Revista Hábitat Sustentable Vol. 14, N°. 1. ISSN 0719 - 0700 / Págs. 08 -21
https://doi.org/10.22320/07190700.2024.14.01.01

Recibido 23/11/2023
Aceptado 17/04/2024

METHODOLOGICAL PROPOSAL FOR MEASURING GLARE IN INDOOR ENVIRONMENTS USING FOUR EYE OPENNESS RANGES

PROPUESTA METODOLÓGICA PARA MEDIR EL DESLUMBRAMIENTO EN AMBIENTES INTERIORES MEDIANTE CUATRO RANGOS DE APERTURA OCULAR

PROPOSTA METODOLÓGICA PARA MEDIR O ENCANDEAMENTO EM AMBIENTES INTERNOS UTILIZANDO QUATRO GAMAS DE ABERTURA OCULA

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RESUMEN

El desarrollo de modelos de deslumbramiento contribuye a una mejor evaluación del confort visual de los ocupantes en espacios interiores. Los indicadores oculares pueden ser una herramienta adecuada para evaluar el deslumbramiento de manera dinámica en climas soleados para evitar las molestias visuales. En este trabajo, se mide el grado de apertura ocular y se propone su medición en cuatro rangos (oclusión, semi-oclusión, semi-apertura y apertura) por medio de un eye-tracker. El objetivo de este trabajo fue evaluar de qué manera se relaciona el grado de apertura ocular con los niveles de iluminancia vertical (Ev) inferiores a 2484 lx (valor donde aparece la sensación de deslumbramiento molesto), así como determinar si la percepción subjetiva del deslumbramiento de las personas corresponde a los rangos de deslumbramientos propuestos por Wienold (2019). Estos parámetros se midieron en tres condiciones de deslumbramiento percibido (notable, perturbador e intolerable). Los resultados mostraron que la medición de apertura ocular en cuatro rangos, tiene el potencial de cuantificar de manera objetiva y dinámica la sensación de deslumbramiento en todos los escenarios evaluados y en cuanto a su relación con los valores de Ev de referencia, los valores percibidos como notable y perturbador, fueron inferiores a los valores de referencia, mientras que los valores percibidos como intolerable fueron coincidentes.

Palabras clave
deslumbramiento, confort visual, indicadores oculares

ABSTRACT

The development of glare models contributes to a better assessment of occupant's visual comfort in indoor spaces. Eye indicators can dynamically assess glare in sunny climates to avoid visual discomfort. In this work, an eye tracker measures the degree of eye openness in four ranges (occlusion, semi-occlusion, semi-openness, and openness). This work aimed to evaluate how the degree of eye openness is related to vertical illuminance levels (Ev) below 2484 lx (value where the sensation of bothersome glare appears), as well as to determine whether people's subjective perception of glare follows the glare ranges proposed by Wienold (2019). These parameters were measured in three conditions of perceived glare (noticeable, disturbing, and intolerable). The results showed that the measurement of eye openness in four ranges has the potential to objectively and dynamically quantify the sensation of glare in all the scenarios evaluated. Regarding its relationship with the reference Ev values, the values perceived as noticeable and disturbing were lower than the reference values, while the values perceived as intolerable coincided.

Keywords
glare, visual comfort, eye indicators

RESUMO

O desenvolvimento de modelos de ofuscamento contribui para uma melhor avaliação do conforto visual dos ocupantes de ambientes internos. Os indicadores oculares podem ser uma ferramenta adequada para avaliar o ofuscamento de forma dinâmica em climas ensolarados para evitar o desconforto visual. Neste trabalho, o grau de abertura ocular é medido e proposto para ser medido em quatro faixas (oclusão, semi-oclusão, semi-abertura e abertura) por meio de um rastreador ocular. O objetivo deste trabalho foi avaliar como o grau de abertura ocular está relacionado aos níveis de iluminância vertical (Ev) abaixo de 2484 lx (valor em que aparece a sensação de brilho incômodo), bem como determinar se a percepção subjetiva de brilho das pessoas corresponde às faixas de brilho propostas por Wienold (2019). Esses parâmetros foram medidos em três condições de percepção de ofuscamento (perceptível, incômodo e intolerável). Os resultados mostraram que a medição da abertura ocular em quatro faixas tem o potencial de quantificar de forma objetiva e dinâmica a sensação de ofuscamento em todos os cenários avaliados e, em termos de sua relação com os valores de Ev de referência, os valores percebidos como perceptíveis e incômodos foram inferiores aos valores de referência, enquanto os valores percebidos como intoleráveis foram coincidentes.

Palavras-chave:
ofuscamento, conforto visual, indicadores oculares

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INTRODUCTION

It is vital to approach daylighting performance in buildings from two perspectives: energy efficiency and the human factor. Regarding the human factor, a pleasant outdoor view and controlled access to daylight are crucial factors for people's visual comfort (Aries et al., 2010). However, these benefits can be obtained only if the window is accompanied by a suitable solar control element to regulate the level of glare. Glare represents one of the most significant challenges in the search for optimal visual comfort and is a fundamental barrier to the efficient use of daylight in buildings (Shin et al., 2012).

Glare is a sensation produced by luminance within the visual field above the luminance to which the visual system is adapted (DiLaura, 2010). Questionnaires can measure subjective glare experienced by people, where Osterhaus and Bailey's four-point scale is one of the most widely used options. Its denomination uses the terms imperceptible, noticeable, disturbing, and intolerable. On the other hand, some glare models describe the subjective magnitude of glare experienced by observers (CIE, 2020). These models consist of photometric measurements adjusted to people's responses, obtained, for example, from the previously mentioned Osterhaus and Bailey 4-point scale. A peculiarity of these models is that they consider the gaze's direction at a fixed point (Hopkinson, 1950). This is a significant limitation of the models since the direction of the gaze is dynamic and forces the eye to readapt to the different photometric conditions of the environment (Kokoschka & Haubner, 1985). Therefore, it is challenging to evaluate the occupants' effective visual comfort from fixed measurements in a workplace (Johra et al., 2021).

The most widely used models are the DGP (Wienold & Christoffersen, 2006) and the Ev metric (vertical illuminance at eye level) (Wienold et al., 2019). However, the applicability of the DGP and Ev metrics is limited by the dataset's scope, as they cannot represent the entire spectrum of lighting scenarios encountered in real-world situations (Quek et al., 2021). There are also many psychological aspects, such as emotional state, level of sensitivity to glare, interpretation of questionnaires and scales, and physiological ones, such as visual correction, ocular pigmentation, and chronotype, that could influence glare sensation and have not yet been well identified. Many of them are described in detail in the literature review article by Pierson et al. (2017).

A recent literature review of people's physiological response to visual discomfort conditions in office spaces showed many things that needed more consistency in the existing models. It also highlighted the need for a more objective method to derive glare indices, such as people's physiological responses (Hamedani et al., 2019). The physiological response recorded using an eye tracker can contribute to a dynamic evaluation of the gaze, considering the setting's light fluctuations (Sarey Khanie, 2015).

The nature of these physiological responses is found in the human body's autonomic nervous system, which, through different reflexes, tries to reduce the fluctuations of the surroundings, such as excess light, and keep the body physiologically stable (Boyce, 2003). Some of the visual adaptation mechanisms have been extensively studied, but those that still require further statistical validation are:

- Degree of eye opening: A first study showed that excess light in the eye area produced changes in the activities of the facial muscles around the eye (Berman et al., 1993). Subsequently, this indicator showed a high correlation with the glare perceived by people under disturbing and intolerable glare (Yamin Garretón et al., 2015; Yamin Garretón et al., 2016).
- Frequency and amplitude of spontaneous eye blinking: Spontaneous blinking can be affected by a source of glare, especially if subjects look slightly upwards (Doughty, 2014). On the other hand, other studies have shown an increase in blinking frequency in office work with the use of VDU (Visual Display Units) (Yamin Garretón et al., 2016).
- Relative pupil size: This indicator showed a medium and significant correlation with the subjective evaluation of people against glare (Lin et al., 2015) and is considered the best predictor of "disturbing and intolerable" glare (Hamedani et al., 2020b).
- Eye movements: Several studies have shown a significant correlation between the feeling of glare and people's responses (Hamedani et al., 2020a; Lin et al., 2015; Sarey Khanie et al., 2013; Yamin Garretón et al., 2016).

These eye indicators initially proved an adequate tool for evaluating glare in sunny climates. However, additional studies are required to validate their use and extend their application since they were studied in glare situations from 3000 lx to 11000 lx of vertical illuminance at eye level (Yamin Garretón et al., 2015). These indicators have not yet been tested in situations of lower vertical illuminance, frequently found in office spaces. A significant value to detect is the threshold value between imperceptible and

Table 1. Three ranges of glare. Source: Preparation by the authors.

Metric	Threshold values ('cut-off')		
	Imperceptible-noticeable BIN	Noticeable-Disturbing BNP	Disturbing-Intolerable BPI
Ev	2484 lx	3359 lx	4384 lx

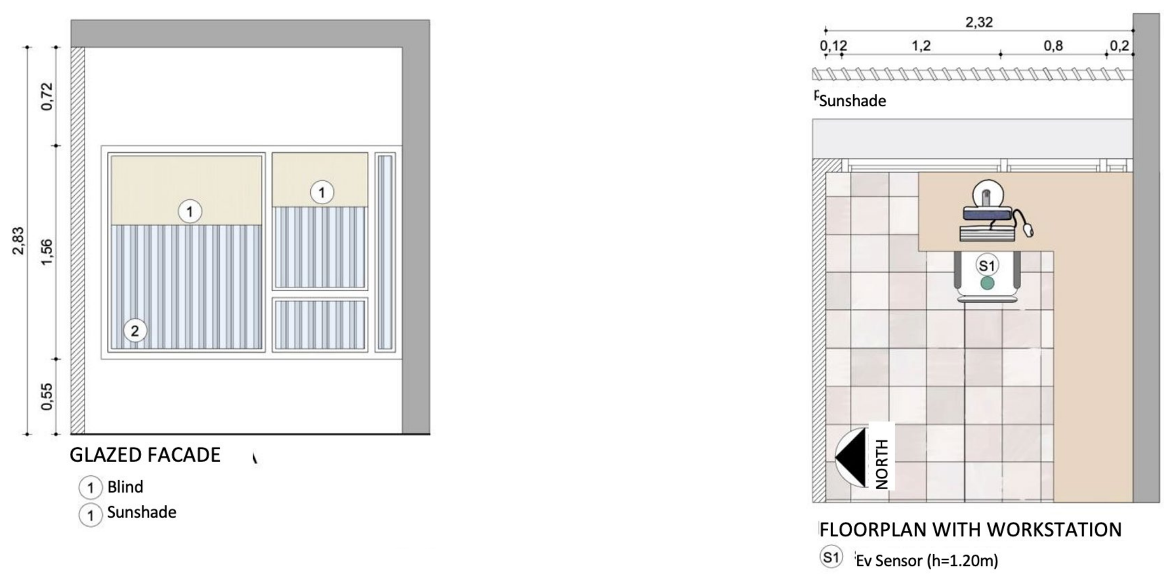

Figure 1. On the glazed facade (top), the two types of control elements used and the window's dimensions are observed. On the ground floor, the workstation and the location of the vertical illuminance sensor are seen. Source: Preparation by the authors.

noticeable glare of 2484 lx established by Wienold et al. (2019). This threshold value determines the boundary between visual comfort and discomfort. This value, also called BCD (borderline comfort discomfort), has its origin in the experiments of Luckiesh and Guth (1949).

The following work proposes using eye opening from an objective and dynamic perspective to quantify the glare using a novel methodology. This indicator will be measured using four opening ranges (occlusion, semi-occlusion, semi-opening, and opening). The objective of validating these eye indicators is to:

- Determine how the degree of eye opening is related to vertical illuminance levels below 2484 lx (the value where discomfort due to glare appears) and whether people's subjective perception of glare follows the Ev ranges proposed by Wienold et al. (2019).
- A more accurate assessment of glare, which considers the dynamism of vision and detects the occurrence of uncomfortable glare in indoor spaces such as offices, can prevent people from blocking windows due to the potential risk of glare. A window with access to controlled daylighting and without glare sources provides the benefits of an outside view, improving cognitive function (Sharam et al., 2023) and the operation of the circadian system (Mathew et al., 2023), among other vital aspects mentioned in Abd-Alhamid et al. (2023).

METHODOLOGY

The research uses an eye tracker to measure eye behavior through eye opening in four ranges (occlusion/semi-occlusion/semi-opening, and opening). These parameters were measured in three lighting conditions: NG (noticeable glare), DG (disturbing glare), and IG (intolerable glare), considering the subjective sensation of glare. The participants defined these by the time they could tolerate each situation with glare (Osterhaus, 1996;

Revista Hábitat Sustentable Vol. 14, N°. 1. ISSN 0719 - 0700 / Págs. 08 -21
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Figure 2. The six figures show an example of the three glare conditions generated by users when adjusting the roller blinds and monitor position on the desk. Only the right blind was adjusted. A photo was taken with a fisheye lens with a viewing angle of 180° to have a complete view of the surroundings. Source: Preparation by the authors.

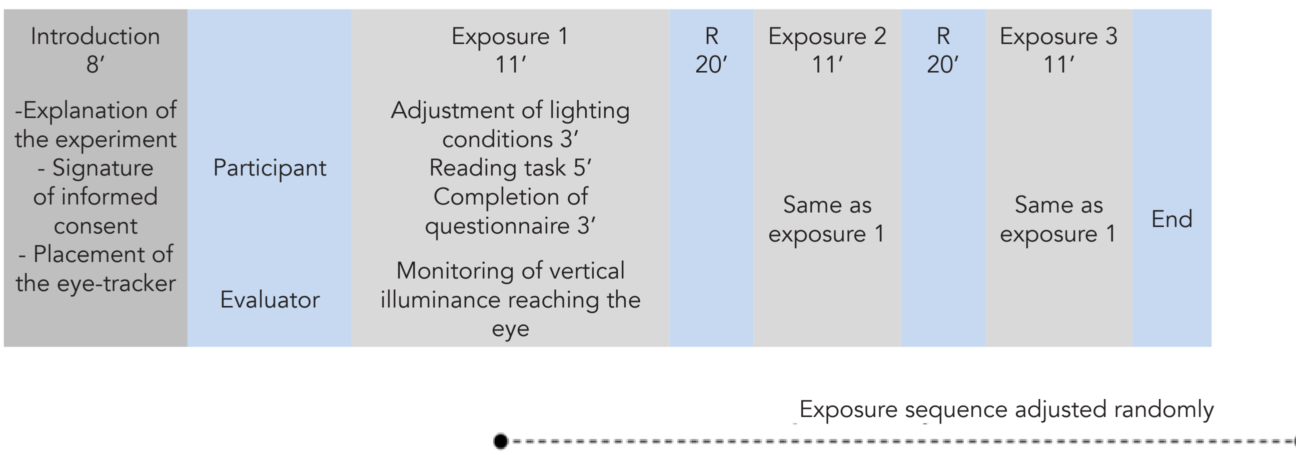

Figure 3. The sequence of activities in the experiment. R (rest time). Source: Preparation by the authors.

Osterhaus & Bailey, 1992). The detailed description can be found in the section: Adjustment of lighting conditions.

Nine participants were evaluated in these three lighting conditions. Each had to perform a reading task in an office at the CCT-Conicet Scientific and Technological Center, Mendoza. The measurements were made from approximately 9:00 to 10:00 a.m. on the spring equinox in September (start time: solar altitude 13.06° and azimuth 108) and October (start time: solar altitude 22°, azimuth 100) 2023. The measurements were made on sunny days. The artificial lighting was turned off during the experiment, and only daylighting from the window was used. The windows are facing east and are 2.00 x 1.56 m in size, with indoor roller shades and outdoor vertical sunshades (Figure 1). The workstation's layout allowed a front, perpendicular, and/or parallel view of the window (Figure 2). The experimental procedure is detailed in depth in the section - Experimental Sequence.

The vertical illuminance reaching the eye (ev) was monitored. This indicator is suitable only when the amount of light reaching the eyes is high and exceeds the effect produced by the contrast between the source's luminance and the background (Wienold et al., 2019), as in this experiment. The objective was to identify how the degree of eye opening is related to vertical illuminance levels below 2484 lx, as well as to determine whether people's subjective perception of glare coincides with the ranges of glare proposed by Wienold et al. (2019) indicated in Table 1.

To participate in the experiment, the nine study participants (7 women and 2 men) had to have specific characteristics, such as normal vision and good health. The ages of the participants were: mean=35, SD=6.39, min=23, max=40. This sample incorporates nine people selected as experimental subjects from a previous study with a larger sample size (Yamin Garretón et al., 2015). Based on epidemiological statistical tests of specificity and sensitivity, the participants were classified as experienced subjects and selected for the trial. Sensitivity is the probability that the person identifies glare as a condition that it effectively is, and specificity is the probability that the person

Table 2. Glare scale used. Source: Preparation by the authors.

Name	Question	Answer
Binary	Are you experiencing any discomfort due to glare at the moment?	Yes No
Osterhaus-Bailey Scale	At this point, how would you describe the level of glare in your field of vision?	Imperceptible Noticeable Disturbing Intolerable

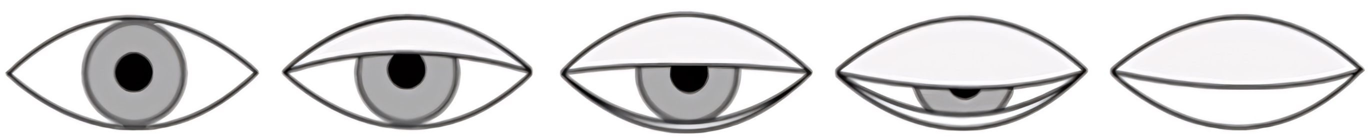

Figure 4. Different percentages of eye opening. Source: Preparation by the authors.

identifies as non-glare, a light condition that is not as such. The relationship between sensitivity and specificity provides diagnostic accuracy. The stepwise calculation of this methodology can be found in Rodriguez et al. (2017). This methodology of working with a small but experienced group has been validated in some glare works (Hopkinson, 1957; Suk et al., 2016).

EXPERIMENTAL SEQUENCE

The sequence of activities performed by the participants and evaluators during the experiment can be seen in Figure 3.

Adjustment of lighting conditions: As shown in Figure 3, the participants (A) had to accommodate their workplace by using the roller blinds, raising or lowering them, and positioning the screen to generate different directions of vision concerning the window. 0° (direct to the window), 90° (parallel to the window), and 45° (perpendicular to the window) view.

By modifying their workspace, the participants were able to experience the three lighting conditions: noticeable, disturbing, and intolerable. Previously, they were provided with a definition of the three conditions based on the time in which they could tolerate each glare situation (Osterhaus, 1996; Osterhaus & Bailey, 1992).

1. Noticeable Glare: This is the point where the glare is noticed for the first time, or there is a slight experience of discomfort, but it can be tolerated for several hours.

Table 3. Opening ranges. Source: Preparation by the authors.

Percentage of opening	Reference name
0-25%	Occlusion
25-50%	Semi-occlusion
50-75%	Semi-opening
75-100%	Opening

2. Disturbing glare: This was defined as an experience of discomfort where glare can be tolerated for 15 to 30 minutes and requires a change of lighting conditions.
3. Intolerable Glare: The subjects cannot stand the glare; they have a tipping point requiring immediate lighting changes.

Reading task: As shown in Figure 3 below, the participants (B) performed a reading task with their eyes fixed on the screen. The text was projected on its upper margin, and the person had to scroll it with the mouse. However, not their vision since directing the vision downwards implies that the eyelids close, lubricating the eye and reducing the appearance of blinking. This task was performed to obtain a cleaner signal with the vision as fixed as possible on the screen. People read the text on the screen in 5 minutes, enough time for the eye to adapt to the specific light conditions.

Filling out the questionnaire: At the end of the task, as shown in Figure 3, the participants (C) filled out a questionnaire for each of the three exposures (Table 2). The order of the exposures was randomized to avoid order bias. The resting time between each exposure was 20 minutes, necessary for the participants' eyes to readjust and prepare for the following exposure.

Vertical illuminance monitoring: As seen in Figure 3, the evaluators (D) monitored and recorded the vertical illuminance at eye level at the beginning and end of the reading task performed by the participants; to corroborate that, the vertical illuminance value did not vary significantly during the completion of the task. Scenarios in which the illuminance value did not differ significantly between the first and second measurements were considered valid. The average value of the two recorded points was reported. The illuminance sensor consisted of an "LMT Lux 2 lux meter," measuring from 0.1 to 200000 lx, and a calibration date in 2023. This sensor was mounted on a tripod and located at the participant's eye level in the direction of the task at a 45° angle.

EYE REGISTRATION

The degree of muscle contraction around the eyes that reduces the incoming light was measured based on the Tsao model (Tsao, 2008) defined by equation (1):

$$DEO = L/L_{max} \quad (1)$$

Where DEO is the eye opening percentage, L is the eye opening level in the presence of a source of glare, and L max is the maximum height of the eye when it is fully open. A threshold value was established to define whether the eye was open or closed: if the ratio was less than 0.2, the eye was considered closed. Otherwise, it was defined as open (Figure 4).

This work proposes classifying the eye openings into four equally distributed ranges (Table 3) to calculate the time when the eyes were in said opening.

DESCRIPTION OF THE EYE-TRACKER

The eye tracker was explicitly designed for this study (Figure 5). It consists of a helmet on which a high-quality webcam (720p quality, 1/4" lens size, lens viewing angle: 68.6°) is mounted using an articulated arm that records the image of the participants' faces. The images are taken at 30 frames per second, showing a fixed portion of the face.

The analysis of the recorded images consisted first of performing facial recognition of the individuals using the MediaPipe Face Landmark Detection model

Figure 5. Eye-tracker in use. Source: Preparation by the authors.

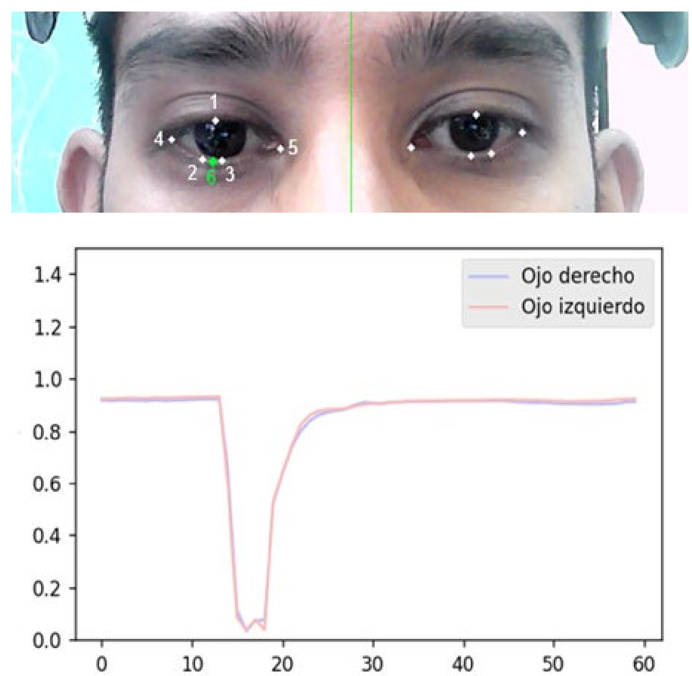

Figure 6. Camera and script in operation. Left: video capturing the 10 points of interest detected in white. Right: Eye opening reading of the last 60 frames. Source: Preparation by the authors.

Table 4. Vertical illuminance (Ev) measurements recorded in the three scenarios evaluated. Source: Preparation by the authors.

Ev	NG	DG	IG
Min	1050 lx	1100 lx	3600 lx
Max	2000 lx	3800 lx	12000 lx
Average	1496.11 lx	2411.11 lx	6966.66 lx
SD	353.07 lx	706.12 lx	2723.96 lx

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https://doi.org/10.22320/07190700.2024.14.01.01

Table 5. Eye aperture values (mean, median, and SD) for the sensation of noticeable glare (NG). Source: Preparation by the authors.

NG	Opening 0-1		
	mean	median	SD
Participant 1	0.92	0.94	0.08
Participant 2	0.83	0.86	0.12
Participant 3	0.86	0.91	0.16
Participante4	0.71	0.76	0.18
Participant 5	0.87	0.88	0.08
Participant 6	0.80	0.84	0.15
Participant 7	0.78	0.80	0.10
Participant 8	0.79	0.80	0.08
Participant 9	0.84	0.84	0.11
Median total	0.82	0.85	0.12
SD total	0.06	0.06	0.04

Table 6. Eye opening values (mean, median, and SD) for the sensation of disturbing glare (DG). Source: Preparation by the authors.

DG	Opening 0-1		
	mean	median	SD
Participant 1	0.85	0.86	0.11
Participant 2	0.80	0.82	0.10
Participant 3	0.75	0.79	0.13
Participante4	0.75	0.81	0.18
Participant 5	0.89	0.90	0.07
Participant 6	0.72	0.75	0.14
Participant 7	0.81	0.82	0.09
Participant 8	0.89	0.90	0.07
Participant 9	0.78	0.79	0.09
Median total	0.80	0.82	0.10
SD total	0.06	0.05	0.04

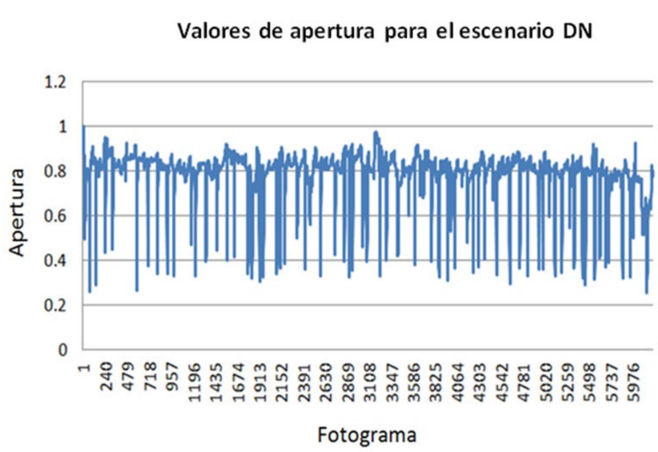

Figure 7. Participant 2's eye opening values for the NG scenario over time (30 frames per second). Source: Preparation by the authors.

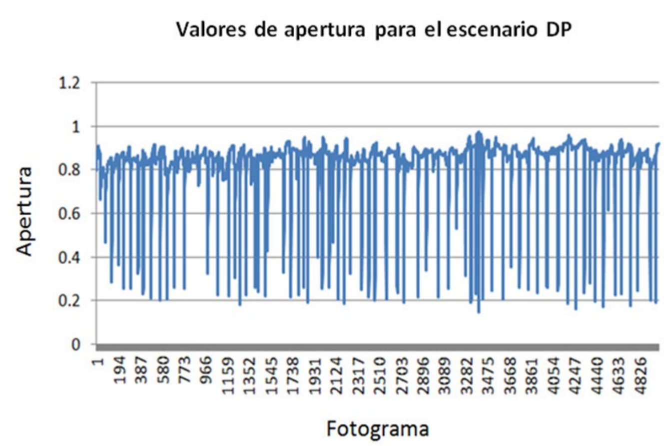

Figure 8. Participant 2's eye opening values for the DG scenario over time (30 frames per second). Source: Preparation by the authors.

(Bazarevsky et al., 2019; Yan & Grishchenko, 2022) using 478 facial points, of which only ten were of interest, those for the eyes. Then, through a script written in Python, the coordinates of the points of interest were calculated. The eye opening was calculated from the distance between two fundamental points, point 1 for the upper eyelid and point 6 for the lower eyelid, which is the average distance between points 2 and 3 (Figure 6. Left).

RESULTS AND DISCUSSION

Table 4 shows Ev's minimum, maximum, mean, and standard deviation (Sd) values recorded under the three conditions.

Table 4 shows the Ev measurements recorded during the visual task performance, which refer to the perceived glare. The average Ev values show that in the scenarios with glare perceived as noticeable and disturbing, the Ev values were lower than the reference values of Table 1. However, the glare values perceived as intolerable coincided with the reference values of Table 1.

On the other hand, the level of coincidence of the people's answers with the reference values was calculated. It was observed that, for the NG scenario, only 2 of the 9 responses coincided with the reference values proposed by Wienold (2019); for the DG scenario, 3 of the 9 responses coincided with the reference values. For the IG scenario, 9 of the 9 responses coincided with the reference values.

From the average Ev values and the level of coincidence of the subjective responses with the values of Table 1, it can be determined that, in the scenarios of glare perceived as noticeable and disturbing, the Ev values did not coincide with the reference values of Table 1. These differences may be due to other factors besides Ev, such as the presence of unwanted glare or reflections, which may have affected the sensation of glare and were not evaluated in this research.

OPENING VALUES

Tables 5, 6, and 7 show the eye opening values (mean, median, and standard deviation "SD") of the nine participants in the three lighting conditions. At the end of each table, you can also see the total mean (mean_tot) and the total standard deviation (SD_tot) to obtain an opening value per scenario. The frequency of openings in Participant 2's three conditions is shown on the right of each table (Figure 7, Figure 8, and Figure 9).

From the analysis of the total mean and the total SD of the opening values of the three scenarios, it was observed that the opening value was slightly higher (m=0.82) in the NG scenario with lower light levels than in the other two scenarios. This value coincides with the opening range (0.75-1). In the DG scenario with intermediate glare values, the average opening value was slightly lower (0.80) but coincided with a total opening range, so the differences between the NG and DG scenarios are not obvious. Finally, in the IG scenario, the opening value was lower (m=0.73), coinciding with a semi-opening range (0.5-0.75). In this scenario, with higher glare levels, the reduction of the eye opening is evidenced.

Although these data show a general trend that the opening values decrease with increasing light levels, that is, the higher the level of glare, the lower the opening level, this trend is only found in some participants. For example, Participant 8 had a higher average eye opening in the DG scenario (0.89) than in the NG scenario (0.79). In the case of Participant 6, a higher average eye opening value was recorded in the IG scenario (0.82) than in the other two scenarios (0.80 and 0.72).

In the NG (Table 5, participant 4) and DG (Table 6, participant 6) scenarios, lower opening values (eye in semi-opening) are also observed compared to the rest of the participants (eye in opening). This shows

Table 7. Eye opening values (mean, median, and SD) for the Intolerable glare (IG) sensation.Source: Preparation by the authors.

IG	opening 0-1		
	mean	median	SD
Participant 1	0.75	0.76	0.07
Participant 2	0.72	0.74	0.09
Participant 3	0.60	0.60	0.09
Participante4	0.69	0.74	0.16
Participant 5	0.73	0.73	0.08
Participant 6	0.82	0.86	0.14
Participant 7	0.78	0.78	0.08
Participant 8	0.72	0.73	0.11
Participant 9	0.75	0.75	0.11
Median total	0.73	0.75	0.11
SD total	0.06	0.07	0.03

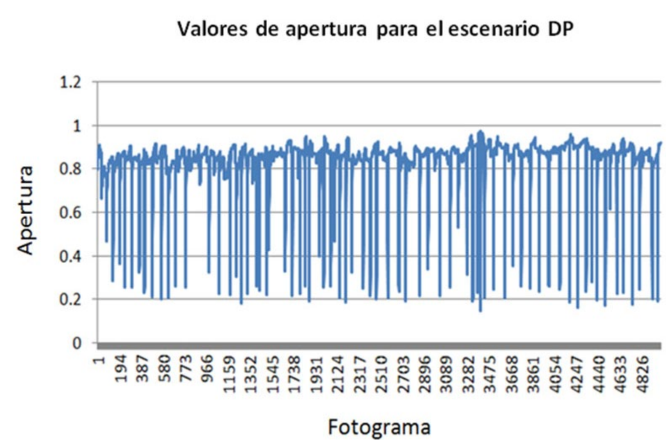

Figure 9. Participant 2's eye opening values for the IG scenario over time (30 frames per second). Source: Preparation by the authors.

Table 8. Wilcoxon Z-tests for comparison of means (non-parametric tests). Source: Preparation by the authors.

	Z-Wilcoxon	Sig. (bilateral)
NG-DG	-0.830	0.407
NG-IG	-2.313	0.021
DG-IG	-2.018	0.044

Table 9. Percentage of time in the 4 opening ranges for the three conditions of perceived glare. The total time for each situation was 100%. Source: Preparation by the authors.

	NG				DG				IG			
	0-0.25	0.25-0.50	0.50-0.75	0.75-1	0-0.25	0.25-0.50	0.50-0.75	0.75-1	0-0.25	0.25-0.50	0.50-0.75	0.75-1
P1	1.8%	2.7%	5.1%	90.4%	1.5%	2.8%	12.4%	83.3%	1.1%	4.0%	38.0%	54.1%
P 2	1.6%	1.9%	3.7%	92.8%	0.2%	2.7%	15.1%	81.9%	0.6%	4.0%	49.8%	45.6%
P 3	1.2%	4.8%	4.4%	89.7%	1.1%	4.4%	17.0%	77.5%	0.0%	13.7%	78.8%	7.5%
P 4	5.0%	4.1%	5.6%	85.2%	5.1%	5.5%	16.8%	72.5%	5.6%	5.0%	39.0%	50.5%
P 5	0.8%	0.4%	1.2%	97.6%	0.2%	0.4%	7.7%	91.7%	0.2%	1.6%	46.1%	52.0%
P 6	1.8%	2.8%	6.7%	88.7%	1.6%	3.4%	14.2%	80.9%	1.6%	4.0%	7.1%	87.3%
P 7	1.2%	0.8%	2.8%	95.3%	0.8%	0.8%	1.4%	97.0%	0.4%	1.4%	12.5%	85.7%
P 8	1.0%	1.0%	6.2%	91.9%	0.2%	0.8%	17.2%	81.8%	0.8%	2.9%	44.3%	52.0%
P 9	1.0%	2.9%	5.3%	90.9%	1.8%	1.8%	14.0%	82.4%	1.0%	4.0%	41.3%	53.8%
Me	1.7%	2.4%	4.5%	91.4%	1.4%	2.5%	12.9%	83.2%	1.2%	4.5%	39.7%	54.3%
	100%				100%				100%			
De	1.3	1.4	1.7	3.6	1.5	1.7	5.2	7.2	1.6	3.6	20.9	23.3

Table 10. Wilcoxon tests for comparison of means, bilateral p-significance. Source: Preparation by the authors.

	Occlusion		Semi-occlusion		Semi-opening		Opening	
	Z	p	Z	p	Z	p	Z	p
NG - DG	-0,984	0.325	-0.254	0.799	-2.549	0.011	-2.192	0.028
NG - IG	-1,544	0.123	-2.673	0.008	-2.666	0.008	-2.666	0.08
DG - IG	-0,511	0.610	-2.442	0.015	-1.599	0.110	-1.599	0.110

that the average opening values (mean) are not a sufficiently robust statistical test to discriminate the three conditions of perceived glare. Although the IG scenario was statistically different from the other two scenarios ($p<0.05$) (Table 8), the NG scenario was not statistically different from the DG ($p>0.05$) (Table 8). To determine the difference between these two scenarios (NG-DG), the duration of the participants' stay in the 4 opening conditions (occlusion, semi-occlusion, semi-opening, opening) was calculated.

ANALYSIS OF THE FOUR OPENING RANGES

Table 9 shows the percentage of time the participants' eyes were in the 4 opening ranges for the three conditions of perceived glare. In general, it can be said that, in the three conditions of perceived glare, the eyes were open longer (0.75-1), and it was also observed that the opening in this range decreased as the glare increased. More particularly, the following observations can be made regarding the four opening ranges. On the one hand, the mean values of the

Revista Hábitat Sustentable Vol. 14, N°. 1. ISSN 0719 - 0700 / Págs. 08 -21
https://doi.org/10.22320/07190700.2024.14.01.01

percentage of time in occlusion (0-0.25) were 1.7% (NG scenario), 1.4% (DG scenario), and 1.2% (IG scenario). The z-Wilcoxon tests (Table 10) show that there were no statistically significant differences (p>0.05) between the three scenarios (Table 9). On the other hand, the mean values of the percentage of time in semi-occlusion (0.25-0.50) were 2.4% (NG scenario), 2.5% (DG scenario), and 4.5% (IG scenario), with significant differences only between the NG and IG scenarios and between DG and IG (p<0.05). Regarding the mean values in the semi-opening range (0.50 - 0.75), it is evident that the time quadruples between the DG scenario (12.9%) and the NG (4.5%) and almost triples between the IG scenario (39%) and the DG (12.9%). Meanwhile, the statistical tests showed significant differences between the NG and DG scenarios and between NG and IG (p<0.05). Finally, in total opening (0.75-1), there were only significant differences between the DG (83.2%) and IG (54.3%) scenarios.

From the previously reported analysis, it is important to emphasize that it is impossible to differentiate the three light scenarios in the total occlusion range. On the contrary, the NG scenario was differentiated from the DG one in the semi-opening and opening ranges. The NG scenario was distinguished from the IG in the semi-opening and semi-occlusion ranges. Finally, the semi-occlusion range was the only one to differentiate the DG scenario from the IG. It is important to highlight that eye indicators could discriminate all the light scenarios evaluated. The three opening ranges that provided the most information were semi-occlusion, semi-opening, and opening.

The percentage of time spent in the different ranges of eye opening defined in the research is a significant indicator of the level of glare since it allows one to differentiate the 3 existing levels (noticeable, disturbing, and intolerable). Considering this, the result is the most relevant of the study.

It is important to highlight the limitations of this work and the proposals for the future:

In future works, the lighting ranges presented to the participants could be considered in two ways: predefined by the evaluators so that all participants experience the same conditions of perceived glare or adjusted by the participants according to their previous experience (as was the case in this experiment).

In future works, vertical illuminance measurements should be complemented by glare models such as the DGP model, which includes luminance contrast measurements. It is also important to evaluate different tasks, not just reading tasks on the screen, as typical office tasks include tasks on a horizontal plane (keyboard, paper).

In addition, it is necessary to include more participants with different levels of glare sensitivity to obtain more robust results. It would also be important to complement the proposed methodology with other eye indicators, such as the number of blinks, or perform frequency analysis to detect patterns in eye behavior that are repeated under different conditions of perceived glare.

In the same way, it would be interesting, in future works, to contrast the information obtained from the questionnaires about visual comfort and relate it to the eye indicators to determine if there are biases in people's responses, a product of the experimental design. Numerous suggestions and criticisms have been made about the validity of the questions used in subjective questionnaires (Fotios & Kent, 2021; Quek et al., 2023). This is related to the appearance of different types of biases in experimental designs, such as the Hawthorne effect, "modification of the participant's response as a result of knowing that they are being studied, and not in response to the experimental study" (Perera, 2023), among other types of bias.

Finally, the research contributes to laying the foundations for creating a control system to regulate the shading devices in offices dynamically, using glare measurements following eye openings in contrast to current light measurements carried out at a fixed measurement point.

CONCLUSIONS

The physical models are adapted to people's answers through questionnaires. However, these questionnaires have limited validity (Quek et al., 2023) and may influence the answers obtained depending on the type of questionnaire used. The eye indicators could provide objective information regarding the degree of glare experienced by the participants to quantify the sensation of people. Another limitation is that the models are placed in a fixed position due to the sensors' location and consider the gaze's direction in a limited direction. On the other hand, eye indicators dynamically provide information about the gaze, registering the different photometric conditions of the environment through ocular fluctuations.

The research aimed to propose four eye opening ranges to evaluate glare. On the analyzed sample, a tendency was found that discrimination of the perceived glare conditions (NG-DG-IG) is possible from three opening ranges: semi-occlusion (0.25-0.50) and semi-opening (0.50-0.75) and opening (0.75-1). While in the occlusion range (0-0.25), it was not possible to differentiate the three light scenarios. The proposed ranges consisted of 4 equally distributed ranges. In future works, the distribution of the ranges could be adjusted to analyze the glare levels more effectively.

Regarding the level of coincidence of people's responses and the values proposed by Wienold et al. (2019), it can be concluded that, based on the average values and the level of coincidence of the subjective responses in the scenarios of perceived glare as noticeable and disturbing, the mean Ev values were lower than the reference values, while the values of perceived glare as intolerable are coincident with the reference values of Table 1. However, more validation studies are needed to confirm these findings.

It is important to note that previous studies to this work (Hamedani et al., 2019) had already found that it was possible to quantify, by eye indicators, the presence of glare in disturbing and intolerable glare. This study visualized the possibility of differentiating between noticeable and disturbing glare conditions. Adjusting the tools, which help develop glare models or increase their validity, could improve the evaluation of the occupants' visual comfort in indoor spaces. In turn, this work aims to lay the foundations for developing an algorithm capable of identifying eye patterns to make automatic adjustments in shading devices.

It is important to note that previous studies to this work (Hamedani et al., 2019) had already found the possibility of quantifying the presence of glare using eye indicators. More specifically, some studies conducted in recent years (Hamedani et al., 2020) showed that blink amplitude and pupillary agitation index could quantify certain relative glare conditions (including imperceptible and noticeable glare conditions), while eye movements (fixations) and pupil diameter could quantify more extreme levels of glare (disturbing and intolerable). The difference in this study, concerning those previously analyzed, is that in this research, the possibility of differentiating the entire spectrum of glare conditions, ranging from noticeable to disturbing and intolerable, was determined using a single eye indicator: the eye opening in its four ranges. Adjusting the tools that help develop glare models or increase their validity can improve the evaluation of the occupants' visual comfort in interior spaces.

ACKNOWLEDGMENTS

This research is funded by the National Council of Scientific and Technical Research (CONICET). Projects: PIBBA-0915 Conicet; PICT-2019-04356, PUE Inahe

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