is expected that the measured vertical illuminance should equal to the calculated vertical illuminance at the camera lens, in this study, the average error between calculated and measured illuminance values was about 4%, and the maximum error was 10% (see Figure 2) which is within the acceptable range [46]. Using the output text file generated by *Evalglare*, luminance values, and discomfort glare indices were utilised in the analysis.

Figure 2 Measured vertical illuminance at the camera lens vs Evalglare calculated vertical illuminance from DHR images

2.4.2 Physiological measurements

The eye-tracking device used in the present study was Tobii eye-tracking glasses (see Figure 3 (c)) which are wearable, lightweight, discreet binocular eye-trackers. The function of Tobii glasses is based on a corneal reflection eye-tracking technique [47]. This device allows ocular data such as eye movements and pupil diameter to be recorded at a rate of 100 Hz.

Figure 3 (a) A participant wearing an eye-tracker, focusing on the target as a part of the calibration process; (b) the section showing the experimental office and the approximate position of the participant; (c) the full HD scene camera and two IR cameras; (d) recorded video and eye images during the calibration process.

2.5 Experimental protocol

The study was conducted in individual experimental sessions of about 30 minutes. After entering the test office, participants were asked to read the information about the research and sign the consent form. At the beginning of each session, photometric measurements were performed and used to calculate DGP.... to capture the characteristics of the luminance field. Then participants were instructed to wear the eye-tracking glasses and adjust their seat and position behind the desk (see Figure 3 (a)). The entire test procedure, including eye-tracking calibration, instructions on how to perform the task, main experimental segments (simulated office tasks and timed vision test), and subjective surveys, was automated using C# programming language. The calibration process took about 3 minutes and included the calibration of the eye-tracking device (the calibration method was integrated into task sequences; see Figure 3 (d)) and instructions on how to proceed with experimental tasks. Following this step, participants responded to a series of demographic questions before

commencing the main tasks. This would permit accustomization to wearing the glasses and proper visual adaptation to the luminous environment.

Figure 4 Experimental procedure

A sequence of tasks was designed to provide a variety of task demands (motor, visual and cognitive) and collect related data regarding each independent variable (see [Figure 4](#)). The main tasks comprised of two blocks, which were randomly ordered. The first block, which consisted of reading, thinking and a comprehension segment, was designed to simulate everyday office tasks provided with explicit instructions. The reading text and the ensuing comprehension test were selected from the Science Research Associates Reading Laboratory (SRA) materials [48], which are graded standard reading and comprehension tests. In this experiment, a low level of difficulty was chosen to avoid task difficulty and content biases [49]. After reading the passage, the monitor went black for 90 seconds, and as directed prior to the test, participants randomly directed their gaze while considering the text they had read. This segment aimed to introduce a non-attention-demanding task to examine user natural ocular behaviour, necessary because visual tasks can alter natural user behaviour and physiological responses [50]. Although writing is an essential component in office tasks, it was not included in this experiment. This decision was made after the trial experiments which revealed that most users were looking at the keyboard while typing, resulting in a significant part of the eye-tracking data being lost due to the position of the eyelid. In addition, the large change in view direction (from towards the monitor to the keyboard) would affect the amount of light received by the eyes. Consequently, the light-induced physiological responses, which are the main objective of this research, could not be considered valid as responses to the measured lighting condition.

The second block included a timed vision test to evaluate user visual performance. In this segment, participants indicated the direction of the opening in a Landolt ring using the arrow keys on the keyboard, and the speed and accuracy of their responses were recorded automatically in an output text file. The Landolt rings were presented one at a time and varied in luminance contrast and direction at each presentation on the screen.

3 Dependent variables

The multidimensional approach was based upon physiological measures, visual performance and subjective responses. Physiological measures were selected according to their sensitivity and reliability in detecting visual discomfort sensation or fatigue. One combined measure of visual performance was captured for each participant. Subjective responses were collected at different steps of the experiment utilising questionnaires comprised of demographic questions, visual discomfort and glare ratings, and the Conlon [51] questionnaire.

3.1 Physiological measures

The six light-induced physiological responses investigated in this research, Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), Fixation Rate (FR) and Fixation Duration (FD), are outlined below:

3.1.1 Pupil size

The human visual system adapts to various lighting conditions through either pupil constriction or dilation known as pupillary light reflexes (PLR). The absolute pupil size characterises the light level to which eyes are adapted. The instability in pupil size in constant lighting conditions, known as pupillary unrest has been referred to as one of the visual discomfort sensation symptoms in a few studies [28, 29].

Recorded pupillary signals by the eye-tracker were pre-processed based on the method introduced by Kret et al. [52]. The process included four main steps: preparing the raw pupil signals for processing; extracting the valid sample subsets via filtering; smoothing and up-sampling the valid samples; and dividing the data into the defined segments for further individual analysis [52]. The mean of pupil diameter values (mm) was calculated for the reading segment with the aim of determining the effect of lighting conditions on pupil diameter (PD).

3.1.2 Pupillary unrest index

Concerning pupil fluctuation over time, pupillary unrest index (PUI) was used to measure pupillomotor instability by calculating the aggregate of pupil diameter changes during a segment based on a sampling frequency of 1.56 Hz [28, 53]. Strong pupil oscillations resulted in greater PUI values. The adapted formula of the PUI for 100 Hz sampling rate is:

$$PUI = \frac{1}{(N-64) \cdot \Delta t} \cdot \sum_{i=2}^N |d_i - d_{i-1}|$$

(1)

Where N is the total number of samples and d_i is the average for periods of 64 consecutive values.

3.1.3 Eye blinks

The eye blink, the eyelid being swiftly shut and reopened, is widely accepted as an indicator of visual fatigue [54, 55]. Previous research has established that spontaneous blinking is highly task-dependent [50, 56], with the lowest Blink Rate (BR) and Blink Amplitude (BA) during a computer-based reading task. This deceleration in BR can, in turn, increase the corneal exposure [56], recognised as a contributor to visual fatigue. For this reason, BR and BA were considered during both the reading phase (visually focused task) and the ensuing thinking phase (non-visually focused task) afterwards.

BR and BA were extracted from the recorded pupillometry signals based on a method proposed by Hershman et al. [57]. In this method, blink onset and offset are detected based on the noise the closing of the eyelid closer creates in pupil size signals. Using this data, BR was then calculated as the number of blink events per minute, as was BA as the average blink durations for each task segment.

3.1.4 Fixational eye movements

Fixation, which is the unvaried alignment of the visual axis on a particular point, is a previously used measure of reading performance [58]. The eye fixations were identified using the Tobii I-VT filter, which is a velocity-based classification algorithm. This filter classifies eye movements based on the angular velocity of the gaze shifts [59]. For this research, the angular velocity threshold was set to 100 degrees per second ($^{\circ}/s$). Afterwards, fixations shorter than 60 milliseconds (ms) were discarded and fixations closer than 75 (ms) in time and 1 ($^{\circ}$) in space were merged. Fixation Duration (FD) was defined as the average dwell

time (ms) of fixations, and Fixation Rate (FR) as the number of fixations per line occurring in reading segment.

3.2 Performance measure

In the vision area of research, reduction in (visual) performance has been addressed as an objective counterpart for visual discomfort [60]. The design of the performance measures, in this study, allowed quantitative measurements of motor and visual elements of computer-based tasks.

3.2.1 Timed vision test

Reaction time and accuracy are two main features in visual performance measurements [40, 61, 62]. A timed vision test was designed to measure user reaction time and accuracy in the experienced experimental condition. In this test, a Landolt ring was presented in the centre of the computer screen to the participant, varying in luminance contrast (from 1.2 to 2.55) and direction (with an opening at either right, left, top or down, in random order). For each presentation, participants were required to indicate the orientation of the opening on the Landolt ring and the reaction time and whether the answer was correct or not were recorded. Time and accuracy then coalesced into one dependent variable as total correct identifications/total reaction time.

3.3 Subjective responses

To evaluate the participant's impression of perceived lighting condition, a screen-based questionnaire was utilised comprised of three main parts. The demographic segment constituted part 1, which was performed at the beginning of the experimental procedure, and included questions about gender, age, the wearing of sunglasses. After performing experimental tasks, each participant was required to respond to questions in parts 2 and 3. Questions in part 2, rated lighting conditions according glare categories, adapted from the four used by Osterhaus and Bailey [21]: imperceptible, perceptible, disturbing, intolerable. It was necessary to avoid the potential overestimation inherent in the Osterhaus and Bailey study [22] since the lowest level of perceived glare corresponds to "imperceptible" and cannot be interpreted as no glare. This lowest category was removed in the present study, and instead the subjects were asked whether they were experiencing glare; if they selected "yes", they were required to make glare magnitude associations based on an adapted three-point scale (perceptible, disturbing and intolerable), accompanied by a description of each category to minimize ambiguity and misinterpretation, as in the methods adopted by Ngai and Boyce

[63] and Osterhaus and Bailey [64]. Furthermore, participants were required to rate the lighting condition comfort level on a 5-point scale, with 1 being very comfortable. Questions in this part were asked in randomized order.

Part 3 consisted of a two-parameter Rasch Rating Scale questionnaire based on a method introduced by Colnon et al. [51] to evaluate visual discomfort. The test was developed based on Wilkins [65, 66] and Irlen's [67] conceptualizations of visual discomfort in order to predict perceptual (e.g., flicker or perception of colour despite the patterns being monochromatic) and somatic (e.g. irritated or fatigued eyes) side-effects, as well as performance difficulties when processing text. According to Conlon et al.'s study, it was expected that participants with higher scores would exhibit greater somatic and perceptual adversity and lower reading performance than lower scoring participants [51]. While author's work was based on reading from a paper, in this research the validated questionnaire was adapted for reading from a screen where applicable. At the end of the experimental session, participants answered these questions and the score for each participant was calculated for analysis.

4 Results

This study set out to assess the extent to which visual discomfort sensation can be operationalised as an objective measure, through a multi-dimensional method employing physiological measurements and visual performance. To this end, the first set of analyses examined the impact of experimental conditions on each physiological measure as well as on visual performance. Further statistical tests examined the relationship between subjective responses and photometric measurements, glare indices, and physiological responses. Together, these results provide important insights into the effect of lighting conditions and visual discomfort on the studied physiological responses.

4.1 Statistical method

The analysis was conducted using SPSS Version 22. Descriptives were run to produce demographics and data checks. Assumptions for independent *t*-tests and one-way, between-subjects Analysis of Variance (ANOVA) were assessed. Shapiro-Wilk and histograms assessed the assumption of normality; Levene's test assessed the homogeneity of variance for both *t*-tests and ANOVAs. Boxplots were produced to identify any extreme outliers across

groups on each Dependent Variable (DV), and any extreme outliers ($>1.5 \times$ interquartile range) were examined to determine whether they were likely to result from equipment/data entry error. No cases were deemed to be due to error, and thus, no data were excluded.

In the first part of the subjective survey (see [section 3.3](#)), participants verified whether they often wear sunglasses as an indicator of being sensitive to bright light, i.e. assuming that people who normally wear sunglasses were more sensitive to bright light. Preliminary analyses of this parameter consisted of a 2 (sensitive to bright light: yes/No) $\times 2$ (experience of glare: none, perceptible/ disturbing, intolerable) chi-square contingency table to assess whether there was a relationship between participants sensitive to bright light and their subjective experience of glare. Phi (Φ) was used as an effect size. A series of independent t -tests were also run to assess whether there were any gender differences across any of the DVs. Cohen's d was used as an effect size for significant t -tests. An alpha level of 0.05 was used in all statistical significance tests.

The analysis consisted of a series of one-way ANOVA tests to determine whether physiological responses differed between the treatment levels. Treatment level was the independent variable (IV), with three glare condition levels: (i) low ($n = 35$), (ii) medium ($n = 30$), and (iii) high ($n = 33$). Seven separate ANOVAs were run, each assessing a different DV: (i) Fixation Rate (FR), (ii) Fixation Duration (FD), (iii) Blink Rate (BR), (iv) Blink Amplitude (BA), (v) Pupil Diameter (PD), (vi) Pupillary Unrest Index (PUI), and (vii) Visual Performance (CVP). Where initial F statistics were found significant, η^2 was used as effect size and Tukey's test was run to assess differences between specific groups. Cohen's d was utilized as an effect size for *post hoc* differences.

4.2 Data Checks

Shapiro-Wilk revealed normality violations for the following DVs/groups: FD, low glare, $W(35) = 0.21$, $p = 0.001$; FD, medium glare, $W(30) = 0.18$, $p = 0.02$; BA, low glare, $W(35) = 0.19$, $p = 0.004$; PUI, low glare, $W(35) = 0.18$, $p = 0.006$; PUI, medium glare, $W(30) = 0.18$, $p = 0.02$). All other groups achieved normality on other DVs (all other $ps > 0.05$). Visual inspection of histograms revealed that all but two groups (FD, low and medium glare) appeared to be approaching normality. However, ANOVA is robust to violations of this kind when group sizes are approximately equal across conditions [68]. Consequently, analysis continued without transformation. Levene's test revealed that the assumption of homogeneity of variance was satisfied across all DVs (all $ps > 0.05$).

Table 2 shows the means and standard deviations of each DV across treatment levels. As shown, CVP was the highest in the medium group, and mean PD was smallest in the low glare condition.

Table 2 Means and standard deviations for each DV between treatment levels

Dependent Variable	Treatment level		
	Low Glare Mean (SD)	Medium Glare Mean (SD)	High Glare Mean (SD)
Fixation Rate (Fixations per Line)	8.80 (2.76)	8.86 (3.28)	11.97 (3.95)
Fixation Duration (milliseconds)	744.71 (436.84)	642.36 (299.38)	592.25 (283.04)
Blink Rate (Blinks per minute)	12.70 (6.23)	12.43(5.10)	8.65 (3.90)
Blink Amplitude (seconds)	0.25 (.09)	0.31 (.10)	0.38 (.13)
Pupillary Unrest Index (millimetre per minute)	3.69 (1.37)	3.60 (1.02)	4.38 (1.30)
Pupil Diameter (millimetre)	2.69 (.23)	2.58 (.21)	2.50 (.20)
Combined Visual Performance	1.44 (.34)	1.37 (.30)	1.17 (.31)

4.3 Physiological responses

A one-way, between-subjects ANOVA was run to assess the differences in physiological responses between treatment levels. Concerning Fixation Rate (FR), results showed there was a significant difference between the groups with a medium effect size ($F(2, 93) = 9.26, p < 0.001, \eta^2 = 0.17$). Tukey's HSD revealed that participants in the high discomfort condition ($n = 31, M = 11.97$) recorded significantly greater FR than the medium condition with large effect size ($n = 30, M = 8.86, p = 0.001, d = 0.86$), and the low condition with large effect size ($n = 35, M = 8.80, p = 0.001, d = 0.93$; see Figure 5 (a)). No difference was observed in FR between those in the low or medium discomfort conditions. Regarding the average Fixation Duration (FD), the ANOVA test showed no significant differences between the groups ($F(2, 93) = 1.62, p = 0.20$), indicating that the FD is not affected by lighting conditions. As such, no further analysis was conducted on this variable.

The ANOVA test results on Blink Rate (BR) and Blink Amplitude (BA) suggested there were significant differences between the groups, with a small ($F(2, 92) = 5.82, p = 0.004, \eta^2 = 0.11$), and medium effect size ($F(2, 92) = 13.26, p < 0.001, \eta^2 = 0.22$), respectively. Further, Tukey's HSD test revealed that the BR frequency for those in the high discomfort group ($n = 30, M = 8.65$) was significantly lower compared to those in the medium with large effect size ($n = 30, M = 12.43, p = 0.02, d = 0.83$) and low discomfort groups with medium effect size ($n = 35, M = 12.70, p = 0.01, d = 0.78$). Additionally, participants in the high

discomfort group ($n = 30$, $M = 0.38$) recorded longer BA than those in the medium group with medium effect size ($n = 30$, $M = 0.31$, $p < 0.001$, $d = 0.69$) and low group with large effect size ($n = 35$, $M = 0.25$, $p = 0.02$, $d = 1.25$). No significant difference was observed in BR and BA between the low and medium discomfort conditions (see [Figures 5 \(b & c\)](#)).

As for the mean PD and Pupillary Unrest Index (PUI), the ANOVA results showed significant differences between different lighting conditions with a small effect size: $F(2, 92) = 0.63$, $p = 0.54$, $\eta^2 = 0.12$, and $F(2, 92) = 3.58$, $p = 0.03$, $\eta^2 = 0.07$, respectively. Further, the results of Tukey's HSD test revealed that participants in the high discomfort group ($n = 30$, $M = 2.69$) recorded a smaller mean pupil diameter than those in the low group with large effect size ($n = 35$, $M = 2.69$, $p = 0.001$, $d = 0.88$), while this was not the case for the medium group ($p > 0.05$). There was no significant difference between the medium and low discomfort groups ($p > 0.05$; see [Figure 5 \(d\)](#)). Regarding PUI, the Tukey's HSD test revealed that PUI was significantly higher in the high discomfort ($n = 30$, $M = 4.38$) condition compared to the medium condition, medium effect size ($n = 30$, $M = 3.6$, $p = 0.045$, $d = 0.67$), but not in the low discomfort condition ($p > 0.05$). Finally, no difference was observed between the medium and low discomfort conditions ($p > 0.05$; see [Figure 5 \(e\)](#)).

Figure 5 Physiological responses by treatment level: (a) Fixation Rate (FR), (b) Blink Rate (BR), (c) Blink Amplitude (BA), (d) Pupil Diameter (PD), (e) Pupillary Unrest Index (PUI); error bars are 95% CI.

4.4 Performance score

A one-way, between-subjects ANOVA was run to assess the differences in participants' Visual Performance (CVP) in different lighting conditions. Results showed there were significant differences between the groups with a small effect size, $F(2, 64) = 4.44$, $p = 0.02$, $\eta^2 = 0.12$. Tukey's HSD test revealed that respondents in the high discomfort group ($n = 23$, $M = 1.17$) recorded a smaller CVP score than those in the low group (large effect size ($n = 23$, $M = 1.44$, $p = 0.02$, $d = 0.83$)), but not the medium discomfort group ($p > 0.05$). There

was no significant difference between the medium and low discomfort groups ($p > 0.05$; see Figure 6).

Figure 6 Combined Visual Performance (CVP) by treatment level. Error bars are 95% CI.

4.5 Subjective responses

Participants were asked to answer questions regarding their visual environment, and rate their perceived visual comfort and discomfort glare levels (see section 3.3, Questions in part 2). Bivariate correlations were undertaken between these subjective responses and photometric measurements as well as physiological variables. There were statistically significant positive correlations between perceived visual comfort level and the main photometric variables contributing to glare sensation, that is, luminance of the glare source ($r = 0.54, p < 0.0001$), task luminance ($r = 0.50, p < 0.001$), illuminance at eye level ($r = 0.47, p < 0.0001$), average luminance ($r = 0.45, p < 0.0001$). There were also relationships between perceived visual comfort level and most glare evaluation metrics, including Daylight Glare Probability (DGP) ($r = 0.51, p < 0.0001$), Daylight Glare Index (DGI) ($r = 0.46, p < 0.0001$) and Visual Comfort Probability (VCP) ($r = -0.45, p < 0.0001$). Among physiological responses PUI, ($r = 0.32, p < 0.003$) was associated with perceived visual comfort level, followed by mean PD ($r = 0.30, p < 0.005$).

Surprisingly, subjective discomfort glare evaluations were not significantly correlated with any photometric measurements or glare metrics. This result indicates that participants may have had a different impression of the meaning of glare, although a clear definition of glare was given at the beginning of the questionnaire. Further analyses explored whether the fact that participants sensitivity to bright light had any impact on their experience of glare or comfort levels during the experiment. A Chi-square contingency table revealed that there was a significant relationship between the likelihood of respondents reporting the regular wearing of sunglasses and their subjective ratings of glare experience with small effect size, $X^2(1, N = 98) = 8.31, p = 0.004, \Phi = 0.29$. As shown in Table 3, participants who wore sunglasses

regularly were also more likely to report perceiving glare, whereas those who did not report wearing sunglasses were less likely to report perceiving glare.

Table 3 2 x 2 Contingency Table for Sunglasses and Perception of Glare

			Was participant sensitive to bright light?	
			Yes	No
Experiencing glare	None	Count	28	11
		Expected	33	6
		Std. Residual	-0.9	2.1
	Perceptible	Count	55	4
		Expected	50	9
		Std. Residual	0.7	-1.7

An independent samples *t*-test explored whether the comfort level of participants in response to glare differed between those who reported regularly wearing sunglasses and those who did not. Noting a discrepancy in the size of each group (were sensitive to bright light $n = 83$; were not sensitive to bright light $n = 15$), Levene's test was run to determine whether variance differed significantly among the groups. Levene's test was non-significant ($F = 1.55, p = .22$), and as such an independent *t*-test was used. Results showed that there was no significant difference between those who were sensitive to bright light ($M = 2, SD = 1.1$) and those that were not ($M = 1.93, SD = 0.88$) on level of visual comfort, $t(96) = 0.221, p > 0.05$. Thus, the participant's glare rating was affected by their sensitivity to bright light, which can explain the inconsistency between the results of two subjective ratings. In other words, more sensitive participants were more likely to consider a bright light as a source of glare. However, sensitivity appeared not to affect a participant's judgement about the comfort level stemming from the brightness and/or contrast.

At the end of the experiment, participants were required to answer a questionnaire adapted from Conlon et al. [51] to evaluate visual discomfort through perceptual and somatic questions (see [section 3.3](#), Questions in part 3). Bivariate correlation analysis between the Conlon test score and photometric measurements shows that this score was positively associated with the main photometric variables, that is, luminance of the glare source ($r = 0.34, p < 0.004$), task luminance ($r = 0.38, p < 0.002$), illuminance at eye level ($r = 0.32, p < 0.009$) and maximum luminance ($r = 0.43, p < 0.0001$). The Conlon test score also had statistically significant positive correlations with FR ($r = 0.34, p < 0.005$), BA ($r = 0.33, p < 0.007$) and PUI ($r = 0.33, p < 0.006$). Taken together, these results suggest that among three main types of subjective ratings (visual comfort level rating, discomfort glare rating and

Conlon questionnaire) visual comfort level rating might be a more reliable indicator in reflecting visual discomfort sensation.

4.6 Confounding variables

There are two main groups of confounding variables in this research: variables affecting studied light-induced physiological responses and individual differences of respondents.

The human physiological responses to light are not purely reflexive. Other factors, such as cognitive load and task difficulty can also affect pupillary reflexes and blink rates [25]. In this research, task-induced responses were controlled through meticulous experiment and task design (see [section 2.5](#)). However, there are other ocular behaviours such as eye convergence that can affect pupil size and are not controllable. When the eyes converge, the lens thickens, and the pupils constrict to give a greater optical depth of field. When a monitor screen (which is a plane at a fixed distance) is viewed, the ‘near triad’ should be as stable as possible. If it is not stable, there will be a need to correct any diplopia (double image due to misconvergence on a depth plane) for the concomitant blurring (lens needs to be adjusted). Thus, the valid pupil data subsets were explored for changes due to eye convergence, and if it was the case, those data were removed accordingly.

As to individual differences, a participant’s age, occupation and gender were factors that could affect the results of this research. The effect of age on a participant’s vision condition was controlled by limiting the eligible age group (see [section 2.2](#)). All participants were university students or staff accustomed to computer-based tasks of this nature. To account for the effect of gender on dependent variables, a series of independent *t*-tests were run. Results showed that the FR value was significantly larger for females than for males with a medium effect size, $t(94) = 2.42$, $p = .02$, $d = 0.5$. The average FD was also significantly shorter for females than for males, with a medium effect size, $t(94) = 2.1$, $p = 0.04$, $d = 0.43$. There was no significant difference found across genders for BR, BA, PUI, mean PD or CVP (all $ps > 0.05$). The study findings warrant further research into these variables; given the equal numbers of males and females, the research validity is unaffected.

5 Discussion

The present study was designed to determine the effect of lighting conditions on involuntary physiological responses, subjective responses and visual performance. Physiological

responses included Fixation Rate (FR), Fixation Duration (FD), Blink Rate (BR), Blink Amplitude (BA), Pupil Diameter (PD), Pupillary Unrest Index (PUI), and Visual Performance (CVP).

The current study found that the FR was significantly higher under high discomfort glare conditions, by indicating that participants exhibited a higher number of fixations when reading under high discomfort glare. Given that saccades are **strongly connected to fixations**, **lower** fixation frequency results in fewer saccades and consequently higher reading performance. However, no significant change was observed in the Fixation Duration (FD) for any of the groups, suggesting that this variable may not be influenced by the changes in levels of the glare in the present study, and instead may be more attributed to extracting visual or linguistic information. This finding to some extent is consistent with that of Siegenthalez et al. [69] and Vaughan et al. [70], who found fixation duration to be a measure of legibility, associated with cognitive processing time.

Concerning BR and BA, results suggested there were significant differences among the groups, with a small, and medium effect size, respectively. BR frequency for those in the high discomfort group was significantly lower compared to those in the medium and low discomfort groups. In accordance with the present results, previous studies have demonstrated that a decreased BR was observed under higher levels of luminance. As spontaneous eye blinking is a mechanism in the human body to maintain a healthy ocular surface and clarity of vision, a lower blinking frequency can result in a higher rate of tear evaporation and possibly dry eyes [56]. However, this finding did not support the previous research of Doughty [37] who found that the presence of a glare source can increase spontaneous eye blink rate [37]. This discrepancy could be attributed to the type of task that participants were performing at the time of measurement, as a lower BR is expected while reading, compared to while sitting or in conversation [37]. On the question of BA, this study found that participants in the high discomfort group recorded longer BA than those in the medium and low group. This result seems to be consistent with other research which found longer blink duration to be linked with visual fatigue [71, 72].

Pupillary light reflex, as an adaptive response, regulates the amount of light reaching the retina by controlling pupil size. Consistent with the literature (Stringham et al. [33] and Lin et al. [27]), this research found that participants experiencing higher discomfort glare exhibited smaller PD. This more indicates the light level to which the eyes are adapted, and could be

interpreted as a higher potential for visual discomfort sensation rather than the pupil size being a direct result of discomfort sensation. Surprisingly, in this research, no difference was found between the medium and low discomfort groups. These results are likely to be related to the small difference between the background luminance of the low and medium experimental conditions and are in line with early findings of Hopkinson [32], later confirmed by Tyukhova et al. [31], wherein background luminance was the predominant factor attributed to pupil constriction.

Results concerning the Pupillary Unrest Index (PUI) which represents pupil size instability suggest that participants in the high discomfort condition exhibited significantly greater PUI compared to the medium group. This indicates that spontaneous pupillary oscillation increases significantly when a glare source entails a high level of discomfort. This finding confirms Hopkinson's [32] observation of cyclical variation in pupil diameter.

Visual performance was studied using a combined score calculated from the accuracy and reaction time during a timed vision test. The CVP was lower in the high discomfort glare group compared to the low discomfort group, and no statistical difference was observed from the medium group.

Investigation of subjective evaluations has shown that participant perception of glare is affected by individual sensitivity to bright light. Participants who indicated usually wearing sunglasses outdoors were more liable to perceive a high level of glare. Further, the analysis revealed that the rating of visual comfort level was not affected by user sensitivity. The perceived visual comfort level significantly correlated with the main photometric variables contributing to glare sensation (luminance of the glare source, task luminance, illuminance at eye level, and average luminance) and most of the glare evaluation metrics (DGP, DGI and VCP). Thus, visual comfort level ratings may be more meaningful than glare ratings that rely on the knowledge and sensitivity of respondents and may not always be appropriate for all participants.

The factor of gender was investigated, and two differences were found, irrespective of glare condition: females fixated a greater number of times per line, and (perhaps relatedly) fixated for shorter durations than males. Although this suggests that female eye movement may constitute a greater number of shorter fixations than male eye movements, the research

validity is unaffected due to the equal numbers of males and females. No other differences were found between the genders on any of the DVs in this study.

6 Conclusion

This study set out to objectively measure and assess discomfort glare sensations through examining user involuntary physiological responses and visual performance. To this end, the eye-tracking method was coupled with photometric measurements and subjective evaluations. Light-induced physiological responses, namely Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), Fixation Rate (FR) and average Fixation Duration (FD) were then calculated from the processed pupil and eye movement data recorded by the eye-tracker. In addition, Combined Visual Performance (CVP) was measured for each participant through a timed vision test during the experiment.

Based on the results, the participants in the high discomfort condition recorded a higher Fixation Rate (FR), lower Blink Rate (BR) and higher Blink Amplitude (BA) than those in both the low and medium discomfort conditions. In addition, participants in the high discomfort condition recorded greater Pupillary Unrest Index (PUI) than those in the medium discomfort group, but not those in the low discomfort group. Further, the high discomfort group also recorded lower Pupil Diameter (PD) and poorer Combined Visual Performance (CVP) compared to the low discomfort group, while no statistical difference was observed for the medium group for either of these variables. The most significant effect size was observed between the high and low discomfort groups on Blink Amplitude (BA), suggesting this variable may be particularly sensitive to manipulations in the presence of glare, which can be regarded as a potential area for further studies. Interestingly, the medium and low discomfort groups were not different across any of the dependent variables, suggesting that the impact of glare on physiological and performance variables may not be linear, but instead may increase significantly as glare increases from medium to high levels. Investigation of subjective evaluations has shown that visual comfort ratings may provide a more meaningful indicator regardless of the participant's sensitivity to bright light.

Findings of this research, by identifying the most sensitive physiological indicators, provides a more definitive glare marker, which can be developed further to shape more efficient predictive models. In addition, these findings may have implications for responsive lighting

solutions in environments with high visual demand tasks, which can tailor to actual occupant need.

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