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Degree of eye opening: A new discomfort glare indicator

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ABSTRACT

The degree of eye opening (DEO) is proposed as a new indicator of glare in sunny climates in the presence of direct sunlight. A laboratory experiment was carried out ($n = 20$) in a simulated office space where volunteers performed computer office tasks. Four lighting situations, based on ranges of vertical illuminance at the eye level were evaluated. By means of a visible spectrum eye-tracker DEO was registered in each scenario. The proposed indicator was obtained by mathematical iterations and showed a good correlation with: vertical illuminance at the eye ($r = -0.503$; $\alpha = 0.0001$), Daylight Glare Probability (DGP) ($r = -0.649$; $\alpha = 0.0001$) and Glare Sensation Vote (GSV) ($r = -0.580$; $\alpha = 0.0001$). This new indicator operates in a broad range of lighting conditions, from a low vertical illuminance at the eye scenario with diffuse daylight to a very high vertical illuminance at the eye scenario with uncontrolled direct sunlight. The proposed new indicator satisfies the following criteria: high validity, reliability, diagnostic power and acceptability and it also addresses unresolved aspects of current glare predictive models: GSV, DGP and DGI.

1. Introduction

In order for daylight to be maximally beneficial for people, indoor design for daylighting must ensure human performance and visual comfort. Visual comfort is mainly achieved by avoiding glare as well as controlling the uniformity, shadows and veiling reflections [1]. Glare is one of the major factors affecting visual comfort [2], thus it should be avoided in general for visual tasks and especially for more visually demanding tasks such as Visual Display Terminal (VDT) office work [3]. Several objective and subjective indices and indicators of glare have been developed over the years.

Indicators measure the behavior of variables and it should be linked to each component tested. Moreover, indices can be the result of a group of indicators. Indices are more complex than indicators, since they are based on equations or mathematical models. Conversely, indices allow us to assign a value to any aspect measured [4].

Hopkinson introduced a subjective appraisal technique for discomfort glare known as Hopkinson Scale, which was based on a multiple criterion scale. This scale consists of 4 points: JP (just perceptible); JA (just acceptable); JU (just uncomfortable); JI (just intolerable) [5]. This scale was applied in an experiment with controlled artificial lighting conditions and an empirical glare index was obtained (GI): JI = 8, JA = 15, JU = 21, JI = 28 [6]. The glare index formula is shown in eq (1)

$$GI = 10\log_{10}\sum\frac{kL_S^{1.6}\omega^{0.8}}{L_b} \tag{1}$$

where, L_S is the source luminance, ω is the solid angle of the source and L_b is the background luminance.

This equation was modified in order to obtain specific daylight glare indices, such as DGI (Daylight Glare Index) [7], DGP (Daylight Glare Probability) [8,9] and DGI$_N$ (Daylight Glare index new) [2]. Subjective indicators of glare are based on Hopkinson scale, one of them being GSV (Glare Sensation Vote) [10].

The DGI index was developed to predict glare from a large area sources, however, it is not reliable when direct light or specular reflections are present in the field of view because of the model

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Abbreviations: L_S, source luminance; ω, solid angle of the source; L_b, background luminance; E_{min}, minimum illuminance; E_{mean}, mean illuminance; Ey, vertical illuminance at the eye; Eh, horizontal illuminance at work space; Ev, vertical illuminance at the center of the computer screen; Eg, horizontal grid illuminance.

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derived from experiments with artificial glare sources [11]. On the other hand, the DGP index performs better than other existing metrics in very bright scenes and in the presence of direct sunlight [12]. The basis of this model is to compare areas of bright luminance against the total vertical illuminance reaching the eye [13]. Finally, the DGI_N has been developed without conclusive experimental studies done with people [12].

Both DGI and DGP models have some limitations for predicting glare in sunny climates with high luminance contrasts. One of those limitations is to ignore the non-uniformity of the glare source [14] in some situations. The discomfort glare sensation of the non-uniform window is lower than the one of the uniform window [15]. Furthermore, those models do not consider either cultural differences [16,17] or physiological aspects or personal preferences [18]. In addition, the calculations required to obtain those indices are cumbersome. Thus, predicting glare in complex scenes may require fundamental changes in existing models [19].

The categories of GSV (imperceptible, noticeable, disturbing and intolerable) are related to the approximate period of time the observer tolerates glare. This method focuses on the glare sensations experienced by the observers. As a drawback, there is a risk of misinterpretation of the scale by users [20].

Studies in a sunny climate have shown low correlation between predictions of objective indices (DGP, DGI) and the actual perception of glare (GSV) [21]. This situation can be due to a higher level of glare tolerance by inhabitants of sunny climates.

In order to overcome the difference between glare index predictions and the actual perception of users, the need to find a new indicator to assess glare in daylit work spaces arises. This indicator should satisfy the following mandatory criteria: high validity, reliability, diagnostic power and low intrusiveness, while maintaining practicality and acceptability [22,23].

The visual system changes its light sensitivity through a process called adaptation, which involve three distinct mechanisms [3]: changes in pupil size (by contraction and dilation of the pupil), neural adaptation (produced by synaptic interaction in the retina) and photochemical adaptation (by bleaching and regeneration of photosensitive pigment). Besides pupil size, there are other adaptation mechanisms that can reduce or increase the amount of light reaching the retina that are visible to the naked eye (i.e. direction of gaze, degree of eye opening and number of blinks) and therefore they can be video recorded. Not all of the mechanisms of light reduction listed above respond solely to lighting changes. For instance, blinks are not fully explained by light variation and also owe their presence to other personal and behavioral aspects [24,25]. On the other hand, direction of gaze is intrinsically related to the type of task (i.e. cognitive demands and task complexity) besides lighting [26,27]. Several factors affect pupil size, including the accommodative state of the eye [28], the observer's age [29] and the monocular versus binocular vision [30].

Finally, the excess of light in the eye area produces changes in the activities of facial muscles, reducing the degree of eye opening [31]. Based on those studies, Berman et al. proposed a method to measure glare by means of the involuntary contraction of the muscles around the eyes [32]. This method measured the activity of facial muscles by electromyography, which can be an invasive method. Following this principle, recent studies have shown that the degree of eye opening can be measured by eye trackers, in a less invasive way. In a previous study, we found a statistically significant correlation between the degree of eye opening and lighting levels ($r = -0.728$; $\alpha = 0.001$), DGP ($r = -0.610$; $\alpha = 0.001$), DGI ($r = -0.350$; $\alpha = 0.001$), and with the user glare perception measured by means of GSV ($r = 0.480$, $\alpha = 0.05$) [33].

It has been demonstrated that facial muscles also react to other variables unrelated to the visual environment [34]. Information obtained by electromyography and from eye-trackers can be affected by cognitive and emotional activity [35]. However, much of this emotional and cognitive information is not visually noticeable from videos. This information can be measurable through electromyography, which can measure muscle activity even in absence of observable facial expressions [36].

An experiment was carried out to test the hypothesis that the degree of eye opening can be useful as an indicator of discomfort glare that addresses some unresolved aspects of current predictive models.

2. Material and methods

Four different lighting conditions were replicated in our experimental lighting laboratory (2.1) and photometric and environmental data were gathered from each one of them (2.2). The participants ($n = 20$) performed office tasks with VDT (2.3), and the degree of eye opening was registered by means of an eye tracker (2.4). Finally glare indices were obtained for later comparison with the ocular data and subjective responses (2.5).

2.1. Experimental lighting laboratory

The experiment was carried out in the experimental lighting laboratory (Fig. 1) at CCT-Mendoza, Argentina (latitude 32°89′S; longitude 68° 87′O). The laboratory has two sections with white walls (reflectance $r = 0.91$), a black floor ($r = 0.07$) and a black ceiling ($r = 0.06$). Both sections have identical geometrical features (1.75 m wide, 3.4 m deep, 2.7 m high): the first section has measuring equipment (reference room), and the other (test room) is equipped with one workstation (a desk, an office chair, and a computer) in which the participants performed the required tasks with a 15.6 Lenovo B570 notebook (r keyboard $= 0.327$). The interior is decorated as an actual office. The only light source is the window, a 1.2 m wide, and 1.14 m high glass area with an apparent size of 1.21 steradians. The window was a 4 mm single-glazed clear glass with visible transmittance (VT) = 89%. A low density built area and scarce vegetation surrounding the structure allowed no obstructions in the window and full access to sunlight.

The room's orientation could be changed by rotating its structure due to a central axis under its floor which allows a wide range of sun altitudes and azimuths to be studied quite independent of the season. The four lighting situations were obtained by rotating the experimental chamber to the north or east, in order to achieve the required lighting levels. Furthermore, no shading devices were used when more light was required. On the contrary, when less daylight was required a solar shading device was used. It was a horizontal opaque white venetian blind at a fixed opening position of 45° (Fig. 2). Subjects were not free to adjust the venetian blinds and the shading device was adjusted only by the researchers.

Data collection took 70 days, between December 2012 and June of 2013 in sessions from 9:30 to 11:00 a.m. Four lighting situations were defined from ranges of vertical illuminance at the eye (Table 1). The lowest illuminance at the eye was 1400lx, which is an amount of light high enough to activate melatonin suppression and to start alertness (1000lx) [37]. It is important to say that these four scenarios differ among them in a factor higher than 1.5, which represents the smallest significant difference in illuminance level perception [38]. The lighting situations achieved are often found in real office spaces, particularly in buildings in sunny climates where the presence of offices with a high percentage of glass increases the risk of glare [39].

Fig. 3 shows the plan of experimental lighting laboratory overlapped with a solar chart for each scenario. Each solar chart shows an outer dotted line demonstrating how the sun enters into the two

Fig. 1. Exterior of light laboratory.

scenarios. The graph on the left corresponds to the Ee high and medium scenarios, which were conducted in the winter season. The graph on the right corresponds to the Ee low and very high scenarios, which were conducted in the summer season. Both diagrams illustrate the sun's path, which is highlighted in orange along with the time at which the data were taken. Furthermore, the measuring points of each photometric variable, and the position of the workstation in relation to the window are included in the graph.

2.2. *Photometric and environmental study*

The temperature and humidity were monitored during the experiment at the beginning and at the end of each trial by means of an LMT 8000 environmental measurement device.

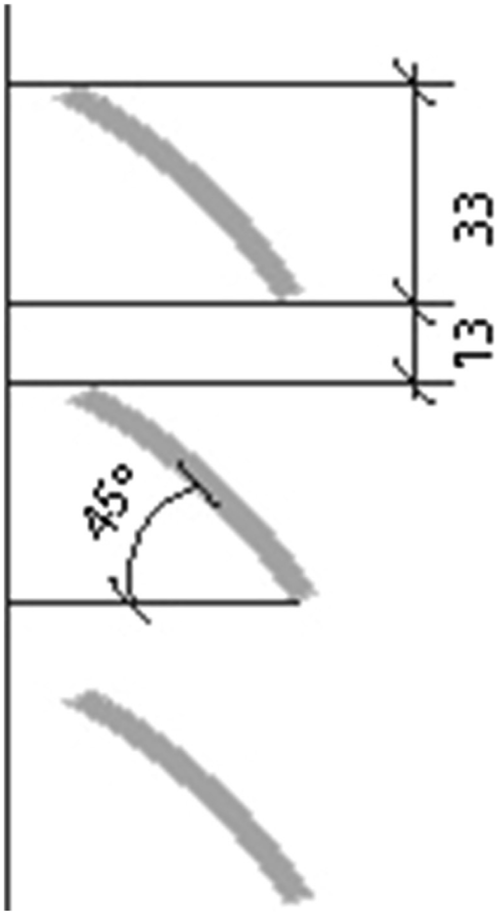

Fig. 2. Dimensions of the venetian blinds.

Regarding the photometric characteristics, these were obtained from the *in situ* measurements carried out with an LMT Lux 2 luximeter with an illuminance sensor on a range of 0.1–1,20,000 lux with cosine corrector and v lambda filter. The work space was characterized by means of an office protocol adapted from Wienold [8] to photometrically describe the space. From this protocol the indicators that were selected to evaluate the daylight quality were: Horizontal illuminance, where the paper task was performed (Eh), vertical illuminance at the center of the computer screen (Ev), and vertical illuminance at the eye (Ey). A vertical illuminance sensor was mounted on a tripod at the approximate eye position pointing to the center of the VDT. This last indicator is the photometric variable which best correlates with glare predictions [9].

2.2.1. *Uniformity and mean illuminance on the workplace*

Four measuring points at regular distances formed a grid at 0.85 m from the floor. This allowed us to obtain both the mean illuminance at the workplace and the illuminance uniformity ratio using the following mathematical relationship (2):

$$E_{\min} \geq E_{\text{mean}}/2 \tag{2}$$

where, $E_{\min}$ is minimum illuminance and E_{mean} is mean illuminance.

2.2.2. *Participant's subjective response*

The subjective evaluation of visual comfort was conducted by means of a survey which consisted in semantic differentials and

Table 1
The four lighting situations with their respective lighting levels and averages. Ey: Vertical eye illuminance. Eh: Horizontal illuminance at work space.

Lighting situation	Description	Ey (Range)	Eh (Mean)
Ee (low)	Diffuse daylight without a venetian blind and no sun patches in the room + window in front of the workstation + north facing window.	1400–2500	910
Ee (medium)	Primarily diffuse daylight with a venetian blind allowing sun patches of direct sunlight on the corner of the desk and away from the task + window on the left of the workstation + east facing window	2500–5000	3000
Ee (high)	Primarily direct sunlight with a venetian blind allowing sun patches spread on the desk surface including the task area + window on the left of the workstation + north facing window	5000–7500	5500
Ee (very high)	Direct sunlight all over the room without a venetian blind + window in front of the workstation + east facing window	7500–30,000	11,519

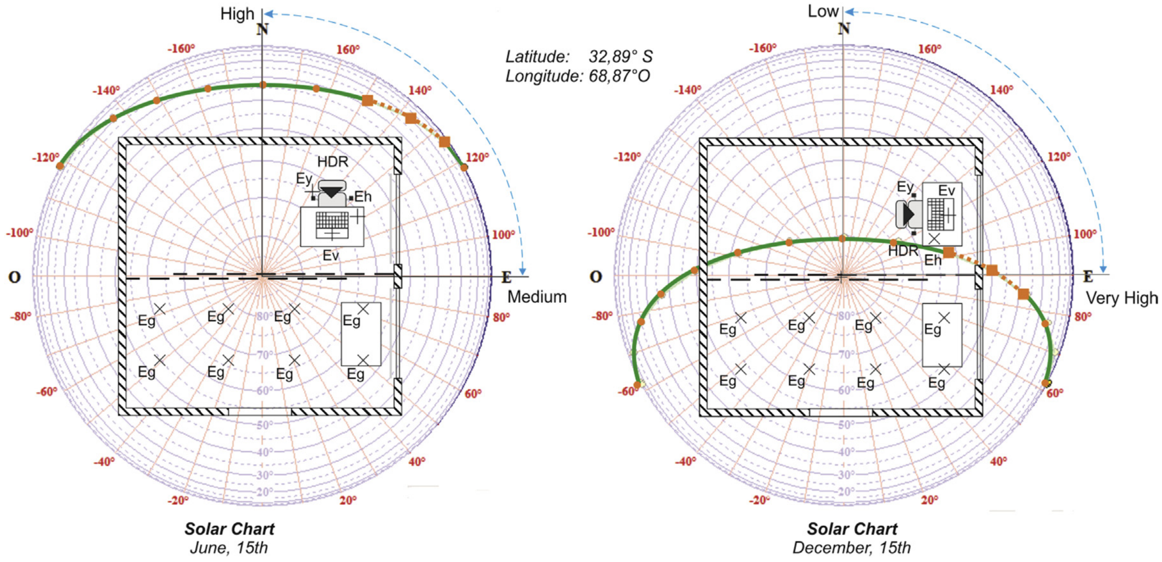

Fig. 3. Plan of experimental lighting laboratory with solar chart for each scenario.

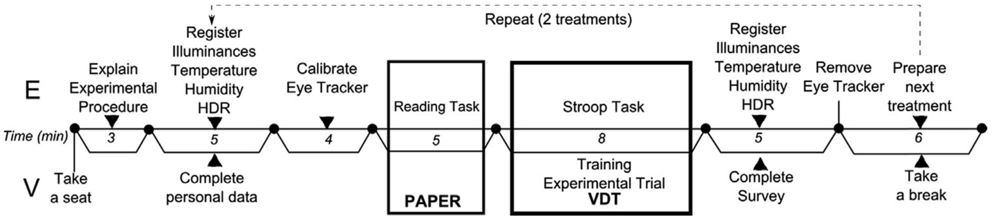

Fig. 4. Experimental flux.

multiple choice questions. The survey was divided into four parts: (i) personal questions; (ii) the "reading on paper" task, which evaluated the conditions of light necessary to carry out the task on paper; (iii) Task on VDT, which evaluated the conditions of light necessary to carry out the task on the screen; and (iv) Environmental conditions within the room.

2.3. Sample and characteristics of the task

The participants ($n = 20$; 12 females and 8 males between 22 and 40 years old) performed office tasks in four lighting situations. No gender correction was made because general or overall workspace satisfaction ratings (including lighting conditions) showed no difference between male and female samples [40].

The participants performed a divided attention Stroop task [41] while performing a working memory span task. This dual task design includes the essential features of office work with computers: high working memory demands [42], divided attention [43] and the coexistence of information presented on paper and on a screen [21].

The working memory span task consisted in reading a randomly selected short text on paper (200 words), give it a title, and define four keywords for that text (memory set). The volunteers were instructed to remember the keywords while performing the Stroop task for later recall. Once the primary task was finished, the participants had to recall the memory set.

The Stroop task presents stimuli to participants in which the relationship between meaning and color is manipulated so that it is congruent (e.g. the word RED presented in the color red) or incongruent (e.g. the word BLUE presented in the color green), resulting in a delay in the color processing of the word, increasing reaction time and promoting errors. This semantic interference is called Stroop effect and its magnitude is an indicator of selective attention by requiring participants to respond selectively to a particular type of goal oriented information while ignoring distraction. Stimuli (RED, GREEN, BLUE) were presented in the center of the VDT, in Arial 16-point font colors (red, green and blue). The amount of congruent and incongruent stimuli was balanced and text/color combinations were randomly presented. Our participants were instructed to report the "ink" color in which the stimuli were displayed. The response of the participants was recorded using their right hand (index, middle and ring fingers) and the computer cursor keys (left, down and right keys). The training consisted of four blocks of 12 repetitions, while the experimental trial consisted of eight blocks of 12 repetitions.

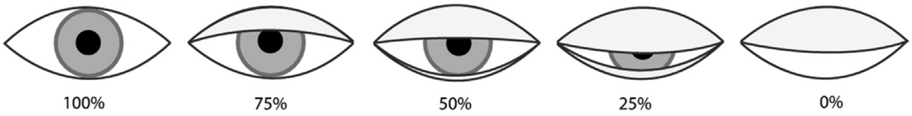

Fig. 5. Different percentages of eye openness.

Table 2
Descriptive statistics of physical and photometric variables. The luminance of the VDT in the absence of any other light is 36 cd/m^2.

	Ee (low)		Ee (medium)		Ee (high)		Ee (very high)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Temperature (°C)	29.01	1.63	20.67	1.70	20.44	1.60	28.62	1.81
Humidity (%)	34.89	9.65	40.30	6.90	43.30	7.31	34.73	8.56
Illuminance in work space (lx)	910.62	230.69	3006.92	1225.21	5506.00	1068.01	11,519.50	2641.82
Vertical illuminance at the eye (lx)	1861.81	256.64	2522.76	692.20	5406.30	813.56	24,438.12	17,888.40
Vertical VDT illuminance (lx)	508.93	201.99	827.69	575.45	1813.07	491.19	3023.50	1009.97
Illuminance uniformity ($E_{\min} \geq E_{\text{mean}}/2$)	$603 \geq 455$ Uniform		$587 < 1507$ Non-uniform		$890 < 2753$ Non-uniform		$7500 < 12{,}229$ Non-uniform	

Table 3
Comparison between the four lighting situations (Paired *t*-tests).

Comparison between scenarios	Temperature		Vertical illuminance at the eye		Vertical VDT illuminance	
	t	*s*	*t*	*s*	*t*	*s*
Ee (very high)–Ee (low)	0.925	0.367	−37.778	0.000	12.027	0.000
Ee (very high)–Ee (high)	14.186	0.000	−23.485	0.000	4.703	0.000
Ee (very high)–Ee (medium)	13.821	0.000	−5.327	0.000	−2.670	0.016
Ee (low)–Ee (high)	12.801	0.000	−17.957	0.000	−13.154	0.000
Ee (low)–Ee (medium)	16.829	0.000	−5.066	0.000	−6.701	0.000
Ee (medium)–Ee (high)	−1.031	0.315	−4.375	0.001	−4.450	0.000

Fig. 4 describes the sequence of activities developed during the experiment, as well as the approximate time each stage demanded. The upper part of the flowchart shows the researchers' activities while its lower part shows the tasks of the volunteers. When entering the laboratory, each volunteer sat down and the experimental proceeding was explained to him/her. Then the participants had to fill in a form with their personal information and basic demographic data. The eye tracker was positioned in the volunteer's head and calibrated. Then, the subject had to complete the reading task and perform the Stroop test. Once both tasks were completed, the volunteer answered the survey in relation to the tasks and the environmental conditions in which they were conducted. During the entire experiment the ocular data was registered. The researcher registered the physical conditions and photometric data before the eye tracker calibration and after both tasks were completed. Finally, the researcher prepared the next scenario, giving the volunteer a break time.

2.4. The degree of eye opening (DEO)

In order to quantify DEO, an eye tracker was developed in our own laboratory LAHV. The instrument consisted in two cameras which capture images within the visible spectrum. The images were captured in real time at a 720 × 480 pixel resolution and 30 frames per second. One of the cameras registered the eye movements and the other one registered the visual field of the observer. The scenes captured were processed with Starburst® algorithm, a free open source software redesigned for the visible spectrum [44].

Table 4
Descriptive statistics of the glare indices and indicator.

	Ee (low)		Ee (medium)		Ee (high)		Ee (very high)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
GSV	1.83	–	2.18	–	2.5	–	3.1	–
DGP	0.271	0.029	0.352	0.068	0.528	0.05	0.79	0.17
DGI	22.48	0.86	22.73	0.92	22.97	0.92	25.5	1.27

Table 5
Interpretation of glare indices.

Discomfort classification	Glare range values		
	GSV	DGP	DGI
Imperceptible	1	<0.30	<18
Noticeable	2	0.30–0.35	18–24
Disturbing	3	0.35–0.45	24–31
Intolerable	4	>0.45	>31

The degree of muscle contraction around the eyes that reduced incoming light was measured based on the model by Tsao [45] defined by Eq. (3):

$$DEO = L/L_{\max} \tag{3}$$

where L is the level of the eye openness in the presence of a glare source and $L_{\max}$ is the maximum eye height, when it is totally open. A threshold value was established to define whether the eye was open or closed: if the relation was lower than 0.2, then the eye in a particular frame was closed, otherwise it was defined as open (Fig. 5).

The percentage of eye openness was monitored continuously during the Stroop task. We obtained the DEO for each frame (30 fps). In order to overcome a problem associated with the continuous oscillation of the eye openness, we calculated the mean DEO for that period. Although we monitored our participant's natural blink rate, blinking was not considered as a variation in the degree of eye opening and it was removed from the DEO analysis.

2.5. Glare indices and subjective indicators

2.5.1. Glare indices

DGI and DGP indices were calculated from luminance mappings obtained from high dynamic range images (HDR). A series of 6 low dynamic range images (LDRI) were taken with various exposures from 3 full stop under-exposure to 3 full stop over-exposures. The

Table 6
Correlation and percentage of predictive success (%) between GSV and DGP, DGI, Ey.

	DGP			DGI			Ey	
	r	*α*	% Success	*r*	*α*	% Success	*r*	*α*
GSV	0.507	>0.0001	31%	0.380	>0.0001	42%	0.38	0.0001

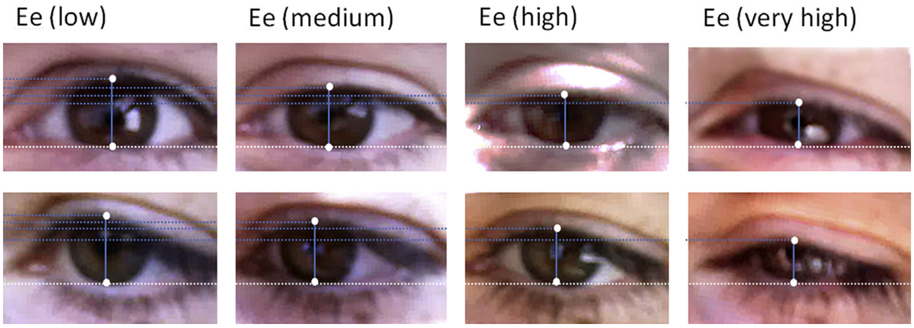

Fig. 6. DEO in the four lighting situation.

Table 7
Descriptive statistics of DEO.

	Ee (Low)			Ee (Medium)			Ee (High)			Ee (Very high)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
DEO	0.904	0.071	0.012	0.825	0.113	0.021	0.752	0.056	0.013	0.627	0.056	0.015

(LDRI) were obtained with the “Nikon Coolpix 5400” camera and with a “Nikon FC-E9” fish eye lens. Each image was taken at eye level, pointing to the center of the computer screen. Each (LDRI) was processed with the “Photosphere” program for Mac, and calibrated with the control luminances obtained with a “Minolta LS100” luminancemeter. Finally the HDR were post processed with the “Evalglare” program [8]. In order to obtain the glare indexes (DGI, DGP); Evalglare calculates the scene's mean luminance, the solid angle subtended by the source, the background and source luminances and the position of each glare source within the HDR scene. Finally, we used the −i option in order to manually introduce Ey values into the DGP calculation.

2.5.2. Subjective indicators

We measured the level of glare perceived with a modified GSV (Glare sensation vote) scale [10]. The GSV scale is a slight modification of Hopkinson Scale: JP (Just Perceptible), JA (Just Acceptable), JU (Just Uncomfortable, JI (Just Intolerable). In this ordinal scale, the borderline between comfort and discomfort (BCD) is between ‘just acceptable’ and ‘just uncomfortable’. GSV was presented to the participant by means of an ordinal scale. In the survey the participants were asked to associate the magnitude of the glare on a four point scale with pre-defined glare criteria: 1 – imperceptible, 2 – noticeable, 3 – disturbing and 4 – intolerable. A definition for each point on the scale was presented to the participants. The glare categories were connected to an approximate period of time that a given degree of glare would be tolerated.

2.5.3. Comparison between indices and indicators

Indices and indicators were evaluated on their ability to assess the four scenarios. Then, DGI and DGP indices were compared with the users' response (GSV) by means of Pearson correlation coefficient and the percentage of predictive success.

Table 8
Correlation between DEO and DGP, GSV, Ey.

	GSV		DGP		Ey	
	r	α	r	α	r	α
DEO	−0.580	0.000	−0.649	0.000	−0.503	0.000

To obtain the new indicator, the mean values of DEO were calculated for the four scenarios. Then, ocular data were linearly correlated with GSV, DGP and DGI. From this preliminary analysis, the indices or indicators that best adjusted with the ocular data were selected. Ranges were determined based on the best mathematical iterations. Then, continuous values of DEO were assigned to a four point ordinal scale where: 1 – imperceptible 2 – noticeable 3 – disturbing and 4 – intolerable. Once the ranges of eye opening were defined, we calculated the mathematical adjustment of the obtained standardized indicator by means of Pearson correlation coefficient (r) and the percentage of predictive success.

3. Results and discussion

3.1. Photometric and environmental data

Table 2 shows mean values and standard deviations of temperature, humidity and horizontal illuminance at the working space, vertical illuminance at the eye and gives uniformity values.

In order to advance in the statistical analysis of the measured values in each scenario, significant differences in the temperature and illuminance between the four scenarios was verified with paired t-test for related samples (Table 3).

Scenarios Ee (medium) and Ee (high) had similar humidity and temperature measurements. On the contrary scenarios Ee (low) and Ee (very high) had higher temperatures than the usually recommended values [46].

To find out if air temperature influenced the degree of eye opening in our experiment, an ordinal regression was performed. The independent explanatory variable was air temperature and the dependent variable was the degree of eye opening. The result show a low Nagelkerke pseudo $R2 = 0.1$ with a p value $= 0.285$ indicating that the temperature did not effectively contribute to the prediction of the degree of eye opening. A study conducted by Laurentin argues there are no significant differences between the air temperatures and glare sensation [47]. Thus, air temperature should not affect DEO as a glare indicator. However, the eyes could be affected when working above the comfort temperature (>27 °C). One of the known effects of high temperatures on the eyes is irritation [48], which is produced by the evaporation of the tear film of the cornea. This eye irritation is compensated by increasing the number of blinks, which cover and redistribute the tear film [25]. Because blink rate were excluded from

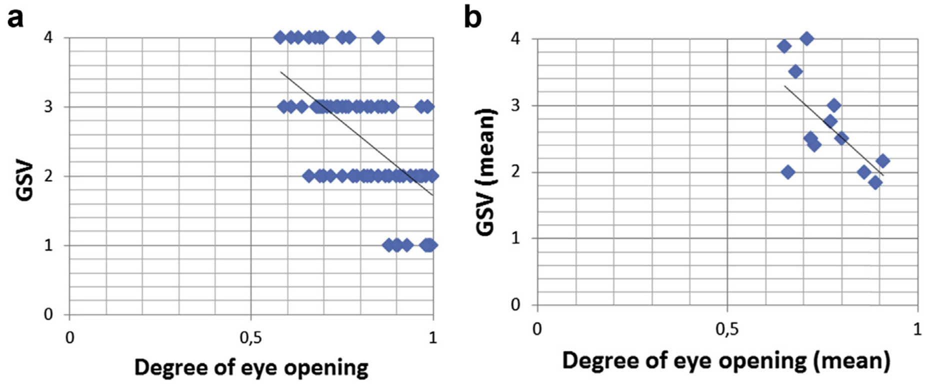

Fig. 7. a – Discrete values b – Continuous values every 1000lx.

the DEO analysis, this already known effect of temperature on ocular behavior would not affect our analysis regarding the DEO.

Illuminance was the environmental factor which presented the greater differences. The vertical illuminance at the eyes was higher in the Ee (very high) scenario as well as the horizontal illuminance at the work space. It should be noted that in the Ee (low) scenario, the illuminance at the work space was in a range between 500 and 2000 lx which is often considered either as desirable or at least tolerable [22]. Concerning the other three scenarios, the horizontal illuminance on the work space was higher than the usually recommended values for VDT work and paper work [49].

Regarding lighting uniformity, the only scenario defined as uniform was the Ee (low) scenario, while the other three were defined as non-uniform, with strips of light and shade produced by the venetian blinds.

Table 4 shows mean GSV, DGI and DGP values while Table 5 demonstrates glare range values for each index. On the one hand, the GSV scale shows that none of our participants considered the glare environment as intolerable in any of the experimental situations, pointing to a high tolerance to glare. On the other hand, the DGP index could not differentiate between the Ee (high) scenario and the Ee (very high) scenario, considering both as intolerable. Finally, the DGI index tended to centralize values, failing to assess extreme values (minimum and maximum).

Table 6 shows that the correlation between the subjective indicator GSV and the objective indices. Correlation between GSV and DGP is moderate ($r = 0.507$) with a low percentage of predictive success (31%) while correlation between GSV and DGI is very low and significant ($r = 0.380$) despite a higher percentage of predictive success (42%). This is in accord with the statistical criterion that considers correlation coefficients above 0.7 as high and coefficients higher than 0.4 as moderate [50].

Because DGI tends to centralize the values and it showed a low correlation with the users' response ($r < 0.4$), DGI will not be included in the subsequent analysis.

3.2. *Degree of eye opening*

Fig. 6 shows examples of different DEO for each scenario. Table 7 shows the mean values, standard deviations, standard errors of DEO for each scenario. We observed that mean DEO values tend to decrease while the risk of glare increases through the different scenarios. Also, we calculated the relative standard error (E%) for each scenario: Ee (low) = 1.3%, Ee (medium) = 2.4%, Ee (high) = 1.7%, Ee (very high) = 2.2%. The small E% observed in each scenario indicates that the sample mean is an accurate reflection of the actual population mean. While Table 8 shows the correlation between DEO and DGP, GSV, E_V. Eye opening is best correlated with DGP ($r = -0.649$, $\alpha = 0.000$) followed by GSV ($r = -0.580$, $\alpha = 0.000$).

The correlation between the discrete values of DEO and GSV was ($r = -0.58$; $\alpha = 0.000$) (Fig. 7a). In order to obtain a better correlation, we calculated the average of eye opening and GSV every 1000 lx, obtaining continuous values with a better correlation ($r = -0.611$, $\alpha = 0.035$) (Fig. 7b).

DEO had a moderate correlation with DGP ($p = 0.69$) and GSV ($p = 0.61$). However, DGP showed limitations for glare diagnosis in extreme sun situations, which are commonly found in sunny climates. Although GSV shows the users' own perception, it has limitations in its application. For this reason, DEO was adjusted to DGP and GSV in order to overcome its limitations.

3.3. *Assignment of ranges*

After selecting the GSV and DGP as benchmarks, DEO ranges were obtained by means of mathematical iterations (Table 9). The best percentages of predictive success achieved were 55% for GSV and 45% for DGP.

Table 10 shows that GSV, DGP and DEO have similar behavior when describing Ee (low) and Ee (medium) scenarios. Regarding the Ee (high) and Ee (very high) scenarios, the behavior of GSV and DEO is similar while DGP differs from the others (Fig. 8).

Finally, Table 11 compares the mean values of DEO, GSV and DGP among scenarios by means of paired t-tests. On the one hand, GSV shows significant differences in 3 of the 6 paired comparisons between scenarios. On the other hand, DGP does not differentiate Ee (high) scenario from Ee (very high) scenario and DEO does not differentiate Ee (medium) from Ee (high) scenario.

Table 9
DEO ranges.

DEO ranges	Category	Discomfort classification
>0.90	1	Imperceptible
0.77–0.90	2	Noticeable
0.66–0.77	3	Disturbing
<0.66	4	Intolerable

Table 10
Descriptive statistics of the standardized glare models.

	Ee (Low)		Ee (Medium)		Ee (High)		Ee (Very high)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
GSV	1.83	–	2.18	–	2.5	–	3.1	–
DEO	1.56		2.29		2.8		3.49	
DGP	1.17	0.029	2.40	0.068	4	0.05	4	0.17

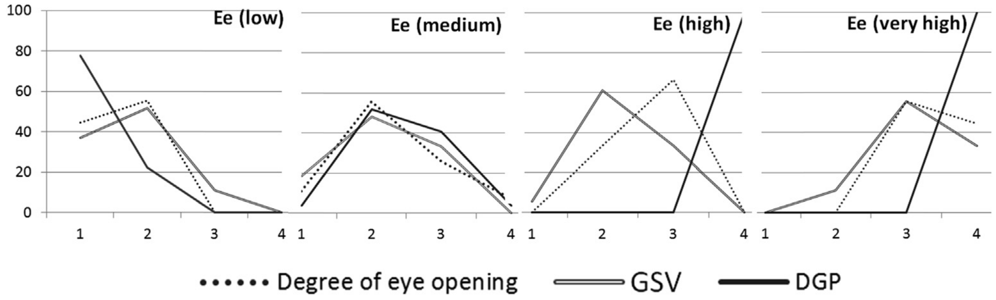

Fig. 8. DEO, GSV and DGP performance. The *x* axis indicates the perception of glare: 1 imperceptible, 2 noticeable, 3 disturbing, 4 intolerable. The *y* axis indicates the percentage of people.

4. Conclusions

The existing glare indices and their underlying theoretical models involve terms exclusively external to the observer. Our research line is seeking for any dependency on variables inherent to the observer such as physiological response to a glaring environment in order to improve current glare models. The indicator developed in this study seeks to improve, on the one hand, the overestimation of glare produced by objective models when applied in sunny climates. On the other hand, it aims to overcome the differences usually found in the subjective responses by people. After analyzing DEO in the four lighting situations, we observed that this indicator is sensitive to lighting variations and that it is able to overcome the known limitations of both objective and subjective glare assessment methods while including the following features:

Validity: DEO showed a significant correlation with the DGP index ($r = -0.649$; $\alpha = 0.001$), with GSV ($r = - 0.580$, $\alpha = 0.001$) and with the vertical illuminance at the eye ($r = -0.503$, $\alpha = 0.001$).

Reliability: The relative standard error of DEO for each scenario (less than 2.5%) showed a good reliability of the measure. However, to ensure a better reliability, future studies of DEO will include measures of stability (test -retest).

Diagnostic Power: The effect of lighting on DEO has higher observable effects on eye opening when compared to other phenomena such as mood and/or psychological states. To overcome this possible practical limitation, ocular data collection could be combined with the use of facial recognition software to isolate psychological states.

Bandwidth: the degree of eye opening has a wide range of variation in predicting large changes in lighting; however, it should be tested in lower lighting situations.

Intrusiveness: the level of intrusiveness in the experiment was high because of the use of an eye tracker. The easiest way to implement this method would be through photography allowing the performance not to be affected.

Acceptability: the level of acceptance by the participant was good; however, less intrusive methods achieved greater satisfaction by the participants.

The aim of this investigation was to validate eye opening as a proper glare indicator based on the individual response to a glare source. Our results showed that the proposed indicator has a post occupational as an assessment tool capable to operate in a broad range of lighting environments. It even works when no controlled light enters the room. . In future stages of development, this ocular indicator might become part of a glare model that include variables inherent to the subjects, and then it could be included in predictive indexes.

Table 11
Comparison between the four lighting situations (paired *t*-tests).

Comparison between scenarios	Degree of eye opening		GSV		DGP	
	t	*s*	*t*	*s*	*t*	*s*
Ee (low)–Ee (medium)	−2.775	0.012	−1.101	0.285	−20.268	0.035
Ee (Low)–Ee (high)	−8.733	0.000	−1.232	0.237	−20.189	0.000
Ee (low)–Ee (very high)	−11.541	0.000	−6.214	0.000	−20.189	0.000
Ee (medium)–Ee (high)	−1.600	0.070	0.251	0.806	−9.638	0.000
Ee (medium)–Ee (very high)	−3.631	0.003	−3.873	0.002	−9.638	0.000
Ee (high)–Ee (very high)	−4.372	0.001	−7.408	0.000	–	–

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