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

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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.

Keywords: Lighting, Discomfort glare, Ocular behaviour, Objective assessment.

1 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 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' were searched thoroughly. 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 [1] based on the aforementioned assessment criteria. Research findings regarding each physiological factor are illustrated in Table [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.

3 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]. To categorize glare in according to impact visual function and comfort, it can be defined as two main types of 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 varies 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. At the beginning of glare research, background luminance was interpreted as the adaptation level. Since glare sources with a large area in the field of view can affect visual adaptation, some indices utilized vertical illuminance at the eye level as an estimator for 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/m²); 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_s represents is the luminance of the background (cd/m²); ω_s represents the solid angle of the window; and L_{win} represents the luminance of the window (cd/m²). 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].

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

Where L_{si} represents the luminance of the glare source(s) (cd/m²); ω_{si} represents the solid angle of the glare source(s); L_b represents the adaptation luminance (luminance of the background) (cd/m²); 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 is a compensation for DGI limitation [60].

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

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/m²]; 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’ in terms of their influence probability. 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 contend 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.

4 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 via the III oculomotor cranial 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].

Fig. 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 Fig. 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 $V(\lambda)$. The same function has been defined for the human eye under dark-adapted conditions (scotopic vision), as $V'(\lambda)$. 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 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). 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 daylight space, smaller changes in the pupil diameter would be observed. Thus, the experiment characteristics are of paramount importance when comparing the results.

Table 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
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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.

1

2 4.1 Physiological measures:

3 According to the studies included in this research, the physiological responses investigated in lighting research
4 are pupil size, eye movement, gaze direction, blink rate, and the degree of eye-opening. Some of these studies
5 merely considered light-induced physiological responses, whereas others investigated a range of responses and
6 examined the correlation of each response with subjective evaluations or existing glare metrics. Pupillary
7 reflexes are the most studied factor among light-induced physiological responses. Afterwards, eye movements
8 and gaze direction ranked second. Table 2 indicates the research outcomes concerning each of the
9 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

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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> An inverse correlation was determined between visual discomfort ratings and pupil diameters.
	Lin et al. (2015) [81]	Artificial	Relative Pupil size: Eye-tracking glasses	<ul style="list-style-type: none"> Subjective evaluation of glare discomfort was highly correlated with pupil constriction. Severe glare discomfort caused larger pupil constriction.
	Garretón et al. (2016) [83]	Natural	Pupil diameter: Eye-tracker	<ul style="list-style-type: none"> Pupil size correlated with vertical illuminance at the eye and glare indices.
	Scheir et al. (2017) [85]	Artificial	Pupil diameter	<ul style="list-style-type: none"> 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)	<ul style="list-style-type: none"> 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. Smaller glare source diameter saws decreased discomfort. 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	<ul style="list-style-type: none"> 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)	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Gaze dynamics are highly task dependent. Gaze directions tended toward lower luminance levels which in turn led to

	Garretón et al. (2016) [83]	Natural	The spatial frequency of gaze direction: Eye-tracker	<p>smaller illuminance at the eye.</p> <ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	Garretón et al. (2015, 2016) [83]	Natural	Degree of eye-opening (DEO): Video, Image processing	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • DEO exhibited better diagnostic performance than DGI, DGP, or Ev. • The usability of DEO required to be improved.

4.1.1 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.

Table 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	<ul style="list-style-type: none"> There is a chance of multiple specular and diffuse components due to the uncontrolled ambient light.
		Infrared spectrum imaging	<ul style="list-style-type: none"> Eliminates uncontrolled specular reflection. During the daytime, it is not suitable for outdoors due to the ambient infrared illumination.
	Intensity		<ul style="list-style-type: none"> In order to separate eye contours from darkness, the intensity of light should be sufficient according to the sensitivity of the camera.
Camera	Sensitivity		<ul style="list-style-type: none"> Camera's sensitivity needs to be close to the infrared region of the electromagnetic spectrum.
	Sampling rate		<ul style="list-style-type: none"> The temporal resolution should be selected based on the pupil characteristics that are intended to be studied.

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].

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 (Fig. 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].

Fig. 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 were 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 are 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 is 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. Fig. 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].

Fig. 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].

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

$$E_{ret} \sim L \cdot \left(\frac{D}{2}\right)^2 \cdot \pi \quad (5)$$

Where D is the pupil diameter (mm), L_s is the average stimulus luminance (cd/m²) and α is the stimulus field size (deg²).

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:

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

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 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. Fig. 4 depicts the correlation of the proposed model with subjective glare evaluations [85].

Fig. 4. The visual discomfort model against the subjective assessment for all stimuli [85].

4.1.2 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.

$$ODR = \frac{\text{Integrated EMG power spectrum with glare source}}{\text{Integrated EMG power spectrum without glare source}} - 1 \quad (7)$$

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)).

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

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 (Fig. 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].

Fig. 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 Fig. 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].

Fig. 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].

4.1.3 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. Beyond eye gaze position, Doughty suggested lighting conditions present during measuring SEBR should be considered primarily glare produced by reflected light sources. 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. Variation under downward gaze was insignificant but under upward gaze, SEBR was 13.0 ± 1.1 with a coefficient of variation (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 and non-cognitive 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, the focus of VDs was around the task area (Fig. 7). In other words, the view direction was attributed to lighting conditions and the type of task they were doing [103].

Fig.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 (Fig. 8) [83].

Fig. 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 (Fig. 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].

Fig. 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].

4.2 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.

4.3 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's [118] and Conlon's [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.

5 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 its 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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Highlights:

- A literature review of lighting research related to light-induced physiological responses
- The effect of visual discomfort on user physiological responses
- A review of the main research outcome regarding each individual light-induced physiological response