Visual Discomfort Assessment in Office Environments

Light-induced Physiological Responses and Visual Performance

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Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

(Signed): 04/11/2019

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Abstract

The benefits of exploiting natural light in office environments are numerous, ranging from enhancing human mood, satisfaction, productivity, health and wellbeing to reducing the energy consumption required for electric lighting. However, excessive sunlight remains problematic in terms of glare and undesirable visual discomfort. The existing discomfort glare predictive models are mainly derived from conventional subjective evaluations and photometric measurements and there is always a degree of uncertainty and bias associated with subjective measurements. For this reason, a more promising research method of pairing subjective assessments with objective measures was proposed as an alternative approach.

In this research, a comprehensive method is utilised to investigate a full range of potential objective measures of visual discomfort, including involuntary light-induced physiological responses, eye movements and visual performance. This method couples physiological measurements and visual performance assessments with conventional photometric measurements and subjective evaluations.

For this investigation, an experimental study was carried out for three different scenarios: low, medium, and high glare probability. Participants were required to perform simulated office tasks, while an eye-tracker recorded the pupil and ocular data. The ocular and pupillary metrics extracted from these data were: mean Pupil Diameter (PD), Pupillary Unrest Index (PUI), spontaneous Blink Rate (BR), Blink Amplitude (BA), number of fixational eye movements during reading (Fixation Rate (FR)), average Fixation Duration (FD), and Eye Convergence (EC). In addition, for each participant, the Combined Visual Performance (CVP) and Combined Reading Performance (CRP) were measured during the experiment.

Analyses of variance were undertaken to determine differences on all measures among three lighting conditions with low, medium and high levels of visual discomfort. The results show significant differences between the high and low discomfort groups across most of the dependent variables. In particular, participants in high discomfort conditions exhibited a higher FR, lower BR, higher BA, smaller mean PD and poorer CVP than participants in both the low and medium discomfort conditions. This indicates that the studied physiological measures can be used as an indicator of high levels of glare or visual discomfort. Nevertheless, EC and CRP were not affected by lighting conditions. The CRP

was better when the FD and the PUI were lower. Correlation and multiple regression analyses suggest that PUI, BA, FR and mean PD could be used as an indicator of visual discomfort, however, PUI and BA was shown to be predicted better with contrast measures and FR and PD with luminance and illuminance levels in the visual field. In addition, investigation of subjective evaluations has shown that visual comfort ratings may be a more reliable metric in reflecting visual discomfort experienced by the occupants.

This holistic approach offers new insight into the application of objective measures in assessment and prediction of visual discomfort, by advancing knowledge on various physiological and ocular responses and identifying the most sensitive indicators and relating all of this to visual and reading performance at work stations.

Publications

Chapter publications

Included in this thesis are three published and in press papers (*Chapters 2, 3, and 4*), all of which were peer-reviewed and co-authored with other researchers, and one co-authored under review paper (*Chapter 5*). My contribution to each paper is outlined at the beginning of the relevant chapter. The bibliographic and status for these papers, including all authors, are outlined below.

Chapter 2:

Z. Hamedani, E. Solgi, H. Skates, T. Hine, R. Fernando, J. Lyons, et al., "Visual discomfort and glare assessment in office environments: A review of light-induced physiological and perceptual responses," *Building and Environment*, vol. 153, pp. 267-280, 2019. *(IF: 4.82)*

Chapter 3:

Z. Hamedani, E. Solgi, H. Skates, M. Sarey Khanie, and R. Fernando, "A calibration and adjustment method for a dynamic visual comfort assessment," 2018 ASHRAE Building Performance Analysis Conference and SimBuild, Chicago, United States.

Chapter 4:

Z. Hamedani, E. Solgi, T. Hine, H. Skates, G. Isoardi, and R. Fernando, " Lighting for work: a study of visual discomfort, physiological responses and visual performance," *Building and Environment*, vol. 167, p. 106478, 2019. *(IF: 4.82)*

Chapter 5:

Z. Hamedani, E. Solgi, T. Hine, and H. Skates, "Revealing the relationships between luminous environment characteristics and light-induced physiological responses: An experimental study," *Building and Environment,* vol. 172, p. 106702, 2019. *(IF: 4.82)*

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Additional publications not included in the thesis

Ten additional papers (outlined below) published in the course of this study, but not comprising part of the thesis.

Refereed journal articles

E. Solgi, **Z. Hamedani**, R. Fernando, H. Skates, and N. E. Orji, "A literature review of night ventilation strategies in buildings," *Energy and Buildings*, vol. 173, pp. 337-352, 2018. (*IF: 4.495*)

E. Solgi, **Z. Hamedani**, R. Fernando, B. M. Kari, and H. Skates, "A parametric study of phase change material behaviour when used with night ventilation in different climatic zones," *Building and Environment*, vol. 147, pp. 327-336, 2019. (*IF: 4.82*)

E. Solgi, **Z. Hamedani**, R. Fernando, and B. M. Kari, "A parametric study of phase change material characteristics when coupled with thermal insulation for different Australian climatic zones," *Building and Environment*, vol. 163, p. 106317, 2019. *(IF: 4.82)*

E. Solgi, **Z. Hamedani**, S. Sherafat, R. Fernando, and F. Aram, " The Viability of Energy Auditing in Countries with Low Energy Cost: A Case Study of a Residential Building in Cold Climates," *Designs*, vol. 3, no. 3, p. 42, 2019.

Refereed conference papers

E. Solgi, **Z. Hamedani**, and R. Fernando "Experimental and numerical investigations on optimal phase change material melting temperature utilized either alone or with night ventilation," *International Building Performance Simulation Association **(IPIBSA)***, Rome, Italy, 2019 (Accepted).

R. Fernando, E. Solgi, K. Dupre, **Z. Hamedani**, H. Skates, "On the use of building information modelling for design integrated approach," *2018 Australasian Housing Researchers Conference (AHRC)*, Gold Coast, Australia.

Conference presentations

Z. Hamedani, E. Solgi, H. Skates, R. Fernando, "Physiological Responses in Relation to Glare: A Case Study in Office Setting," *2018 International Commission on Illumination (CIE) Conference*, Copenhagen, Denmark.

Z. Hamedani, G. Isoardi, and T. Hine, " A feasibility study of using ocular behaviour as an indicator for assessing glare in an office setting," to be presented at the 2019 *IESANZ Conference (Light in Focus: Human-Centred Design)* in Melbourne, 21-22 November 2019.

Note: (**IF**: Impact Factor in 2019)

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E_p	Retinal illuminance map per pixel weighted with the position index
E_v	vertical eye illuminance (lx)
L_m	Average luminance (cd/m^2)
L_b	Background luminance determined by taking the average luminance of areas not identified as sources of glare (cd/m^2)
L_{max}	Maximum luminance
L_s	Luminance of the sources of glare (cd/m^2)
L_t	Average task luminance
L_{win}	Luminance of the window (cd/m^2)
ω_{pix}	Pixel solid angle
ω_s	Solid angle subtended by the source in relation to the observer line of sight (sr)
C	Centre kernel
P	Weight factor based on position in a viewing hemisphere, the position index
T	Sampling cycle interval
V	EOG value at a certain time
$V(\lambda)$	spectral luminous efficiency function under daylight conditions (photopic vision)
$V'(\lambda)$	spectral luminous efficiency function under dark-adapted conditions (scotopic vision)
WF	surround-to-centre weighing factor
D	Pupil diameter (mm)
α	Stimulus field size (deg^2)
S	Surround kernel

List of Abbreviations

AEMS	Average Eyeball Movement Speed
APDF	Amplitude Probability Distribution Function
BA	Blink Amplitude, average blink duration in seconds
BGI	British Glare Index
BR	Spontaneous eye Blink Rate, number of blinks per minute
CCT	Correlated colour temperature
CGI	CIE Glare Index
COV	Coefficient of Variation
CRP	Combined Reading Performance, the correct answer rate divided by the average time spent on reading each word (seconds per word)
CVP	Combined Visual Performance, the number of correct answers divided by the total reaction time
DEO	Degree of Eye-Opening
DGI	Daylight Glare Index
DGI_{mod}	Modified Daylight Glare Index
DGP	Daylight Glare Probability
DGR	Discomfort Glare Rating
DVs	Dependent variables
EC	Eye Convergence
ECG	Electrocardiogram, measuring fluctuations in heart rate
E_{dir}	Direct Illuminance
EEG	Electroencephalogram, measuring brain activity using an
EMG	Electromyography, measuring response of surrounding facial muscles
EOG	Electrooculogram, measuring eyeball movement
FD	Fixation Duration, average fixation duration in milliseconds
FOV	Field of view
FR	Fixation Rate, number of fixational eye movements per line
GPI	Guth position index
HDR	High dynamic range image

I-VT	Velocity-Threshold Identification
L_{avg}	Average luminance of image
L_{avg_pos}	Position Index Weighted Average Luminance of Image
LDR	Low dynamic range image
MEMs	micro-electro-mechanical system
MP	Macular Pigment
ODR	Objective Discomfort Ratio
OSM	Ocular Stress Monitor
PD	Pupil Diameter in millimetre
PGSV	Predictive Glare Sensation Vote
POE	Post Occupancy Evaluation
PUI	Pupillary Unrest Index, millimetre per minute
SEBR	Spontaneous eyeblink rate
UGP	Unified Glare Probability
UGR	CIE Unified Glare Rating
UGR_{exp}	Experimental Unified Glare Rating
VCP	Visual comfort probability
VD	View Direction
VDM	Visual Discomfort Model
VDT	Visual display terminal
WWR	Window-to- wall ratio

Chapter 1: Introduction

1. Introduction

Exploiting natural light in office building design has been emphasised in various building standards due to the myriad benefits. According to the Department of Climate Change and Energy Efficiency, Australia, from 1999–2012, in terms of total electricity consumption of buildings, lighting fixtures ranked second at 26% [1]. As a response, enhancing building energy performance through the utilization of daylighting and solar control warrant consideration.

Daylight availability in office spaces not only reduces energy consumption, but also affects workers' mood, satisfaction, productivity, health, and wellbeing by boosting serotonin suppression, improving sleep quality, reducing the health risks of fluorescent lighting, and synchronising circadian rhythms [2-7]. Daylighting, with its invaluable benefits, plays a pivotal role in sustainable design. Nowadays, most countries use an international rating system to rate the sustainability of green buildings. Sustainability rating systems, BREEAM (UK), LEED (US) and Green Star (AU), aim to encourage architects and building practitioners to provide the abovementioned benefits for occupants. Given the recent changing trend in lifestyle to increased indoor activity, occupants' physical and psychological health cannot be assured unless natural light can be accessed daily for a certain amount of time. More recent standards, namely the new European standard [8] and the WELL Building Standard [9], call for minimum natural light exposure periods. Therefore, there is a tendency to employ highly-glazed façades, particularly in green-rated or sustainable office buildings to afford their occupants all the benefits of daylight. However, providing daylight while retaining visual comfort for office spaces can be challenging for designers. However, the challenge for a designer is to provide daylight while retaining visual comfort for office spaces.

The transition of office tasks from paper-based to predominantly screen-based tasks has also added more emphasis to the role of visual comfort in maintaining worker satisfaction and performance. This is because, for computer tasks, the user's line of sight is closer to the horizon and consequently the glare from windows can be a substantial issue. Research has shown that subjects performing a computer-based task exhibited less tolerance than those working on horizontal reading and writing tasks [10]. In addition, task luminance is quite constant, being defined by the display terminal luminance; meanwhile, the background luminance can change dramatically during some periods of the day, which makes adaptation to the task luminance difficult [11].

One of the major challenges in providing comfortable lighting for work is glare. Glare can be attributable to inappropriate distribution of luminance range or extreme contrast when these effects are remarkably greater than the range to which the visual system is adapted [12, 13]. Glare is categorised into two main conditions: disability or discomfort glare. The former can cause a reduction in the ability to see details or even objects, and is more likely to cause the worker to stop working and take action; the latter does not necessarily impair the vision but has an irritating or distracting effect, and can lead to long term effects from experiencing visually uncomfortable lighting conditions such as unexpectedly early fatigue or headaches [13-15]. The lack of action implicit in discomfort glare makes the latter the main concern in lighting design for office environments.

Perceived glare by an observer is related to the position of an individual in relation to the light source, the amount of light the individual is adjusted to, and their ability to adapt to the changing light. Therefore, the accepted range of light luminance can be very wide. In theory, glare is a phenomenon which depends on the luminance of the light source within the user's field of view, the background luminance, and the angular size of the source. Petherbridge and Hopkinson [16] formulated the influential factors on glare sensation as below:

$$G = \left(\frac{L_S^e \, . \, \omega_S^f}{L_b^g \, . \, f(P)} \right) \tag{1}$$

Here, L_S stands for the glare source luminance (cd/m^2); ω_s is the solid angle subtended by the source in relation to the observer line of sight; L_b represents the adaptation luminance (cd/m^2); P is the position index; and the e, f and g exponents are variable weight factors, different for each glare index. Most of the glare evaluation metrics approximate the degree of perceived discomfort glare based on subjective evaluations.

Recent foci in glare studies include the significance of subjective factors and other hidden variables [17], inconsistencies between existing glare indices [18] and inconsistencies between predicted measures, and POE (Post Occupancy Evaluation) results. These inconsistencies, as highlighted by various comparative studies, can be attributed to the specific boundary conditions of each experimental study, the reliance on subjective evaluations, and the difference between field and laboratory study circumstances.

Given the specific boundary conditions of each experimental study, existing glare metrics fail to yield accurate evaluations for all conditions and configurations. Many validity studies have found inaccuracies and discrepancies based on which, either a new modification of the studied metric/new metric was suggested [19-21] or the application of that metric was circumscribed [19, 22]. Also, many of the glare metrics are laboratory-driven under highly controlled conditions, and have been shown to yield different results in field studies [23-25]. Further, glare indices developed under lighting conditions simulated by artificial lights cannot perform well under daylight since subjects show higher tolerance towards daylighting glare than to those caused by other sources [26].

All the proposed metrics to date are derived based on subjective evaluations utilizing semantic response labels including the De Boer scale [27], imperceptible–intolerable four-point scale (originally introduced by Osterhaus and Bailey) [28], and the Glare Sensation Vote (GSV) [29] and visual comfort rating [30], each of which has its own limitations [31]. Although these evaluations are valuable in expanding the knowledge, the inevitable uncertainties stemming from the stimuli experienced by the observer or the procedure for recording responses along with limitations of each subjective rating scales remain limitations [32].

Considering the abovementioned limitations of existing glare indices, incorporating objective indicators with the potential of predicting an individual's visual discomfort sensation is required. In addition, post-occupancy studies show that occupant perceptions of their actual visual environment may differ from controlled laboratory situations. Hence there is a need to assess discomfort glare in the actual environment, under real sky conditions in full-scale rooms, despite this approach having its own challenges. Thus, for this research, an experimental study was designed to be conducted in a single office with a high proportion of glazing, employing natural light as its main daytime light source.

1.1 Research gaps and objectives

Based on the detailed literature review conducted in Chapter 2, despite previous research with reference to objective measures of visual discomfort, limited analyses have been found regarding some of the studied factors, and there exist uncertainties in the predictive power of some introduced indicators of discomfort glare perceptions such as spontaneous eye blink rate and pupillary unrest. The literature illustrates a high potential for further investigation of these factors. Additionally, the eye-tracking technique enables some other ocular measurements, such as different types of eye movements, with the potential of indicating the individual's visual discomfort sensations which can, in turn, lead to inefficiencies in the user's visual and task performance.

The research thus aims to evaluate objective measures of visual discomfort that have the potential to quantify the individual's sensations under discomfort glare conditions. To this end, a wide range of light-induced physiological responses as well as visual performance were investigated, along with conventional photometric and subjective evaluations. The physiological responses investigated in this study included mean Pupil Diameter (PD), Pupillary Unrest Index (PUI), spontaneous Blink Rate (BR), Blink Amplitude (BA), number of fixational eye movements during reading (Fixation Rate (FR)), average Fixation Duration (FD), and Eye Convergence (EC). To investigate a fuller range of objective measures, this study also explores the relationship between the visual and reading performance, and discomfort glare sensations; thus, Combined Visual Performance (CVP) score and Combined Reading Performance (CRP) score were defined for this research. In order to achieve the research aim, the following objectives are identified:

- To explore the effect of lighting conditions and in particular visual discomfort on physiological and ocular responses, namely PD, PUI, BR, BA, FR, FD and EC, as well as on visual performance.

- To seek the relationships between each objective measure (physiological, ocular and performance indicators), and absolute glare factors (vertical illuminance at eye level, average glare source luminance, average luminance, and maximum luminance).

- To investigate the relationships between each objective measure (physiological, ocular and performance indicators), and relative glare factors: luminance ratios and existing glare predictive models (DGP, DGI, CGI, UGR_{exp}, UGP).

- To determine the relationships between subjective assessments and physiological responses as well as visual performance and reading/comprehension efficiency.

- To ascertain the extent to which the identified physiological indicators can predict an individual's visual discomfort sensation.

To attain these objectives the following core hypotheses are tested:

- Subjects who experience a higher degree of discomfort glare will exhibit smaller pupil size (PD) and greater pupillary unrest (PUI, fluctuations in pupil size).

- Experiencing a higher degree of discomfort glare will result in a lower blink rate (BR) and a higher blink amplitude (BA) while performing a reading task.

- Experiencing a higher degree of discomfort will also lead to more saccadic eye movements and consequently higher fixation rate (FR), as well as greater fixation duration (FD).

- Subjects who experience a higher degree of discomfort glare will exhibit a lower score of both visual and reading performance.

1.2 Research design and pilot experimental study

In order to investigate the objectives of this research, an experimental study was carried out in an office setting. An eye-tracker was utilized to record pupil size and eye movement data from which physiological metrics were calculated. As with any other measurement technique, eye-tracking provided useful data along with a considerable amount of noise.

In addition, having recorded at a 100Hz sampling rate, the eye-tracking device provided one data point every 10 milliseconds, which resulted in millions of data points for each participant. Thus, these data required pre-processing and extensive coding and scripting to transform raw data into clean meaningful data. For this research, a MATLAB script/code was prepared to provide a clean base-line corrected pupil size signal, as well as to detect onset and offset of blinks. With this aim, the pupillometry data pre-processing guideline suggested by Kret et al. [33] was integrated with the blink detection method proposed by Hershman et al. [34]. Through this algorithm, invalid pupil diameter samples, such as outliers and artefacts due to blinks, were identified and subsequently removed or replaced. Finally, a baseline-corrected pupil size signal along with the frequency and duration of blinks were recorded for each experimental segment for further analysis. The algorithm for pupil data processing is summarised in Figure 1.1. The initial eye movement classifications were performed using Tobii I-VT filter, which is a velocity-based filter. Then, using these data, related metrics were calculated through coding in MATLAB.

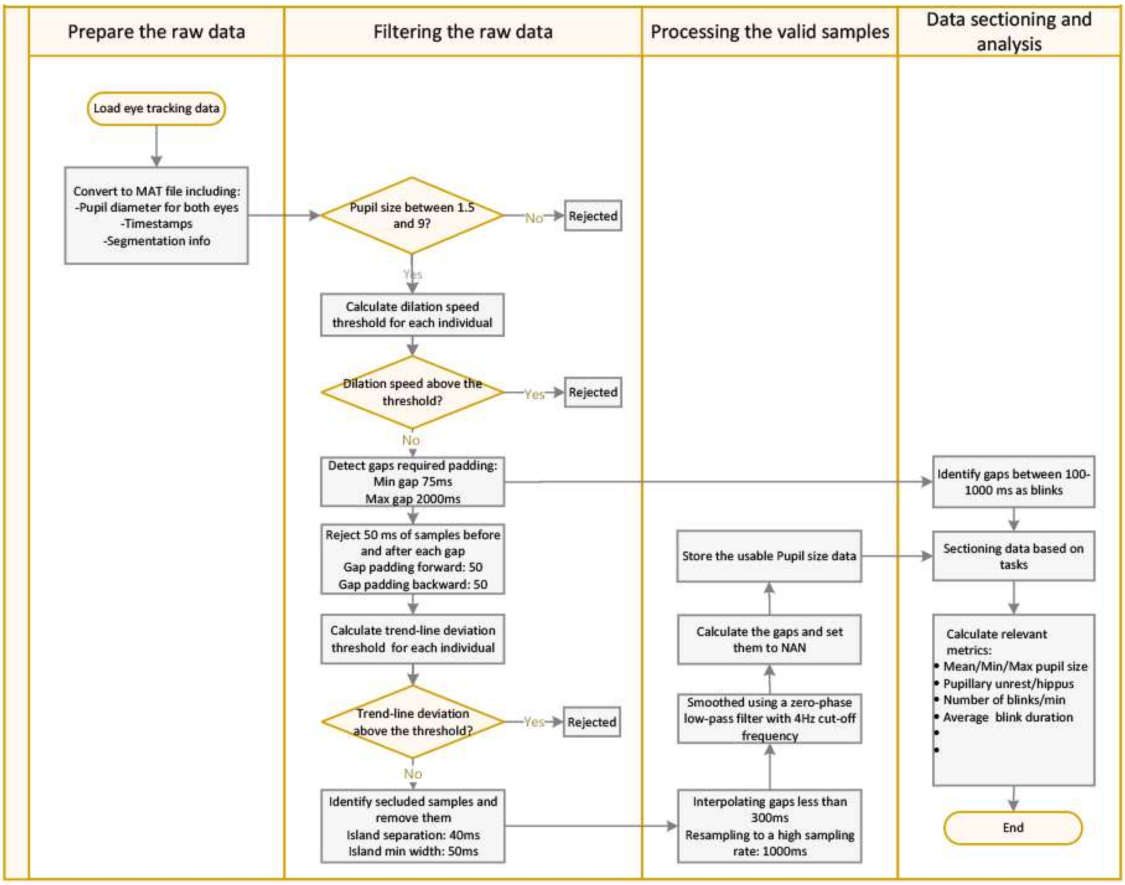

Figure 1.1 The pupil data processing algorithm

After calibration and adjustment of each item of equipment employed in this research, a pilot study was conducted for initial hypothesis testing and optimization of the experimental procedure and tasks. The pilot study was conducted in an office setting with a north-west orientation and a high proportion of glazing (see Figure 1.4 & 1.5). The experiment comprised three main blocks, each of which consisted of a series of simulated office tasks: reading, thinking, responding, and writing (see Figure 1.2). Each participant experienced one lighting condition as a between-subject factor. Each experimental session took 40 minutes on average. A long duration of experiment was chosen to examine the effect of length of exposure on participants' performance and responses as a within subject factor. To avoid boredom, the office tasks were divided into three blocks. At the end of each block, participants answered a short questionnaire regarding their perception of lighting conditions at that point in time.

A total of 30 subjects were recruited from students or staff members of Griffith University (GU Ref No: 2017/356), Australia, aged between 18 to 36 with healthy vision, and native English speakers. These inclusion criteria were set to avoid age-related vision impairment and biases associated with any lack of linguistic comprehension [35].

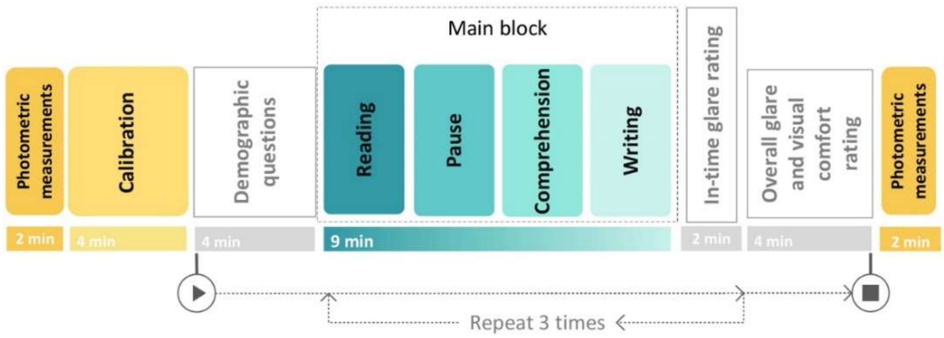

Figure 1.2 Pilot experimental procedure and tasks

Two main findings of the pilot experiment that affected the main experimental design of this research were the effect of length of exposure and results from the writing segment. Bivariate correlations were undertaken between the length of exposure and all physiological variables to examine if increasing length of exposure can affect the physiological responses subject to the present research. Results indicated that there was no statistically significant correlation between the time of exposure and any of the dependent variables. Therefore, the office task blocks were reduced to one block for the main experiment.

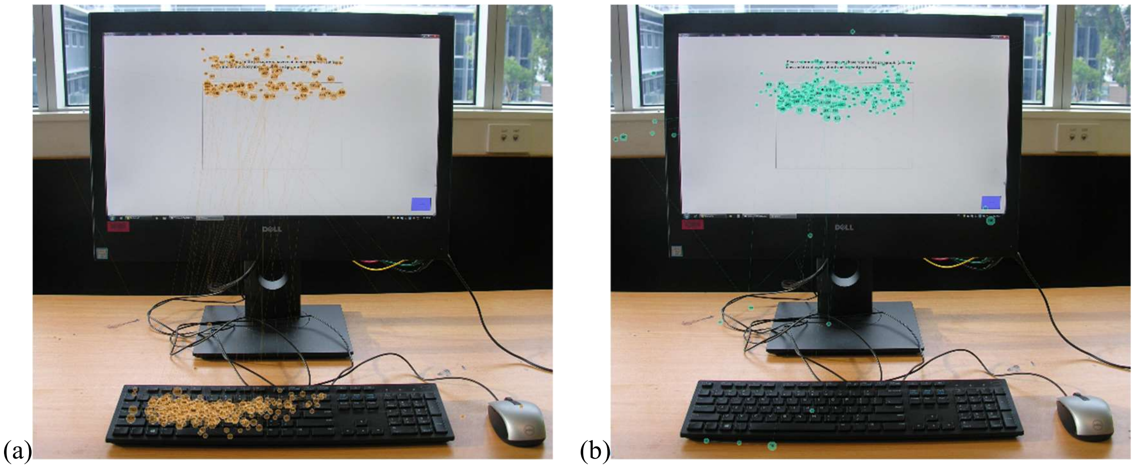

Figure 1.3 Mapped gaze points during the typing (writing) task showing gaze point for a participant who could not touch-type (a) versus a participant who could touch-type (b)

Notably, while it had been assumed that most of the participants could touch-type, most were looking at the keyboard (their hands) during the writing segment (see Figure 1.3(a)). As a result of looking downward which was approximately 70 percent of the time spent on the task, the eyelid blocks the pupil and cornea from the illuminator, resulting in long durations of data loss in raw data points of the eye-tracker. Additionally, while participants were looking down (at their fingers), a different amount of light from what was measured (assuming the line of sight is towards the screen) reached their eyes and consequently the potential for glare was reduced. Thus, even if a sufficient amount of data was recorded during this task, the data could not be attributed to the recorded photometric measurements or glare levels. Consequently, the writing segment was removed from the office tasks. The final experimental design and description of each segment are extensively explained in Chapter 3.

Figure 1.4 Pilot experimental setup

Figure 1.5 Participant’s view (left) and participant wearing the eye-tracking device(right)

1.3 Thesis outline

The format of this thesis is by publication, laid out in six chapters (the introduction, four publications, and conclusion). The structure of this thesis is in accordance with the Griffith University PhD thesis requirements as a series of published and unpublished papers. The results of this study have contributed to three peer-reviewed journal papers and one peer-reviewed conference paper. Thus, each chapter is in the form of manuscripts formatted to meet the requirements of the peer-reviewed academic journals in which they have been published. Consequently, some repetition may be apparent in the introduction, methodology, and reference lists of result chapters. Some aspects of the results presented in Chapters 4 and 5 have also been published as extended abstracts and were presented at two international conferences.

Chapter 1 represents a general introduction and a brief outline of the topic followed by the research aims and objectives of the project. Chapter 2 (presented as a published journal paper) is the first review paper published on physiological responses and visual performance in relation to visual discomfort and glare. This chapter presents an overview of conventional measures of photometric measurements and subjective evaluations, and of the deficiencies in the existing glare predictive models that emphasise the need for incorporating more objective measures into lighting research methods. Subsequently, a critical literature review of previously studied physiological responses in lighting studies, as an alternative approach, was carried out with respect to the studies’ experimental methodologies, the metrics utilized for their analysis, and potential confounding variables. Through this analysis, established factors and those requiring further evidence are identified as the gap in this area.

Considering the potential of utilizing the eye-tracking technique, and drawing upon the previous chapter, Chapter 3 (presented and published as a peer-reviewed conference paper) illustrates the calibration and adjustments required for the holistic approach of this study, which incorporates the eye-tracking method into visual discomfort studies. Consequently, this chapter elaborates on the calibrations required for photometric measurements, the calibration process for the eye-tracking device, and data processing techniques required for translating optic and ocular data (recorded by the eye-tracker) into useful data for visual comfort and performance analyses. This chapter provides the basis for experimental design and data interpretations.

In Chapter 4 (presented as a published journal paper), following the outcomes of Chapter 2, an experimental study was carried out to examine the extent to which visual discomfort sensation can be both operationalised and measured objectively, utilising various light-induced physiological measures. These measurements were coupled with visual performance evaluations, in combination with conventional measures of photometric measurements and subjective evaluations. Further, the effects of lighting conditions on each physiological measure were analysed in detail. This holistic approach offers new insight into the application of objective measures in the assessment and prediction of visual discomfort.

Chapter 5 (presented as a published journal paper) provides a more in-depth investigation to uncover the relationships between each physiological response that were found to be sensitive to visual discomfort and luminous environment characteristics. Through this investigation, the relationships between each physiological and performance indicator and the absolute and relative glare factors are revealed. Chapter 6 represents a summary of the outcomes stemming from the preceding chapters, in contribution to the lighting research field, as well as a research perspective on objective measures of visual discomfort.

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Chapter 2: Literature review

The introductory chapter provided a general background to the research, including the need for incorporating objective measures into lighting research, thesis aims and objectives, the pilot study and methodology approach, and the thesis structure. Chapter 2 provides a thorough literature review on the previously studied physiological factors in lighting research.

Chapter 2 of this thesis has been published as a co-authored paper in the journal, *Building and Environment*. The chapter has been formatted to meet the standards of the journal style for bibliographies. My contribution to the paper involved: selection of relevant literature, synopsis of findings, analysis of the literature, interpretation of experimental and theoretical results, writing and editing the manuscript, and submitting the paper to the journal. The bibliographic details of the co-authored paper, including all authors, are:

Z. Hamedani, E. Solgi, H. Skates, T. Hine, R. Fernando, et al., "Visual discomfort and glare assessment in office environments: A review of light-induced physiological and perceptual responses," ***Building and Environment***, vol. 153, pp. 267-280, 2019. (https://doi.org/10.1016/j.buildenv.2019.02.035)

2. Visual discomfort and glare assessment in office environments: A review of light-induced physiological and perceptual responses

2.1 Abstract

Lighting in office environments has many benefits, ranging from decreasing energy consumption to enhancing human health and well-being. However, visual discomfort such as glare has a negative impact on occupants, causing a sensation of annoyance or pain, thereby reducing user satisfaction and productivity. Current methods and metrics established for evaluating glare are mainly derived from physical measurements of luminance distribution and conventional subjective evaluations. However, significant inconsistencies and inaccuracies reported by a number of comparative studies highlight the need for a more objective method in the derivation of glare indices. This paper reviews the existing literature to provide a holistic overview of implemented methods in measuring light-induced physiological responses to objectify perceived glare. Physiological responses investigated within the reviewed literature include: pupil size, eye movement, gaze direction, degree of eye-opening, and blink rate. Research outcomes regarding each individual response are then analysed based upon their experimental methodology, the metric utilized for their analysis, and confounding variables that may contribute to misleading results. Through this analysis, established factors and those requiring further evidence are identified.

2.2 Introduction

The study of lighting is a multifaceted area of research, since light influences human health and well-being [1-4], as well as visual comfort [5, 6] and behaviour [7-9]. The study, therefore, encompasses a range of speciality disciplines from architecture to building engineering, physics, psychology and neuroscience. Although mutually concerned with understanding vision and visual perception, the disciplinary perspectives of vision science (neuroscience) and lighting differ. The former discipline analyses the physiological and biophysical features of the human visual system, while the latter focuses on investigating the relationship between light and vision with the aim of providing standards and guidelines for different lighting applications such as task performance, security lighting or reducing visual discomfort [10].

The main aim of lighting design is to support the visual perception of the lit setting. ‘Visual perception’ can be defined as the viewer’s usage of the reflected light array from surfaces in order to see shapes and affordances [11, 12]. Poor lighting design can lead to visual discomfort, which can have a negative impact on the visual perception of users. Visual discomfort is a term referring to discomfort or pain in or around the eyes, sometimes accompanied by itchy, watering or red eyes that may contribute to the effects associated with glare which can cause headache and/or nausea [13]. Visual comfort thus is an essential requirement for user satisfaction [14] and productivity [15] in every workspace. However, glare is widely accepted as the principal factor for occupant discomfort and the reason why shading devices are necessary [5, 16]. Visual comfort and glare analysis have been subject to numerous studies aiming to analyse different glare indices and propose new metrics, clarify the application of different glare metrics, and refine standards [17-21]. The variability inherent in human subjective perceptions of glare has made discomfort glare assessment a matter of contention [22]. The subtlety of discomfort due to lighting adds to the complexity of analysis, and manifests in degraded occupant performance over longer periods of time, as well as in more subjective experiential aspects of a space.

To date, studies have provided a comprehensive overview of glare indices [23, 24], influencing factors of glare perception [25], daylight and health [26], standards and recommendations [27], visual and biological effects of light in a working environment [28], occupant preferences and satisfaction [14, 29, 30], utilization of discomfort glare models in lighting control systems [31-33], and optimization of design strategies [24, 34, 35]. The literature has primarily reviewed vision studies from one or other of the main perspectives: vision lighting or vision neuroscience, and there appears to be no study analysing both perspectives simultaneously. As a result, drawing upon two strands of research into vision, this study systematically reviews the existing literature, aiming to provide an overview of implemented methods in visual comfort studies rooted in applied science, to measure physiological responses as a means to objectify perceived glare by users and reduce the uncertainties inherent in glare models. The aim is to provide researchers with an analytical overview of methods undertaken to date and thereby establish a base for future research in this area.

This review will first present the methodology adopted for selecting and analysing qualified papers (Section 2). Section 3 then outlines the prevalent methods in glare evaluation studies based on photometric measurements, visibility and subjective evaluation, raising the consideration of more objective evaluation methods. Finally, Section 4 reviews the light-induced physiological dimensions studied by examining the methodology and findings in this area. It also identifies and lists physiological response that has been investigated in experiments, followed by a full description and analysis of each parameter and highlights the existing gap in the knowledge.

2.3 Methodology

This section provides an explanation of how the search for qualified studies was carried out. It also discusses the assessment criteria, inclusion and exclusion criteria and the analysis method in this review.

In the first step, a thorough search was made of three general databases, ScienceDirect, SAGE, and Google Scholar. In addition, a detailed search was also made of specific journals namely, 'Lighting Research and Technology', 'LEUKOS' (formerly known as the 'Journal of the Illuminating Engineering Society'), 'Building and Environment' and 'Energy and Buildings'. Studies were selected describing lighting and its visual effects on physiological responses through experimental studies. These studies might consider one or more physiological reflexes in conjunction with subjective glare evaluations, photometric measurements or visual performance, or a combination thereof. The search for the studies was undertaken in September 2018 and this review covers research published from 1956 onwards.

Certain studies were excluded from the list despite addressing physiological responses in a lit environment such as fluctuations in heart rate using an electrocardiogram (ECG) and brain activity using an electroencephalogram (EEG, e.g. Ref. [36]), due to the uncertainties in their research method [37] as well as insufficient information on their acquired data and analysis. In addition to these types of research, studies that have adopted a proactive approach and assessed the efficacy of some biological factors namely cortical hyperexcitability [38] and macular pigment optical density [39-41] on user glare sensation were excluded as well. Only studies in peer-reviewed journals were selected of which the full article is publicly available in English. The studies that remained after the exclusion criteria were applied were then assessed on the basis of three different criteria:

Research characteristics: This study focuses on how lighting conditions can affect human responses in terms of physiology. Therefore, only the characteristics related to this issue are considered. First, human responses are affected largely by the type of light source whether it is artificial or natural light [42, 43] and the reasons for this were argued in numerous studies explaining light-induced neurobehavioral (i.e. subjective alertness) and neuroendocrine (i.e. melatonin suppression) responses [44, 45]. Hence, lighting characteristics were chosen as one of the categories. To provide a better understanding of the natural lighting characteristics, some contextual factors such as location and the time of the year [46] in which the study was performed were also considered. Studies were also categorized as one of three study types: laboratory study, field study or theoretical study.

Experimental design characteristics: The experimental setting also has an impact on user responses. Therefore, the type of tests used for the experiment, the number of participants, the methods, the measures and tools utilized were reported for each study.

Research findings: To identify future research directions, the analysis did not only include the aspects mentioned above, but also the findings of the studies and whether they resulted in a model for glare evaluation. This led to a more complete overview of the research questions of current relevance to the scientific community.

The results for research and experimental design characteristics are presented in Table 2.1 based on the aforementioned assessment criteria. Research findings regarding each physiological factor are illustrated in Table 2.2. Afterwards, each of the investigated physiological factor (variable) in a visual comfort study are described followed by a critical analysis of their methods and findings in order to identify areas where research is still lacking.

2.4 Visual discomfort and discomfort glare evaluation methods

Visual discomfort from glare has been known as the main factor for visual discomfort in workplaces. Glare can occur due to an unsuitable range or distribution of luminance, considerably higher than which the visual system is adapted, or to extreme contrasts in luminance [47, 48]. Glare can be defined as two main conditions of vision: either disability glare, in which there is a reduction in the ability to see details or even objects or discomfort glare, an irritating or distracting effect which does not necessarily impair the vision [48]. Identifying disability glare is less challenging due to its objective character which has its own set of predictive models that are not outlined in this paper. Disability glare will cause occupants to stop working and take actions. On the contrary, under discomfort glare condition, the observer experiences unexpectedly early fatigue, feelings of discomfort, or headaches [24, 49] which are long term effects of being exposed to that lighting condition and are the main concern in lighting design for workplaces.

Discomfort glare has been subject to numerous studies over a number of decades and has led to the derivation of a number of indices to evaluate discomfort glare in different lighting situations and contexts. All these indices have been arrived at based on conventional subjective evaluations and physical measurements of the luminance distribution in the user's field of view [50]. Thereafter, a general mathematical function was derived describing the relationship between physical measurements and the perceived glare. The main variables in glare sensation are given below in Equation (1)[51]:

$$G = \left(\frac{L_S^e \cdot \omega_s^f}{L_b^g \cdot f(P)}\right) \quad (1)$$

In this equation, L_S accounts for the luminance of the glare source (cd/m2); ω_s is the solid angle subtended by the source with respect to the point of view of the observer; L_b is the adaptation luminance (luminance of the background) (cd/m2); P is the position index; the exponents (e, f and g) are weight factors for each parameter which vary in different glare formulae. The equation indicates that four principal physical quantities are contributing factors in perceived discomfort glare: luminance of the glare source, solid angle subtended by the source at the eye, adaptation luminance and position index [47]. We will now deal with each of these variables in turn.

The luminance of the glare source is interpreted as the intensity of the luminous flux emitted per unit area of the glare source. It is widely accepted that the greater the luminance of the glare source, the higher the perceived glare level. The second factor is the solid angle of the glare source, which allows for defining the effect of the size of the glare source as seen by the user and the distance from the glare source on perceived discomfort glare. However, to account for this factor a clear definition of glare source is required as it has a variety of interpretations in different research.

The adaptation level also plays a role in glare perception. This phenomenon refers to an individual adaptation in response to the amount of light and that individual's ability to adjust to various levels of light. The human visual system adapts to new light levels through mechanisms like pupillary light reflexes which results in adjusting the amount of light that reaches the retina. In lighting conditions with a small glare source, the adaptation level can be estimated using background luminance. However, in conditions with large glare sources that occupies a significant area in the field of view, the adaptation level will be affected by both background and source luminance. Thus, some indices utilized vertical illuminance at the eye level to estimate the adaptation level.

The final factor, the position index, accounts for the perceived discomfort glare being affected by the angular displacement (azimuth and elevation) of the glare source from the observer's view direction [52]. Iwata and Tokura, [53] highlighted sensitivity to glare engendered by a source below the line of sight was greater than the sensitivity to glare engendered by a source above the line of sight. Since then, efforts have been made to demonstrate relative sensitivity to glare throughout the visual field [54].

The values for the weights described in Equation (1) which relates the four photometric quantities to subjective discomfort glare responses have been researched and have resulted in several predictive models. These are: the Daylight Glare Index (DGI) [55, 56], the British Glare Index (BGI) [57], the CIE Glare Index (CGI) [58], the CIE Unified Glare Rating (UGR) [59] and the Daylight Glare Probability (DGP) [60]. However, there is susceptibility to significant bias among quantitative subjective evaluations utilizing semantic response labels such as the Hopkinson's multiple criterion scale [61, 62].

Of the common glare models, at least three predictive models are most frequently used: Daylight Glare Index (DGI), Unified Glare Rating (UGR) and Daylight Glare Probability (DGP). The DGI, also known as Cornell equation metric, was the first predictive model to provide an index based on subjective human studies [55, 56]. This index only deals well with large glare sources with uniform illuminance such as diffused light coming into an interior space through windows, described by its luminance L_{win}.

$$DGI = 10 \times \log_{10}\left[0.478 \sum_{i=1}^{n}\left(\frac{L_{si}^{1.6} \cdot \omega_{si}^{0.8}}{L_b + 0.07\,\omega_{si} \cdot L_{win} \cdot P_i^{1.6}}\right)\right] \quad (2)$$

In the above equation, L_{si} accounts for the luminance of the glare source(s) (cd/m^2); ω_{si} represents the solid angle subtending each source from the point of view of the occupant, modified with respect to the field of view and the Guth position index of each luminaire (P_i), L_b represents is the luminance of the background (cd/m^2); ω_s represents the solid angle of the window; and L_{win} represents the luminance of the window (cd/m^2). The DGI does not account for direct light or interior specular reflection, and is not reliable when the source fills almost the whole field of view or when the background luminance equals the source luminance.

The Unified Glare Rating index (UGR) was introduced by the CIE to simplify the calculations involved in the formerly proposed glare model, the Daylight Glare Index (CGI), while maintaining the same rating thresholds i.e. "imperceptible" glare for values lower than 13 and "intolerable" glare for values higher than 28 [59].

$$UGR = 8 \times log_{10}\left[\frac{0.25}{L_b}\ \sum_{i=1}^{n}\left(\frac{L_{si}^2\,\omega_{si}}{P_i^2}\right)\right] \tag{3}$$

Where L_{si} represents the luminance of the glare source(s) (cd/m^2); ω_{si} represents the solid angle of the glare source(s); L_b represents the adaptation luminance (luminance of the background) (cd/m^2); and P_i represents the position index relative to the glare source(s). The UGR is only appropriate for very small glare sources caused by artificial lighting with a solid angle between 3×10^{-4} and 10^{-1} sr.

Wienold and Christoffersen [60] carried out an extensive study and adopted precisely calibrated CCD cameras as a photometric measurement method and proposed DGP in 2006. This glare metric by incorporating the vertical eye illuminance (E_v) as adaptation level has corroborated a better correlation with subjective evaluations. E_v is used as its sole input in the first part of the equation and demonstrates the impact of exceeding brightness in glare occurrence even without considerable contrast. More importantly, DGP has the capacity to evaluate direct sunlight and specular reflection which makes up for DGI limitation [60].

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

In the above equation, E_v is the vertical eye illuminance received from the light source (lux); P_i is the position index relative to the glare source; L_{si} is the luminance of the source (cd/m^2); ω_{si} is the solid angle of the source seen by an observer. The above equation is valid for vertical eye illuminance (E_v) above 380 lux, and for DGP ranging between 0.2 and 0.8. A DGP value ranging from 0.3 to .45 corresponds to imperceptible glare to intolerable glare respectively. In addition, it can be interpreted as the percentage of people perceiving discomfort in a lighting situation [60]. With the addition of vertical eye illuminance, the DGP includes the most known photometric variables contributing to the glare phenomenon in analysing glare; the interpretation of perceived glare, like other models, still relies on self-reported subjective assessment. Notable inconsistency and inaccuracy issues depicted by a number of comparative studies [63, 64] highlight the need for a more objective method in glare indices derivation.

Besides the aforementioned fundamental factors attributed to glare sensation, other physical quantities have been investigated empirically to determine the effect of those factors on perceived glare; however, they have not been included in any predictive discomfort glare model. Pierson et al. [25] provided a comprehensive overview of factors influencing discomfort glare perception ranging from factors related to the lighting environment to the context and observer's characteristics. They rated potential influencing factors in glare perception as either *'certain', 'likely', 'unlikely', 'uncertain'* or *'null'*. The main influential factors as related to the lighting environment included: the luminance of the glare source, adaptation level, size and the position of the glare source as seen by the observer, have been rated '*certain'*. There are also some contextual factors, such as light spectrum and color temperature, as well as temporal factors, which received attention in glare studies. The influencing factors which are labelled as '*certain'* or *'likely'* are assumed to be established factors contributing to glare perception. There are also factors related to individuals, namely, gender, age and vision correction, which have been labelled as *'null'* and could be considered as non-contributing factors in glare perception. The authors conclude that factors like physiological characteristics of the observer such as iris pigmentation [65] need an additional investigation to determine the influence of those factors.

The physical factors causing glare are so far well-documented; however, regardless of extensive effort to provide precise indices, the issue of the subjectivity of human perception of glare, whilst valuable, makes these evaluation indices contentious. In that regard, identifying and validating objective measures with the potential for incorporation into the experimental methodology of glare evaluation models can be valuable. It is to this end that we now provide a summary of the relevant aspects of the physiological responses of the visual system to light.

2.5 Light-induced Physiological responses

Human physiological responses to light, involve various mechanisms in the eye and nervous system. The visual system enables humans to acquire information from their surroundings. The perceived image by the eye is defined by the 2D luminance distribution that reaches the retina. The retinal illumination is proportional to the pupil area, which is governed by the activity in the optic nerve. In a lit space, the iris sphincter muscles decrease the pupil aperture and limit the retinal illuminance whereas, in a dim space, iris dilator muscles enhance the incident light by increasing the pupil area. This phenomenon referred to as the pupillary light reflex [66].

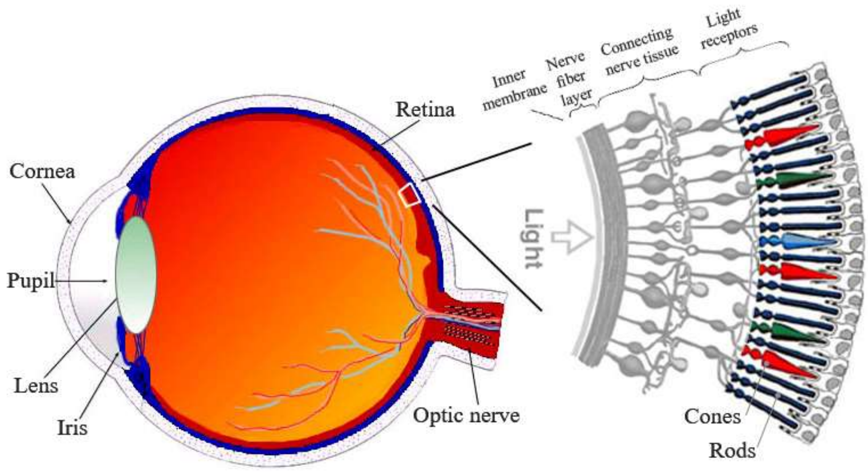

Figure 2.1. Schematic section through the human eye with an enlargement of the retina, adapted from [67].

Within the retina, receptor cells are located that are named for their morphology: either rods or cones. Collectively, these are known as photoreceptors [67] (see Figure 2.1). There are approximately 120 million rods and 6 million cones contained within the human retina. Cones, while greatly outnumbered by rods, provide the majority of information about the environment via the fovea – the area of high spatial resolution. Predominantly, the cones are responsible for daytime, photopic vision and provide humans with chromatic information [67]. Since the 19th century, it has been established that there are three types of cone photoreceptors used for daylight vision in human eyes [68]. The presence of these three photoreceptors enables physical light of a certain spectral distribution to be perceptible by the human eye. This spectral distribution varies over the wavelength range between 380 and 800 nm [69]. CIE has defined the spectral sensitivity function of the average human eye under daylight conditions (photopic vision) as spectral luminous efficiency function V(λ). The same function has been defined for the human eye under dark-adapted conditions (scotopic vision), as V`(λ). The spectral composition of the light source influences the discomfort glare sensation. With identical photopic illuminance at the eye, greater short wavelength content is associated with higher discomfort glare sensation [10, 70, 71]. This is due to the optics and light scattering that occurs due to the intra-ocular optics [72]. Human eyes also exhibit different contrast sensitivity depending on the light level to which the eyes are adapted. Contrast sensitivity is fundamental for visual function and to the detection and recognition of shapes, including text. Under mesopic circumstances (twilight or dim office lighting conditions) in which both rods and cones are active, in the presence of glare, the human subjects exhibit a greater decline in their contrast sensitivity [73] than under daylight (photopic) light levels [74].

There is a relatively small body of literature in lighting research that is concerned with user physiological responses in relation to visual discomfort or glare. Table 2.1 provides a list of studies reviewed in this paper mapped against their experimental design and methods. The research findings are discussed according to each physiological factor (see Table 2.2). It is significant to note that all these studies were carried out in laboratory conditions due to the need for testing specific lighting under controlled conditions and minimizing the effect of confounders. Research methods including physiological and photometric measurements have been coupled with subjective evaluations and/or visual performance.

The visual task, the light stimuli and the duration of data recording are also important in this type of research. The type of visual task can affect some physiological responses like pupil dilation and blink rate due to the cognitive load of the task. The light stimuli can range from artificially generated glare source to daylight with various exposure times and each of these conditions can result in different responses. For instance, in an experiment in a dark room when a light source is turned on, the pupil will constrict rapidly as an adaptive response to the new light level, whereas in a daylit space, smaller changes in the pupil diameter would be observed. Thus, the experiment characteristics are of paramount importance when comparing the results.

Table 2.1. Characteristics of included studies considering physiological responses in relation to visual discomfort.

Author (Year)	Research objectives	Subjects	Physiological Measurement	Subjective Evaluation	Visual Test/Duration
Hopkinson (1956) [75]	To understand the relationship between pupil diameter, luminance and sensation glare discomfort.	N = 2	✓	✓	NA
Howarth et al. (1993) [76]	To identify what role, pupillary unrest or 'hippus' plays in the genesis of discomfort felt under conditions of glare.	N = 4 2M, 2F	✓	×	Varying background and glare luminance/10-seconds recording time.
Berman et al. (1994) [77]	To present an objective method for determining physiological responses to discomfort glare.	N = 20 8M, 12F Aged 18-35	✓	✓	A total of 36 lighting conditions/ 1 hour per subject.
Murray et al. (2002) [78]	To demonstrate a new physiological method for evaluating discomfort glare using the Ocular Stress Monitor to measure EMG activity of extra-ocular muscles.	N = 10 Aged 19-49	✓	✓	EMG activity recorded for 4 seconds under various glare conditions with 1-minute intervals between trials.
Stringham et al. (2011) [41]	To examine the effect of Macular Pigment (MP) level on three aspects of visual performance in glare: photo stress recovery, disability glare, and visual discomfort.	N = 26 Aged 23-50	✓	✓	Correct identification of a 1° Gabor patch's orientation.
Doughty (2014) [79]	To further, evaluate the spontaneous eyeblink rate (SEBR) of healthy adult human subjects according to the direction of gaze, especially in the presence of bright light reflective glare.	N=32 19M 13F Aged 18-24	✓	×	Viewed a target at 3 elevations with fixed glare source and background illuminance 5-minutes recordings between 10:30 - 16:30.
Garretón et al. (2015) [80],	To provide an objective indicator for the prediction of discomfort glare.	N= 20	✓	✓	A series of computer-based tasks: Stroop task and memory task Under four natural lighting conditions between 9:30 – 11:00.
Lin et al. (2015) [81]	To demonstrate a new physiological method for examining eye movement and pupil size in response to glare discomfort.	N=20 10 young: 8M, 2F 10 seniors: 3M, 7F	✓	✓	Viewed a target for 3 seconds at 24 different lighting conditions for senior participants and 96 different lighting conditions for young participants and 1-minute intervals.
Sarey Khanie et al. (2015) [82]	To integrate gaze dynamics into visual comfort assessment to overcome fixed-view assumption.	N=125 63 M, 34 F Aged 20-60	✓	✓	On-screen phase and On-phone phase: each included reading, thinking, responding, typing; each for 6 minutes.
Garretón et al. (2016) [83]	To investigate the ocular behaviour of office workers in the presence of sunlight.	N=18	✓	✓	4 office tasks: reading from a screen and from paper, writing and socializing.
Rodriguez et al. (2017) [84]	To extend methodologies of analysis derived from medical disciplines into discomfort glare assessment in office environments.	N =45 For DEO=32	✓	✓	A computer-based task: Stroop task.
Scheir et al. (2017) [85]	To present a discomfort model (VCD) incorporating circular receptive field mechanism, pupillary light reflex and correction for retinal position in an attempt to develop a more physiologically justified model.	N=20 Aged 20–38	✓	✓	4 tests covering 17 stimuli over one 1/2-hour session approx.
Scheir et al. (2018) [86]	To propose a visual discomfort model based on receptive fields as an alternative to the CIE UGR method.	N= 16	✓	✓	8 stimuli of varying luminance uniformity presented in 56 pairs during one 15-minutes session.

2.6 Physiological measures

According to the studies included in this research, the physiological responses investigated in lighting research are pupil size, eye movement, gaze direction, blink rate, and the degree of eye-opening. Some of these studies merely considered light-induced physiological responses, whereas others investigated a range of responses and examined the correlation of each response with subjective evaluations or existing glare metrics. Pupillary reflexes are the most studied factor among light-induced physiological responses. Afterwards, eye movements and gaze direction ranked second. Table 2 indicates the research outcomes concerning each of the abovementioned responses to provide a comprehensive understanding of conducted research.

Most of the reviewed research is performed under artificial lighting conditions (see Table 2). In addition to the previously mentioned effects of daylight on human neurobehavioral and neuroendocrine responses, daylight gradually changes throughout the day. Therefore, results obtained under artificial lighting conditions and short-term light stimuli require field studies before extrapolating them to a real scenario.

Different parameters have been studied regarding each physiological factor. This variety could be owing to the theoretical framework of the research or simply to the instrument being utilized, and to the type of data acquired in the study (see Table 2). Eye movement, for example, was addressed in different studies using data collected from either Electromyography (EMG) [77] or Electrooculogram (EOG) [81] (see section 4.1.2).

Table 2.2. Reviewed papers results categorised by physiological response factors.

Factors	Author	Light source	Metric/Instrument	Findings
Pupil Size	Hopkinson (1956) [75]	Artificial	Pupil diameter: Low light flash photography	• Pupil size highly correlated with overall background luminance. • Experiencing glare lead to cyclical variation in pupil diameter.
	Howarth et al. (1993) [76]	Artificial	Pupillary unrest (hippus): Infra-red pupillometer	• Increased luminance, affects the amplitude spectrum of hippus and causes a reduction in the amplitude of the oscillatory components.
	Stringham et al. (2011) [41]	Artificial	Pupil diameter: Infra-red pupillometer	• An inverse correlation was determined between visual discomfort ratings and pupil diameters.
	Lin et al. (2015) [81]	Artificial	Relative Pupil size: Eye-tracking glasses	• Subjective evaluation of glare discomfort was highly correlated with pupil constriction. • Severe glare discomfort caused larger pupil constriction.
	Garreto´n et al. (2016) [83]	Natural	Pupil diameter: Eye-tracker	• Pupil size correlated with vertical illuminance at the eye and glare indices.

	Scheir et al. (2017) [85]	Artificial	Pupil diameter	• The inclusion of pupillary light reflex in the model increased the coefficient of determination.
Eye Movements	Berman et al. (1994) [77]	Artificial	Response of surrounding facial muscles: Electro-myography (EMG)	• EMG revealed correlating outcomes. As such, an objective discomfort relation was proposed for estimating glare discomfort. • Subjective evaluation revealed increased discomfort as ambient illumination was decreased while the glare source remained. • The signal amplitude is proportional to the vertical illuminance at the eye.
	Murray et al. (2002) [78]	Artificial	Extra-Ocular muscular stimulation: Ocular Stress Monitor, Medlec amplifier	• The signal amplitude is proportional to the vertical illuminance at the eye, and can, therefore, be used as an objective index of the discomfort induced. • The results compare favourably with subjective assessment.
	Lin et al. (2015) [81]	Artificial	Eyeball movement speed (vertical EOG): Electro-oculogram (EOG)	• Subjective evaluation of glare discomfort was highly correlated with eye movement. • Severe glare discomfort increased eye movement speed. • Larger variations of eye movement were found among seniors.
Gaze Direction	Doughty (2014) [79]	Artificial	Gaze position: Eye-tracker	• Having the gaze directed toward the glare source, higher SEBR variability is expected, if the source is on/above the line of sight.
	Sarey Khanie et al. (2015) [82]	Natural	Spatial frequency of gaze direction: Eye-tracker	• Gaze dynamics are highly task dependent. • Gaze directions tended toward lower luminance levels which in turn led to smaller illuminance at the eye.
	Garreto´n et al. (2016) [83]	Natural	The spatial frequency of gaze direction: Eye-tracker	• Heavily dependent on the cognitive demand and complexity of the task. • Unsuitable as a predictor for discomfort glare.
Blink Rate	Doughty (2014) [79]	Artificial	Spontaneous eye blink rate: Video, manual counting	• Spontaneous eye blink activity can be affected by the presence of a glare source, especially if the subject is looking slightly upwards.
Degree of eye-opening	Garreto´n et al. (2015, 2016) [83]	Natural	Degree of eye-opening (DEO): Video, Image processing	• DEO is applicable in sunny climates in the presence of direct sunlight. • DEO correlated highly with vertical illuminance at the eye, Daylight Glare Probability (DGP) and Predictive Glare Sensation Vote (PGSV).
	Rodriguez et al. (2017) [84]	Natural	Degree of eye-opening (DEO): A digital camera fixed to the participant's head	• DEO exhibited better diagnostic performance than DGI, DGP, or E_v. • The usability of DEO required to be improved.

2.6.1 Pupil size

Pupil diameter plays a fundamental role in the optical transfer function of the eye and can vary between approximately 2 to 8 mm. The absolute pupil size is dependent upon the luminance condition to which the eye is adapted. Changes in pupil size adjust the retinal illuminance which can, in turn, affect the contrast sensitivity. The other function of pupil size variation is in adjusting the depth of field in an inverse way as the smaller the pupil size, the greater the acceptable depth of field.

Previous research findings into pupillary reflexes in relation to lighting conditions have been inconsistent and contradictory (i.e. [76] vs [87]), however, among light-induced physiological responses, these reflexes have received the most attention since the 1990s. Such a contradiction can be a result of the method implemented in the analysis or the experimental design. In this regard, the metric identified as a base for the analysis can make a difference as some of the research focused on absolute pupil diameter [75, 88], whilst others used pupil oscillation, or relative pupil diameter [81, 89].

It is worth noting that since the initial interest in pupillary reflex measurements (pupillometry), the accuracy and user-friendliness of utilized equipment have vastly improved. In the early studies of pupillary reflexes in lighting research such as the method employed by Hopkinson in 1956 [75] subjects were required to be positioned at a specific distance from an external camera; recorded images were then printed on paper, from which pupil diameter measurements could be made. Nowadays, however, accessible technologies for measuring pupil diameter have implemented comparatively non-invasive and simple methods. Pupil data acquisition includes three main sequential features namely illumination, camera, and pupil detection algorithms. Illumination and camera characteristics of the equipment are needed to meet the requirements of the research objectives and experimental conditions. Table 3 illustrates the characteristics of the equipment related to the illumination and camera phases. Image processing algorithms are then used to estimate pupil diameter from the raw data. Algorithms utilized in this area implement various approaches such as thresholding pupil detection procedures [90, 91], edge detection procedure [92, 93], curvature algorithm [94], discrete level set approach [95] and active contour procedure [96]; however, these algorithms are mentioned only in a few pupillometry studies.

In 1956, Hopkinson [75] initiated his research based on previous works of Stiles [101] and Crawford [102] in which pupillary measurements were used under different degrees of glare. Hopkinson noted a lack of understanding in relation to discomfort glare caused by the presence of a glare source in the field of view and undertook an experiment to develop an understanding of the relationship between pupil diameter, the luminance of the glare source and the sensation of discomfort glare [75].

Table 2.3. The main characteristics and considerations of illumination and camera in pupil data recording [97-100].

	Characteristics	Types	Considerations
Illumination	Wavelength range	Visible spectrum imaging	• There is a chance of multiple specular and diffuse components due to the uncontrolled ambient light.
		Infrared spectrum imaging	• Eliminates uncontrolled specular reflection. • During the daytime, it is not suitable for outdoors due to the ambient infrared illumination.
	Intensity		• In order to separate eye contours from darkness, the intensity of light should be sufficient according to the sensitivity of the camera.
Camera	Sensitivity		• Camera's sensitivity needs to be close to the infrared region of the electromagnetic spectrum.
	Sampling rate		• The temporal resolution should be selected based on the pupil characteristics that are intended to be studied.

Results demonstrated a regular relationship between pupil diameter and source luminance, but also some variation under different background luminance. Pupil diameter was found not to have a strong relationship with perceived glare sensation and the dominant factor affecting pupil constriction is background luminance, which presents a high level of illumination at the eye. Under intolerable exposure to glare, cyclical variation in pupil diameter was observed. Hopkinson suggests discomfort may be linked to the iridomotor system, so stimulation of the sphincter and dilator muscles may be occurring in response to contradictory signalling from a highly stimulated retina under high glare stress. This is not a rigorously supported suggestion [75].

Howarth et al. [76] attempted to identify what role, if any, pupillary unrest or hippus (the fluctuations in size of the pupil) has in generating discomfort under glare conditions. This investigation built upon earlier work by Hopkinson [75] which reported pupillary unrest under extreme glare, and determined that the coinciding discomfort may be caused by the stimulation of opposing dilator and sphincter muscles which control pupillary response [76].

To test the hypothesis raised by Hopkinson's research and to determine the role of pupillary hippus in relation to discomfort glare, Howarth et al. [65] compared pupil size under various glare and non-glare conditions which were designed to elicit a pupillary response in the subject. The findings recognised that increased luminance affects the amplitude spectrum of hippus, while there is a reduction in the amplitude of the oscillatory components of hippus (Figure 2.2). The attempts to substantiate the Hopkinson's suggestion that discomfort could be linked to the pupillary movement has not been successful. It was concluded that such movement was unlikely to cause discomfort experience under glare conditions [76].

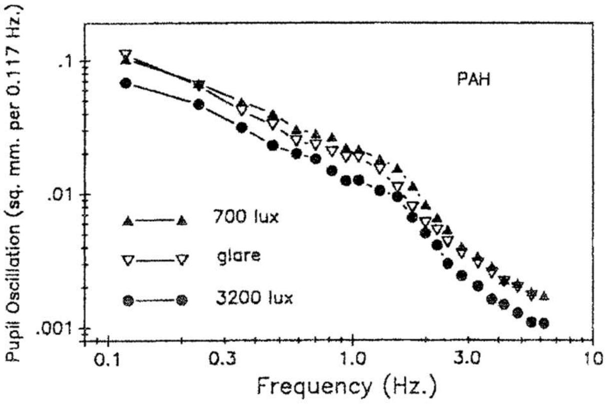

Figure 2.2. Amplitude spectra for a participant being subjected to three specific light levels: two not causing discomfort (black shapes) and one causing discomfort (White shapes) [76].

Although pupillary unrest might not be the cause of discomfort sensation, considering this factor as a potential physiological response in relation to glare is worthwhile. The relationship between light intensity and amplitude or frequency of light-induced pupillary oscillations was investigated by Warga et al. [87]. They confirmed that the pronounced oscillations existed and uninfluenced by other factors; however, they could not determine a regular relationship between light intensity and the amplitude or frequency of oscillation.

Stringham et al. [41] examined pupil diameter fluctuations under three lighting conditions, two background light levels and one glare luminance. They reported an inverse relationship between pupil diameters and subjective evaluations of visual discomfort in glare presentation. In other words, there was a reduction in pupil diameter as discomfort glare became more unbearable for the subject, notwithstanding that a smaller amount of light reached the retina [41].

Garretón et al. [83] sought to establish a correlation between vertical illuminance at the eye and the physiological parameters of pupil size, gaze direction and degree of eye-opening, in a laboratory-simulated office environment with natural lighting conditions. The physiological determinations were then used to evaluate the inconsistencies of glare prediction models: Predictive Glare Sensation Vote (PGSV), Daylight Glare Probability (DGP) and Daylight Glare Index (DGI). This was investigated in the context of minimising glare discomfort in office environments where natural daylighting is utilised in the workspace. Two scenarios were presented to participants: the first with direct sunlight on the working surface, the second with sunlight on the subject's face. In each scenario, subjects were required to complete 4 tasks: reading from a paper, reading from a computer screen, socialising, and filling out questionnaires. The frequency of changes in pupil size, the direction of eye gaze and eye-opening were measured throughout using a customized eye-tracker. Using image processing techniques to evaluate pupil diameter, Garretón et al. examined pupil size fluctuations during the reading task from the screen and found a significant correlation with lighting levels. However, they found a better correlation in the presence of direct sunlight. They concluded that the pupil size could be considered an indicator of visual discomfort in highly lit spaces [83].

Lin et al. [81] investigated relative, rather than absolute, pupil size to provide a more reliable exploration of the factors that induce discomfort glare. The authors claim that this method demonstrated a higher correlation between pupil size and discomfort glare as reported by the subjects than earlier studies. Their physiological analysis showed a strong correlation with the subjective ratings given on the de Boer scale which is a 9-point scale with having a rating of 9 as just noticeable glare and rating of 1 as unbearable glare. Figure 2.3 illustrates relative pupil size correlation with the de Boer rating scale, having a rating of one as unbearable glare and a rating of 9 as just noticeable glare. It was also reported that glare source illuminance, background illuminance, and viewing angle have significant effects. However, the interaction of the glare source illuminance and the background illuminance, as well as the correlated colour temperature (CCT) was found not to have a significant effect [81].

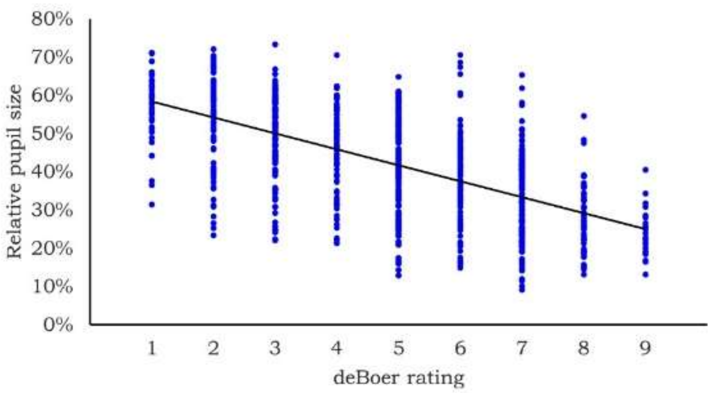

Figure 2.3. The relationship between relative pupil size and the de Boer rating of glare [81].

Since the advent of infra-red video techniques to study the pupil, several variables have been measured including velocity, acceleration and latency, though the principle consideration has been the amplitude of the pupillary light reflex in either absolute or relative form. Rarely considered is the interdependency of these variables [89].

Scheir et al. [85] have adopted a new approach by considering the receptive field mechanism along with pupil size and have presented a new model for predicting discomfort glare which accounts for non-uniform luminaires. This model overcame the limitations of traditional metrics, which typically only included the average luminance of a source such as UGR, and thus inadequately considered the increased discomfort produced by non-uniform sources and specularities. To improve the physiological accuracy of their model, Scheir et al. incorporated the receptive field mechanism, pupillary light reflex, and a correction for the retinal position. Pupil diameter is calculated from the average of stimulus luminance and field size (Equation (4)), and is then used to estimate retinal illuminance (E_{ret}, Equation (5)) [85].

$$D = 5 - 3\ \tanh(0.4 \log \frac{L_s a}{40^2}) \tag{4}$$

$$E_{ret} \sim L\,.\,(\frac{D}{2})^2.\,\pi \tag{5}$$

Where D is the pupil diameter (mm), L_s is the average stimulus luminance (cd/m^2) and α is the stimulus field size (deg^2).

The Guth position index (GPI) was used to account for the reduction in perceived brightness as a source is moved away from the line of sight. A retinal illuminance map can then be calculated using Equation (4) with each pixel weighted by the GPI. Other factors, such as the absolute signal value of the convoluted retinal illuminance map, were considered in order to model a centre-surround receptive field and develop the equation for their visual discomfort model:

$$\text{Visual Discomfort Model} = \left(\omega_{pix} \sum_{pix} \left|(C - WF.S) * E_p\right|\right)^{\frac{1}{3}} \tag{6}$$

Where ω_{pix} is the pixel solid angle; C is the centre kernel; S is the surround kernel; WF the surround-to-centre weighing factor; E_p is the retinal illuminance map per pixel weighted with the position index and $*$ is the convolution operator. The experiment was found to validate the model, though its effectiveness with stimuli presenting low-level discomfort was weak, thus, a lower limit for the model required investigation. The model was corroborated by others who observed an increase in discomfort with increases in total luminous flux and non-uniform luminance. The inclusion of the pupillary light reflex and

GPI introduced a more accurate model. Scheir et al. concluded that the model was a promising alternative to current glare metrics, especially when non-uniform luminaires are considered. Figure 2.4 depicts the correlation of the proposed model with subjective glare evaluations [85].

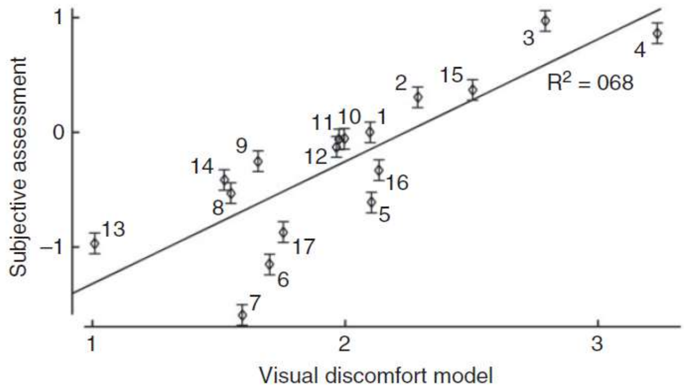

Figure 2.4.The visual discomfort model against the subjective assessment for all stimuli [85].

2.6.2 Eye movements

Due to the existing debate on pupillary reflexes in the presence of glare discomfort, some researchers have attempted to test other factors that can represent discomfort sensations in the eye. Berman et al. [77] utilized an electromyography (EMG) device to measure micro voltage muscular impulses in the area surrounding the eye. This is being presented as a potential objective physiological measure response in an effort to find a correlation between physiological and subjective responses to discomfort glare. To allow for more detailed analysis of recordings and help eliminate contaminants, Fourier analysis was chosen over integrated EMG analysis, and Amplitude Probability Distribution Function (APDF) analysis [77].

Berman et al. [66] found a correlation between subjective and physiological evaluations, which both showed an increase in discomfort glare as room illumination decreased in the presence of a steady glare source, and that at smaller glare source apertures, discomfort decreased. This allowed for the proposal of an Objective Discomfort Ratio (ODR) (Equation (7)) which could be used as a predictive model for estimating discomfort glare. They also recognise however that the muscular response measured by EMG is likely not originating from the source of the discomfort glare, but is a reflection of a more general muscular response to discomfort.

$$\text{ODR}=\frac{Integrated\ EMG\ \ power\ spectrum\ with\ glare\ soure}{Integrated\ EMG\ \ power\ spectrum\ witho\quad glare\ soure}-1 \qquad (7)$$

As an alternative to electromyography (EMG) for measuring extraocular muscle neural activity, Lin et al. [81] employed Electrooculography (EOG) which measures the corneo-retinal standing potential that exists between the front and back of the eye and this can be used to measure the angle of the eyeball in its orbit. Their pilot study observation confirmed that EOG activity occurs in the first 0.5 seconds and then returns to the base level. Therefore, only the first 50 EOG values were utilized to calculate the average eyeball movement speed (AEMS) as an indicator for determining physiological response to glare (Equation (8)).

$$AEMS = \frac{\sum_{i=1}^{n-1} \frac{|V_{i+t} - V_i|}{T}}{50} \qquad (8)$$

Where V is the EOG value at a certain time and T is the sampling cycle interval. The equation indicates that faster eye movement leads to higher AEMS value. A similar observation to pupil dilation (section 4.1.1) was made regarding eye movement speed, since with deteriorating glare discomfort, the eye movement speed increased and was more significant in higher glare discomfort conditions, especially for senior participants (Figure 2.5). Lin et al. also suggested that glare source illuminance, background illuminance, and their interaction had a significant effect, whereas colour as measured CCT is not an affecting factor [81].

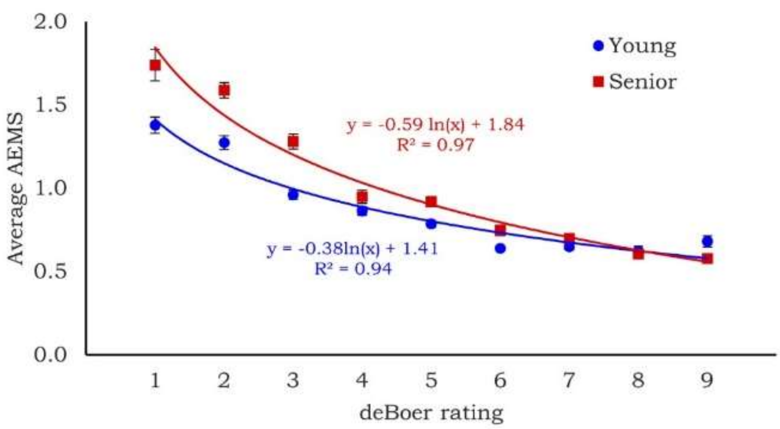

Figure 2.5. The average AEMS plotted against de Boer rating for two age groups illustrated with the standard error. De Boer ratings of > 5 represent conditions providing a lower level of glare while de Boer ratings of ≤ 5 represent conditions providing a higher level of glare [81].

Murray et al. [78] proposed a physiological method for determining discomfort glare using a new device for detecting electromyographic (EMG) activity in the extra-ocular muscles, the Ocular Stress Monitor (OSM). This new device aimed to provide a more rigorous basis for the development of discomfort glare models and, shed light on the potential physiological origin of pain experienced under discomfort glare conditions. The device was developed and tested to be portable and therefore able to be utilized in conditions outside the lab, such as when driving to evaluate conditions on a motorway. Both a typical Medelec broad-band amplifier and the specialised narrow-band OSM were used to track EMG activity in subjects so that the effectiveness of each could be compared [78]. The OSM device was demonstrated to be more effective at filtering artefacts such as noise, and signals generated by blinks. As shown in Figure 2.6, the sharp negative wave at 0.25 seconds prior to the glare source being switched off in the Medelec raw signal was induced by a blink in the subject and was filtered by the OSM [78].

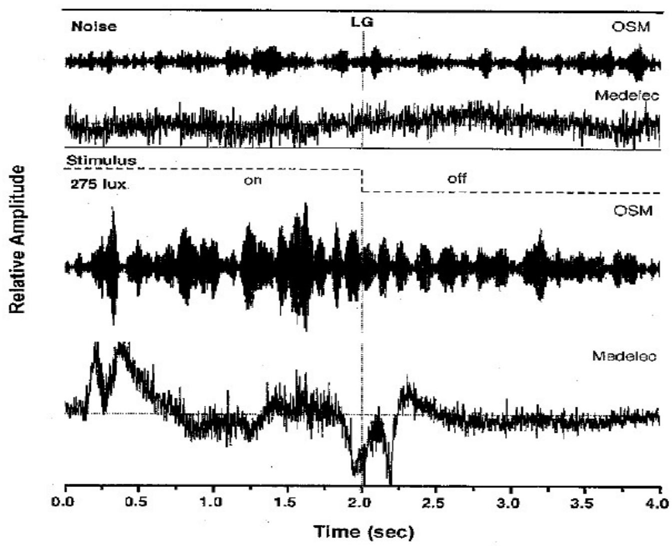

Figure 2.6. The comparison of the noise (upper panel) and the raw signal induced by a glare source of 275 lux obtained from the OSM and the Medelec (lower panel). Stimulus timing is depicted by a dashed line [78].

2.6.3 Blink rate, gaze direction and degree of eye-opening

The autonomic nervous system of a human body, by using several reflexes, attempts to decrease the fluctuations in the ambient environment and keep the body physiologically stable. Visual adaptive mechanisms are not limited to pupil dilation. Blink rate [79], gaze direction [83, 103] and degree of eye-opening [80, 83] are other factors that have been investigated in lighting research so far.

Spontaneous blinking is expected in a normal, healthy and alert subject for maintaining the clarity of vision and a healthy ocular surface, which can also be considered as a marker for central dopaminergic activity [104]. Much of the Spontaneous Eye Blink Rate (SEBR) research has focused on identifying and evaluating it as a measure of vision and ocular comfort from a health perspective. Several studies are recognised for noting significant variability in average SEBR between individuals with rates of between 2.9 and 29.0 eyeblinks/minutes. This variability is in part attributed to the various tasks being completed at the time of measurement with lower rates expected while reading, intermediate rates while sitting or in primary eye gaze, and higher rates while in conversation [79].

Doughty [79] evaluated the effects of gaze direction on the SEBR of healthy adult subjects while exposed to a glare light source. A baseline assessment was made of all 32 subjects under ambient lighting (without glare source) after which subjects were split into two groups of 16. The first group was reassessed under ambient light with either having the gaze directed toward a high or low target position, then reassessed under the same conditions, but with the target moved from high to low or vice versa. The second group was assessed under glare conditions (with tungsten lamps turned on) with the gaze directed toward a target at either normal or high position then reassessed with the target moved from high to normal or vice versa [79].

The SEBR under ambient conditions with primary gaze direction was 11.7 ± 0.9 with a coefficient of variation (COV) of 20.5%. Variation under downward gaze was insignificant but under upward gaze, SEBR was 13.0 ± 1.1 with a COV of 26.1%. Under glare conditions, SEBR in primary gaze position increased significantly to 14.4 ± 2.4 with a progressive increase in blink rate over the 5-minute recording. Under glare condition with upward gaze, SEBR was further increased to 15.0 ± 2.4, as did COV to 29.2%. The results are to some extent concordant with the previous findings that perceived glare from a source under the line of sight is greater than a source above the line of sight [53, 54]. Doughty concludes that SEBR can be affected by the presence of a glare source, especially if the subject has an upward gaze [79].

Gaze direction is another adaptive human behaviour in a lit environment. Sarey Khanie et al. [103] carried out an experimental study to find out how illuminance distribution and outside view in a daylit office can adjust View Direction (VD) over time as occupants carry out their office tasks. Their research revealed that during a non-visual (thinking phase) office task, occupants tended more often to look out the window, and this effect was higher under low contrast conditions. In addition, this research showed that while users performed tasks involving cognitive and visual activities (input, response and interaction phase), the focus of VDs was around the task area (Figure 2.7). In other words, the view direction was attributed to lighting conditions and the type of task they were doing [103].

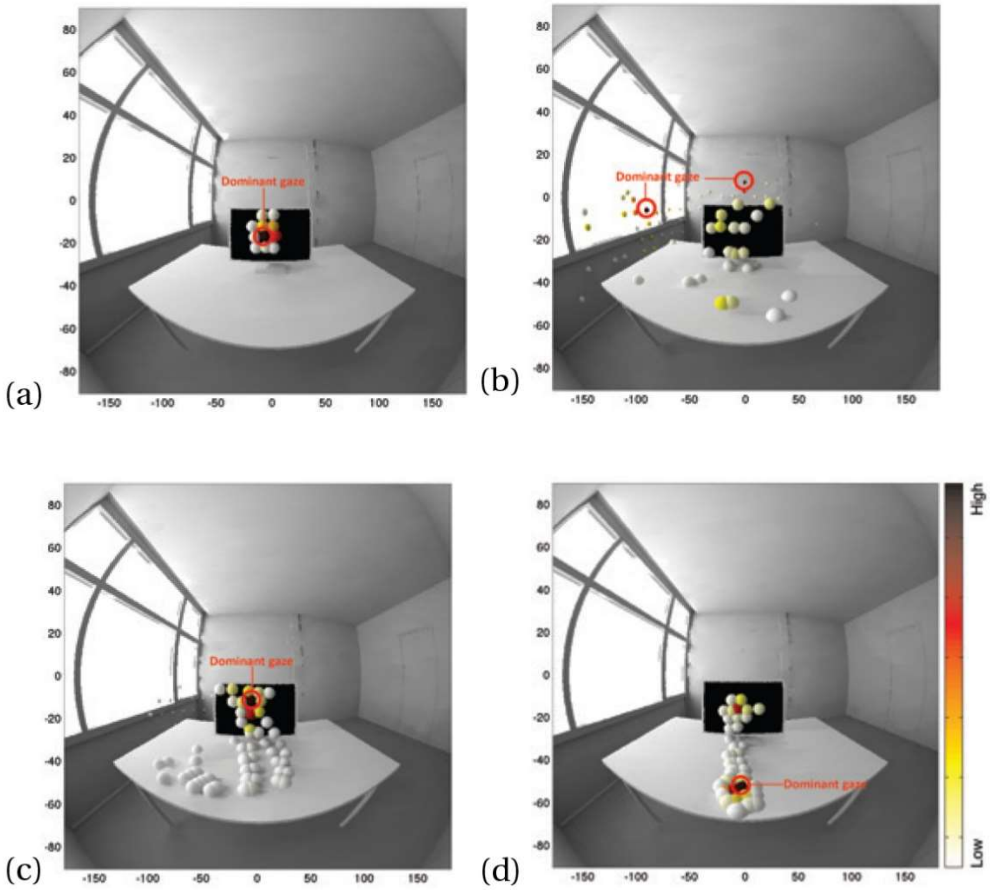

Figure 2.7. 3D visualisation of the gaze allocations of one participant in each task phase: (a)Input phase, (b)Thinking phase, (c) Response phase, (d) Interaction phase [103].

Garretón et al. [83] determined that gaze direction as an indicator for detecting discomfort glare and found it to be heavily affected by the cognitive demand and complexity of the task which made it unsuitable as a predictor for discomfort glare Figure 2.8) [83].

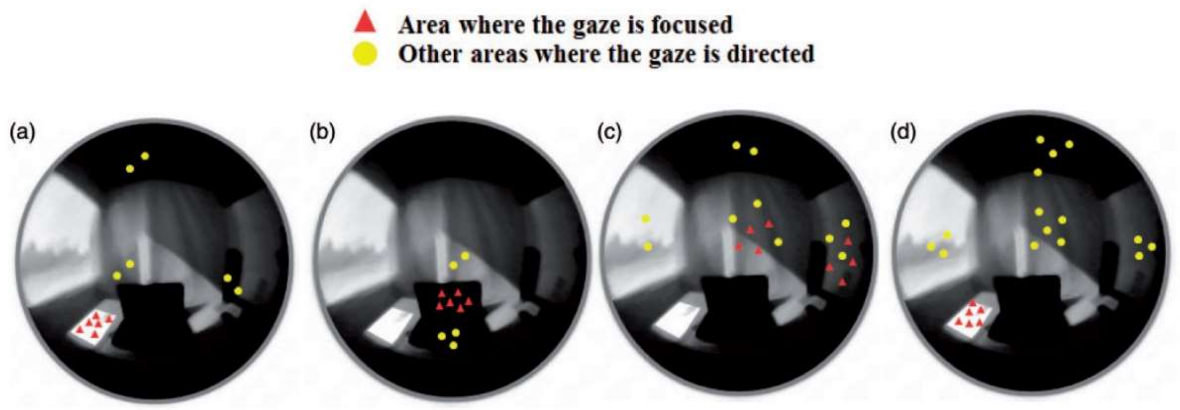

Figure 2.8. Gaze pattern. (a) Reading on paper task. Moderate cognitive difficulty; (b) reading on PVD task. High cognitive difficulty; (c) socializing. Moderate cognitive difficulty; (d) questionnaire filling task. Low cognitive difficulty [83].

Along with spontaneous eye blink rate and gaze direction, eyelid movements and its kinematics have received attention in health studies. Eyelid movements can also be considered as an adaptive behaviour to protect the retina from receiving excessive illuminance. Garretón et al. [80, 83] investigated the degree of eye-opening along with gaze direction and pupil size to test the feasibility of it as an indicator for experiencing visual discomfort. The authors claimed that the degree of eye-opening (DEO) was the most reliable indicator of glare. A good correlation was found between DEO, PGSV and DGP (Figure 2.9), meaning the degree of eye-opening (DEO) could be a suitable index of visual comfort in a situation of glare risk in sunny climates. Besides, in contrast with pupil diameter, DEO is not affected by workload variations [83].

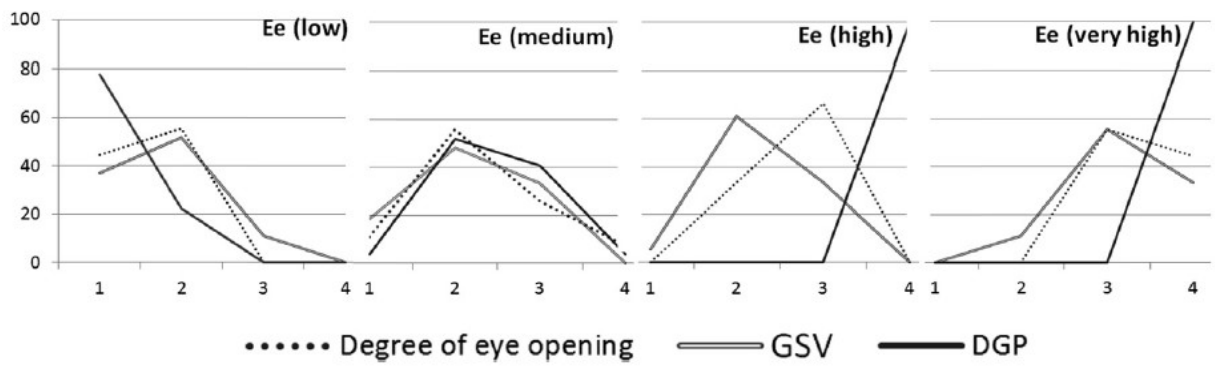

Figure 2.9. DEO, PGSV and DGP performance. The x-axis indicates the perception of glare: 1 imperceptible, 2 noticeable, 3 disturbing, 4 intolerable. The y-axis indicates the percentage of people [80].

2.6.4 Confounding factors

Lighting factors are not the only potential causes of visual discomfort. The color and reflectance of the surrounding surfaces, as well as task characteristics, also contribute to visual discomfort sensation [13]. Even though these factors are not within the direct scope of the review, they can play a role as confounders and lead to a false demonstration of an association between dependent and independent variables in an experimental study.

There are factors such as task difficulty (cognitive, perceptual and visual load), that can affect user physiological responses namely pupillary reflexes and blink rates while they are performing a visual task. Task-induced pupil diameter, blink rate and eye-lid kinematics have been discussed by numerous studies as physiological measures of inferring cognitive load [105] with various applications such as amending human-computer interaction and monitoring operators' cognitive load in flight tasks or combat management [106]. In addition, the eye convergence which is a part of refocusing mechanism of the eye can also affect the pupil size and eye movement data in an experiment looking for light-induced reflexes [107].

It is unclear why colour has affected visual stress symptoms, and it was proposed that 'glare' plays a major role [108]. Historically, Wilkins suggested pattern-glare causes a 'localized hyper-excitability' of the visual cortex due to a hypersensitivity to contrast, with perceptual distortions occurring through the same mechanisms [109, 110]. Contrast sensitivity is the luminance difference required to reliably discern a target from its background [111]. Wilkins [109] proposed colour suppresses this hyper-excitability, preventing the spread of excitation responsible for the distortions. Using fMRI, Huang et al. [112] investigated the haemodynamic response (changes in blood oxygen levels) to gratings in the visual cortex in 11 migraine patients aged between 16 and 65. Precision tinted lenses reduced cortical activation in area V1 by 5%, and significantly reduced cortical activation in V2 to V4 areas of the extra-striate cortex by 19%. However, brain responses in sub-cortical areas in response to colour need investigation, as the colour is known to have emotional effects [113].

Color is not only involved in visual discomfort but also the human mood and level of arousals. Aggression-lowering effects have been found when inmates were placed in rooms painted in Baker-Miller pink - a bright, low-saturation, red-purple [114]. Jacobs and Suess [115] investigated the emotional effect of the colours red, yellow, green and blue by projecting colours onto a screen with State-Anxiety Inventory scores the dependent variable. Highest state-anxiety scores resulted from red and yellow. Using physiological measures (e.g. skin conductance response), long-wavelength colours (e.g. red) have been demonstrated as being more arousing than short-wavelength colours (e.g. blue) [113]. However, Valdez and Mehrabian [116] conducted a series of studies that provided evidence for relations of colour brightness and saturation to affect emotional reactions.

Given that, typical symptoms of visual discomfort can be caused by other factors rather than lighting characteristics, identifying the cause of visual discomfort needs to be performed with cautious and accounting for confounding factors. It is interesting to note that none of the papers in Tables 1 and 2 mentioned possible confounding factors.

2.7 Challenges of physiological responses in glare studies

In spite of the advantages outlined in the previous sections regarding the incorporation of physiological responses in glare studies, there are some challenges in objectifying glare sensation. In most of the presented studies, physiological responses were finally analysed based on subjective evaluation of perceived glare. Thus, there is a need for establishing more objective methods to reduce the bias associated with subjective assessments. For instance, Boyce et al. [117] included some performance measures using different tasks such as timed vision test, Conveyor Belt task and typing task, and utilized the accuracy and speed of their performance as quantitative measures in their analyses. Wilkin [118] and Conlon [119] asked subjects to look at a stripe pattern and report any kind of visual perceptual distortions namely colors, fading, shimmer/flicker, shadowy shapes, bending or blurring of lines that were perceived. However, measuring visual performance might not be the best alternative method to overcome the limitations associated with subjective assessments since discomfort glare in many cases might not lead to reductions in performance.

2.8 Conclusion

This study reviews the existing literature of implemented methods in measuring light-induced physiological responses in order to objectify perceived glare and identifies the factors that were found to have a high correlation with user visual comfort assessments. The review suggests that a holistic synthesis that includes light-induced physiological assessments along with regular image and photometric data recording, as well as occupant visual comfort assessment, would allow lighting researchers to make progress towards solving the inconsistencies in glare predictive models and result in a more objective method. The need for further research is clearly identified.

A systematic review of qualified studies was conducted. It was found that there is still limited scientific proof for the link between lighting conditions and some potential physiological responses. According to this review, studied physiological responses can then be categorized into:

Very promising (established factors)

- Relative Pupil size: Inversely correlated with visual discomfort ratings, correlated with vertical illuminance at the eye and glare indices

Just statistically significant (require further investigation)

- Pupillary unrest (hippus): Affected by the luminance intensity
- Eye Movements: Compared favourably with subjective assessment
- Spontaneous eye Blink Rate: Affected by glare while the subject is looking slightly upwards
- Degree of eye-opening: Applicable in the presence of direct sunlight; correlated highly with vertical eye illuminance, DGP and PGSV; exhibited better diagnostic performance than DGI, DGP, or vertical illuminance at the eye

Irrelevant

- Absolute pupil diameter: Correlated with overall background luminance.
- Gaze position/direction: Heavily depends on the cognitive demand and complexity of the task, unsuitable as a predictor for discomfort glare

Among light induced physiological responses, pupillary light reflex received the most attention; however, the research findings might not be consistent. This heterogeneity is a consequence of methodological diversity. Pupil diameter variation is a visual adaptation mechanism, which is accessible for observation. However, the absolute pupil diameter could not be considered as a comparable measure due to individual differences in pupil size and shape. Studies that examined pupil diameter itself concluded that pupil size is proportional to the overall background illuminance including the glare source. Relative measures derived from the raw measurements namely the first derivative, velocity or oscillation of pupil diameter can better serve as a comparison between subjects. Moreover, it was found that light stimuli and their duration are other factors that can affect pupillary light reflexes. As such, sudden intense stimuli can produce significant short-term responses. Other factors namely eye movement and spontaneous blink rate (SEBR) although showing a statistically significant correlation require further investigation to be established as a promising factor.

Since light is not the only reason for visual discomfort sensation a meticulous experimental design is required to control the effect of confounding factors. In some research, the effect of glare discomfort on user ocular behaviour was investigated while subjects were performing a visual task requiring high cognitive and motor performance. A note of caution is due here since in visual tasks, such as the divided attention Stroop task in conjunction with the memory span task, although being realistic regarding the simulated office work, the high cognitive load makes them difficult to discuss the eye-lid kinematics or pupillary light reflex as a light-induced response. Furthermore, when it comes to the pupillary light reflex, it might also be affected by eye convergence if subjects look at points with different distance from the eye. Therefore, researchers need to be aware of confounders in their experimental design to acquire accurate results.

A limitation of this study was that in reviewed studies the utilized survey tools for subjective assessments and types of office task were inconsistent. The subjective visual discomfort assessments were performed based on different methods and scales. In addition, some experimental studies used computer-based tasks, while others utilized variations such as paper-based tasks or socializing. The aforementioned issues thus made the comparison between studies complicated.

Although it is evident that more objective measures need to be coupled with prevalent visual discomfort evaluation methods in order to generate more robust metrics, this area of research still requires further experimental studies for a better understanding of physiological and behavioural responses to electromagnetic radiation.

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Chapter 3: A preliminary study of utilizing eye-tracking data in visual comfort assessment

The previous chapter of this thesis uncovered the need for incorporating objective methods in visual comfort assessments, and critically reviewed the previous works regarding physiological responses under visual discomfort conditions. The chapter identified the established factors in this area, as well as that required further investigation. Considering the potential of utilizing eye-tracking technique and drawing upon the previous chapter, Chapter 3 specifically focuses on utilizing eye-tracking data in evaluating visual discomfort, and all potential indicators provided, the required data processing for each type of data, and to how to generate clean, meaningful data to be used in this research.

Chapter 3 of this thesis includes a published co-authored conference paper which has been presented in *2018 ASHRAE Building Performance Analysis Conference and SimBuild*, Chicago, United States. The chapter has been formatted to meet the standards of this journal in terms of style and formatting. My contribution to the paper involved: designing and conducting the experiment, data collection, the computer programming, analysis of results, and writing and editing the manuscript. The bibliographic details of the co-authored paper, including all authors, are:

Z. Hamedani, E. Solgi, H. Skates, M. S. Khanie, and R. Fernando, "A calibration and adjustment method for a dynamic visual comfort assessment," *2018 Building Performance Analysis Conference and SimBuild*, Conference Proceeding by ASHRAE, Chicago, United States, 2018.

3. A calibration and adjustment method for a dynamic visual comfort assessment

3.1 Abstract

Glare is known as one of the main causes of visual discomfort in office space and yet remains difficult to evaluate quantitatively. Most discomfort glare models have limitations when attempting to represent the reality of user behaviour. One reason is that models are developed based only on subjective surveys. This research aims to probe the influence of experiencing glare on user ocular and dynamic gaze behaviour as an objective response. To do so, an experimental study was conducted utilizing an eye-tracking device to record user's gaze responses to the surrounding environment. High dynamic range imaging was also used to record luminance distribution. This paper documents the calibration process for the variety of equipment utilized in this research.

3.2 Introduction

In the contemporary workplace, productivity [1], satisfaction [2] and comfort [3] are highly contingent upon the visual environment. However, glare as one of the principal reasons for visual discomfort [4], gives rise to such unexpected experiences as early fatigue, headache and so on [5]. Additionally, owing to various human tolerances and attitudes towards glare, evaluating discomfort glare has been controversial [6].

The existing glare models, driven by photometric measurements in the field-of-view (FOV), visibility, and subjective evaluations, have been utilized to quantify the perceived glare [7]. The influential factors on glare are known to be as formulated below [8]:

$$G = \left(\frac{L_s^e \cdot \omega_s^f}{L_b^g \cdot f(P)} \right) \qquad (1)$$

In this equation, L_S accounts for the luminance of the glare source which is received by the user's eye from a specific viewpoint; ω_s is the solid angle subtended by the source with respect to the eye of the observer; L_b is the adaptation luminance; P is the position index, and stands for the discomfort perceived depending on the location of the glare source in the FOV with respect to the line of sight (view direction); the exponents (e, f and g) are weight factors for each parameter which vary in different glare formulae. The empirical correlation between these photometric quantities and subjective responses through different studies on discomfort glare has resulted in several prediction models. The prevalent quantitative subjective assessments such as the de Boer (1967) scale, which is a category rating scale to evaluate glare, are, however, susceptible to uncertainties associated with people's understanding of terms and language used or the test procedure in a particular experiment [9]. Another limitation that the existing models have is making certain assumptions about user-behaviour such as fixed-view direction assumption.

Physiological involuntary responses, which are now easier to record on account of novel advanced technologies, have been considered in a few studies in order to overcome uncertainties about category rating scale assessment methods that have so far been used to quantify glare. The pupillary response has been the main objective feature investigated by researchers to address light-induced physiological reflexes. There is a consensus that the pupil diameter itself cannot be used as an indicator of experiencing glare whereas the fluctuations and irregularity of pupil dilation and constriction should be considered [10-15]. The inclusion of involuntary user ocular behaviour, which includes but is not limited to user physiological responses such as pupillary oscillation, has proven to be an alternative and complementary objective assessment of discomfort glare.

The fixed-view assumption deficiency has been addressed through arbitrary predefined orientations for view direction [16] without considering user natural behaviour. This issue has been addressed more rigorously in a series of experimental studies where the effect of different lighting conditions on view direction orientation and the actual perceived visual comfort was investigated, which resulted in a gaze-driven model [17]. Sarey Khanie et al. [18, 19] through use of a head-mount mobile head and eye-tracking device, conducted these experiments to assess the impact of luminance distribution and outside view in a daylight office on view direction behaviour.

To date, the spatial frequency of user view directions based on different lighting distributions and office task types has been investigated. However, adjusting view direction is a user adaption behaviour. Thus, to have a profound understanding of user behaviour regarding glare, and to see how they can affect glare predictive models, differing ways of evaluation and individual preferences, as they reveal rather than report, should be considered. It is worthwhile therefore to investigate the influence of experiencing glare on user ocular and gaze behaviour in addition to their visual performance.

In order to explore further the gaze and ocular behaviour as involuntary physiological responses to glare, this experimental study, by means of an eye-tracking device and High Dynamic Range (HDR) imaging for luminance mapping, aims to tackle the mentioned limitations in studies to date in relation to discomfort glare. A vital sensitive step in this study was the calibration phase to produce accurate results. The key challenge of this method was in translating acquired data from the eye-tracker to useful data for glare analysis.

This method consisted of three phases: the calibration process for the eye-tracking device; the calibration process for HDR imaging and finally processing the acquired data. In this paper, the calibration phase and data processing are described in detail.

3.3 Methodology

Each device used in the experimental set up required a sensitive calibration procedure in order to obtain accurate data. The first instrument to be calibrated was the eye-tracking device, the aim being to interpret various ocular data and translate its inertial measurements into spatial coordinates and vectors. Calibrations included adjusting for drift and mapping the data-stream with task activity.

The second calibration pertains to creating HDR images as a record of the luminance distribution in the room. HDR imaging is a well-known technique for obtaining a larger spectrum of luminance values than standard imaging. Several calibration studies on HDR imaging have been published, including [20-26]. Devebec and Malik [27] present one of the best-known approaches for recovering radiance data from HDR images. Although the various details and options in creating HDR images were recorded, problems included calculating the response curve of the camera, accounting for the vignetting effect of a Fisheye lens, and adjusting the luminance scale to a measured point in the image.

The final step in calibration dealt with understanding the recorded gaze data. The gaze data can be categorised into 4 types of eye movement: small rapid (*saccadic),* smooth tracking *(pursuit),* focusing *(fixation),* and rapid corrective for head movements (*vestibule-ocular*) [28]. Recognising these subtle behaviour 'features' and processing the data will provide a deeper understanding of user physiological behaviour and visual performance. In this study, to classify eye movements from the raw data, a Velocity-

Threshold Identification (I-VT) fixation classification algorithm [29] was adopted, which is a velocity-based classification algorithm.

3.3.1 The calibration process for the eye-tracking device

The Tobii eye-tracking glasses are wearable, lightweight, discreet binocular eye trackers, which work based on the corneal reflection eye-tracking technique [30]. Using this device, gaze data including but not limited to head-referenced gaze direction and pupil diameter can be recorded on a 100 Hz sampling rate. This device has an integrated micro-electro-mechanical system (MEMs) incorporated in the eye-tracker, which aggregates translational acceleration and rotational velocity, demonstrating body movements.

The adopted eye-tracking glasses utilize one-point calibration method. In this type of calibration, only one calibration marker is required for personal calibration (Common calibration methods require the user looks at nine to twenty calibration markers in succession) [31]**.** The calibration needs to be performed just once, before commencing the data recording.

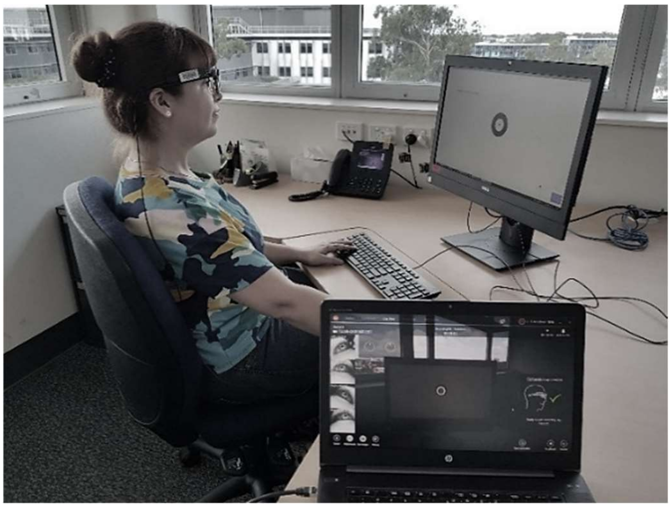

Figure 3.1 A participant wearing an eye-tracker and the calibration process

In this research, the calibration process was integrated into the visual tasks of the experiment. It was used at the beginning of the experiment task sequences to calibrate the eye-tracker which is normally required for recording gaze data. The calibration marker was also added to the end of the experiment tasks for two reasons: first, to validate the captured data during the experiment, and estimating accuracy and precision of the acquired data and second, to utilize the calibration marker as a measure for visual discomfort experienced by the user at the end of the experiment (see Figure 3.1).

3.3.2 The calibration process for HDR imaging

High dynamic range (HDR) imaging allows for capturing luminance values over a wide range, with accuracies in the range of ±10% [24]. However, creating HDR images with reasonably affordable equipment requires an extensive calibration process to ensure that luminance data and derived spatial information is correct [20]. The most common HDR calibration process steps determined in the literature [20, 21, 32, 33] are:

- capture of multiple exposure images,
- camera response curve derivation,
- HDR image generation,
- calibration adjustment by spot luminance measurement and geometrical re-projection

The luminance maps acquired during the research were captured using a Canon EOS 5D MARK III digital camera with Full Frame CMOS (36.0x24.0) sensor fitted with the EF 8-15mm f/4L Fisheye USM lens.

In acquiring luminance maps, a sequence of multiple exposure Low dynamic range (LDR) images is required. In this study, thirteen RAW images [23] were captured with exposure time ranging from 1/1000s - 4s. A sequence of multiple exposure images has to be taken by varying the exposure time between photographs, since changing the aperture would increase the problem associated with vignetting, which is a light fall-off at the periphery of the captured image [34], shutter speed is a more reliable measure than aperture size [25]. Small aperture sizes are correlated with greater potential for lens flare [22], and large aperture sizes suffer from a low maximum captured luminance value [32] and a large vignetting effect [35]. For this reason, the aperture of the lens was kept constant at a mid-range aperture size, F/11[20, 32].

The camera response function relates pixel values to relative radiance [21] and is specific for each camera, even if they are the same model [36]. There are several algorithms to estimate the camera response function. In this research, the software *Photosphere* has been implemented, which uses Mitsunaga and Nayar's method to approximate the response factor. To retrieve the real luminance values from HDR images, the centre of the target was measured at 1° with a Konica Minolta spot luminance meter LS-100 (measurement range 0.01–50,000 cd/m^2, accuracy ±0.2% at 1°), before and after the multiple exposure photographs were taken (see Figure 3.3).

Having achieved the map of the individual radiance values at each pixel, the next step was to create an HDR image. The largest available bracketed sequence was then selected to ensure that over- and under-exposed photographs were captured. In order to select the sequence of useful exposures, a mask file was applied to set all pixels outside the LDR Fisheye view images to a neutral colour (such as black; Figure 3.4) [37]. A script was then used to automatically count the pixels in the usable area of the LDR images and then select the right sequence. After selecting appropriate LDR images and the derivation of camera response function, HDR images were generated using Photosphere.

(a) (b)

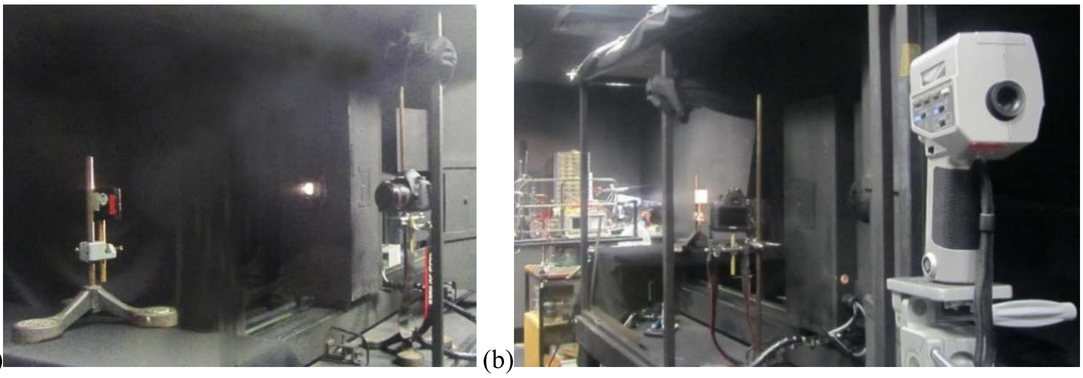

Figure 3.2 (a)The position of the camera, the target and the light source with constant luminous flux; (b) The position of the target, camera and the spot luminance meter

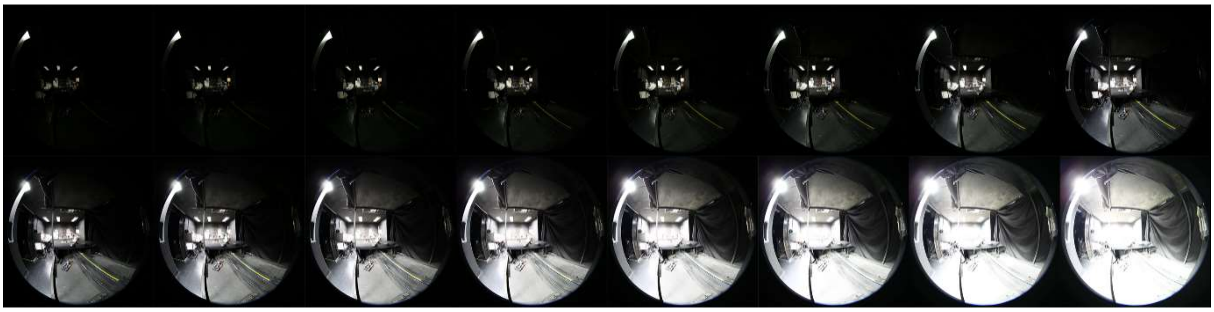

Figure 3.3 A range of LDR images was used to calculate the camera response factor

The vignetting effect is strongly dependent on the aperture size (or F-number) of the lens and increases with larger apertures [24]. The light fall-off from the optical axis of the Fisheye lens was measured in laboratory conditions for an aperture size of f/11, and a digital correction filter was created [21, 22, 37].

Figure 3.4 The captured LDR image and the usable area for making the HDR image

3.3.3 Glare source detection

Regarding glare source detection, the *Evalglare* program was used which is part of Radiance [38]. It is a command-line program with the purpose of identifying sources of glare in a given HDR image. For VDT (visual display terminal) tasks, it is recommended to use the average task-zone luminance as a threshold luminance [39]. Therefore, a target task-zone with an opening angle of about 0.9 steradians was used so that it covered most parts of the computer screen and parts of the desk. Pixels with a luminance value four times higher than the average task-zone luminance were detected as a glare source.

3.4 Data processing

In each experimental trial, three different sets of data were acquired from the eye-tracking device (ocular and inertial); luminance camera and the light sensors which were used due to their potential for investigating physical and physiological responses, along with user visual performance. Figure 3.5 illustrates Research scheme for the data stream and data processing.

The eye-tracker and the embedded gyroscope and accelerometer (as part of MEMs) were 3 different devices with different sampling rates, 100 Hz, 95 Hz and 100 Hz [30] respectively. Hence, they do not have the same periodicity; further actions are required to synchronize all data. The drift from the gyroscope and accelerometer were consistent enough to be expressed as a linear equation and adjusted.

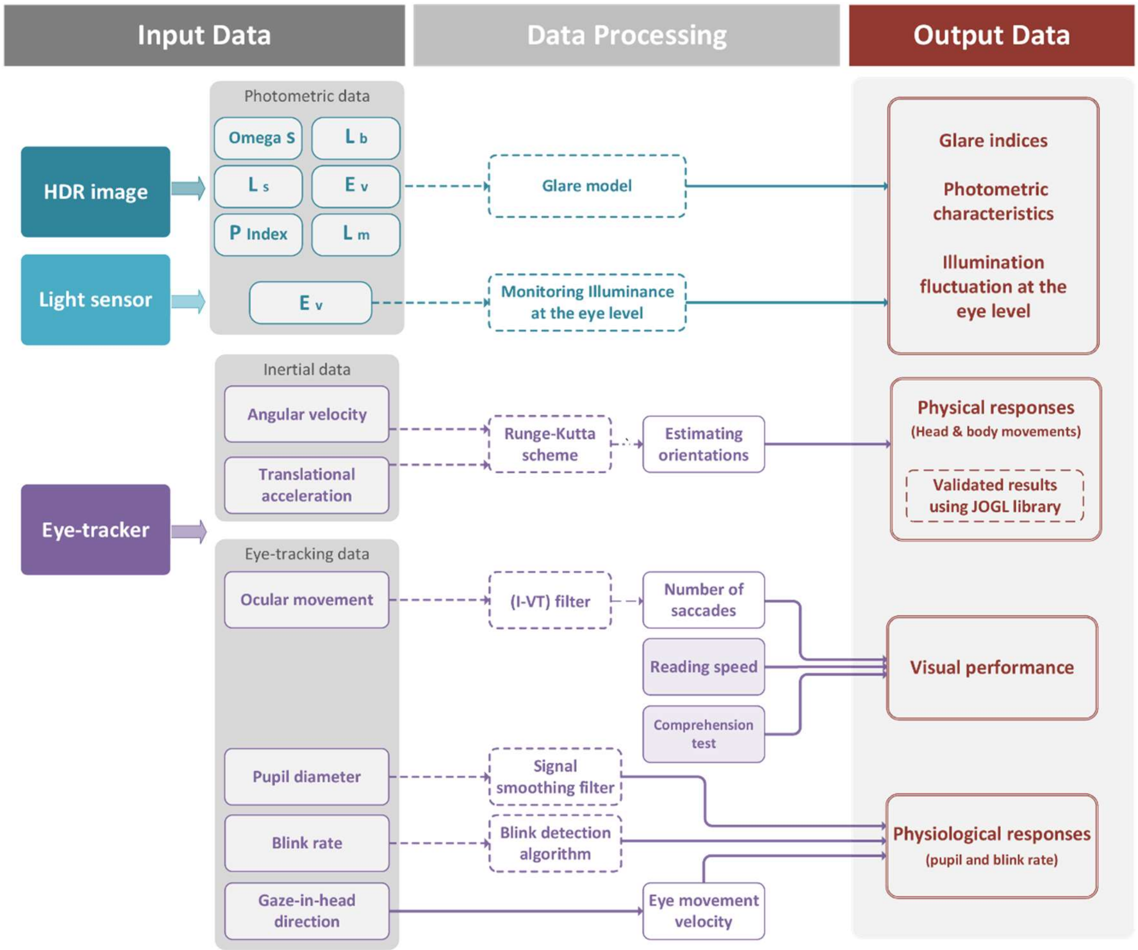

Figure 3.5 Research scheme for data stream and data processing

Figure 3.6 Comparison between eye-tracker scene camera and simulated 3D model

The comparison between the captured video data and the visualization demonstrated (Figure 3.6) that this approximation encapsulates the recorded movement with the accuracy that is needed for this research. The interpolated data was visualized in a 3D model of the space and tested against the video recorded from the eye-tracking glasses. An application was made in Java using the JOGL library to create the visualization.

In order to address physiological responses as well as visual performance, the acquired data required extensive data processing. In this step, an intermediate calibration, matching the eye related data as recorded by the eye-tracker, with other data sets and task activities was performed. The first step was translating eye-tracking raw data into a useful set of information. For this purpose, pupil diameter signals are de-noised using a smoothing filter, as shown in Figure 3.7.

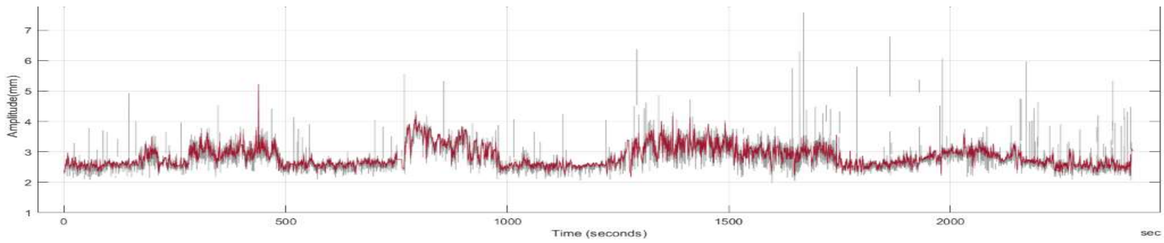

Figure 3.7 Variation of pupil diameter: raw data (grey line) and de-noised data (red line)

In the next step, the eye-blink rate was provided by means of a novel algorithm which was developed for this thesis and detects the user's eye blinks from the raw data and analyses the pattern and duration of the blinks. Figure 3.8 depicts the pupillary oscillation and blink rates during the entire experimental course and each visual task activity. In order to compare the frequency of pupil diameter oscillation for participants, the first derivative of pupil diameter is utilized. It is important to segment each task relative data since each type of experimental task differs in terms of required responses. Figure 3.9 shows the first derivative of the pupil diameter (blue line) added to the pupil diameter (dashed line) graph to demonstrate pupillary oscillation during each task activity (light grey horizontal bar indicates reading; medium grey horizontal bar indicates pause and dark grey horizontal bar indicates writing).

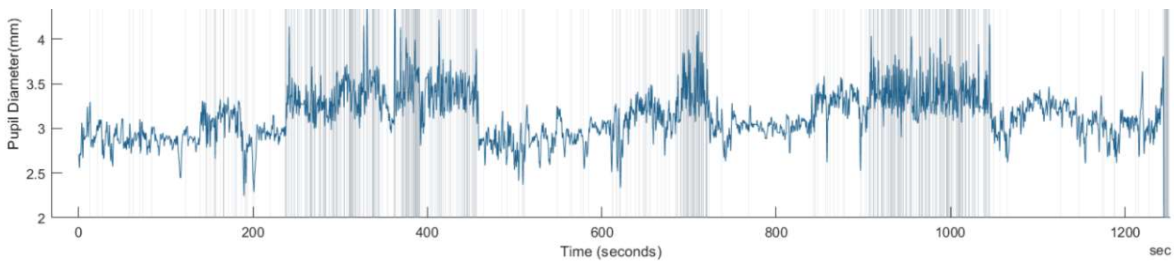

Figure 3.8.The reflex of the pupil (blue line) to a light stimulus as well as blink rates (vertical lines)

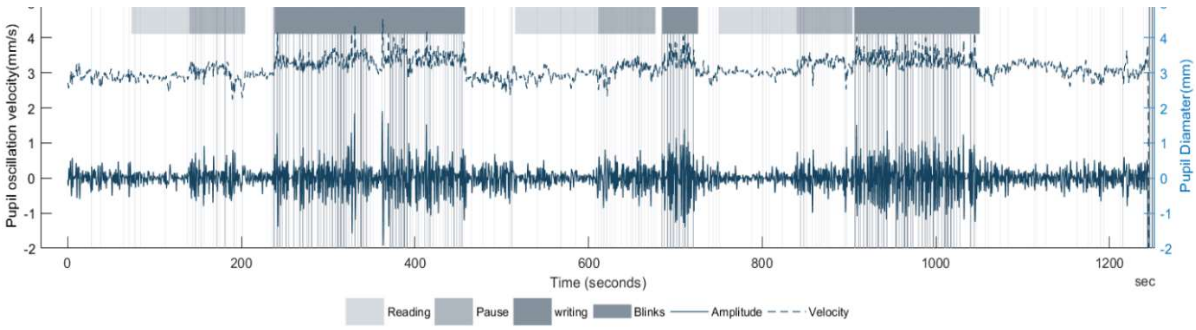

Figure 3.9. The first derivative of pupil diameter (blue line) and pupil diameter (dashed line) during each task activity

In this experiment to evaluate visual performance the total time spent on reading each passage was automatically recorded during the experiment. Fixations and saccades were also detected by applying a I-VT filter on eye-tracker raw data, and the accuracy was tested with a comprehension test at the end of each reading task. Figure 3.10 demonstrates gaze fixation points in sequence and their dwell time as the diameter of the circle. As a result, a new method for the future experimental research on glare evaluation and physiological response has been defined.

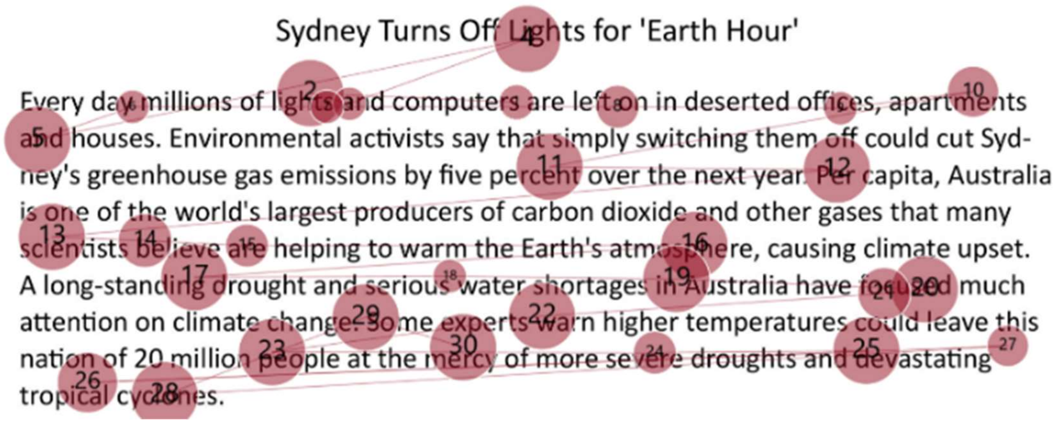

Figure 3.10. Gaze fixation points and dwell time as well as gaze trail and order for a reading task

3.5 Conclusion

An exhaustive calibration procedure was conducted in order to obtain accurate data for evaluation of human responsive behaviours in relation to glare. Moreover, a novel method was considered so as to study further the interrelations of glare, gaze and visual performance.

The calibration procedure was carried out in three steps starting with calibrating the eye-tracking device followed by the calibration process for HDR imaging and finally processing the captured data sets and translate them into a useful dataset for investigating the objectives of this research. As an immediate next step, the resultant data consistency with lighting conditions and subjective glare evaluations should be further examined.

The established method was employed in an experiment, in which four lighting conditions with different light distribution and glare level will be considered. Participants will be asked to perform different types of office tasks while their eye and gaze data were recorded in conjunction with photometric measurements to provide a deeper understanding of light-induced user behaviour.

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Chapter 4: Relationships among discomfort glare, physiological responses, and visual performance

The previous chapter explored the viability of utilizing eye-tracking data in visual discomfort studies. It explored different types of data recorded by the eye-tracking device, and the calibration and data processing procedures to study further the interrelations of glare, ocular data and visual performance. Thus, it provided the basis for the pilot and main experimental studies for this research. This chapter focuses on results from the main experimental study and brings together a wide range of objective, subjective and photometric measures. The holistic approach undertaken in this research provided new insight into the application of objective measures in the assessment and prediction of visual discomfort.

Chapter 4 of this thesis has been published as a co-authored paper in the journal, *Building and Environment*. The chapter has been formatted to meet the standards of the journal style for bibliographies. My contribution to the paper involved: conducting the experiment, data collection, the computer programming, data processing, analysis of results, writing and editing the manuscript, and submitting the paper to the journal. The bibliographic details of the co-authored paper, including all authors, are:

Z. Hamedani, E. Solgi, T. Hine, H. Skates, G. Isoardi, and R. Fernando, "Lighting for work: A study of visual discomfort, physiological responses and visual performance," ***Building and Environment***, vol. 167, p. 106478, 2019.
(https://doi.org/10.1016/j.buildenv.2019.106478)

4. Lighting for work: A study of visual discomfort, physiological responses and visual performance

4.1 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.

4.2 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):

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

L_{si} indicates the luminance of the glare source(s) (cd/m^2); 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/m^2); ω represents the solid angle of the window; and L_{win} is considered as the luminance of the window (cd/m^2). 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:

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

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 the luminance of the source (cd/m^2); 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 psychometric 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' differences [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 [27-34], eye movement [27, 35], eye blink [36] and degree of eye-opening [33, 37] 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 [38]. To this end, Boyce et al.

[39] 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.

4.3 Methodology

4.3.1 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. Main daylight conditions were initially identified using a parametric lighting simulation for the estimated duration of data collection throughout the 8 am–5 pm working hours at 15-minute intervals. The simulations were conducted to determine the frequency of similar solar positions through any given day that could be anticipated for experimentation under actual conditions. The simulations were performed using DIVA 4.0 for grasshopper, in Rhino. Thereafter, by utilizing the actual field measurements, three main lighting conditions were identified 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). In order to account for dynamics of daylight, if the changes in lighting conditions during the session were observable, or if the measurements at the beginning and end of each session differed by more than 10%, then those participants' data were excluded from the dataset. Lighting condition characteristics of the experiment based on the actual field measurements are listed in Table 4.1. To avoid introducing confounds, the order of stimuli and the number of each gender allocated to experimental conditions were counterbalanced.

Table 4.1 Three main lighting condition characteristics

Lighting Condition	DGP	Average L_m [cd/m2]	Average E_v [lux]
Low	< 0.35	560	2100
Medium	0.35 < DGP < 0.40	810	3400
High	> 0.40	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. Figure 4.1 shows the seasonal sun paths during the course of the experiments in relation to the experimental room. The continuous and the dashed blue line represents the winter and summer solstice sun path, respectively. The sun path gradually moves between the summer and winter solstice paths throughout the year. The solid hatch (light blue) shows the duration of data collections conducted for this research and its corresponding sun paths. The azimuth and elevation angles of the sun for each time of the day (the dashed curve lines are also known as hour line) can be extracted by utilizing the angles run around the edge of the diagram and concentric circular lines respectively. The plan of the experimental room was also added to the chart to depict the experimental room orientation and the workstation position.

4.3.2 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 [40]. The Griffith University Human Research Ethics committee approved the experimental protocol (GU Ref No: 2017/356), 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.

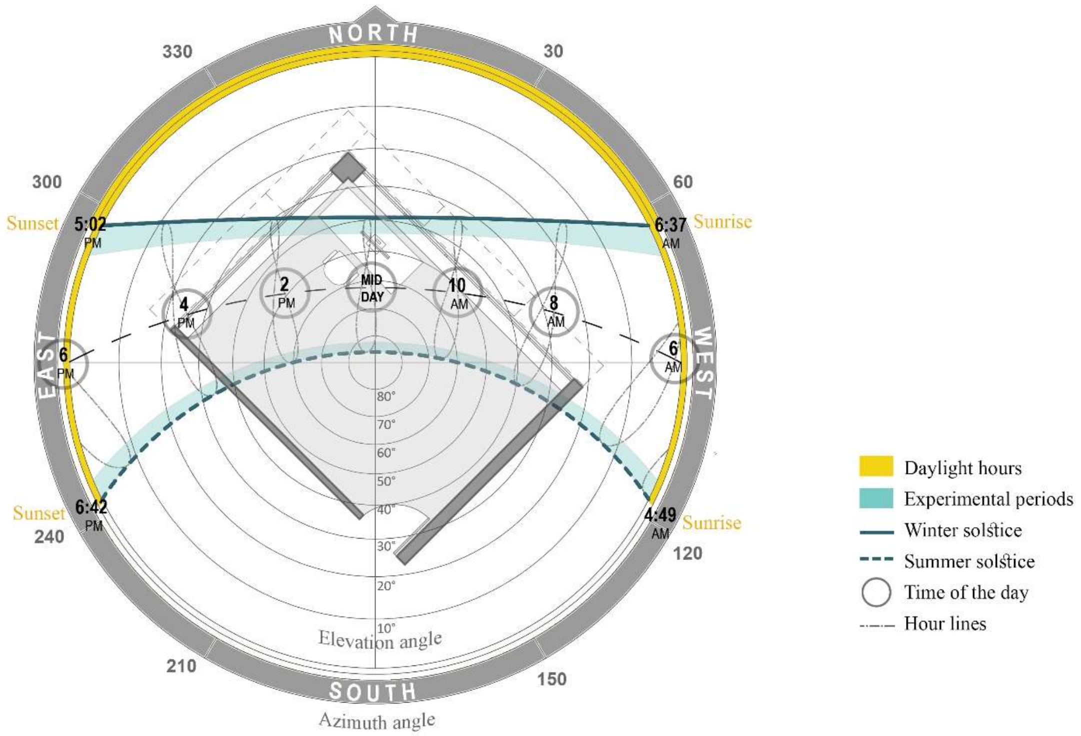

Figure 4.1 Sun paths during the course of the experiments

4.3.3 Experimental setting

The experiment was conducted in an office with a north-west orientation (see Figure 4.1), Gold Coast, Australia (latitude S 27° 57' 47.3463"; longitude E 153° 23' 2.5444"). The office (dimensions, L: 5.16 × W: 3.89 × H: 2.70 m) had a high window to exterior wall ratio (WWR = 0.48) and two adjacent sides with glazing. The window contained a 6 mm single tinted glass pane with visible transmittance (VT) measured at 46%. The visible transmittance of the glass was determined by simultaneously measuring vertical illuminance behind the window and outside the window and calculating the ratio of transmitted light. The white wall and ceiling (measured at 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 4.3 (b)).

4.3.4 Measurements

4.3.4.1 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 (measurement range 0.01–50,000 cd/m^2, accuracy ±0.2% at 1°), and Konica Minolta illuminance meter T-10MA (measurement range 0.01–300,000 lux, accuracy ±3%) 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 [41-43].

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 [43]. In the next procedure, glare assessments were performed using *Evalglare*, a Radiance-based command-line program, and validated for research purposes [44]. 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 0.55 steradians 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.

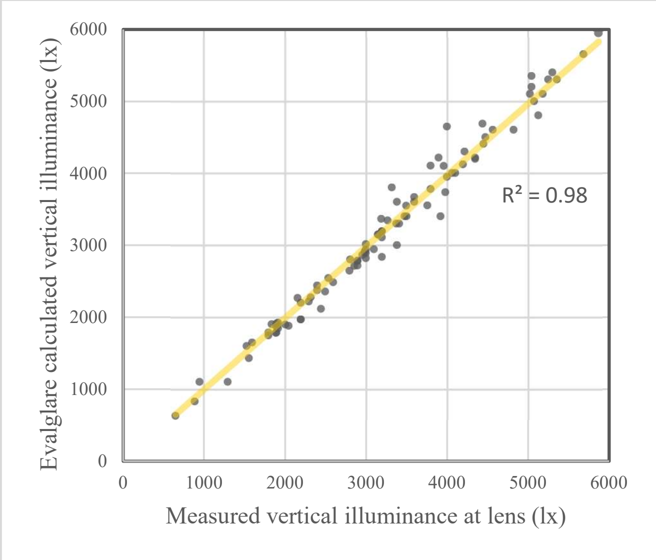

Figure 4.2 Measured vertical illuminance at the camera lens vs Evalglare calculated vertical illuminance from DHR images

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 4.2) which is within the acceptable range [45]. Using the output text file generated by *Evalglare*, luminance values, and discomfort glare indices were utilised in the analysis.

4.3.4.2 Physiological measurements

The eye-tracking device used in the present study was Tobii eye-tracking glasses (see Figure 4.3 (c)) which are wearable, lightweight, discreet binocular eye-trackers. The function of Tobii glasses is based on a corneal reflection eye-tracking technique [46]. This device allows ocular data such as eye movements and pupil diameter to be recorded at a rate of 100 Hz.

4.3.5 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 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 4.3 (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 4.3 (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.

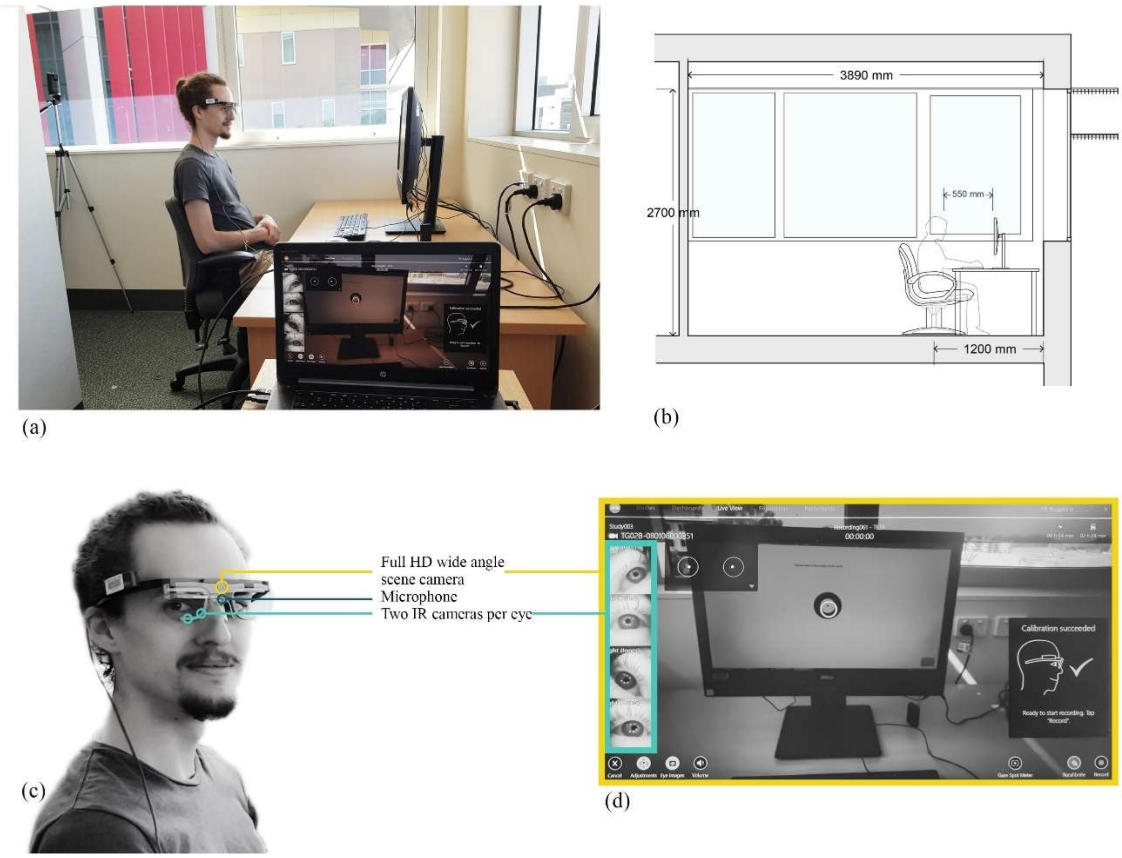

Figure 4.3 (a) A participant wearing an eye-tracker, focusing on the target as a part of the calibration process; (b) the section showing the experimental office and the approximate position of the participant; (c) the full HD scene camera and two IR cameras; (d) recorded video and eye images during the calibration process.

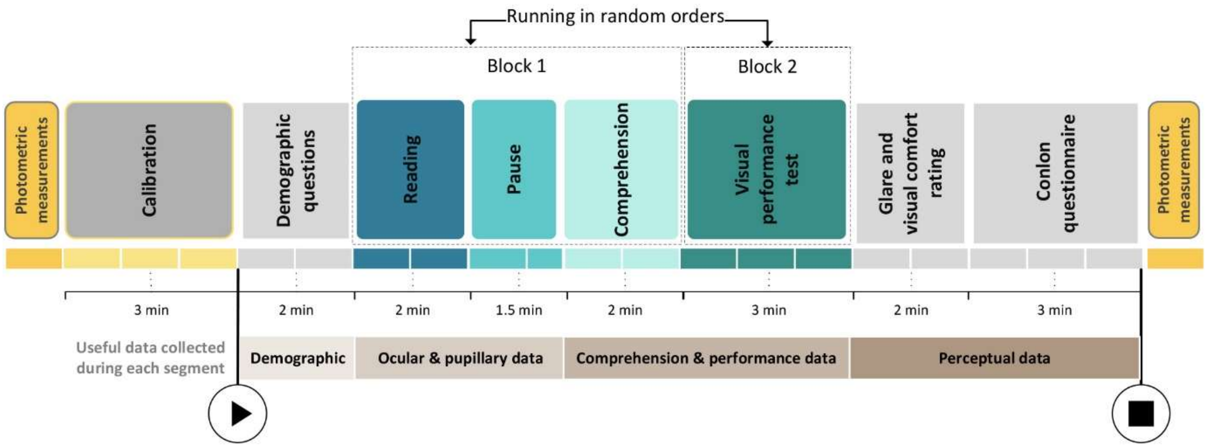

Figure 4.4 Experimental procedure

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 4.4). 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 [47], 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 [48]. 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 [49]. Although writing is an essential component in office tasks, it was not included in this experiment (see section 1.2). 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.

4.4 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 [50] questionnaire.

4.4.1 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:

4.4.1.1 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. [51]. 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 [51]. 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).

4.4.1.2 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, 52]. Strong pupil oscillations resulted in greater PUI values. The adapted formula of the PUI for 100 Hz sampling rate is:

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

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

4.4.1.3 Eye blinks

The eye blink, the eyelid being swiftly shut and reopened, is widely accepted as an indicator of visual fatigue [53, 54]. Previous research has established that spontaneous blinking is highly task-dependent [49, 55], 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 [55], 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. [56]. 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.

4.4.1.4 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 [57]. 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 [58]. For this research, the angular velocity threshold was set to 100 degrees per second (°/s). Afterwards, fixations shorter than 60 milliseconds (ms) were discarded and fixations closer than 75 (ms) in time and 1 (°) 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.

4.4.2 Performance measure

In the vision area of research, reduction in (visual) performance has been addressed as an objective counterpart for visual discomfort [59]. The design of the performance measures, in this study, allowed quantitative measurements of motor and visual elements of computer-based tasks.

4.4.2.1 Timed vision test

Reaction time and accuracy are two main features in visual performance measurements [39, 60, 61]. 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 (CVP) as total correct identifications/total reaction time.

4.4.3 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 [62] and Osterhaus and Bailey [63]. 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. [50] to evaluate visual discomfort. The test was developed based on Wilkins [64, 65] and Irlen's [66] 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 [50]. While Conlon et al.'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.

4.5 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.

4.5.1 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 × 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 4.4.3), 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) × 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 in this chi-square test. 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.

4.5.2 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 [67].

Consequently, analysis continued without transformation. Levene's test revealed that the assumption of homogeneity of variance was satisfied across all DVs (all *p*s > 0.05).

Table 4.2 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 4.2 Means and standard deviations for each DV between treatment levels

	Treatment level		
	Low Glare	Medium Glare	High Glare
Dependent Variable	Mean (SD)	Mean (SD)	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 (millimeter per minute)	3.69 (1.37)	3.60 (1.02)	4.38 (1.30)
Pupil Diameter (millimeter)	2.69 (.23)	2.58 (.21)	2.50 (.20)
Combined Visual Performance	1.44 (.34)	1.37 (.30)	1.17 (.31)

4.5.3 Physiological responses

A one-way, between-subjects ANOVA was run to assess the differences in physiological responses among 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 4.5 (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.

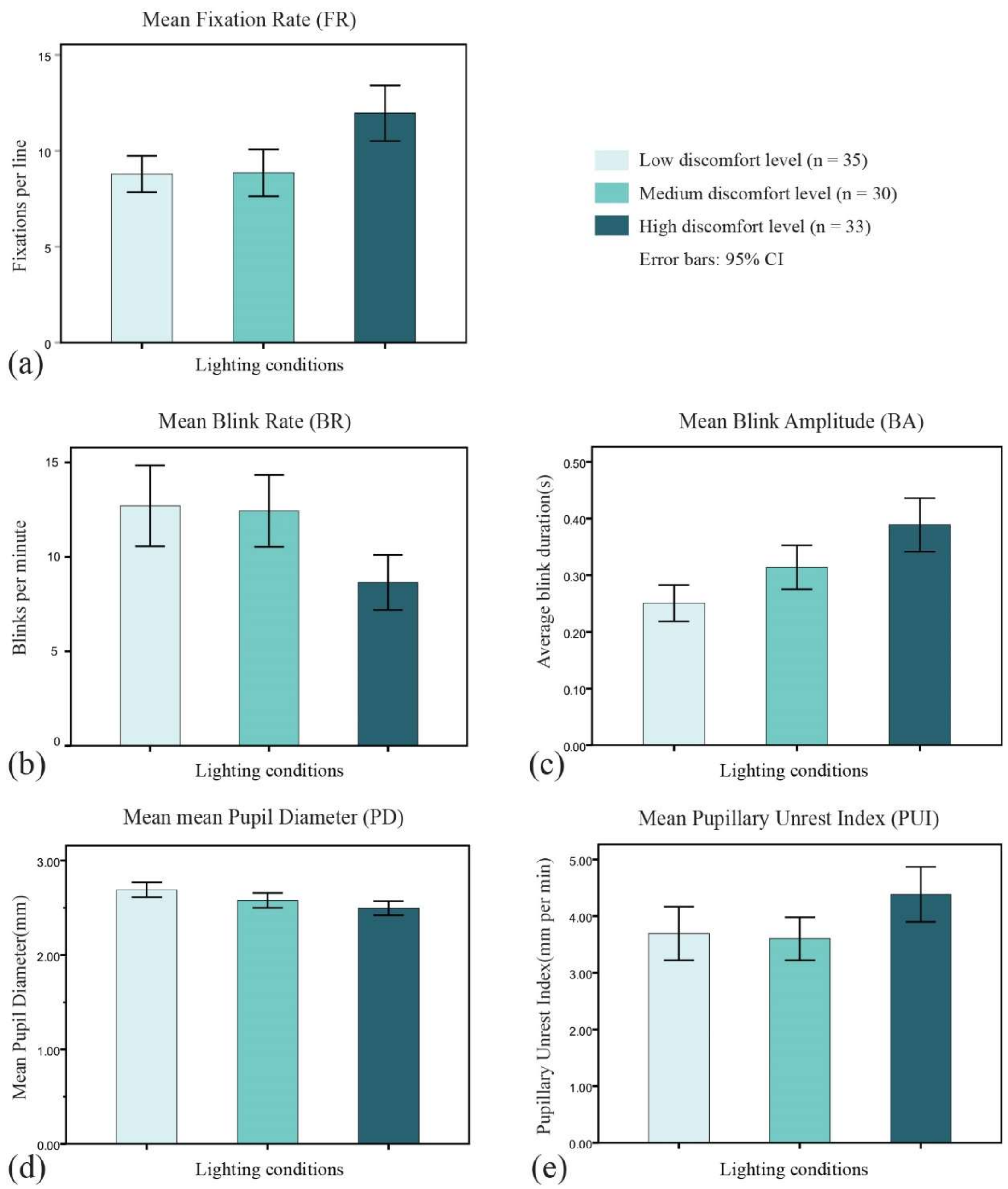

Figure 4.5 Physiological responses by treatment level: (a) Fixation Rate (FR), (b) Blink Rate (BR), (c) Blink Amplitude (BA), (d) Pupil Diameter (PD), (e) Pupillary Unrest Index (PUI); error bars are 95% CI.

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 4.5 (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, η^2 = 0.12, and F (2, 92) = 3.58, p = 0.03, η^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 4.5 (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 4.5 (e)).

4.5.4 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, η^2 = 0.12.

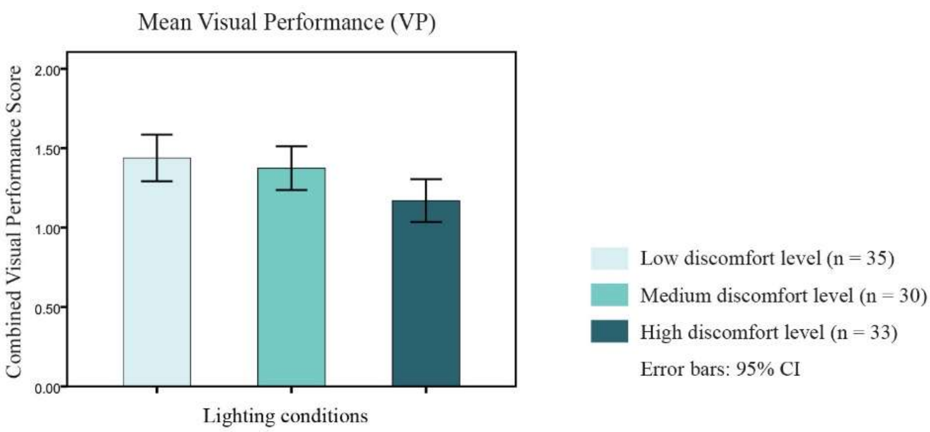

Figure 4.6 Combined Visual Performance (CVP) by treatment level. Error bars are 95% CI.

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 4.6).

4.5.5 Subjective responses

Participants were asked to answer questions regarding their visual environment, and rate their perceived visual comfort and discomfort glare levels (see section 4.4.3, 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, Φ = 0.29. As shown in Table 4.3, 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 4.3 2 × 2 Contingency Table for Sunglasses and Perception of Glare

			Was participant sensitive to bright light?	
			Yes	No
Experience of glare	None, Perceptible	Count	28	11
		Expected	33	6
		Std. Residual	-0.9	2.1
	Disturbing, intolerable	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. [50] (see section 4.4.3, 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.

4.5.6 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 4.3.5). 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 4.3.2). 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 theses variables; given the equal numbers of males and females, the research validity is unaffected.

4.6 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).

This 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. [57] and Vaughan et al. [68], 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 [55]. However, this finding did not support the previous research of Doughty [36] who found that the presence of a glare source can increase spontaneous eye blink rate [36]. 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 [36]. 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 [69, 70].

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. [32] 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 [31], later confirmed by Tyukhova et al. [30], 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 [31] 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.

4.7 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.

4.8 References

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Chapter 5: Relationships between glare factors and objective measures

The previous chapter investigated a wide range of physiological responses as well as visual performance under discomfort glare conditions. It advanced the knowledge on various involuntary physiological responses in relation to glare, and identified the most sensitive indicators. Chapter 5 will now investigate the relationships between each of the objective measures that showed significant difference, and luminous environment characteristics. The luminous environment characteristics were considered through two main categories of variables, absolute and relative glare factors.

Chapter 5 of this thesis has been submitted to the journal, *Building and Environment* as a co-authored paper. The chapter has been formatted to meet the standards of the journal style for bibliographies. My contribution to the paper involved: conducting the experiment, data collection, the computer programming, data processing, analysis of results, writing and editing the manuscript, and submitting to the journal. The bibliographic details of the co-authored paper, including all authors, are:

Z. Hamedani, E. Solgi, T. Hine, and H. Skates, "Revealing the relationships between luminous environment characteristics and light-induced physiological, ocular and performance measures: An experimental study," ***Building and Environment*****,** vol. 172, p. 106702, 2019. (https://doi.org/10.1016/j.buildenv.2020.106702)

5. Revealing the relationships between luminous environment characteristics and light-induced physiological, ocular and performance measures: An experimental study

5.1 Abstract

This study examined human subjects and their physiological, ocular and performance responses under different levels of visual discomfort. The experiment was carried out in an office with daylight as its primary light source. Physiological and ocular data which were recorded by eye-tracking glasses included mean Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), eye Fixation Rate (FR), and Eye Convergence (EC). Performance measures included Combined Visual Performance (CVP) and Combined Reading Performance (CRP), both critical for office workers' overall performance and productivity at workstations. Correlation and multiple regression analysis were used to determine the relationships between glare factors and the physiological, ocular and performance measures, and studies of variance were used to assess differences on all measures among three groups undergoing low, medium and high levels of visual discomfort.

Data analysis suggests that PUI, BA, FR and mean PD could be used as a visual discomfort proxy. PUI and BA could be predicted better with relative glare factors (contrast), and FR and PD could be predicted better with the absolute glare factors (luminance and illuminance values). Concerning performance measures, this study identified that the CVP was negatively correlated with vertical illuminance at eye (E_v) and the average luminance (L_m). The reading performance (LogCRP) was also better when the FD and the PUI were lower.

5.2 Introduction

Minimising discomfort glare is an essential requirement in lighting and daylighting design for office buildings with visually demanding tasks. The International Commission on Illumination (CIE) defines discomfort glare as "glare that causes discomfort without necessarily impairing the vision of objects"; however, it has an irritating or distracting effect, and can lead to long-term effects of experiencing visually uncomfortable lighting conditions such as unexpectedly early fatigue or headaches [1-3]. Glare can be attributable to extreme contrast, known as contrast effect, or inappropriate distribution of luminance range, known as saturation effect when these effects are significantly higher than the range to which the visual system is adjusted [1, 4].

In previous studies of discomfort glare, principle variables (outlined below) have been found to be related to perceived discomfort glare by occupants. Petherbridge and Hopkinson [5] proposed a general mathematical function, which described the association between physical measurements and perceived glare and was the basis for all discomfort glare indices established thereafter. The four main variables in glare sensation are given below in Equation (1) [5]:

$$G = \left(\frac{L_s^e \cdot \omega_s^f}{L_b^g \cdot f(P)}\right) \qquad (1)$$

In this equation, L_S represents the glare source luminance (cd/m^2); ω_s is the solid angle subtended by the source in regard to the observer point of view; L_b accounts for the adaptation luminance (cd/m^2); P is the position index; the e, f and g exponents are weighting factors for each parameter, varying according to glare index. The equation indicates that the higher the luminance of the glare source and the greater the angular subtense of the source, the higher the user's perceived discomfort glare. Adaptation level has been indicated by utilising either average background luminance or vertical illuminance at eye level to address the fact that visual adaptation can be affected by a high proportion glare source in the field of view.

Subsequent to research, the other predictive models differ according to the values for weighting factors, introduced in Equation (1), which attributes the four photometric variables to the subjective discomfort glare evaluations. Given that each predictive model is developed under boundary conditions specific to its particular experimental study, each can perform best in similar circumstances. Comparative studies described the discrepancies when testing each index in other conditions, and a large variability in subjective responses resulted [6, 7]. In addition, the reliance of these indices on quantitative subjective evaluations utilising semantic response labels such as the four-point scale introduced by Osterhaus and Bailey [8], whilst valuable, can be considered as a limitation [9]. Pierson et al. [10] listed a number of general characteristics of participants that can have a potential influence on their discomfort glare perception from daylight such as gender, age, culture, sensitivity to glare, and the lighting conditions participants are accustomed to. Thus, there is a need for a method that can measure an individual's discomfort perception. These deficiencies have been addressed by a few studies [11-14] where attempts were made to incorporate compensatory objective measures into the visual discomfort assessment methods.

Through technological advancements in oculometry methods, it is now feasible to monitor user optical and ocular behaviour in a less invasive way. The eye-tracking method provides researchers with useful information about how occupants perceive their visual environments. Eye-trackers have been utilised in many disciplines, ranging from behavioural science and psychology to neuroscience and lighting. Due to the recent emphasis on coupling objective methods with subjective evaluations in lighting research [13-15], eye-tracking is receiving increased attention. Hamedani et al. [15] provided a comprehensive review of all previously studied physiological responses in relation to glare and visual discomfort. According to their review, among light-induced physiological responses to date, absolute and relative pupil diameter [16-23], eye movement velocity (using EEG and EOG to measure) [12, 16], and eyeblink rate [24] have received some attention.

Pupil size was shown to be negatively correlated with visual discomfort ratings [19, 21] and glare source luminance [16] where relative pupil size was taken into account. However, this finding was basically determined in laboratory conditions with artificial light as the primary light source. Other research under daylight conditions found a better correlation with vertical illuminance received by the eyes [22], which represents the adaptation light level and somehow confirms the early findings of Hopkinson [20] wherein the actual pupil size was shown to be sensitive to the overall background luminance. Hopkinson [20] also observed cyclical variation in pupil diameter under intolerable discomfort glare. This phenomenon (fluctuations in pupil size under constant lighting conditions), known as pupillary unrest or hippus, was later tested by Howarth et al. [65], albeit they found no association between glare level and pupillary unrest. In a more recent observation, Warga et al. [17] corroborated that the oscillations did exist and were unaffected by factors other than lighting; however, they could not determine a relationship between the light intensity and the amplitude or frequency of oscillations. Further, spontaneous blink rate as a potential indicator of visual discomfort was investigated and found to be affected by the presence of a glare source, especially if the subject’s line of sight is above the horizon [24]; however, more research was recommended in this regard [15].

To overcome the limitations associated with the subjectivity and individuality aspects of visual discomfort evaluations, Hamedani et al. [15] proposed a holistic approach based on user physiological responses and performance. Thus, in this research, the objective measures of the participants' response in the areas of physiological, ocular and performance were coupled with conventional methods in lighting research, including photometric measurements and subjective evaluations. In addition to the previously studied physiological parameters, other factors such as the number of fixations, the average dwell time of the eye while reading a particular text, and the eyeblink duration were also considered as an objective proxy.

This research investigates the relationships between photometric variables and measurable physiological and ocular responses as well as performance variables. To this end, a full range of objective metrics was studied, namely mean Pupil Diameter (meanPD, the average pupil diameter), Pupillary Unrest Index (PUI, the aggregated pupil diameter changes during each trial), Blink Rate (BR, number of blinks per minute), Blink Amplitude (BA, the average blink duration), Fixation Rate (FR, the average number of fixational eye movements per line), mean Eye Convergence (meanEC, the average convergence depth plane), Eye Convergence standard deviation (ECsd, the convergence depth plane variation), Combined Visual Performance (CVP, the number of correct answers divided by the total reaction time), Combined Reading Performance (CRP, the correct answer rate divided by the average time spent on reading each word), and the log of CRP (LogCRP). To gain in-depth knowledge about each of the abovementioned physiological metrics, this paper examines the relationships between each objective measure and various measures of luminous environment characteristics. With this aim, an experimental study was carried out, and ocular, pupillary, performance, and subjective data were collected along with photometric measurements. Luminous environment characteristics included two main categories: absolute and relative glare factors. Correlation analysis was carried out between each glare factor and physiological, ocular and performance metrics to uncover the relationships between influential factors of the luminous environment on each of the objective variables. Then, multiple regression analysis was conducted to further identify the influential glare factors on each objective measure. In the latter regard, to simplify the results of this research for future implementation and to reduce the number of variables in the multiple regressions, 'composite' variables were defined for each category of data, which were regressed against two main performance responses namely CVP and CRP. These results provide a comprehensive understanding of individuals' responses to visual discomfort and their applicability as an objective marker of the visual discomfort experience.

5.3 Method

The experiment was carried out in a single office with north-west orientation, on the third floor of a four-storey building on the Gold Coast, Australia. Participants were required to sit at a desk at a 1.2 m distance from the window, wearing eye-tracking glasses and performing tasks according to the given instructions for each stage of the experiment. The experimental design was a between-subject with three levels of lighting conditions as treatment levels. In other words, each participant experienced one lighting condition, with either low, medium or high visual discomfort level (Table 5.1). Since the Daylight Glare Probability (DGP) is recognised as the more robust metric in daylight-dominant offices [6], the treatment levels were categorised based on DGP values and the introduced adaptive levels related to the average luminance in the visual field (L_m), and the vertical illuminance at eye level (E_v) (Table 5.1).

Table 5.1 Lighting condition characteristics

Lighting Condition	DGP	Average L_m (cd/m^2)	Average E_v (lx)
Low	< 0.35	560	2100
Medium	0.35 < DGP < 0.40	810	3400
High	> 0.40	1100	4800

A total of 98 participants, ranging from 18 to 36 years of age (M = 23.56 years; SD = 4.81 years), including 48 males and 50 females, were recruited for this experiment for two series of data collections. The first data collection was performed during sunny days from 3 to 28 June (winter solstice in the southern hemisphere) and the second one from 10 to 27 December (summer solstice in the southern hemisphere). Performing the experiment at winter and summer solstice provided us a variety of conditions with the sun at its lowest and highest elevations in the sky.

The prerequisites for participation in this experiment were the native language, vision health, and age. All participants were native English speakers aged between 18 to 40 with no required vision aids, and all were students and staff members of Griffith University, Australia. The experimental protocol was approved by the Griffith University Human Research Ethics committee (GU Ref No: 2017/356) with volunteers signing an informed consent form prior to commencing participation. The three different lighting conditions were randomly allocated to the participants.

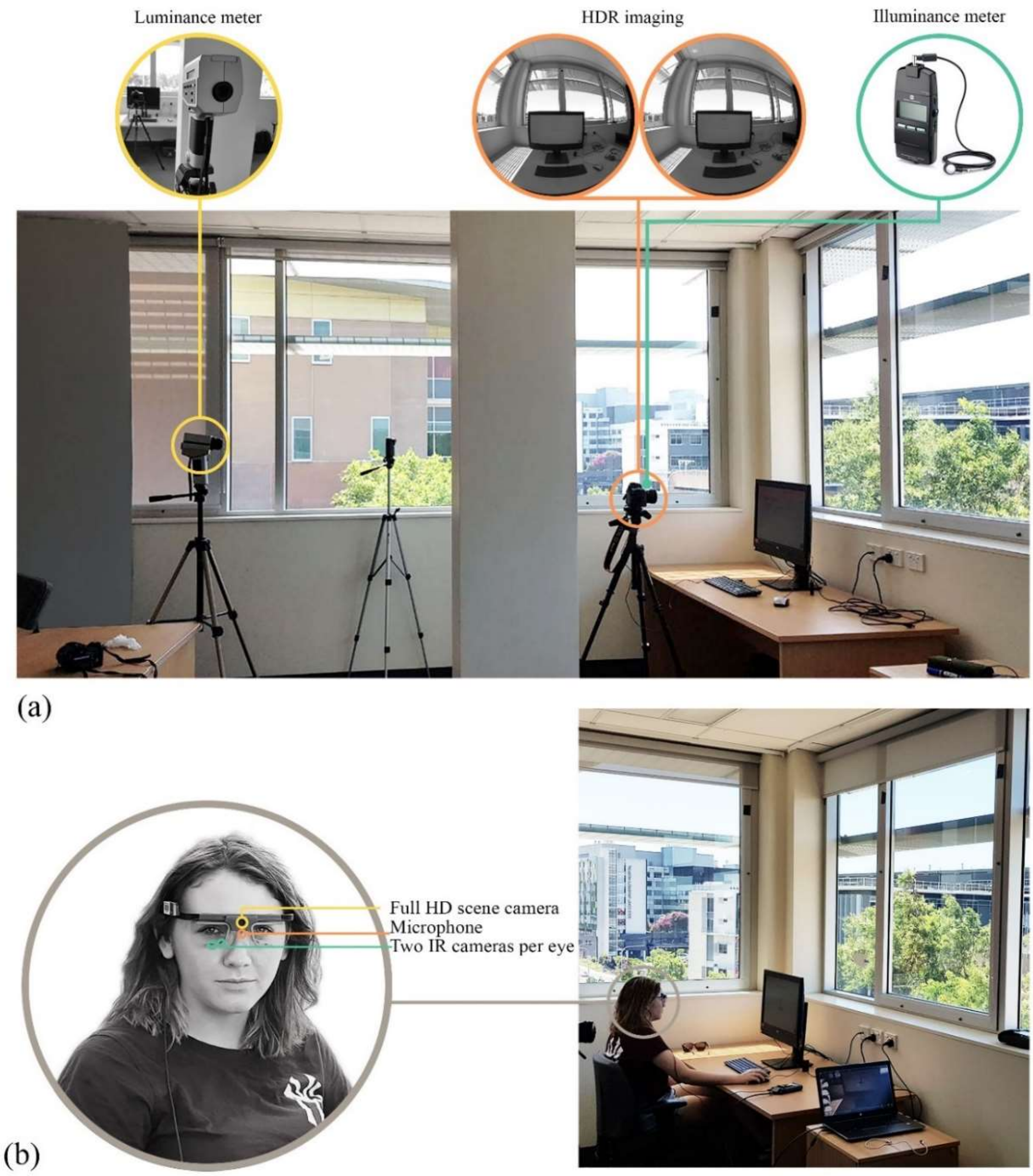

Figure 5.1 (a) The experimental apparatus for photometric measurements before and after each experimental session; (b) physiological measurement by means of an eye-tracker during the experiment

5.3.1 Equipment

Three main datasets were captured for each participant: eye-tracking and photometric data. The physiological data were recorded using Tobii Pro eye-tracking glasses which is a lightweight mobile eye-tracker. This eye-tracking system comprised four IR cameras to capture eye movements and pupil diameter, and a full HD scene camera [25]. These eye-tracking data were recorded at a rate of 100 Hz.

Photometric measurements were carried out by means of a Canon digital camera fitted with a fisheye lens, a Konica Minolta spot luminance meter LS-100, and a Konica Minolta illuminance meter T-10MA. High dynamic range (HDR) imaging was utilised as a luminance mapping technique. In this regard, the digital camera recorded a 15 multiple exposure low dynamic range (LDR) fisheye image sequence, while the luminance value of the target (at the centre of the image) and vertical illuminance at camera lens level were captured. Figure 5.1 illustrates the experimental setup. The luminance values were then utilised to calibrate the generated HDR images.

5.3.2 Experimental procedure

Individual experimental sessions took 30 minutes in average including reading and signing the consent form, the accustomization to the sitting position, the calibration process for the eye-tracker, answering the demographic questions, performing simulated office tasks and answering questions about their perception of the lit environment. Photometric measurements were carried out at the beginning and end of each session to record the characteristics of the luminous environment. Instructions were given on how to proceed on experimental tasks after participants placement and adjustment behind the desk. The experimental procedure constituted the calibration of the eye-tracking device, answering demographic questions, performing office tasks, performing timed vision test and completing questionnaires regarding the participants' perception of the lighting conditions. The office tasks included two main blocks, simulated office task and timed vision test. The simulated office tasks comprised of a reading and a comprehension test from which the Combined Reading Performance score (CRP) was calculated. In order to avoid task difficulty and content biases [26], a reading text and its ensuing comprehension test with a low level of difficulty were selected from the graded standard reading and comprehension tests of the Science Research Associates Reading Laboratory (SRA) materials [27]. During the timed vision test segment participants' accuracy and reaction time were recorded resulting in a Combined Visual Performance score (CVP).

5.3.3 Photometric measurements

Recorded LDR images at the beginning and end of each experimental session required a rigorous calibration process to yield accurate luminance maps. To this end, first, appropriate images were selected from the captured LDR photos. Then, camera response curve derivation, HDR image generation, and calibration adjustment by spot luminance measurement were carried out utilising *photosphere* software [28]. A script was provided in MATLAB to automatically post-process the HDR images and perform the glare assessments. The process included resizing, cropping, vignetting correction, geometrical re-projection correction, editing image header, glare assessment and calculating the metrics of interest. The digital filters for vignetting effect correction and geometrical re-projection were extracted from laboratory data collection [14] and the research-validated Radiance-based command-line program, *Evalglare* was used to perform glare assessments [29]. Finally, the measured vertical illuminance at camera level was employed to verify the accuracy of HDR images. In this study, the average error between the *Evalglare* calculated vertical illuminance and the recorded illuminance values in the field were within the acceptable range at approximately 4% [30]. The photometric variables for analysis were then calculated by using the *Evalglare* output data file.

In lighting literature, the main types of glare including but not limited to discomfort and disability glare has been categorised based on their effect on a subject. As far as discomfort glare is concerned, the cause of glare can be categorised into two main factors: absolute and relative factors [31]. The former refers to the excessive levels of luminance of the glare source where the impact of the absolute luminance value is the dominant factor for glare sensation whereas the latter refers to the ratio between the adaptation luminance and the glare source luminance (contrast effect). All glare predictive models and defined luminance/contrast ratios fall into this category. In this article, all objective factors are analysed based on the abovementioned glare factors.

5.4 Glare factors

5.4.1 Absolute glare factors

Absolute glare factors have always been of interest due to the simplicity of their measurement, interpretation and implementation by practitioners. In this category, luminance and illuminance thresholds have been broadly discussed in the literature [7, 32-36] and standards. Nevertheless, the reported comfort or discomfort threshold might be inconsistent.

For a comfort-based lighting design, providing an adequate light level while minimizing glare is essential. The amount of light needed for an occupant to accomplish a task comfortably has been determined in many standards and building codes by using a simple illuminance threshold. Illuminance is a physical quantity used for measuring the amount of light that a particular point on a surface receives, and refers to the illuminated surface and the luminous flux of the entire range of light wavelengths. Although simple and easy to measure, horizontal illuminance cannot be considered as a measure of visual comfort/discomfort due to its independence of the observer or the type and features of the light source(s). The recent transition of the nature of office tasks from paper-based to screen-based tasks also adds to its inefficiencies.

Unlike horizontal illuminance, vertical illuminance at eye level (E_v) has been widely used as an independent variable for indicating visual discomfort sensation or as an input in some glare indices, such as DGP [37, 38]. Vertical illuminance received by the eyes showed an acceptable performance in indicating adaptation levels as well as in predicting discomfort sensations in daylight-dominant spaces. Wymelenberg and Inanici [39] suggested vertical illuminance lower than 875 lx to be considered comfortable whereas Bian and Luo [40] reported 2000 lx. As well, values ranging from 1250 lx [39] to 3000 lx [40] were proposed by previous research on visual discomfort threshold. Nonetheless, higher values were suggested when the participant's view direction is towards the window [41] with 1479 lx and 8624 lx as respective comfort and discomfort glare thresholds. Given the primary objectives of this research studying ocular and optical variables, it is more likely that vertical illuminance at eye level yields meaningful results in predicting some physiological responses.

In addition to the illuminance, the luminance values in the visual field have been considered as an absolute indicator of visual discomfort sensation. Luminance is a physical quantity which represents the intensity of visible light emitted from a surface per unit of the visible area in a given direction around a given point. Similar to the illuminance thresholds, luminance thresholds have been used to define the upper and lower bounds of visual discomfort. Luminance values lower than 1500 [34] to 2800 cd/m^2 [42] have been suggested to be comfortable [42]. However, a large range of luminance threshold, 2570

[35] to 6000 cd/m^2 [34], have been claimed to be the lower bound of discomfort glare sensation.

In this research, vertical illuminance (E_v), average luminance (L_m), background luminance (L_b), the luminance of the glare source(s) (L_s), task luminance (L_t), and maximum luminance (L_{max}) were investigated as absolute factors of discomfort glare. Table 5.2 shows the descriptive statistics of absolute photometric variables of the experimental conditions.

Table 5.2 Descriptive statistics of absolute photometric variables.

Treatment level	Low discomfort		Medium discomfort		High discomfort	
	Mean	SD	Mean	SD	Mean	SD
Vertical illuminance (E_v)	2103.89	577.68	3435.17	314.25	4771.46	588.91
Average luminance (L_m)	564.12	159.74	812.44	85.43	1091.70	117.60
Background luminance (L_b)	157.31	50.85	163.66	29.71	260.33	90.76
Source luminance (L_s)	2273.19	449.06	2995.28	561.45	3816.25	1088.09
Task luminance (L_t)	132.92	19.70	127	16.40	219.07	94.84
Maximum luminance (L_{max})	13025.59	7180.36	26515.42	21075.86	66536.99	39400.66

5.4.2 Relative glare factors

Contrast thresholds are simply relative values between background luminance/task luminance and glare source luminance to determine the lower bound of visual discomfort due to contrast effect, although the recommended values in different standards and research vary [43]. To explore the effect of contrast on different objective measures, five ratios were investigated namely: luminance of the glare source(s) to background luminance (L_s/L_b), background luminance to task luminance (L_b/L_t), luminance of the glare source(s) to task luminance (L_s/L_t), task luminance to maximum luminance (L_t/L_{max}), and luminance of the glare source(s) to vertical illuminance (L_s/E_v).

Glare indices have been developed to predict visual discomfort comparatively using complex formulae, each of which were developed under specific boundary conditions and perform well in similar conditions. For this reason, validation studies report over- or under-estimation of the glare perceptions under specific situations.

Some of the established glare metrics like CGI (CIE Glare Index), DGI (Daylight Glare Index), and their modifications, such as DGI_{mod} (Modified Daylight Glare Index), and

UGP (Unified Glare Probability), were basically developed under glare conditions due to the contrast effect. Some other glare metrics such as L_{avg_pos} (Position Index Weighted Average Luminance of Image) [44], and E_{dir} (direct illuminance at eye) were based on saturation effect, and consider the amount of light at the eye as the main contributor in their equation. In the case of DGP (Daylight Glare Probability) [37] and UGR_{exp} (Experimental Unified Glare Rating), both effects are considered in their formulae [6]. Wienold et al. [6] investigated the robustness and performance of 22 glare indices for daylight-dominant office spaces. Saturation-effect based metrics have been proved to be the more robust indicators of discomfort glare [6] as their main equation variable is the amount of light at the eye. In particular, for daylight-dominant office spaces, DGP, E_v [37, 45], L_{avg} [39], and L_{pos_avg} ranked highest. Wienold et al. also found the CGI to be the best performing and most robust among the contrast-based metrics, compared to the other metrics within its category [6]. It can be concluded that a ubiquitously applicable metric for all lighting conditions has not been established to date. In this research, 7 glare indices are included in the analysis, which encompasses all three types of glare indices. The descriptive statistics of all indices under experimental conditions of this research are summarised in Table 5.4.

Table 5.3 Descriptive statistics of glare indices.

Treatment level	Low discomfort		Medium discomfort		High discomfort	
	Mean	SD	Mean	SD	Mean	SD
DGP	0.30	0.02	0.38	0.01	0.46	0.03
UGR_{exp}	26.55	1.31	30.11	1.20	31.23	1.54
$E_{v\text{-}dir}$	1716.87	529.88	3076.32	331.50	4199.27	457.23
$L_{avg\text{-}pos}$	179.26	46.88	274.30	26.27	375.76	42.57
CGI	28.36	1.88	31.21	1.90	33.2	2.82
DGI	19.95	1.72	21.24	1.75	22.66	2.46
UGP	0.82	0.07	0.90	0.07	0.93	0.07

5.5 Results and discussion

Hamedani et al. [46] conducted ANOVA analyses to investigate the effect of lighting conditions on Fixation Rate (FR), Fixation Duration (FD), Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), and Combined Visual Performance (CVP). They found that participants in high discomfort conditions exhibited a higher FR, lower BR, greater BA, smaller PD, higher PUI and lower CVP compared to the low and medium discomfort conditions (see Chapter 4). The current research goes further to determine the luminous environment characteristics that could affect each of the studied objective factor. In addition to the previously investigated parameters, a new performance parameter, Combined Reading Performance (CRP) was defined which characterises the efficiency of office workers in different lighting conditions. Eye Convergence (EC), as an adaptive behaviour, was also examined in detail. To simplify the research outcome, a series of composite variables were defined for each category of data and explored through multi regression analysis to identify the impact of each category on user performance (both visual performance and reading performance) as important criteria in office lighting designs. The statistical analyses were performed using SPSS Version 25.

Table 5.4 Correlation matrix between physiological variables and absolute factors, luminance ratios and glare indices.

		FR	BR	BA	Mean PD	PUI
Absolute factors	Vertical illuminance ($\boldsymbol{E_v}$)	0.409**	-0.237*	0.427**	-0.418**	0.292**
	Average luminance ($\boldsymbol{L_m}$)	0.400**	-0.243*	0.343**	-0.412**	0.232*
	Background luminance ($\boldsymbol{L_b}$)	0.435**	-0.288**	0.177	-0.360**	0.297**
	Sources luminance ($\boldsymbol{L_s}$)	0.367**	-0.231*	0.301**	-0.292*	0.392**
	Task luminance ($\boldsymbol{L_t}$)	0.428**	-0.313**	0.244*	-0.317**	0.372**
	Maximum luminance ($\boldsymbol{L_{max}}$)	0.419**	-0.197	0.459**	-0.355**	0.504**
Luminance ratios	L_s/L_b	-0.19	0.077	0.106	0.237	0.069
	L_b/L_t	0.066	0.077	-0.153	-0.187	-0.167
	L_s/L_t	-0.118	0.171	0.072	0.067	0.001
	L_t/L_{max}	-0.233*	0.011	-0.558**	0.225	-0.435**
	L_s/E_v	-0.184	0.017	-0.166	0.337**	0.028
Glare indices	DGP	0.423**	-0.247	0.440**	-0.416**	0.330**
	UGR_{exp}	0.305**	-0.08	0.465**	-0.344**	0.272**
	E_{dir}	0.374**	-0.214	0.444**	-0.403**	0.260**
	$L_{avg\text{-}pos}$	0.410**	-0.261*	0.374**	-0.420**	0.254*
	CGI	0.371**	-0.17	0.369**	-0.308**	0.406**
	DGI	0.329**	-0.131	0.347**	-0.21	0.421**
	UGP	0.228*	-0.08	0.373**	-0.173	0.359**

***. Correlation is significant at the 0.01 level (2-tailed).*

**. Correlation is significant at the 0.05 level (2-tailed).*

5.5.1 Fixational eye movements

Fixation is when the visual gaze remains positioned on a given point [47]. The velocity-based classification algorithm, the Tobii I-VT filter, was used to identify saccadic eye fixations, basing eye movements on gaze shift angular velocity [48]. An angular velocity threshold of 100 degrees per second (°/s) was used in this study. Subsequently, fixations under 60 milliseconds were eliminated and those nearer than 1° in space and 75 milliseconds in time were consolidated. Fixation Rate (FR) is the frequency of fixational eye movements observed during the reading segment per line.

Bivariate correlation analysis showed moderate positive association between FR and all absolute glare factors, with vertical illuminance (E_v) (r = 0.409, p < 0.001; Figure 5.2), average luminance (L_m) (r = 0.400, p < 0.001; Figure 5.2), background luminance (L_b) (r = 0.435, p < 0.001), luminance of the glare source(s) (L_s) (r = 0.367, p < 0.001), task luminance (L_t) (r = 0.428, p < 0.001), and maximum luminance (L_{max}) (r = 0.419, p < 0.001). There was also weak, negative relationships between the luminance ratio L_t / L_{max} and FR (r = -0.233, p = 0.02). Among glare indices DGP (r = 0.423, p < 0.001), $L_{avg\text{-}pos}$ (r = 0.410, p < 0.001) showed the best correlation with FR.

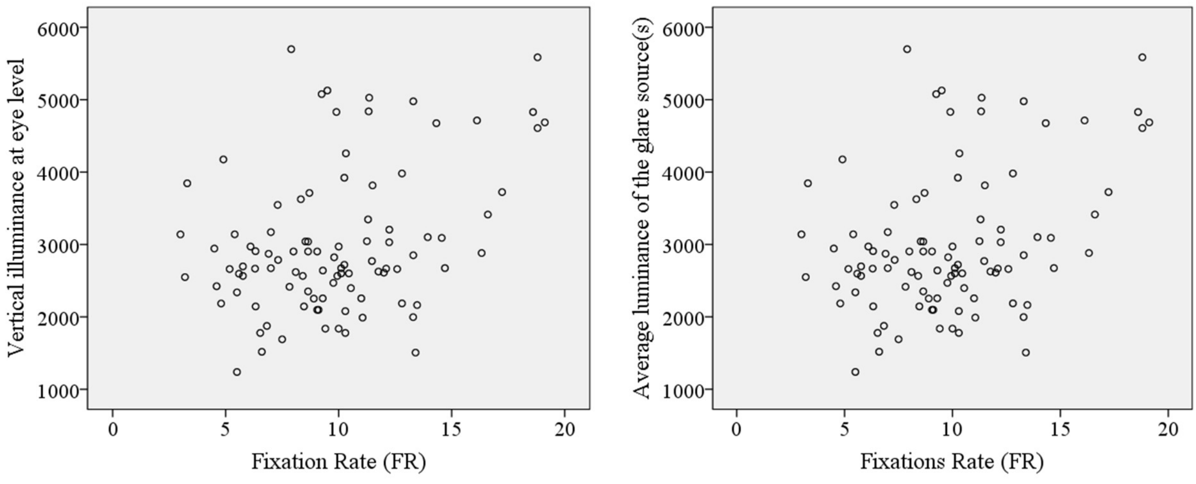

Figure 5.2 Scatterplot Fixation Rate (FR) and vertical illuminance (E_v, lx) (left), scatterplot FR and luminance of the glare source(s) ($L_s, cd/m^2$) (right)

5.5.2 Eye blinks

Eye blink is an accepted visual fatigue indicator [49, 50]. Blink rate (BR) and Blink Amplitude (BA) were calculated using the Hershman et al. method [51] from the pupillometry data. In this method, the detection of blink onset and offset are based on the blink noise introduced to pupil size signal. Then, BR was calculated as the frequency of blink events per minute, and BA as the average blink durations for the reading segment.

As illustrated in Table 5.5, BA was moderately correlated with E_v (r = 0.43, p < 0.001; Figure 5.3), L_{max} (r = 0.46, p < 0.001) and L_s (r = 0.30, p = 0.003). There was also moderate, negative correlation between the luminance ratio L_t / L_{max} and BA (r = -0.56, p < 0.001) (see Figure 5.3). Regarding glare metrics, DGP (r = 0.44, p < 0.001) and UGR_{exp} (r = 0.47, p < 0.001) showed the best correlation with BA, followed by E_{dir} (r = 0.45, p < 0.001), $L_{avg\text{-}pos}$ (r = 0.38, p < 0.001) and UGP (r = 0.38, p < 0.001). BR showed to be moderately associated with task luminance (L_t) (r = -0.32, p = 0.002) and background luminance (L_b)(r = -0.29, p = 0.005). These findings can be interpreted as BR being more associated with the adaptation luminance (L_t or L_b) rather than being affected by the glare source luminance. These findings are somewhat surprising given that other research shows increased blink rate in the presence of glare [24]. This result may be explained by the fact that spontaneous blinking has been established to be highly task dependent [52, 53], with the computer-based reading task exhibiting the lowest Blink Rate (BR). However, the increased corneal exposure effect of this decrease in BR is a recognized visual fatigue contributor [53]. Since the BR and BA were calculated for the reading component of the experiment, further studies will need to be undertaken which take the type of task as a moderating variable into account.

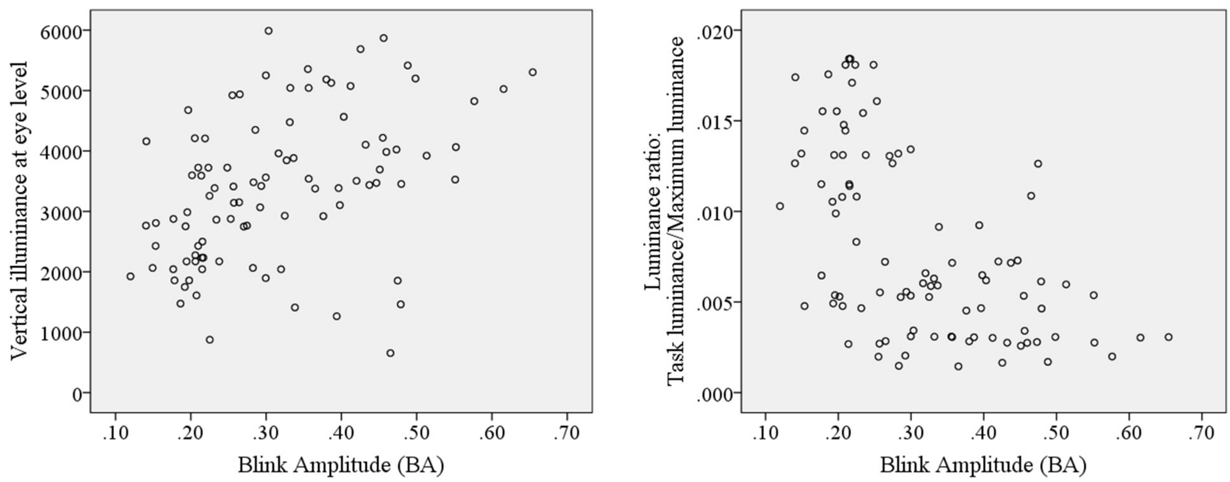

Figure 5.3 Scatterplot Blink Amplitude (BA) and vertical illuminance (E_v, lx) (left), scatterplot Blink Amplitude (BA) and luminance ratio L_t/L_{max} (right)

5.5.3 Pupil size

Pupillary light reflexes constitute either pupil constriction or dilation, and enable adaptations to the luminous environment variations for the human visual system. The light level to which eyes have adjusted is indicated by the actual pupil size. Nevertheless, periodic pupillary constriction and dilations have also been found to occur spontaneously in unchanging lighting conditions. This phenomenon, known as pupillary unrest, is recognised in a few studies as a visual discomfort sensation symptom [17, 18]. Using pupil size data, two variables, namely pupil size (PD) and Pupillary Unrest Index (PUI), were analysed. To this end, the first step was to clean the recorded pupil data and remove invalid samples attributed to blinks as well as outliers in terms of dilation speed and trend line deviation. The Kret et al. method [54] was used to pre-process the eye-tracker pupillary signals. Four main steps were included in this process: preparation of the raw pupil signals for processing; extraction of 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 [54]. The basis for analysis was the mean pupil diameter signal from both eyes (mm) for the reading segment (see Figure 5.4 & 5.6).

The correlation between PD and absolute glare factors indicated that PD is significantly associated with E_v ($r = 0.42$, $p < 0.001$), L_m ($r = 0.41$, $p < 0.001$) and L_b ($r = 0.36$, $p < 0.001$). There was also moderate, positive correlation between the ratio L_s / E_v and PD ($r = 0.34$, $p = 0.001$) (see Figure 5.5). Regarding glare metrics, DGP ($r = 0.42$, $p < 0.001$) and $L_{avg\text{-}pos}$ ($r = 0.42$, $p < 0.001$) showed the highest correlation with PD.

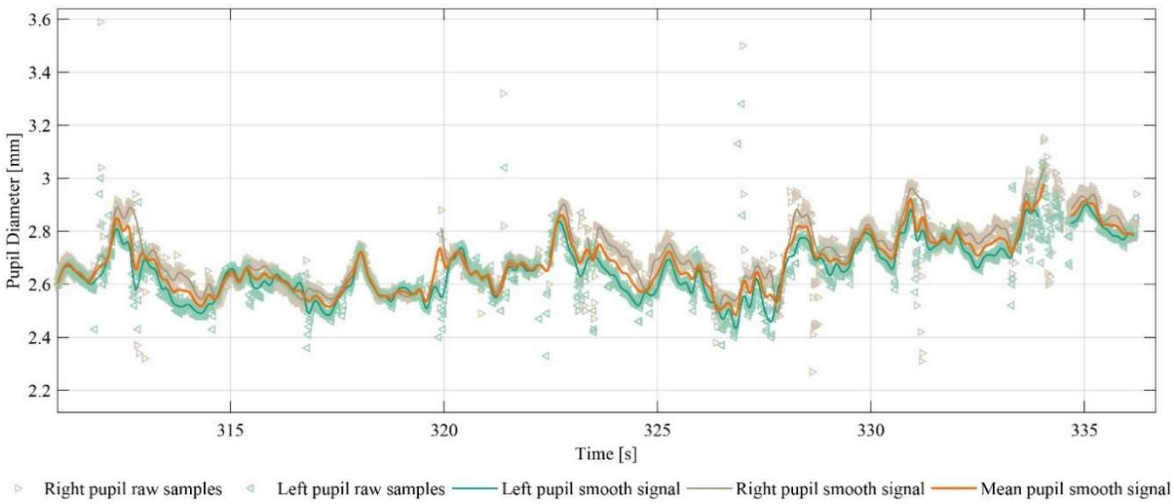

Figure 5.4 PD signal pre-processing showing the raw data for both eyes (green and red dots), and cleaned, interpolated and up-sampled data for both eyes (green and red lines), as well as the mean signal as the PD final signal (yellow line).

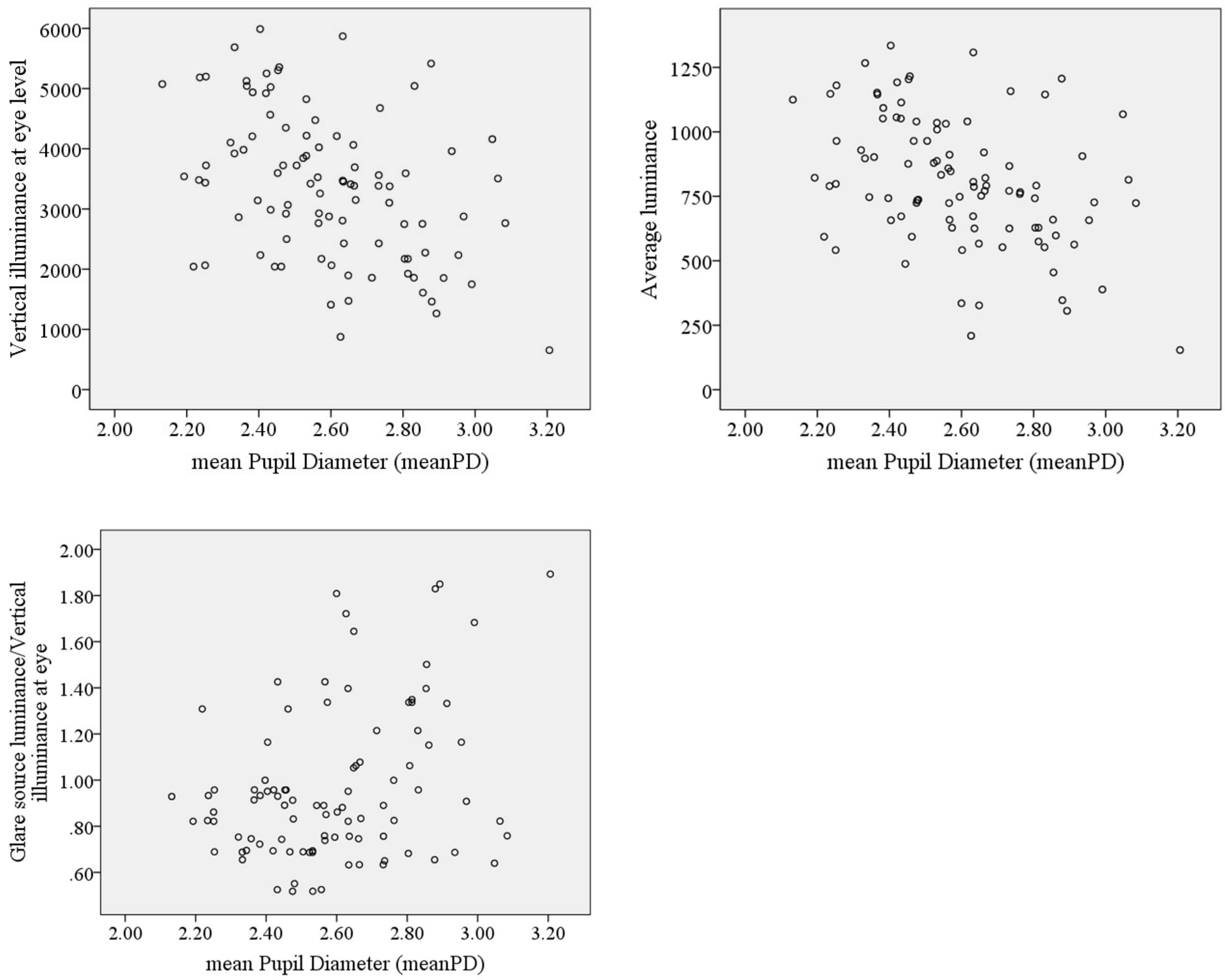

Figure 5.5 Scatterplots mean Pupil size (meanPD, mm) and vertical illuminance (E_v, lx), average luminance (L_m, cd/m^2) and the ratio of L_s/E_v

Pupillary unrest index (PUI) was used to proxy the pupillomotor instability by aggregating the pupil diameter changes during each segment, based on a sampling frequency of 1.56 Hz [17, 55]. The PUI value increases with a higher incidence of pupil oscillations. The adapted formula at a sampling rate of 100 Hz is:

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

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

Bivariate Pearson correlations between each glare factor and PUI revealed that there were moderate, positive correlations between the PUI and maximum luminance (L_{max}) (r = 0.51, $p < 0.001$), luminance of the glare source(s) (L_s) (r = 0.39, $p < 0.001$), luminance ratio L_t / L_{max} (r = 0.436, $p < 0.001$) and vertical illuminance (E_v) (r = 0.30, p = 0.004) (see Figure 5.7). Among glare indices, CGI (r = 0.40, p < 0.001), DGI (r = 0.42, p < 0.001), and DGP (r = 0.33, p = 0.001) showed the highest correlation with PUI.

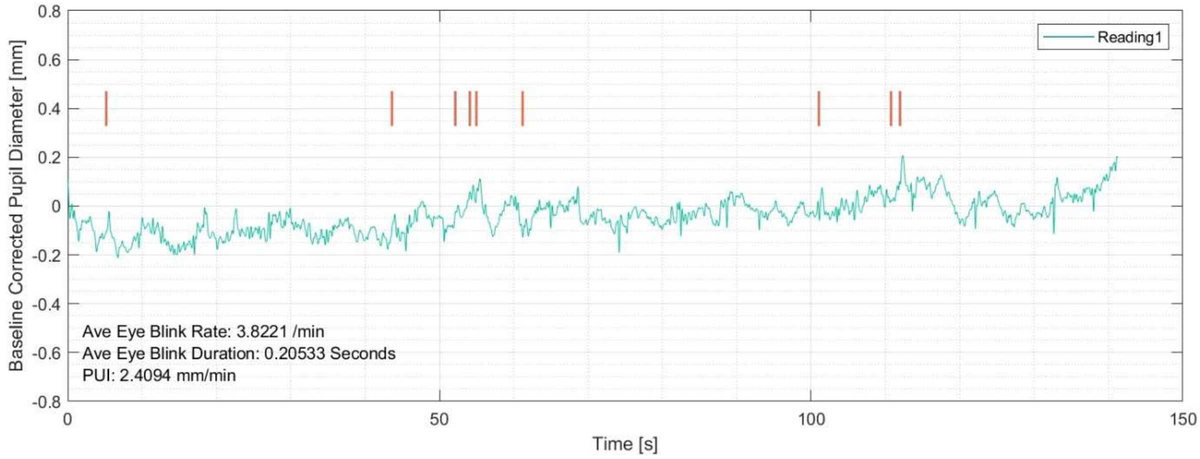

Figure 5.6 An example of the baseline-corrected pupil size signal and detected blinks as well as calculated PUI, BR and BA for the reading segment.

It can be concluded that PD is more attributed to the adaptation light level and not surprisingly the higher the light level the higher the chance of experiencing glare. This finding is in line with the previous finding of Hopkinson [20] and Tyukhova et al. [19] wherein the pupil diameter was found to be correlated with background luminance. On the contrary, PUI showed to be associated with the glare source luminance (L_s) as well as the maximum luminance (L_{max}), thus making this variable a better indicator of glare occurrence. This finding is also in accordance with Warga et al. [17].

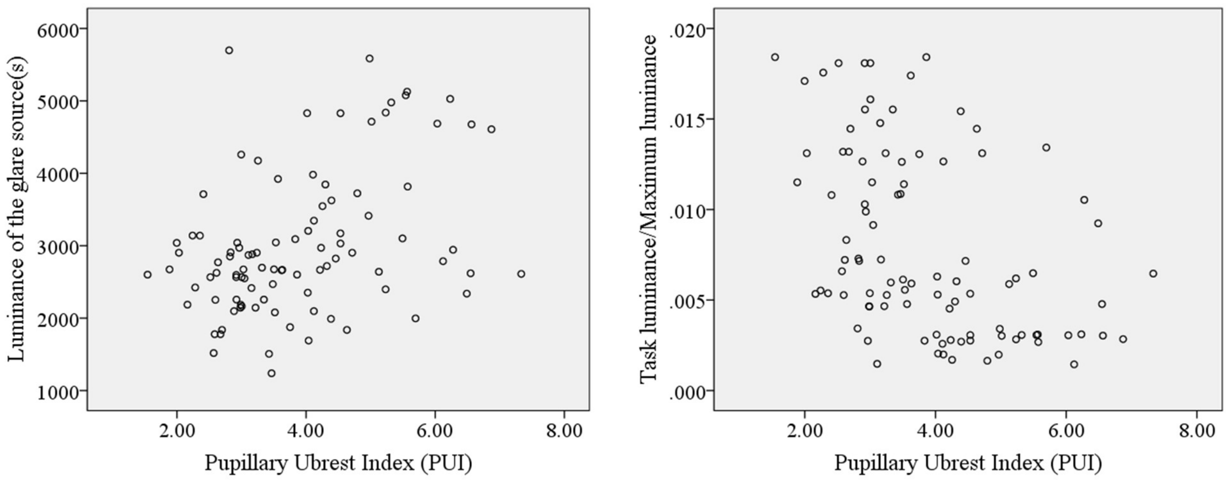

Figure 5.7 Scatterplots Pupillary Unrest Index (PUI) and glare source luminance (L_s, cd/m^2) as well as luminance ratio L_t/L_{max}

5.5.4 Eye convergence

Eye convergence is a simultaneous movement of eyes towards each other to maintain focus or refocus so as to acquire a single binocular vision. The convergence depth plane (*z*- or depth axis) can be calculated from the point in space where the gaze direction (visual axis) of both eyes intersect.

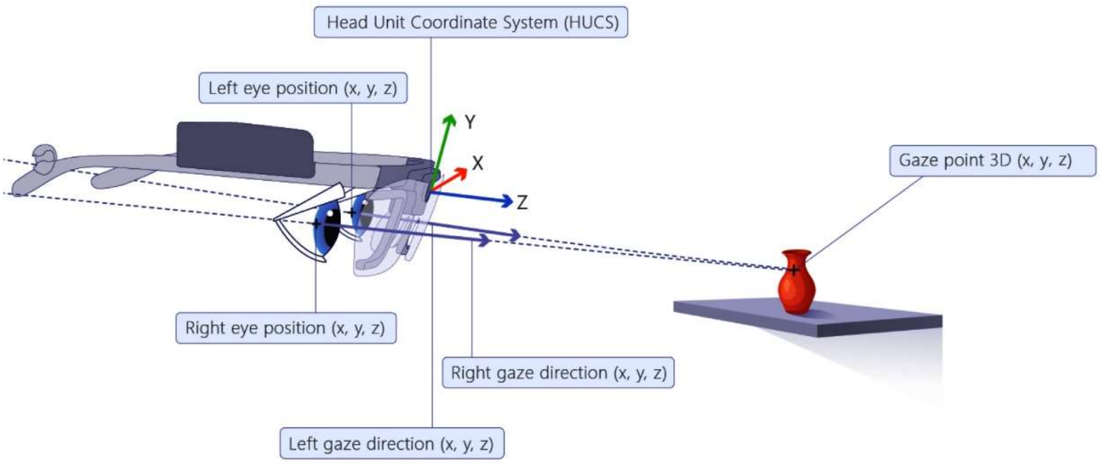

Figure 5.8 Coordinate system of the eye-tracker [25]

Two convergence variables were calculated from the eye-tracking gaze point data: Eye Convergence standard deviation (ECsd) – a measure of how much the convergence depth plane varied across the trial, and mean Eye Convergence (meanEC) – a measure of the average convergence depth plane across the duration of the trial. Figure 5.8 illustrates the eye-tracking coordinate system, gaze directions and the gaze point in the space. As depicted in Figure 4.3b in the thesis, the EC depth plane can be estimated to be around 550 mm when using the keyboard. Please note that no head/chin rest was used, but head position is normally quite stable while performing a task at the workstation. This estimated value of 550 mm will be subsequently used. Table 5.6 illustrates the descriptive statistics of the Eye Convergence standard deviation (ECsd) and mean Eye Convergence (meanEC).

First, the participant numbers for each variable (see Figure 5.9) are less than the total number of 98 because 19 participants did not contribute data for ECsd, and three did not contribute data for meanEC due to measurement issues. For meanEC, boxplots indicate no outliers, no significant skewness, and no kurtosis, and thus no need for any transform. For ECsd, boxplots indicate no outliers; however, the data are moderately positively skewed (Skewness/SE = 2.246). A new transomed variable SqrtECsd was created, being the square root of ECsd with no skew (Skewness/SE = 0.691).

Table 5.5 Descriptive statistics of Eye Convergence standard deviation (ECsd) and mean Eye Convergence (meanEC)

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
ECsd	78	25.36	149.57	76.1295	32.12302	.611	.272	-.270	.538
meanEC	95	308.07	757.81	540.784	101.81974	.190	.247	-.432	.490
Valid N (listwise)	78								

One-way ANOVAs were performed on each of these three DVs across the three groups: low discomfort, medium discomfort, and high-discomfort. There were no significant differences among conditions for each of the three variables. For the meanEC, each group's value was compared with the nominal 550 mm using one-sample *t*-tests. There were no significant differences between each group's convergence mean on the nominal convergence depth plane.

Correlation analysis showed that ECsd, meanEC and SqrtECsd were correlated with many of the other variables using a bivariate Pearson's *r*. Apart from the inter-correlations between ECsd, meanEC and SqrtECsd, the significant correlations were (with *p*-values two-tail).

ECsd is associated with FR (r = -0.251, p = 0.027) and SqrtECsd was correlated with FR (r = 0.233, p = 0.040) as well as FD (r = -0.264, p = 0.020). It can be concluded that the greater the variation in the convergence angle (that is, variation in the depth plane onto which the eyes are converging), the lower the FD and the higher FR. Reading is, therefore, less efficient. The correlation effect sizes are small to medium here.

Regarding meanEC, this variable was correlated with CVP (r = 0.260, p = 0.035), and subjective assessment of comfort level (r = -0.263, p = 0.010) and glare rating (r = 0.233, p = 0.023). Therefore, the smaller the convergence angle (that is, the further from the eyes the depth plane onto which the eyes are converging is), the greater the visual performance. However, along with this comes the greater experience of glare and lower level of visual comfort. Again, the correlation effect sizes are small to medium.

This finding might be explained by the fact that when participants experience visual discomfort/glare, they come closer to the display as an adaptive behaviour to maintain clear vision or focus and also to block a part of the view to reduce the effect of glare source/ the amount of light received by their eyes from the glare source. This behaviour results in a bigger EC angle which can, in turn, lead to eye strain.

5.5.5 Performance measures

Performance measures have been investigated in this research as an objective counterpart for visual discomfort sensation. Two measures, namely Combined Visual Performance (CVP) and Combined Reading Performance (CRP), were utilised to characterise all aspects of computer-based task performance including motor and visual elements.

5.5.5.1 Combined Reading Performance

Reading performance was also included in this research due to its dominance in contemporary clerical tasks. Combined Reading Performance (CRP) is computed as the correct answer rate (the number of correct answers/total number of questions) divided by the average time per word (second/word). The initial data check revealed that this set of data was strongly positively skewed (Skewness/SE = 2.922). Thus, a new transformed variable was created, being the Log of CRP (LogCRP) with no skew (Skewness/SE = -0.588).

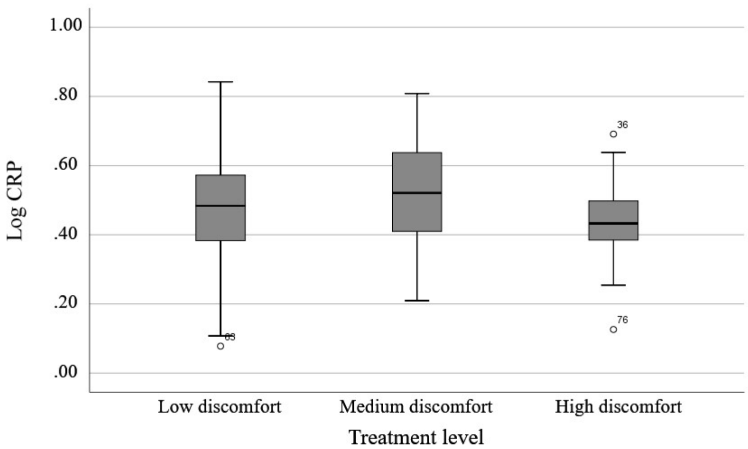

Figure 5.9 The box plot showing LogCRP by lighting conditions

One-way ANOVAs were performed on each of these two DVs across the three groups: low, medium and high discomfort. The results indicated that there were no overall significant differences among conditions for each of the two variables having CRP at p =

0.054 and LogCRP at p = 0.104. The trend was significantly different between the medium and high visual discomfort groups. The medium group outperformed the low group and was almost significantly better than the high group (see Figure 5.9; note outliers as indicated). Further independent groups t-test analysis between medium and high discomfort groups, also confirmed that medium discomfort groups outperformed the high discomfort groups for CRP (t = 2.593, df = 47.1, p = 0.014) and LogCRP (t = 2.320, df = 60, p = 0.024), where both tests were two-tail.

The LogCRP were correlated with many of the other variables using a bivariate Pearson's r. Tables 5.7 and 5.8 illustrate the correlation matrix, and the significant correlations were determined with p-values two-tail. Correlation analysis showed moderate significant correlations between this factor and FD (r = -0.285, p = 0.005), CVP (r = 0.364, p = 0.003) and average reaction time (r = -0.395, p = 0.001), and weak correlation with PUI (r = -0.255, p = 0.013). The LogCRP was associated with L_s/L_b (r = -0.216, p = 0.034), L_b/L_t (r = 0.217, p = 0.032), L_t/L_{max} (r = 0.254, p = 0.012), DGI (r = -0.238, p = 0.019), and UGP (r = -0.225, p = 0.027) as relative glare factors, all with small effect sizes. Further, the Conlon test score was moderately correlated with the CRP (r = -0.377, p = 0.002) and LogCRP (r = -0.303, p = 0.013).

Table 5.6 Correlations between performance and physiological and ocular measures

	FR	FD	BR	BA	Mean PD	PUI	Mean EC	ECsd	Sqrt ECsd	CVP
CVP	-0.309*	0.070	0.039	-0.257*	0.141	-0.213	0.260	0.201	0.194	-
LogCRP	-0.164	-0.285**	-0.029	-0.179	0.006	-0.255*	0.130	0.133	0.105	0.364**

***. Correlation is significant at the 0.01 level (2-tailed).*

**. Correlation is significant at the 0.05 level (2-tailed).*

5.5.5.2 Combined Visual Performance

Combined Visual Performance (CVP) was measured through recording the reaction time and accuracy while performing a timed vision test, as two main components of visual performance [56-58]. During this test, a Landolt ring 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) was presented in the centre of the computer screen in relation to the participant [46, 59]. Participants were required to indicate the orientation of the opening on the Landolt ring for each presentation and their reaction time and accuracy of answers were recorded. Time and accuracy then combined into one dependent variable, Combined Visual Performance (CVP), as total correct identifications/total reaction time.

The CVP was significantly associated with vertical illuminance at eye level (r = -0.347, p = 0.004), average luminance (r = -0.326, p = 0.007) and maximum luminance (r = -0.278, p = 0.023) as absolute glare factors, and with L_t/L_{max} (r = -0.296, p = 0.015), DGP (r = -0.344, p = 0.004), UGR_{exp} (r = -0.290, p = 0.017) and $E_{v\text{-}dir}$ (r = -0.359, p = 0.003) as relative glare factors (see Table 5.7 and 5.8).

Table 5.7 Correlations between performance measures and absolute factors, luminance ratios and glare indices.

		CVP	Log CRP
Absolute factors	Vertical illuminance ($\boldsymbol{E_v}$)	-0.347**	-0.059
	Average luminance ($\boldsymbol{L_m}$)	-0.326**	-0.003
	Background luminance ($\boldsymbol{L_b}$)	-0.144	-0.033
	Source luminance ($\boldsymbol{L_s}$)	-0.22	-0.169
	Task luminance ($\boldsymbol{L_t}$)	-0.15	-0.098
	Maximum luminance ($\boldsymbol{L_{max}}$)	-0.278	-0.196
Luminance ratios	L_s/L_b	-0.101	-0.216*
	L_b/L_t	0.073	0.217*
	L_s/L_t	-0.089	-0.082
	L_t/L_{max}	0.296*	0.254*
	L_s/E_v	0.192	-0.156
Glare indices	DGP	-0.344**	-0.088
	UGR_{exp}	-0.29	-0.115
	$E_{v\text{-}dir}$	-0.359**	-0.058
	$L_{av\text{-}pos}$	-0.332**	-0.03
	CGI	-0.22	-0.179
	DGI	-0.182	-0.238*
	UGP	-0.204	-0.225*

***. Correlation is significant at the 0.01 level (2-tailed).*

**. Correlation is significant at the 0.05 level (2-tailed).*

5.5.6 Subjective evaluations

Subjective evaluations included comfort level, Conlon test score and experiencing glare. The comfort level was a five-alternate, forced-choice scale. Even though the distribution was not skewed (Skewness/SE = 0.295) with no outliers, the distribution was bimodal and normality was violated (Shapiro-Wilk (68) = 0.882, $p < 0.001$). For these reasons, non-parametric statistics were used in the analysis of this variable.

The Conlon test score was a Rasch scale variable. The distribution was not skewed (Skewness/SE = 0.647) with no outliers, and the distribution was nearly normal (Shapiro-Wilk (68) = 0.963, $p = 0.043$). Given the robustness of ANOVA through minor violations of assumptions, this parametric test was used in the analysis of this variable.

Regarding comfort level, a Kruskal-Wallis independent sample non-parametric test showed a significant difference among the group means ($p < 0.001$). Follow-up Mann-Whitney U-tests showed a significant difference between low discomfort and high discomfort ($z = 4.732$, $p < 0.001$) and medium discomfort and high discomfort ($z = 3.231$, $p = 0.001$), but not between low discomfort and medium discomfort ($z = 1.421$, $p = 0.155$) (see Figure 5.10).

For the Conlon test score, a one-way ANOVA was conducted: $F(2, 65) = 3.88$, $p = 0.026$, $\eta^2 = 0.11$, where Levene's test revealed no violations of homogeneity of variances. This is a small effect size, and a Tukey HSD *post-hoc* test revealed a difference between each of the low ($p = 0.049$) and medium ($p = 0.049$) discomfort groups and the high discomfort group. Experiencing glare was a nominal variable with four values: *None*, *Perceptible, Disturbing and Intolerable*. There was no test showing any significant group differences on this variable.

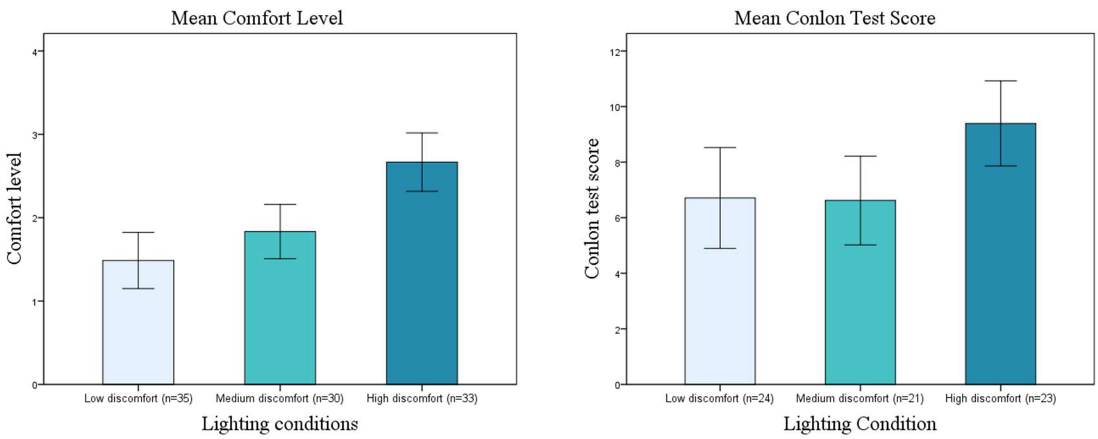

Figure 5.10 Subjective responses by treatment level: Comfort level (left), Conlon test (right)

Non-parametric Spearman's ρ was conducted for all inter-correlations. The Conlon test score correlated with Comfort level ($\rho = 0.279$, $p < 0.05$, one-tail, $n = 68$) and experiencing glare correlated with comfort level ($\rho = 0.287$, $p < 0.01$, one-tail, $n = 98$).

5.5.7 Composite variables

Two critical performance measures were investigated in this research, Visual Performance (CVP), defined as the number of correct identifications on the visual acuity task (Landolt "C") divided by the time taken to complete the task, and Reading Performance (CRP), defined as the number of correct answers to comprehension questions divided by the average time (seconds) taken reading each word of reading. The latter was positively skewed (Skewness/SE = 3.92), thus LogCRP was computed and included in the analysis.

In addition to performance measures, a broad range of variables involving different responses of office workers in the luminous environment were investigated as detailed above. Due to problems with multicollinearity between variables measuring similar phenomena (e.g. different luminance measures, or different psychological ratings of comfort levels), a series of composite variables were derived by z-transforming each variable within a category and averaging the resultant normalised scores. In some cases, variables were reverse-coded if the scale used was the opposite of scales used by other constituent variables in their respective composite variable. Further, some of the constituent variables of the composites have been transformed before normalisation to eliminate skewness in these variables. A number of candidate constituent variables for a composite were left out because of floor effects, extreme skew that could not be eliminated, bimodality etc resulting in severe violations of statistical assumptions. Finally, five composite variables were constructed representing one category of variables subject to this research as follow:

- **Composite Psychological Response score**: This is the participant's self-reported response of visual discomfort/glare to the lit environment. It was computed by the average of the normalised (z-scores) of glare rating across four points, comfort level rating, and Conlon test score.
- **Composite Glare Index Score**: This is a combination of physical, standardised measures of glare and discomfort. It was computed by the average of the normalised (z-scores) of DGP, DGI, CGI, UGP, UGR_{exp}.
- **Composite Luminance Score**: This is a composite of various measures of luminance. It was computed by the average of the normalised (z-scores) of E_v, $SqrtL_b$, $LogL_s$, $L_{avg\text{-}pos}$, and E_{v-dir}.

- **Composite Contrast Score**: This is a composite of the various measure of luminance **contrast** in the work environment. It was computed by the average of the normalised (z-scores) of Log (L_t/L_{max}) and Log (L_s/E_v).
- **Composite Visual Clarity Score**: This is a composite measure of the clarity of the image. It was computed by the average of the normalised (z-scores) of SqrtBR, SqrtBA, SqrtPUI. The greater the score here, the less the visual 'clarity'.

One-way ANOVAs were carried out on each of these composite variables across the three groups: low, medium and high discomfort. The results indicated that there were significant differences among conditions for each of the composite variables (see Figure 5.11: CVP (p = 0.016, η^2 = 0.12), LogCRP (p = 0.104, η^2 = 0.05), Composite Visual Clarity (p = 0.087, η^2 = 0.05, *ns*), Composite Psychological Response (p < 0.001, η^2 = 0.18), Composite Luminance score (p < 0.001, η^2 = 0.56), Composite Contrast (p < 0.001, η^2 = 0.51), Composite Glare Index (p < 0.001, η^2 = 0.48). The trends were quite linear in all composite variables except for CRP. The composite contrast was also linear but in a reverse direction since in the constituent variables the lower luminance was divided by the higher luminance (L_t/L_{max}), therefore the smaller value means higher contrast.

5.5.8 Regression analysis

5.5.8.1 Composite variables

Once composite variables were formed, eight multiple, linear regression models were run to determine which of a set of predictors contributed most to the variance of outcomes. For each model, the following assumptions were assessed: (i) Normality of outcome variable; (ii) Existence of a linear relationship between predictors and outcome; (iii) The absence of multicollinearity between predictors; (iv) Homoscedasticity; and (v) Normality of the residual distribution. As previously noted above, two outcome variables were identified as skewed (skewness statistic/skewness standard error > ±1.96) and were thus transformed to satisfy the assumption of outcome normality. These included Combined Reading Performance, which was log-transformed, and Pupillary Unrest Index, which was square-root-transformed (see above). All other assumptions were satisfied for all regression models.

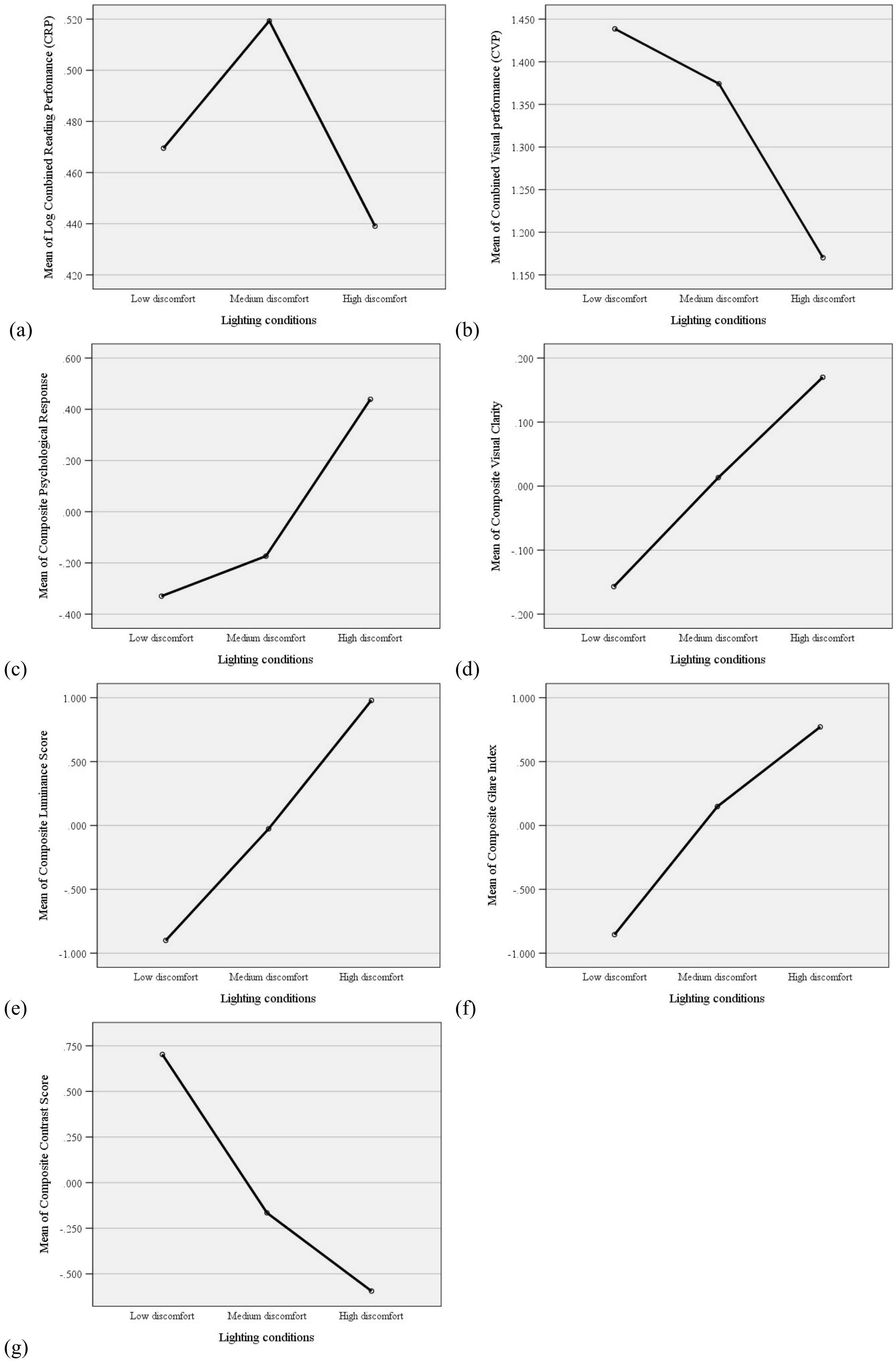

Figure 5.11 Mean composite variables by treatment levels (lighting conditions)

Zero-order correlations were calculated for all study measures. Each model will include a correlation matrix to illustrate where relationships existed prior to partialling of variance. Table 5.9 shows the relationship between Combined Visual Performance (CVP; outcome) and the composite variables. As shown, CVP was correlated negatively with the Glare Index, Luminance and visual Clarity Composite, and positively correlated with the Contrast composite. There was no correlation between the psychological Response composite and CVP, and as such this composite was not used as a predictor in the regression model. All predictors were significantly related to one another.

Table 5.8 Intercorrelations between Combined Visual Performance and composite predictor variables.

		1	2	3	4	5	6
1.	CVP	-					
2.	Composite Psychological Response score	-0.17	-				
3.	Composite Glare Index score	-0.27*	0.46**	-			
4.	Composite Luminance score	-0.314**	0.51**	0.79**	-		
5.	Composite Contrast score	0.35**	-0.21*	-0.50**	-0.66**	-	
6.	Composite Visual Clarity score	-0.23*	0.22*	0.38**	0.24**	-0.42**	-

* *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001

Multiple linear regression was run to explore the unique variance explained in CVP by the five predictors. The overall model was not significant, $R^2 = 0.14$, $F\,(4, 61) = 2.44$, $p = 0.057$. It was thus interpreted that none of the composite variables explained any unique variance in the visual performance of participants.

Table 5.9 Intercorrelations between Combined Reading Performance (CRP) and composite predictor variables

		1	2	3	4	5	6
1.	CRP	-					
2.	Composite Psychological Response score	-0.1	-				
3.	Composite Glare Index score	-0.186*	0.46**	-			
4.	Composite Luminance score	-0.07	0.51**	0.77**	-		
5.	Composite Contrast score	0.05	-0.21*	-0.50**	-0.66**	-	
6.	Composite Visual Clarity score	-0.28**	0.22*	0.38**	0.24**	-0.42**	-

* p < 0.05, ** p < 0.01, *** p < 0.001

The next model explored the potential impact of the composite variables on the Combined Reading Performance (CRP) of participants. Table 5.10 shows the zero-order correlations between this outcome and the various composite variables. As shown, only the physical glare and visual clarity composites were significantly related to the outcome (both negatively). As such, only these variables were included in the regression model. Again, all predictors were significantly associated with one another.

Multiple linear regression was run to explore the unique variance explained in Combined Reading Performance (CRP) by the two relevant predictors. The overall model was significant, R^2 = 0.08, F (2, 92) = 4.01, p = 0.02. The Visual Clarity composite significantly predicted CRP, b = -0.06, t(92) = -2.24, p = 0.03. The Glare Index composite did not significantly predict CRP, (p > 0.05). Examination of the semi-partial correlation suggested that Glare Index composite accounts for 5% of the unique variance in CRP, such that increases in visual clarity composite variable should decrease reading performance.

5.5.8.2 Optical and luminance variables

Zero-order correlations were run to explore the relationships between the mean Pupil Diameter (mean PD; outcome variable), Vertical Illuminance (E_v; predictor) and the ratio of Ls/ E_v (predictor).

Table 5.10 Intercorrelations between mean Pupil Diameter (mean PD) and predictor variables

		1	2	3
1.	MeanPD	-		
2.	E_v	-0.42**	-	
3.	Ls/ E_v	0.34**	-0.63**	-

* p < 0.05, ** p < 0.01, *** p < 0.001

Multiple linear regression was run to explore the unique variance in mean PD explained by E_v and Ls/ E_v. The overall model was significant, R^2 = .18, F (2, 92) = 10.40, p <.001. MeanPD significantly (but very weakly) predicted by E_v, b < -.001, t(92) = -2.80, p = .006. Conversely, Ls/ E_v did not significantly explain variance in meanPD once variance shared with E_v was partialled out (p > 0.05). Examination of the semi-partial correlation revealed that E_v accounted for only 0.7% of the unique variance in mean PD.

Zero-order correlations were then run to explore the relationship between Fixation Rate (FR; outcome variable), E_v (predictor) and luminance ratio L_t/L_{max} (predictor). As shown, there was a positive relationship between FR and E_v, and a negative correlation between FR and L_t/L_{max}. Both predictors were negatively related to one another.

Table 5.11 Intercorrelations between Fixations Rate (FR) and predictor variables

		1	2	3
1.	FR	-		
2.	E_v	0.41***	-	
3.	L_t/L_{max}	-0.23*	-0.56***	-

** p < 0.05, ** p < 0.01, *** p < 0.001*

Multiple linear regression was run to explore the unique variance in FR explained by E_v and luminance ratio L_t/L_{max}. The overall model was significant, R^2 = 0.17, F (2, 93) = 9.37, p < 0.001. FR was significantly, positively predicted by E_v, b = 0.001, t(93) = 3.56, p = 0.001. Conversely, L_t/L_{max} did not significantly predict any unique variance in FR (p > 0.05). Examination of the semi-partial correlation revealed that E_v explained 11.4% of unique variance in participant's ocular fixations per line of text.

Zero-order correlations were run to explore the relationships between Blink Amplitude (BA; outcome variable), E_v (predictor) and L_t/L_{max} (predictor). As shown, there is a positive relationship between BA and E_v, and a negative correlation between BA and L_t/L_{max}.

Table 5.12 Intercorrelations between Blink Amplitude (BA) and predictor variables

		1	2	3
1.	BA	-		
2.	E_v	0.43***	-	
3.	L_t/L_{max}	-0.56***	-0.56***	-

** p < 0.05, ** p < 0.01, *** p < 0.001*

Multiple linear regression was run to explore the unique variance in BA explained by E_v and L_t/L_{max}. The overall model was significant, R^2 = 0.35, F (2, 92) = 24.80, p < 0.001. BA was not significantly predicted by E_v (p > 0.05), but was significantly, negatively predicted by L_t/L_{max}, b = -16.15, t(92) = 4.76, p = 0.001. Examination of the semi-partial correlation revealed that L_t/L_{max} explained 16% of the variance in participant blink rate, such that higher rates of L_t/L_{max} predicted smaller blink rates.

Zero-order correlations were run to explore the relationship between the Pupillary Unrest Index (PUI; outcome variable), source luminance (L_s; predictor) and L_t/L_{max}. As shown, L_s was positively correlated to PUI, and L_t/L_{max} was negatively correlated to PUI. The predictors shared a negative correlation.

Table 5.13 Intercorrelations between Pupillary Unrest Index (PUI) and predictor variables

		1	2	3
1.	PUI	-		
2.	L_s	0.39***	-	
3.	L_t/L_{max}	-0.45***	-0.54***	-

** p < 0.05, ** p < 0.01, *** p < 0.001*

A multiple regression model was run to explore the unique variance in PUI explained by L_s and L_t/L_{max}. The overall model was significant, R^2 = 0.23, F (2, 92) = 13.77, p < 0.001. The PUI was not significantly predicted by L_s (p > 0.05), however L_t/L_{max} significantly negatively predicted unique variance in PUI, b = -21.18, t(92) = 3.09, p = 0.001. Examination of the semi-partial correlation revealed that L_t/L_{max} explained 8% of the variance in PUI, such that higher rates of L_t/L_{max} predicts less pupillary unrest.

Zero-order correlations were run to explore the relationship between Combined Visual Performance (CVP; outcome variable), E_v (predictor) and L_t/L_{max}. As shown, CVP was negatively related to E_v, and positively related to L_t/L_{max}. The predictors shared a negative relationship.

Table 5.14 Intercorrelations between Combined Visual Performance (CVP) and predictor variables

		1	2	3
1.	CVP	-		
2.	E_v	-0.35**	-	
3.	L_t/L_{max}	0.30**	-0.56***	-

** p < 0.05, ** p < 0.01, *** p < 0.001*

Multiple linear regression was run to explore the unique variance in CVP explained by E_v and L_t/L_{max}. The overall model was significant, R^2 = 0.13, F (2, 64) = 4.86, p = 0.01. Despite this, neither E_v nor L_t/L_{max} significantly explained any unique variance in CVP (both ps >.05). This suggests that neither of these variables alone accounts for variability in participants' visual performance during the task.

Zero-order correlations were run to explore the relationships between CRP (outcome variable), L_s (predictor) and L_t/L_{max} (predictor). As shown, CRP was negatively correlated with L_s, and positively correlated with L_t/L_{max}. The predictors shared a negative relationship.

Multiple linear regression was run to explore the unique variance in CRP explained by L_s and L_t/L_{max}. The overall model was significant, R^2 = 0.07, F (2, 94) = 3.31, p = 0.04.

Despite this, neither L_s nor L_t/L_{max} predicted any unique variance alone in CRP (both ps >.05). This suggests that neither L_s or L_t/L_{max} had any significant individual impact on reading performance on participants during the task.

Table 5.15 Intercorrelations between Combined Reading Performance (CRP) and predictor variables

		1	2	3
1.	CRP	-		
2.	L_s	-0.17*	-	
3.	L_t/L_{max}	0.25**	-0.54**	-

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Overall, this analysis sought to explore which of a range of environmental factors linked to glare predicted important performance outcomes and physiological measures. First, a series of composite variables were calculated and used to predict performance measures. Results of the first regression model suggested that none of the composites (psychological responses to glare, physical glare measurements, luminance measurements, luminance contrast, or visual clarity) predicted the visual performance of participants during the reading task. The second model revealed that increases in the visual clarity composite variable (greater score means the less the visual 'clarity') decreased reading performance on the task.

Following this, a series of regression models explored the relationship between specific, theoretically relevant luminance scores on physiological measures. The first of these models revealed that higher levels of E_v in the environment predicted significantly lower smaller mean Pupil Diameter (ratio L_s/E_v did not have any effect once E_v was accounted for). Further, the second model showed that higher levels of E_v also significantly predict a more significant number of ocular fixations per line of text read (FR) (luminance ratio L_t/L_{max} did not have any effect after controlling for E_v). The third model demonstrated that the average blink duration (BA) is shorter when the luminance ratio L_t/L_{max} is higher (with E_v having no impact on blink duration after controlling for L_t/L_{max}). Similarly, the fourth model showed that pupillary unrest (PUI) is reduced when the luminance ratio L_t/L_{max} is higher (with L_s having no impact after controlling for L_t/L_{max}). Finally, the fifth model revealed that neither E_v, nor Luminance ratio L_t/L_{max} had any unique impact on visual performance. The final model similarly showed that neither source of luminance or Luminance ratio L_t/L_{max} had any unique impact on combined reading performance.

5.6 Conclusion

This study has examined the relationships among three categories of objective measures of visual discomfort and two main types of glare factors, absolute and relative glare factors. Objective measures of visual discomfort included physiological, ocular and performance measures. In particular, mean Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), eye Fixation Rate (FR), and Eye Convergence (EC). Performance measures included Combined Visual Performance (CVP) and Combined Reading Performance (CRP) were investigated. Correlation and multiple regression analysis were employed to identify the relationships among the studied parameters. Further, analyses of variance were utilised to determine differences on all measures among three lighting conditions with low, medium and high levels of visual discomfort.

Regarding physiological and ocular responses, PUI and BA were shown to be associated with the maximum luminance (L_{max}), and luminance of the glare source(s) (L_s). Further, mean PD was associated with the average luminance or adaptation light levels as smaller PD was observed in higher vertical illuminance (E_v), average luminance (L_m) and background luminance (L_b). Fixation rate (FR) was also shown to be moderately correlated with all absolute glare factors, however, among luminance ratios was only correlated with luminance ratio (L_t / L_{max}) with a small effect size.

Regression analysis suggested that the ratio of the task luminance/maximum luminance (L_t / L_{max}) predicted PUI and BA as when L_t / L_{max} decreased (which means higher contrast), the pupillary unrest (PUI) and the average blink duration (BA) are increased. The vertical illuminance at eye level (E_v) also predicted mean Pupil Diameter and ocular fixations per line of text read (FR). Blink rate (BR) found to be associated with the overall light levels rather than being affected by the glare source luminance, however, due to the moderating effect of the nature of the task it requires further investigation. It is possible, therefore, that PUI and BA serve as indicators of glare due to contrast, and FR and mean PD as indicators of glare due to excessive luminance.

Concerning performance measures, it was concluded that the lower fixation duration (FD), the smaller the PUI, and the higher the visual performance (CVP), the better the reading performance (LogCRP). The LogCRP also showed to be sensitive to contrast as it was significantly correlated with L_s/L_b and L_t/L_{max}. The results concerning the CVP indicated a negative association with glare factors. That is, the higher the vertical illuminance (E_v) and the average luminance (L_m), the lower the visual performance (CVP).

Variance analysis suggested that the Eye Convergence (EC) was not affected by lighting conditions. However, ECsd was shown to be associated with FD and FR. That is, the more the variation in the convergence angle (ECsd), the less the fixation duration (FD) and the more fixations per line (FR). Further, results suggested that the smaller the convergence angle (meanEC), the higher the visual performance (CVP). The regression analysis of composite variables suggested that lower visual 'clarity', reduced reading performance (CRP) on the task.

Findings of this research, by identifying the contributing factors in each objective measure (physiological, ocular and performance), provides in-depth insight for further implementation of these factors in discomfort glare predictive models.

5.7 References

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Chapter 6: Conclusion

6. Conclusion

6.1 Summary

Creating objective measures of visual discomfort sensation is valuable in overcoming the limitations associated with the psychophysical methods/procedures implemented in developing visual discomfort predictive models. The major limitations in the existing predictive models have been identified as the wide variability of individual responses in relation to discomfort glare, inconsistencies between predicted discomfort level and the Post Occupancy Evaluation (POE) results, and inconsistencies between various predictive models. These inconsistencies are partly due to the different boundary conditions of each experimental study that resulted in new metrics, such as characteristics of the lighting conditions, or the experimental setup and design. Further, there is always bias associated with the subjective evaluation methods employed to approximate the magnitude of discomfort glare sensations. Thus, there is a need for more definitive and objective glare markers which can lead to the development of efficient predictive models.

In the literature on objective measures of discomfort glare, physiological responses have often been the focus. Some physiological responses, such as pupillary responses, have received considerable attention, and therefore there is established knowledge on this light-induced reflex. Nevertheless, much uncertainty still exists regarding some other studied factors and their predictive power, namely spontaneous eye blink and pupillary unrest. Furthermore, investigating different types of eye movements (fixational and saccadic eye movements) can provide valuable insight into user ocular behaviour and responses in various lighting conditions, which can, in turn, lead to performance inefficiencies for office workers. Thus, the overall objective of this thesis, considering a wide range of physiological and performance indicators, was to provide new insights into the application of objective measures which could be applied to assess and predict discomfort glare and its effects on performance.

In this thesis, an experimental study was undertaken to analyse physiological responses in different lighting scenarios. To facilitate these analyses, a holistic approach was proposed in which conventional light measurements and subjective evaluations were coupled with two types of objective measures: physiological and performance measures. Light-induced physiological measures included mean Pupil Diameter (PD), Pupillary Unrest Index (PUI), Blink Rate (BR), Blink Amplitude (BA), number of fixational eye movements during reading (Fixation Rate) (FR), average Fixation Duration (FD), and Eye Convergence (EC). Combined Visual Performance (CVP) and Combined Reading Performance (CRP) indicators were calculated using the participant's accuracy and speed while performing a timed vision test and a reading task, respectively.

In brief, more definitive glare markers were demonstrated by the results of this research through identification of the most sensitive physiological indicators; further development potential lies in shaping more efficient glare predictive models. Taken together, this research found that physiological indicators subject to this research could serve as metrics of high levels of discomfort glare sensation. In addition, the key lighting characteristics that primarily affected these physiological indicators were identified. Significant findings emerging from this study are outlined below.

- The human visual system adapts to different lighting conditions by controlling the amount of light reaching the retina through the pupillary light reflex. The mean Pupil Diameter (PD) and the Pupillary Unrest Index (PUI) were investigated to examine the first hypothesis of this research: "Subjects who experience a higher degree of discomfort glare will exhibit smaller pupil size (PD) and greater pupillary unrest". The mean Pupil Diameter (PD) was studied as an indicator of the general lighting condition to which the eyes are adapted. Results of this research indicated that the participants in the high discomfort group recorded lower Pupil Diameter (PD) compared to the low discomfort group, which is consistent with previous research on this parameter. Although the smaller pupil size decreases the amount of light reaching the retina, participants reported higher degrees of visual discomfort. One reason is that the pupil size presents the light level that the eyes are adapted to, and in higher levels of light availability there is a higher chance of glare. This result also confirms the rationale behind the basic glare formula in which a glare source is defined according to the adaptation light level. Furthermore, the Pupillary Unrest Index (PUI) which represents the instability in pupil size was studied as a measure of visual discomfort sensation. Participants in the high discomfort condition also exhibited greater Pupillary Unrest Index (PUI) than those in the medium discomfort group, suggesting that cyclical variation in pupil size increases when a glare source causes a high level of discomfort.

Correlation analysis indicated that mean PD was associated with the average luminance or adaptation light levels as smaller mean PD was observed in higher vertical illuminance (E_v), average luminance (L_m) and background luminance (L_b). Therefore, PD can be considered to indicate the adaptation level and possibly be used as a predictive indicator of glare due to overall excessive light level or when the glare source filled a large proportion of the visual field where the source luminance and background luminance are quite the same. Further, regression analysis revealed that higher levels of E_v in the environment predicted significantly smaller mean Pupil Diameter. PUI was positively correlated with the maximum luminance (L_{max}), followed by luminance of the glare source(s) (L_s) and the ratio of the task luminance/maximum luminance (L_t / L_{max}). Consequently, this parameter can possibly be used as a discomfort glare marker. The regression analysis considering the contributing factors suggested that pupillary unrest (PUI) is increased when the contrast between the task luminance (L_t) and maximum luminance (L_{max}) increases.

- Spontaneous eye blinking is a human body mechanism for maintaining a healthy ocular surface and clarity of vision. Spontaneous blink rate (BR) and its average duration (BA) were investigated to test the second hypothesis of this thesis: "Experiencing a higher degree of discomfort glare will result in a lower blink rate (BR) and a higher blink amplitude (BA) while performing the reading task".

According to the results, the participants in the high discomfort condition exhibited a lower Blink Rate (BR) and higher Blink Amplitude (BA) than those in both the low and medium discomfort conditions. A lower BR can be critical since it contributes to a higher rate of tear evaporation and possibly dry eyes. Nonetheless, due to its dependency on the type of task performed by the user wherein the lowest BR is attributed to the reading tasks, further investigation including different types of tasks is required to provide a comprehensive picture. Participants in the high glare situation also recorded significantly higher BA, which can present an indicator of visual strain or fatigue.

Blink Amplitude (BA) was shown to be significantly correlated with vertical illuminance (E_v), maximum luminance (L_{max}) and source luminance (L_s). There was also moderate, negative correlation between the luminance ratio (L_t / L_{max}) and BA. BR found to be more associated with the adaptation luminance rather than being affected by the glare source luminance; however, due to the moderating effect of the nature of the task, it requires further investigation. The regression model demonstrated that the average blink duration (BA) is shorter when luminance ratio L_t/L_{max} is higher.

- Fixational eye movements (FR) and the dwelling time at each fixation (FD) have been investigated as ocular metrics in response to the lighting conditions with the potential of affecting user performance, in order to examine the third hypothesis of this research: "Experiencing a higher degree of discomfort will lead to more saccadic eye movements and consequently higher fixation rate (FR), as well as greater fixation duration (FD)". The current study found that participants exhibited a higher number of fixations (FR) when reading under high discomfort glare. Knowing that fixational eye movements are strongly connected to the saccades, higher FR results from a greater number of saccadic eye movements, and more saccades mean lower reading performance. Therefore, it can be concluded that high glare levels can lead to higher FR, followed by lower reading performance. However, Fixation Duration (FD) was not affected by lighting conditions and could be attributed to the cognitive processing time resulting from extracting visual or linguistic information.

FR was shown to be moderately correlated with all absolute glare factors; however, among luminance ratios was only correlated with luminance ratio (L_t /L_{max}) with a small effect size. Further, the regression model showed that higher levels of E_v also significantly predict a greater number of ocular fixations per line of text read (FR).

- Concerning performance measures, two performance scores were determined, Combined Visual Performance (CVP) and Log Combined Reading Performance (LogCRP) to test the fourth hypothesis of this thesis, "Subjects who experience a higher degree of discomfort glare will exhibit a lower score of performance". The former was calculated from the accuracy and reaction time while performing a timed vision test, and the latter from the precision in answering the comprehension test after reading task and the average time spent reading each word while reading the given text. The results indicate that high discomfort glare levels resulted in lower CVP score; however, no statistical difference was observed from the medium group. Regarding the LogCRP, no significant difference was found among conditions, which indicates that this variable is not sensitive to discomfort glare. However, correlation analysis revealed a moderate to strong correlation with CVP, FD and PUI. That is, the lower the fixation duration (FD), the smaller the PUI, and the higher the visual performance (CVP), the better the reading performance (LogCRP). This parameter was also sensitive to contrast as it was significantly correlated with L_s/L_b and L_t/L_{max}. The results concerning the CVP indicated a negative association with glare factors. That is, the higher the vertical illuminance (E_v) and the average luminance (L_m), the lower the visual performance (CVP).

- For all the abovementioned dependent variables (DVs), no difference was found among the low and medium discomfort groups. The implication is that rather than being linear, glare impact on physiological and performance variables may increase significantly with glare increase from medium to high levels.

- Eye Convergence (EC), as an adaptive response, was investigated by using two variables, mean Eye Convergence (meanEC) and Eye Convergence standard deviation (ECsd). The former was employed as a measure of how much the convergence depth plane (*z*- or depth axis) varied across the trial and the latter as a measure of the average convergence depth plane across the duration of the trial. The statistical analysis showed that Eye Convergence (EC) was not affected by lighting conditions. However, ECsd showed to be associated with FD and FR, as the greater the variation in the convergence angle (ECsd), the lower the fixation duration (FD) and the more fixations per line (FR). Further, results indicated that the smaller the convergence angle, that is, the further from the eyes the depth plane onto which the eyes are converging, the greater the visual performance and the lower the comfort level. It can also be interpreted as when participants experience visual discomfort/glare, they decrease their distance from the computer display, to either maintain focus or reduce the effect of the glare source by obstructing a more considerable amount of their visual field with the display, even though this adaptive behaviour can lead to eye strain due to a larger EC angle.

- Five composite variables were defined to simplify the various measures measuring similar phenomena. The regression analysis on composite variables suggested that increases in the visual clarity composite variable which equates to lower visual 'clarity', significantly contributed to decreased reading performance on the task.

- In order to quantify participants' perception, two types of questions were utilised. One question asked subjects to rate the magnitude of glare using a four-point scale (no glare, perceptible, disturbing, intolerable). However, this question implies the existence of a glare source. For this reason, participants were also asked to rate their visual comfort on a five-point Likert scale. The correlation analysis indicated that the perceived visual comfort level significantly correlated with the main photometric variables contributing to glare sensation (luminance of the glare source, task luminance, the illuminance at eye level, and average luminance) as well as the most common glare evaluation metrics (DGP, DGI and VCP). However, glare ratings did not show any significant correlations. For further investigation, the answers related to each of these two questions were tested according to subjects' sensitivity to bright light, and it was revealed that the rating of glare was affected by user sensitivity. Thus, visual comfort level ratings can be considered to be a more meaningful indicator than glare ratings, which may not always be appropriate for all participants since these ratings rely on the knowledge and sensitivity of respondents.

Further statistical analysis on comfort level, showed a significant difference among the group means ($p < 0.001$). However, follow-up tests showed a significant difference between low discomfort and high discomfort and medium discomfort and high discomfort, but not between low discomfort and medium discomfort.

- The effect of gender was analysed as a confounding factor in this research, and two differences independent of lighting conditions were found. For females, Fixation Rate (FR) was higher, and Fixation Duration (FD) was lower than for males. Given the equal numbers of males and females, despite the suggestion that female eye movement may constitute a greater number of shorter fixations than male eye movements the research validity is unaffected. In this study, no other dependent variable (DV) differences were found across the genders.

6.2 Limitations and future work

As with any research, there were some limitations to this study. Due to the exploratory nature of this research, multiple correlations were examined in order to determine which of the variables are relevant to our outcomes of interest. It is important to stress that running large numbers of hypothesis tests carries with it the risk of finding positive results by chance, and thus all correlations should be treated with due caution. It is expected that these findings will serve as a foundation for future research, in which relationships reported in this analysis can be tested for replication.

In the experimental design, the typing task was excluded from the office tasks since most participants could not touch-type and they were looking downwards while typing, which resulted in significant eye-tracking data loss with respect to the screen. In addition, looking downward changes the illuminance reaching the eyes and consequently the measured photometric values could not be considered as the lighting condition that participants experiencing during the writing task. For further investigation the ability to touch-type should be considered as an eligibility criterion for the participant recruitment.

Since one of the objectives of this research was to provide visual comfort in buildings with a high proportion of glazing (that is, a high window-to-wall ratio), for the experimental work an office with a high level of daylight availability was utilised. Therefore, the discomfort glare was predominantly due to the undesirable luminance distribution or direct sunlight. It would be useful if the results of this study could be tested in conditions where the predominant cause of visual discomfort is contrast.

In terms of directions for future research, the results of this research have implications for adaptive lighting strategies which can be integrated into lighting control systems to provide tailored office lightings. The existing responsive lighting solutions, either controlling artificial lighting or kinetic/responsive facades, work based on pre-set parameters stemming from the existing predictive models, as well as from sensors that collect environmental data. Nevertheless, the behaviour and performance of the end-users are not considered, which can result in inefficiencies in the existing control systems. In this sense, the performance of control innovations for building lighting systems in providing a healthy and quality environment for office workers without considering individual differences is brought into question. The human physiological and ocular metrics particularly Pupillary Unrest Index (PUI) and Blink Amplitude (BA), have the potential to be incorporated into a data-driven model for human-responsive lighting control systems.

The results of this research are based on semi-controlled short experimentations; hence a field study is required involving all the investigated factors for a longer period of time. It would be interesting to evaluate all the studied parameters in the field and examine the possible repercussions of other parameters such as office layout, adjacent buildings, and the view from the window.

Due to the confirmed effect of user sensitivity on discomfort glare perception, while performing office tasks, further research is required to examine both perceived and objective individual sensitivity to brightness. It would be valuable to categorise office workers based on their sensitivity to contrast and consider this parameter as an independent variable.

To develop a full picture of office workers' performance additional studies will be needed that include more motor components in their task design. Tasks that require using cursor/mouse as it is an important component of today's computer-based tasks.

7. Appendices

7.1 Appendix A: Subjective surveys

7.1.1 Demographic Questions

1. What is your gender?

- ☐ Female
- ☐ Male
- ☐ Prefer not to say

2. What is your age?

   Enter in the box: ☐

3. Do you normally wear corrective eyewear during office or office-like work?

- ☐ No
- ☐ Yes

If Yes:

- ☐ Contact lenses
- ☐ Glasses

4. Do you often wear sunglasses? (Mark as many as apply)

- ☐ No
- ☐ Yes, outdoors
- ☐ Yes, indoors

5. In general terms, which category describes your job best?

- ☐ Student
- ☐ Professionals
- ☐ Technicians and Trades Workers
- ☐ Clerical and Administrative Workers
- ☐ Community and Personal Service Workers
- ☐ Other (please specify) ☐

6. In my usual workplace the lighting is mainly:

- Electric light
- Daylight
- A combination of daylight and electric light

7.1.2 Lighting environment perception

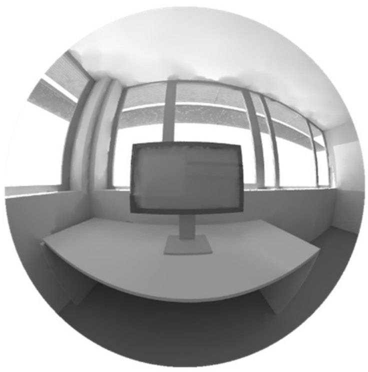
1. Are there any light sources, which are distracting or uncomfortable during the test?

- No
- Yes

If Yes, please indicate the type of light source you found uncomfortable at this time (Mark as many as apply)

- Direct sunlight in workspace area
- View of sky
- Daylight on computer screen
- Other reflections (please specify)

Please mark the positions of light sources which were distracting or uncomfortable during the test (Please mark as many as possible).



2. Did you experience discomfort during the test session?

- No
- Yes

If Yes, please mark the degree of discomfort:

- Perceptible (I am aware of the presence of the light source, but it does not bother me)

- ☐ Disturbing (I am aware of the light source and I would complain about it)
- ☐ Intolerable (I am aware of the light source and I cannot stand it)

3. Would you like to change anything in this office to improve your visual comfort?
   - ☐ No
   - ☐ Yes

If Yes, please mark the type of change you would like to implement. (Mark as many as apply)

- ☐ Blinds
- ☐ Desk position
- ☐ Computer screen position/orientation
- ☐ Electric lighting
- ☐ Other (please specify) [ ]

4. How do you rate the current light level?

	Too little light		About right		Too much light
a. In the room in general	☐	☐	☐	☐	☐
b. In the workplace	☐	☐	☐	☐	☐
c. At the monitor	☐	☐	☐	☐	☐

5. How do you rate the comfort level of lighting condition during the test? from very *comfortable* (left) to very *uncomfortable* (right).

	Very	Somewhat	Neutral	Somewhat	Very	
Comfortable	☐	☐	☐	☐	☐	Uncomfortable

7.1.3 Conlon test

Please rate the following statements using the scale 0 1 2 3 where:

0	1	2	3
Event never occurred	Event occasionally occurred, a couple of times	Event occurred often, every few seconds	Event occurred almost all the time

1. Did your eyes ever feel watery, red, sore, strained, tired, dry, gritty, or do you rub them a lot, when reading the text on the computer screen?

   0 1 2 3

2. Did your eyes ever feel watery, red, sore, strained, tired, dry or gritty, after you have been reading the text with small fonts and good image quality on the computer screen?

   0 1 2 3

3. When reading on the screen, did you unintentionally reread the same words in a line of text?

   0 1 2 3

4. When reading, did you unintentionally reread the same line?

   0 1 2 3

5. did you have to use the cursor to keep from losing your place when reading the text?

   0 1 2 3

6. When reading on the computer screen, did you have to squint to keep the words from going blurry or out of focus?

   0 1 2 3

7. When reading on the computer screen, did the words appear to fade into the background then reappear?

0 1 2 3

8. did the letters ever go blurry when you were reading on a computer screen?

0 1 2 3

9. Do the letters ever appeared as a double image when you were reading on the computer screen?

0 1 2 3

10. When reading on the computer screen, did the words ever begin to move or float?

0 1 2 3

11. When reading on the computer screen, did you ever have difficulty keeping the words in focus?

0 1 2 3

12. When you were reading the text in black on a white background on the computer screen, did the background ever appear to overtake the letters making them hard to read?

0 1 2 3

13. When reading, did you ever have to move, or continually blink to avoid glare which seems to come from the background?

0 1 2 3

14. did you have difficulty seeing more than one or two words on a line in focus?

0 1 2 3

15. did you have difficulty reading the words on a page because they begin to flicker or shimmer?

0 1 2 3

16. did you have to move your eyes around the page, or continually blink or rub your eyes to keep the text easy to see when you were reading?

0 1 2 3

17. did the white background behind the text appear to move, flicker, or shimmer making the letters hard to read?

0 1 2 3

18. When reading on the computer screen, did the words or letters in the words ever appear to spread apart?

0 1 2 3

19. As a result of any of the above difficulties, did you find reading on the computer screen a slow task?

0 1 2 3

7.2 Appendix D: Information sheet and consent form

Glare Evaluation Study

INFORMATION SHEET

GU Ref No: 2017/356

Who is conducting the research

Senior investigators

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Why is the research being conducted?

This is a PhD project which is conducted by Griffith University. This research focuses on daylighting and glare evaluation models for office buildings to provide a tool for the designer to design a glare free daylight innovation for offices.

What you will be asked to do

You will be asked to answer questions in the questionnaire sheet, which are about perceived lighting conditions in the workplace. Afterwards, you will be asked to wear lightweight eye tracking glasses, and to perform some typical office tasks. The eye tracking glasses will detect the direction of your gaze.

The basis by which participants will be selected or screened

The participants will be students, academic staff, managerial staff, technical staff and/or administration staff of Griffith University. An invitation letter will be sent to Griffith University staff and students via e-mail. When volunteers initially express a verbal interest to the researcher(s), they will be directly given a copy of the informed consent materials to receive information. If they are still interested, a schedule will be arranged for their participation.

The number of participants varies between 30 to 60 participants for each case study. Participants are required to fill in the questionnaire as a part of office tasks while they are wearing the eye-tracking glasses. The study will take about 45 minutes including introduction, calibration and the survey itself. Volunteers who are long- sighted and wear prescription glasses (who have difficulty in seeing objects close to them) will not be eligible to take part in this research.

The expected benefits of the research

The aim of this thesis is to incorporate user behaviour, including gaze direction and view angle, into a glare analysis for green buildings with a high proportion of glazing in their facade. The result would be an optimised hot-desking, open plan layout which provides satisfactory results in terms of visual comfort and view for green buildings.

Risks to you

There is negligible foreseeable risk associated with participation in this research.

Your confidentiality

The data is collected in anonymous form and will be presented in research publications in a way that will not identify you or allow you to be identified by third parties. Participants will be sent copies of the results (via e-mail) to access a convenient, plain language summary of results and confirm the accuracy of the recorded materials.

Your participation is voluntary

Participation in this research is voluntary and you are free to withdraw from the study at any time.

Questions / further information

As required by Griffith University, all research data (questionnaire responses, eye tracking data and analysis) will be retained in a locked cabinet and/or a password protected electronic file at Griffith University for a period of five years before being destroyed.

If you have any question(s) or you need further information about the project, please do not hesitate to contact me.

Zahra Hamedani (zahra.hamedani@griffithuni.edu.au)

Contact phone 0472 690 315

The ethical conduct of this research

If you have any concerns or complaints about the ethical conduct of the research project you should contact the Manager, Research Ethics on 3735 4375 or research-ethics@griffith.edu.au.

Privacy Statement

The conduct of this research involves the collection, access and/or use of your identified personal information. The information collected is confidential and will not be disclosed to third parties without your consent, except to meet government, legal or other regulatory authority requirements. A de-identified copy of this data may be used for other research purposes. However, your anonymity will at all times be safeguarded. For further information consult the University's Privacy Plan at http://www.griffith.edu.au/about-griffith/plans-publications/griffith-university-privacy-plan or telephone (07) 3735 4375."

Glare Evaluation Study

CONSENT FORM

GU Ref No: 2017/356

Senior investigators	**Dr Henry Skates** (h.skates@griffith.edu.au) **Dr Ruwan Fernando** (r.fernando@griffith.edu.au) **Dr Trevor Hine** (t.hine@griffith.edu.au)
Research Team	**Zahra Hamedani** **School of Engineering and Built Environment** zahra.hamedani@griffithuni.edu.au Contact phone **0472 690 315**

By signing below, I confirm that I have read and understood the information package and in particular have noted that:

- I understand that my involvement in this research will include giving information about glare perception.
- I have had any questions answered to my satisfaction;
- I understand the risks involved;
- I understand that there will be no direct benefit to me from my participation in this research;
- I understand that my participation in this research is voluntary;
- I understand that if I have any additional questions, I can contact the research team;
- I understand that I am free to withdraw at any time, without explanation or penalty;
- I understand that my name and other personal information that could identify me will be removed or de-identified in publications or presentations resulting from this research;
- I understand that I can contact the Manager, Research Ethics, at Griffith University Human Research Ethics Committee on 3735 4375 (or research-ethics@griffith.edu.au) if I have any concerns about the ethical conduct of the project; and
- I agree to participate in the project.

Name	
E-mail	
Signature	
Date	