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Glare indicators: an analysis of ocular behaviour in an office equipped with venetian blinds

Julieta A. Yamín Garretón, Roberto G. Rodriguez and
Andrea E. Pattini

Abstract

This article studies the ocular behaviour of office workers in the presence of glare. Additionally, the study seeks to obtain a new indicator for glare prediction that compensates the inaccuracies of glare predicted by the existing models of glare sensation vote (GSV), daylight glare probability (DGP) and daylight glare index. A laboratory experiment was carried out ($n = 18$) simulating an office space. The volunteers participated in four office tasks (reading from a screen and from a paper, writing and socializing). Two scenarios were evaluated: one with sunspots on the faces of the subjects and the other with sunspots on the working area. By means of a visible spectrum eye tracker these ocular parameters were registered: direction of gaze, the degree of opening of eye and pupil size. These ocular parameters were correlated with vertical illuminance at the eye. The results show that the degree of reduction of opening of the eye was the best predictor of visual discomfort with statistically significant differences between scenarios ($p = -0.728$, $s = 0.001$). The other important predictor was the pupil size. The degree of opening of eye and pupil size was correlated with glare indices. The degree of eye opening has a good correlation with GSV and DGP and it could be a future index of visual comfort under situations of the risk of glare.

Keywords

Visual comfort, Daylight glare, Visual performance, Ocular indicator, Glare sensation vote, Daylight glare probability, Daylight glare index

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Introduction

One of the objectives of contemporary architecture is to create energy efficient buildings with access to daylight. It has been shown that daylight has positive effects on health and the sense of well-being of the users.¹ However, the analysis and predictive calculation of sun control on façades with access to direct sunlight is necessary in order to avoid sun filtrations on work surfaces and on the visual field of the people present^{2,3} so as to achieve visual comfort.

Visual comfort is influenced mainly by the level of illuminance in the space, the glare index and uniformity.⁴ It refers to the psycho-physical aspects of the observer–environment relationship. Natural lighting conditions in a room can change drastically due to the dynamics and variability of sunlight.

Uniformity is an aspect that should be considered in order to secure the achievement of typical visual tasks in an office.⁵ Natural light creates a high luminance contrast in interior spaces, which is challenging for human vision.⁶ Therefore, it is necessary to locate sun control elements on windows. The most commonly used element of sun control at office work in sunny climates such as in the case of Mendoza city, Argentina, is venetian blinds.⁷

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Venetian blinds as elements of light control have limitations in avoiding direct light on the work space. The elimination of direct sun depends mainly on the active use of the people present. Previous studies have shown that users do not regulate the position of venetian blinds very often,^{8–10} which results in inefficient light control which causes dynamic sunspots.

These situations are often found in real office spaces. A study in offices with daylight access reached the conclusion that the luminance levels were far from the recommended one (03:01 y 10:01).¹¹ Particularly in buildings in sunny climates as in the case of our region where the presence of offices with a high percentage of glass increases the risk of glare.¹²

Access to direct light has effects on the health of occupants. On the one hand, direct light affects the circadian system which regulates the hormonal activity, which puts the daily biological clock in motion. When this access of light on the human body is not controlled, the exposure to ultraviolet and infrared rays can cause tissue damage. This situation is not very common at office work; however, visual discomfort and stress are observable in this context when the visual system operates within this spectrum.¹³

Visual discomfort can be determined by characteristics of the visual system where individual differences are included.^{14,15} Within the characteristics of the visual system, the pupil size would reduce incoming light in an order of magnitude.¹⁶ The diameter of the pupil would vary between 2 and 8 mm in young people. The size of the pupil would depend mainly on luminance, the size of the adaptation field or the density of the flow over the cornea.^{17,18} This variation in the diameter can account for a change of luminance of just 16:1. Additionally, changes in face muscles around the eye take place in order to reduce excess light.^{19,20} Constant shifting between intraocular and extra ocular muscles in attempts to obtain a clear image can produce eyestrain.²¹ Very few studies have investigated the relationship between the direction of view and visual comfort in an office, which indicates that direction of view is mostly aimed at the work area or a moving stimulus. If the person takes a break from the computer, his or her vision is directed towards the window.^{22,23} However, glare has also been associated with the displacement of vision with respect to the glare source.¹⁴

In addition, blinking plays a role in protecting the ocular globe against external aggression such as excessive light, heat, cold and dust.²⁴ However, previous studies show that lighting as well as attentional and personal factors, such as fatigue, cognitive demands and mental workload,²⁵ would increase the number of blinks.

Since the eye is an important source of information input for an individual, a large number of functions

have been studied as potential workload assessment techniques.²⁶ Some of them are candidates for discomfort glare indicators for this study. Pupillary response has been shown to be a consistent measure of the relative workload. Pupil size changes in response to levels of light. However, this very sensitivity is difficult to measure because changes in ambient light as well as emotions can cause pupillary responses larger than those attributable to the work space. The absolute position of the eye at any time can be used to infer the information required for carrying out a task. Many studies have used this type of measurement to determine the processing requirements of a task. The scan pattern analysis appears to reflect the subject's response to the perceived workload and could be considered as a global indicator of both perceptual and central processing of the amount of work, at least in situations where there are no externally imposed visual-motor output differences. Most early studies relating eye blinks to workload have been criticized. Simple measures of blink frequency per unit of time appear to show great variability, thus are confined to rigidly controlled experimental settings.

Studies on visual comfort are based on physical measures of light combined with conventional psychophysical procedures. From these measures, objective indices of glare prediction are obtained.⁵ The most accepted objective indices for glare of natural light are daylight glare index (DGI)²⁷ and more recently daylight glare probability (DGP).^{28,29} Some subjective indices of glare are glare sensation vote (GSV)³⁰ and Osterhaus' subjective rating. These models have certain limitations. Thus, evaluating glare in complex scenes may require fundamental changes in their construction.³¹

The starting hypothesis of this work is that pupil size, direction of gaze and the degree of eye opening are indicators of visual discomfort in contexts of sunspots filtered by venetian blinds. These ocular parameters may serve as indicators between the objective and subjective indices, allowing for a better prediction of discomfort glare with sunspots.

Material and methods

The experiment was carried out in the experimental lighting laboratory (Figures 1 and 2) at CCT-Mendoza, Argentina (latitude 32°53'S; longitude 68°52'O). The room's orientation can be changed by rotating its structure due to a central axis under its floor which allows a wide range of different sun altitudes and azimuths to be studied quite independent of the season. 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



Figure 1. Exterior of light laboratory.

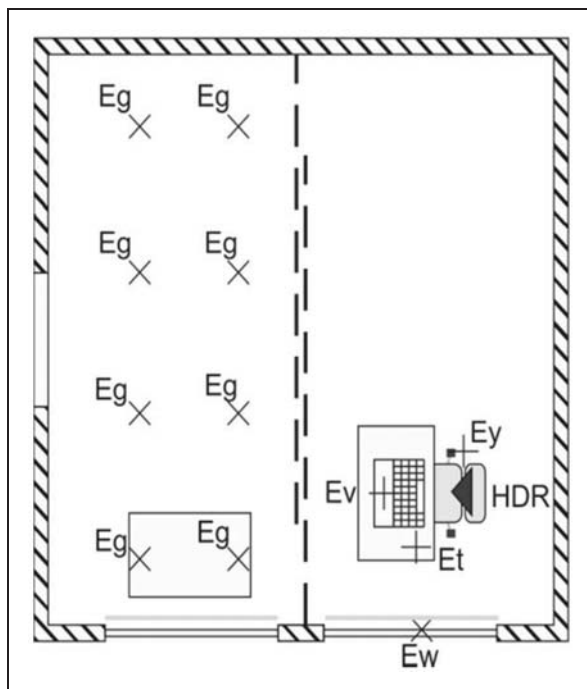


Figure 2. Plan of experimental lighting laboratory. (Et): Horizontal task illuminance. (Ey): Vertical eye illuminance. (Ev): Screen vertical illuminance. (Ew): Window vertical illuminance. (Eg): Horizontal grid illuminance.

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).

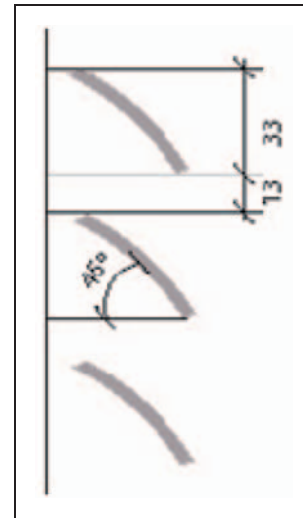


Figure 3. Dimensions of the venetian blinds.

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 1.78 sr. The window was a 4 mm single-glazed clear glass with visible transmittance = 89%. A low density built area and scarce vegetation surrounding the structure allowed no obstructions in the window and full access to sunlight. The solar shading devices used was horizontal opaque white venetian blinds on a fixed position of 45° opening (Figure 3). The interior temperature was monitored during the whole experiment, ranging from 19°C to 26°C (comfort temperature of the environment).

In spaces lit with natural light, two different situations can be frequently observed. One situation results in having sunspots on the face, and the other resulting in sunspots on the work space (Figure 4). In the first situation, the light spots directly affecting the eyes produce a masking effect on the vision.³² In the second situation, when work is done with visual display terminal (VDT), the light reflects on the screen and can cause strong glare. The luminance resulting from this additional light also constitutes a veiling luminance.³³ Therefore, the experiment was planned to reproduce both situations (Figure 5).

Experimental procedure

Two situations were evaluated: (i) the presence of sunspots on the work space (SS_{desk}) and (ii) presence of sunspots over the face (SS_{face}). The participants were randomly evaluated in both scenarios in order to keep a balanced order. The collection of data took 20 days, between June and July of 2013, in sessions from 9:30 to 11:00 a.m.

Figure 6 describes the sequence of activities developed during the experiment, as well as the approximate

time of each stage. In the upper part are the tasks of the researchers and the lower part shows the tasks of the volunteers. When entering the laboratory, each volunteer sat down and was explained the experimental proceeding. They filled in a form with their personal information and basic demographic facts. In the meantime, the researcher registered the physical conditions and initial photometric data. Then, the subject read a Stroop test and completed the experimental tasks. Once both tasks were completed, the volunteer answered the surveys in relation to the tasks and the environmental conditions in which they were conducted. During the entire experiment the ocular data were registered. Finally, the researcher prepared the next scenario, time during which while the volunteer rested.

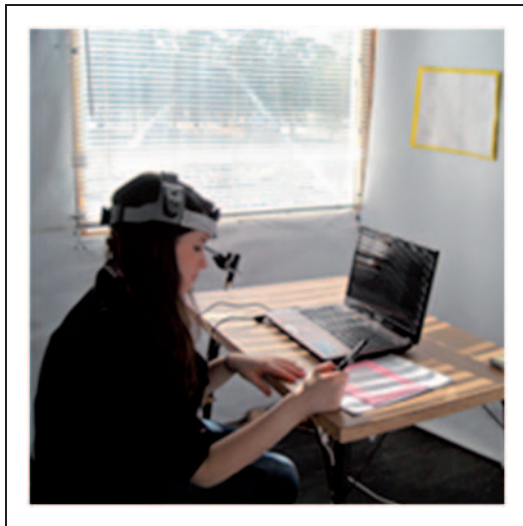


Figure 4. Sunspots over work space.

Characteristics of the task. In the experiment, the volunteers used a VDT to carry out a divided attention Stroop task.³⁴ Before starting the Stroop task, the volunteers had to read a text on paper, give it a title, write four key words and remember them, demanding both the storing and processing of information. Under the paradigm of simultaneous tasks, the memory capacity of the volunteer was measured by remembering the four words. Finally, they filled in a questionnaire. This task design includes the essential characteristics of office work with a VDT: a high demand of memory,³⁵ divided attention³⁶ and the coexistence of information on paper and screen.³⁷

The register of data used to evaluate the indicators of visual demand was carried out with four tasks: 1 – reading on paper, 2 – reading from a screen (Stroop task), 3 – socializing and 4 – a questionnaire filling.

Photometric and environmental study of subjective answers and ocular analysis

The methodology for data gathering can be divided into four main stages: 1 – physical and photometric data, 2 – participant's subjective response, 3 – glare index and 4 – register of the ocular response of the volunteers.

Photometric and environmental study. The temperature and humidity were monitored during the whole experiment, at the beginning and end of each trial by means of an LMT 8000 (Illuminance Meters LMT® POCKET LUX 2) instrument of environmental measurements.

Regarding the photometric characteristics, these were obtained from the in situ measurements carried out with an LMT luximeter with illuminance sensor on a range of 0.1 to 120.000 lux with cosine corrector

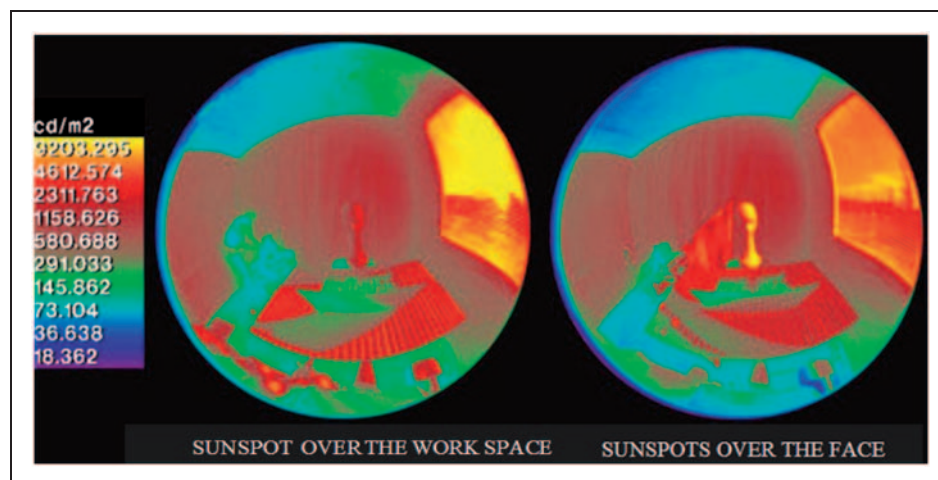


Figure 5. Luminance mapping over the work space and face.

and v lambda filter. The work space was characterized by means of an office protocol adapted from Christoffersen and Wienold³⁸ to describe the space photometrically. From this protocol the indicators were selected to evaluate the daylight quality: Horizontal illuminance, where the paper task was performed (Et), vertical illuminance at the centre of the computer screen (Ev), vertical illuminance at the centre of the window (Ew) and vertical illuminance at the eye (Ey). This last indicator is the photometric measurement which best correlates with the glare prediction.²⁸

Uniformity and mean illuminance on the workplace. Four measuring points at regular distances formed a grid at 0.85m from the floor. This allowed calculation of the mean illuminance on the workplace and illuminance uniformity by equation (1)

$$E_{min} = E_{mean}/2 \quad (1)$$

where E_{min} is minimum illuminance and E_{mean} is mean illuminance.

Participant's subjective response. The subjective evaluation of visual comfort was conducted by means of a survey which consists of semantic differentials and multiple choice questions. The survey was divided into four parts: (i) personal questions; (ii) the 'reading on paper' task, which evaluates the conditions of light necessary to carry out the task on paper; (iii) task on VDT, which evaluates the conditions of light necessary to carry out the task on the screen and (iv) environmental conditions within the room.

The glare level perceived was measured with a GSV scale³⁰ modified and divided into four points: 1 – imperceptible, 2 – noticeable, 3 – disturbing and 4 – intolerable. Perceived glare level was collected for the paper task (GSV_{paper}) and the task on VDT (GSV_{VDT}).

Glare index. The DGI and DGP indices were calculated from the luminance mappings obtained from the high dynamic range (HDR) images. A series of low dynamic range images (LDRI) were obtained with the 'Nikon Coolpix 5400' camera with a 'Nikon FC-E9' fish eye lens. Each image was taken at eye level, taking the screen as centre.

Each LDRI was processed with the 'Photosphere' program for Mac, each image was calibrated with the control luminances obtained with the luminance meter 'Minolta LS100'. Finally the HDR was post-processed with the 'evalglare' program developed by Wienold.³⁹

Register of the ocular response of volunteers. In this analysis, samples were taken from 18 people (n=18), 12 females and six males between 22 and 38 years old. In order to quantify the indicators previously described (the degree of eye opening, direction of gaze and pupil size), an eye tracker was developed in our own laboratory LAHV (Laboratorio de Ambiente Humano y Vivienda). The instrument was made up of two cameras which capture images within the visible spectrum. The image captured was in real time with cameras of 720 × 480 resolution and 30 frames/s. One of the cameras registered eye movement and the other camera registered the visual field of the observer. The scenes captured were processed with a Starburst[®] algorithm, program redesigned for the visible spectrum. It is a free and open source program.⁴⁰

Measured indicators

Direction of gaze. The directions of gaze were quantified as the vision range was distributed, so as to know if there was an angular movement with respect to the glaring source dependent on if participants were attracted to a light source, if they avoided it, or tolerated it and kept working. Direction of gaze was quantified for the four tasks. For each task the centre of the gaze was first determined. Thus, the direction of gaze

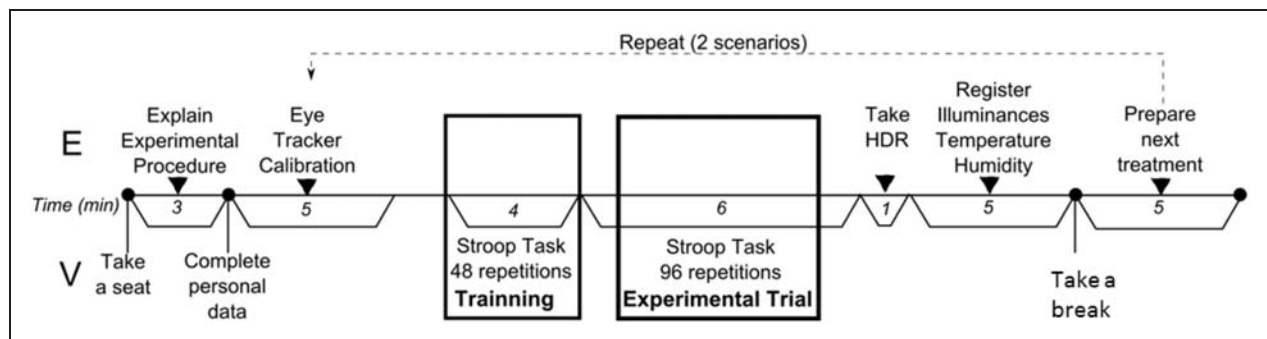


Figure 6. Experimental flux.

was quantified according to seven pre-established areas (Figure 7).

Gaze distribution was measured with the Starburst® algorithm. This software can measure the user's eye movements from videos recorded with the eye tracker cameras.

To calculate the correspondence between the eye position and the scene, the user should see a grid of nine points, a process called calibration. After calibration, a relationship can be established between the direction of gaze and the scene constructed by second-order polynomial mapping. The average error in terms of visual angle was about 1° after calibration.

The degree of opening of eye. The degree of muscle contraction around the eyes that reduced incoming light was measured based on the model by Tsao⁴¹ defined by equation (2)

$$\text{Degree of eye opening} = L/L_{\max} \quad (2)$$

where L is the level of the eye openness in the presence of a glare source and L_{\max} is the maximum height the eye can have, when totally open.

A threshold value was established by judging if the eye was open or closed: if the relation was lower than 0.2, the eye in this frame was closed, and was defined as open by the contrary (Figure 8).

Pupil size. The diameter of the pupil was measured during the Stroop task (front view); image processing was carried out with Inkscape, an open source vector graphic editor. The method proposed by Bianchetti⁴² was used. This method consists of processing eye image which defines the pupillary region. First, the image noise (shadows, light reflections) was removed. Then, a contrast image correction was conducted using a gray scale to make the image easier to process. Then, to detect the pupil edge, a threshold level was determined in order to differentiate the iris and the pupil. This threshold level should be greater than the gray level of the pupil and less than the gray level of the iris. After the edge detection, the pupil diameter was calculated from the length of the eye ratio (mm). For a greater precision, six pupil diameters were measured. The final diameter would be the diameter average (Figure 9).

Results and discussion

Photometric and environmental data

Table 1 presents mean values and standard deviation of temperature, humidity and horizontal illuminance on the working space, vertical illuminance at the eye and uniformity values.

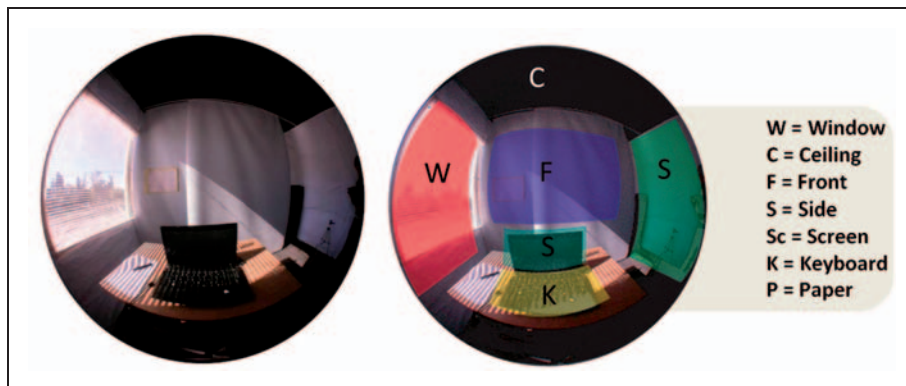


Figure 7. vision areas defined.

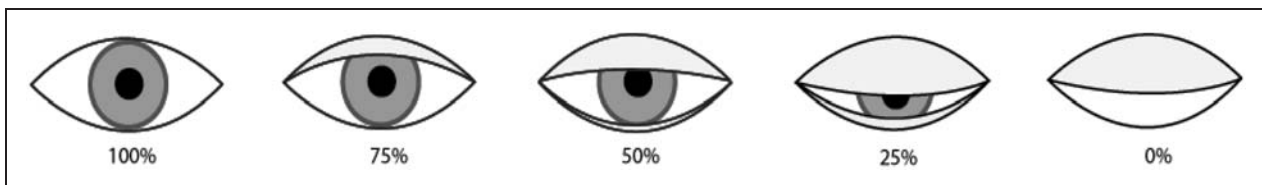


Figure 8. Different percentages of eye openness.

Both scenarios showed similar humidity and temperature. Illuminance was the environmental factor which presented the greater differences. The vertical illuminance at the eyes was superior in the SS_{face} scenario and the horizontal illuminance on the work space was superior in the SS_{desk} scenario. It should be noted that in both scenarios the horizontal illuminance on the work space was higher than usually recommended values for work with VDT and paper. An international comparison identified large variations in VDT work recommended E_h , with 500lx as the most frequent value.

With respect to the uniformity of lighting, both scenarios were defined as non-uniform, with strips of light and shade produced by the blinds.

In order to advance in the statistical analysis of the measured values in each scenario, the normality of the temperature, humidity and illuminance values on the work space and illuminance at the eye was verified with the Kolmogorov–Smirnov test. All variables were normally distributed ($p > 0.05$). On the basis of this result, parametric tests were used, the paired t -tests being the most adequate for related samples. Temperature and humidity did not show significant differences in the scenarios (SS_{face} and SS_{desk}). There were, however, significant differences in the illuminance between the two scenarios: vertical eye illuminance

($t = 5.013$, $p = 0.000$), VDT illuminance ($t = -3.234$, $p = 0.007$), workstation horizontal illuminance ($t = -2.748$, $p = 0.018$).

Subjective data and objective glare indices

The perception of glare experienced was measured with a GSV scale and with DGP and DGI glare indices. Table 2 presents mean values of the three used indices: GSV, DGI and DGP. Table 3 presents the interpretation of the glare indices.

On the one hand, the GSV scale shows that in the SS_{face} scenario, the glare level of screen reading was considered ‘disturbing’ (55.6%) and ‘noticeable’ (38.9%). Whereas in the SS_{desk} scenario, it was considered ‘disturbing’ (22.2%) and ‘noticeable’ (67.7%).

The Wilcoxon test shows that in both scenarios there are statistically significant differences in the level of glare perceived in screen work ($z = -1.848$, $s = 0.04$) and non-significant differences for the paper work ($z = -0.050$, $s = 0.617$), the SS_{face} scenario was the least satisfactory for work with VDT.

On the other hand, the DGP indexes the level of glare for the SS_{face} scenario as ‘intolerable’ (70.6%) and ‘disturbing’ (17%). For the SS_{desk} scenario, glare was ‘noticeable’ (44%) and ‘imperceptible’ (30%). The

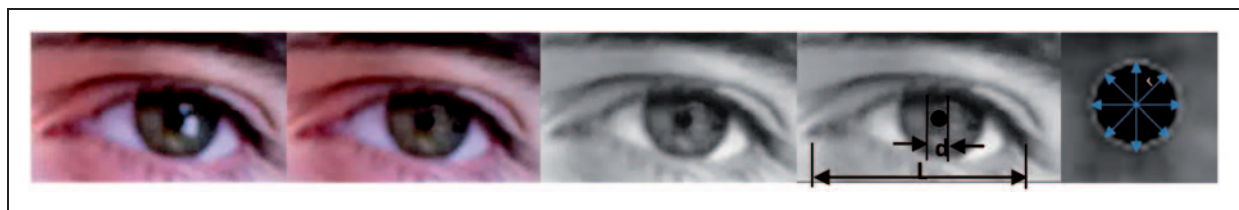


Figure 9. Procedure to determine the pupil diameter. 1. Front view of the eye, 2. noise elimination, 3. contrast correction, 4. pupil diameter determination and pupil mean diameter.

Table 1. Descriptive statistics of physical and photometric variables.

	SS_{face}		SS_{desk}	
	Mean	DS	Mean	DS
Temperature ($^{\circ}C$)	20.44	1.60	20.67	1.70
Humidity (%)	43.30	7.31	40.30	6.9
Illuminance in work space (lux)	3006.92	1225.21	5506.15	1068.38
Vertical illuminance at the eye (lux)	5406.30	813.56	2522.76	692.20
Horizontal VDT illuminance (lux)	1813.07	491.19	4827.69	1575.45
Uniformity of lighting ($E_{min} \geq E_{mean}/2$)	(587 < 1071) Not uniform		(790 < 3004) Not uniform	

E_{min} : minimum illuminance; E_{mean} : mean illuminance.

Table 2. Descriptive statistics of the glare indices.

	SS _{face}				SS _{desk}			
	GSV _{paper}	GSV _{VDT}	DGP	DGI	GSV _{paper}	GSV _{VDT}	DGP	DGI
Mean	2.11	2.5	0.49	22.98	2	2.11	0.31	22.69
Median	2	3	0.48	23.12	2	2	0.31	23.08
Mode	2	3	–	–	2	2	–	–

DGI: daylight glare index; DGP: daylight glare probability; GSV: glare sensation vote.

Table 3. 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	>28

DGI: daylight glare index; DGP: daylight glare probability; GSV: glare sensation vote.

Table 4. Correlations between objective and subjective indices.

		GSV _{paper}	GSV _{VDT}
DGP	Pearson correlation	0.307	0.247
	Sig. (bilateral)	0.068	0.146
DGI	Pearson correlation	–0.026	0.020
	Sig. (bilateral)	0.880	0.907

DGI: daylight glare index; DGP: daylight glare probability; GSV: glare sensation vote.

DGI index qualified glare in both scenarios as noticeable.

Table 4 presents that the correlation between the subjective GSV index and the objective DGI and DGP as low and not significant, reaffirming the need to find new indices for glare prediction.

Ocular data

The frequency of the change in direction of gaze, eye opening and the change of pupil size was measured in the two situations (SS_{face} and SS_{desk}) during the four tasks: 1 – reading on paper, 2 – reading on screen (Stroop task), 3 – socializing, 4 – filling out questionnaires.

Direction of gaze. The four tasks were classified according to the cognitive demand and complexity of the task in the Subjective Scale of Cognitive Difficulty⁴³ (Figure 10).

In the ‘reading on paper’ task the eye was focused on the paper. This was considered a task with a moderate cognitive difficulty and with a medium visual demand (the vision angle was displaced with respect to the glare source area). This type of exercise would fix the eye on the task paper with a low number of saccades. The participants were not focusing their vision on the window in either situation. The paired t-tests showed no significant differences in both scenarios (Table 5).

In the Stroop task, the eye was focused on the screen. This was very cognitively demanding and with a high visual demand (the angle of vision faces the glare source). This task asked the participants to keep their vision fixed on the screen, with saccades to the keyboard and a limited number of saccades to other areas. The paired t-tests showed no significant differences in both scenarios (Table 6).

Socializing was considered moderately cognitively demanding and with a low visual demand (free movement of vision regarding the glare source). A higher number of saccades were observed and many were toward the window. The paired t-tests showed no significant differences in both scenarios. Possibly because the person was free to move vision from the glare source when they wanted. For this reason both scenarios imposed the same visual demand (Table 7).

The questionnaire filling task was considered lowly cognitively demanding and with a low visual demand. The paired t-tests show that the numbers of saccades to the wall (side) and to the window were significantly higher in the SS_{desk} scenario than in the SS_{face}, whereas the number of ceiling saccades was significantly higher in the SS_{face} scenario than in the SS_{desk} (Table 8).

In the questionnaire filling task there were significant differences in gaze direction between both scenarios. This was possibly due to the low cognitive component of the task, which demanded fewer fixations on the task while allowing the individual to gaze anywhere. This increased the interaction between the visual system and the lighting environment. The cognitive demand

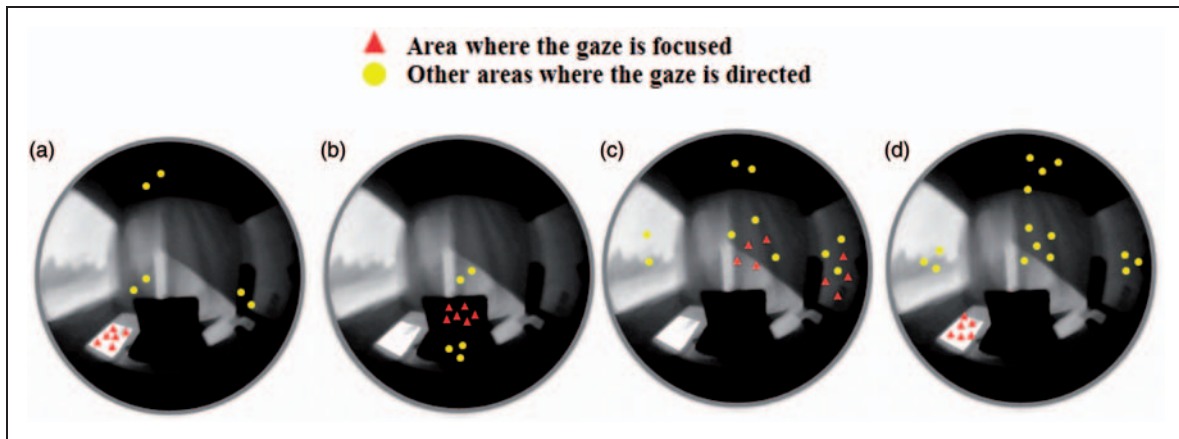


Figure 10. Gaze pattern. (a) Reading on paper task. Moderate cognitive difficulty; (b) reading on PVD task. High cognitive difficulty; (c) socializing. Moderate cognitive difficulty; (d) questionnaire filling task. Low cognitive difficulty.

Table 5. Numbers of saccades and mean comparisons (t-tests) for the reading on paper activity.

Reading on paper task Approx. time 5 min	SS _{face}		SS _{desk}		t-tests	
	Mean	SD	Mean	SD	t	p
Front saccade	0.83	0.781	1.06	1.251	-0.606	0.552
Side saccade	0.22	0.641	0.11	0.321	0.622	0.542
Ceiling saccade	0.33	0.682	0.22	0.100	0.697	0.495

Table 6. Numbers of saccades and mean comparisons (t-tests) for reading tasks on VDT.

VDT task (STROOP) Approx. time 3 min	SS _{face}		SS _{desk}		t-tests	
	Mean	SD	Mean	SD	t	p
Stroop keyboard	4.22	8.751	5.331	7.313	-0.841	0.412
Stroop front	0.17	3.836	0.392	0.580	-1.458	0.163

of the other tasks was higher, demanding the subject to maintain vision on the task thus no significant differences were found.

Finally, even though the effect of lighting could be seen on the questionnaire filling task, this did not show a significant linear correlation between saccades during the task and the vertical eye illuminance. In the SS_{face} scenario the correlation was: wall ($p = -0.68$, $s = 0.787$), ceiling ($p = 0.057$, $s = 0.869$), window

Table 7. Numbers of saccades and mean comparisons (t-tests) for the activity of thinking and saying key words.

Socializing Approx. time 1 min	SS _{face}		SS _{desk}		t-tests	
	Mean	SD	Mean	SD	t	s
Front saccade	0.85	0.514	0.94	0.721	0.622	0.542
Side saccade	1.17	0.381	1.28	0.460	-0.697	0.495
Ceiling saccade	0.83	0.514	0.83	0.510	0.000	1.000
Window saccade	0.61	0.660	0.33	0.485	1.761	0.096

Table 8. Numbers of saccades and mean comparisons (t-tests) for the questionnaire filling task.

Questionnaire filling task Approx. time 1 min	SS _{face}		SS _{desk}		t-tests	
	Mean	SD	Mean	SD	t	s
Front saccade	6.06	3.415	5.83	3.714	0.444	0.665
Side saccade	1.87	1.320	3.39	2.680	-3.04	0.007
Ceiling saccade	5.28	3.800	2.94	2.486	2.96	0.009
Window saccade	3.17	1.605	4.17	2.59	-6.000	0.000

($p = -0.196$, $s = 0.822$). In the SS_{desk} scenario: wall ($p = 0.101$, $s = 0.69$), ceiling ($p = 0.022$, $s = 0.101$), window ($p = -0.101$, $s = 0.689$).

Eye opening. The degree of eye opening was measured in the VDT reading task. The SS_{face} scenario



Figure 11. Degree of eye opening of six participants.

showed the following opening for the Stroop tasks and the reading and thinking tasks: ($M = 0.758$, $SD = 0.07$) and in the SS post-scenario ($M = 0.84$, $SD = 0.089$) (Figure 11).

The paired t-tests show that the degree of eye opening was significantly higher in the SS_{desk} scenario than in the SS_{face} ($t = 3.523$, $s = 0.003$).

A significant linear correlation was found between the degree of opening and the vertical eye illuminance. In the SS_{face} scenario results were: $p = -0.728$, $s = 0.001$ and for the SS_{desk} scenario results were: $p = -0.390$, $s = 0.049$, thus degree of eye opening is the indicator that would provide the best correlation with lighting.

Pupil size. The SS_{face} scenario showed a pupil size in the Stroop task of: $M = 4.0817$, $SD = 0.602$; in the SS_{desk} of: $M = 4.762$, $SD = 0.573$.

The paired t-tests show that the pupil size was significantly larger in the SS_{desk} situation than in the SS_{face} ($t = 4.848$, $-s = 0.000$).

A significant linear correlation was found between the pupil size and the vertical eye illuminance in the SS_{face} scenario ($p = -0.539$, $s = 0.02$). On the contrary, in the SS_{desk} scenario no correlation was found ($p = -0.269$, $s = 0.281$). This indicator presented a good correlation with lighting only in the presence of sunspots over the face, thus pupil size is a possible indicator of visual discomfort in highly lit conditions.

Correlations of ocular indicators with glare indices

The indices used to predict glare situations with natural lighting (subjective and objective) demonstrate the difficulty of achieving desired expected results. The collected subjective analyses indicate less glare than those indicated by objective methods DGP, whereas the DGI cannot show the lighting differences in both scenarios. This would indicate that while DGP overestimates glare, the GSV underestimates it.

First, as observed in Table 9, the degree of eye opening shows a statistically significant moderately negative correlation with GSV_{VDT} and a considerably significant

Table 9. Correlation of ocular indicators with the glare indices.

		GSV_{paper}	GSV_{VDT}	DGP	DGI
Opening	Pearson correlation	-0.302	-0.484	-0.610	-0.324
	Sig. (bilateral)	0.063	0.003	0.000	0.054
Pupil size	Pearson correlation	-0.387	-0.323	-0.611	-0.328
	Sig. (bilateral)	0.022	0.058	0.000	0.054

negative correlation with DGP. Expected results in relation to the lighting sources in the case studies showing the moderate predictive capacity between the subjective and objective methods. Second, pupil size showed a moderate and negative significant correlation with GSV_{paper} and a highly negative significant correlation with DGP. Although pupil size variation is a visual adaptation mechanism easily accessible for observation, the effects of the individual's workload while performing the task must be taken into account.⁴⁴

The degree of eye openness, on the other hand, is not affected by workload variation, making this physiological response as the most promising indicator of visual discomfort among those included in this study.

Conclusion

It is important to predict how solar control design could impact office spaces and more specifically on the inhabitants' visual comfort. Ocular analysis was evaluated during the performance of four typical office work tasks, with different degrees of attentional and cognitive demand. These were reading from a screen and from paper, writing and socializing.

On the one hand, the results of the analysis of the subjective test data (GSV) showed that the evaluation of the perceived glare was different in both scenarios: 'disturbing' in the SS_{face} (55.6%) and 'noticeable' in the

SS_{desk} scenario (67.6%). Although there was glare in both scenarios, there was more discomfort when the light source was over the face. Therefore, it is advisable to avoid any lighting situation that allows direct sunlight on the face.

On the other hand, the analysis of objective indices data (DGI, DGP) showed that the DGI would differentiate both scenarios, whereas the DGP would qualify glare as 'intolerable' in the SS_{face} scenario (70.6%) and 'noticeable' in the SS_{desk} scenario (44%).

The first conclusion is that the use of DGP would overestimate glare when relating to personal responses through GSV. The use of GSV, however would underestimate the personal response to glare. This situation can be due to a higher level of tolerance on the part of inhabitants of sunny climates; however, what are the consequences of this tolerance? One of the challenges in assessing discomfort glare with subjective methods such as GSV is the large variation of responses normally found when comparing individual subjects.⁴⁵ In addition, the responses of individual subjects were often inconsistent when assessing the same situation.⁴⁶ While studying the influence of window views on the subjective evaluation of discomfort glare, wide variations were found in the glare discomfort evaluation of their subjects.

Given this difference between both glare indices, it is necessary to find a new indicator that reflects the evaluated situation better in order to adequately predict lighting situations at work spaces with natural lighting.

In order to study this new glare predictor, the possible ocular indicators were first correlated (direction of gaze, degree of eye opening and pupil size) with vertical eye illuminance so as to know which indicator would better respond to the lighting conditions. The following conclusion was drawn from the results:

- Direction of gaze was intrinsically related to the type of task (cognitive demand and complexity of the task) and with the displacement of the vision angle with respect to the glare source. Filling out a questionnaire was the only task that showed significant differences in the saccade patterns in both scenarios ($t = -6.00$, $s = 0.000$). A larger number of saccades to the window were observed in the SS_{desk} scenario, which means that the person with sunspots over the face avoided the glare source (window). Whereas when the lighting is less annoying (SS_{desk}) the person would tend to direct the vision to the exterior.
- The degree of eye opening and pupil size showed significant correlation with lighting levels. The degree of eye opening for the SS_{face} scenario was ($p = -0.728$, $s = 0.001$) and for the SS_{desk} scenario ($p = -0.390$, $s = 0.049$). This was the indicator that would best predict the lighting levels. Finally, pupil size showed significant correlation in the SS_{face}

scenario ($p = -0.539$, $s = 0.02$) thus being an important indicator for this lighting situation.

- The degree of eye opening is the main indicator of glare as established by this study. A good correlation between GSV and DGP was found. Thus, the eye opening is a viable indicator and can be easily obtained which can compensate the over- or underestimates of glare prediction. Therefore, the degree of eye opening could be a good index of visual comfort under the situations of glare risk in sunny climates.

Author's Contributions

Julieta A. Yamín Garretón contributed substantially to the concept and design, acquisition of data, analysis and interpretation of data.

Roberto G. Rodriguez contributed to the acquisition and analysis of data.

Andrea E. Pattini revised the article critically for important intellectual content and approved the version to be published.

Declaration of conflicting interest

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