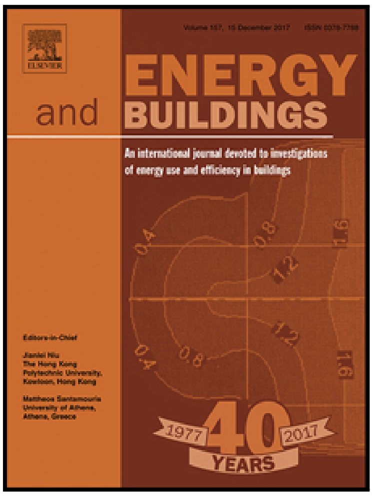

A Global Evaluation of Discomfort Glare Metrics in Real Office Spaces with Presence of Direct Sunlight

Julieta Alejandra Yamin Garretón , Elisa Margarita Colombo , Andrea Elvira Pattini

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Highlights

- A new equation was proposed for evaluating glare in offices with direct sunlight
- Absolute and relative glare values were evaluated in real working conditions
- Percentage of central and near FOV over 2000cd/m2 was tested as absolute glare factor

A Global Evaluation of Discomfort Glare Metrics in Real Office Spaces with Presence of Direct Sunlight

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Abstract

Existing glare metrics are usually tested in controlled studies and have certain limitations when predicting extremely bright scenes typical of clear sky with great daylight availability. A field-based research was carried out, where 26 real offices with direct sunlight were evaluated. Different daylight glare metrics were selected (luminance and illuminance levels, luminance ratios, luminance distribution). These were divided into two categories: "absolute glare values" and “relative glare values” following a study made by Suk et al. (2016). The contributions of these metrics about glare sensation (GSV scale) were statistically analyzed. In addition, the DGP model and uniformity values were calculated to complement this analysis. This paper demonstrates that Suk’s proposal is a viable alternative; however, the “percentage of central and near FOV with luminance greater than 2000cd/m^{2}” metric showed a better correlation with the subjective response. Finally, a glare equation based on an absolute and a relative glare factor was proposed. This model is recommended to be used specifically when direct sunlight is present in the work area.

Keywords: Visual comfort, discomfort glare, glare model, daylight, human subject study

1 Introduction

The building sector consumes approximately 40% of the world's energy [1,2]. Artificial lighting represents an important part of the total energy consumption in non-residential buildings (between 20% and 30%) [3]. Lighting is an important issue in reducing overall energy consumption [4], particularly through the use of daylight. Daylight has great potential for energy conservation in buildings, especially in sunny sky condition. In addition, this light source has important benefits on visual comfort and health. However, when daylight is not properly controlled glare problems occur, and their consequences on visual comfort.

The International Commission on Illumination (CIE) holds that visual comfort is associated with the control of the luminance distribution, illuminance, glare, the direction of the light, color temperature of light, shading, among other factors [5]. Carlucci et al. (2015) affirm that visual comfort indices study the relationship between human needs and the light environment, and they proposed a more recent classification, which evaluates a lit environment in order to achieve visual comfort: a) Glare, b) Quantity of light, c) Uniformity of light, and d) Quality of light [6]. In addition, visual comfort is characterized largely by individual differences and context [7,8]. Both definitions of visual comfort are compatible, and both consider glare as one of the most important features of an environment with clear sky and great daylight availability. For this reason, glare is one of the factors that require appropriate control during daylight hours [9], especially in offices.

Over the years, many methods have been developed to assess glare. However, the existing methods are not able to consistently predict glare problems in extremely bright scenes [10]. The most common methods found in the literature are: 1) Glare predictive models, 2) Absolute glare values such as luminance and illuminance values, 3) Relative or contrast values usually expressed as luminance ratios, and 4) Relation between absolute and contrast values.

The most validated model for daylight are the DGP index (Daylight glare probability) [11]. The basis of the DGP model is to compare areas of high luminance with respect to vertical eye illuminance. This last factor is the principal component of the equation. The DGP index performs better than the existing metrics in the presence of daylight [12,13]. However, DGP showed limitations for glare prediction in extreme sun situations, which are frequently found in sunny climates [13].

Regarding absolutes glare values, on the one hand, vertical eye illuminance is a reasonable and simple indicator for discomfort glare [11]. Many studies have been carried out to find the best way of avoiding glare by analyzing proper eye illuminance values. Different situations have shown different illuminance values, for example, reasonable threshold values for avoiding glare are accept at: between 1000 and 1500 lx [14], or values up to 2551 [15]. On the other hand, the maximum luminance value of a scene is also recommended. Some authors advise levels of up to 2500 cd/m^2 [16,17], while other values go up to 6000 cd/m^2 for avoiding uncomfortable glare and 8000 cd/m^2 for avoiding intolerable glare [18]. Another way to address the glare problem is to calculate the glare area. One study suggests that “preferred" scenes never exceed 10% of the field of view with 2000 cd/m^2 [19].

Regarding relative and contrast ratios, typical recommendations assume a 1:3 ratio between the visual task and its immediate surroundings, a 1:10 ratio between the visual task and other closer surfaces in the visual field and a ratio of 1:20 for the more distant surfaces in the visual field [20,21]. There is a lack of specification as to how to calculate this data [12]. However, a recent study made under daylight conditions showed that the ratio between the mean luminance of the task and the average luminance of the glare source showed the best correlation with subjective response. This study recommends a ratio from 0 to 22.0 for achieving an imperceptible glare zone [22].

Suk et al. (2013) argue that existing glare methods do not specify the cause of a glare issue; these methods only specify the levels of visual discomfort [23]. In order to solve this problem, they propose addressing the glare problem from the relation between absolute and relative glare values. Understanding the dominant glare factor (absolute or relative factor) could help in finding a more suitable solution for resolving glare problems.

Besides glare, uniformity also plays an important role in visual comfort. The tolerated degrees of uniformity also vary greatly, especially in climates with clear skies. Many authors recommend high levels of uniformity by avoiding sun filtration over work stations or above the visual field of the office workers, in order to achieve visual comfort [24]. However, numerous studies also support the presence of uncontrolled direct sunlight in offices. The presence of direct sunlight is related to the pleasurable effect that the entry of daylight produces [19,25].

This study was focused on discomfort glare in real working spaces with the presence of direct sunlight in sunny climates. There is a lack of consensus within the scientific community about which metric to employ and with what criteria to apply it with, especially, in spaces with direct sunlight. This lack of consensus is due to inconsistencies in visual comfort studies that support contradictory recommendations [12,26]. This analysis aims to evaluate different daylight glare metrics from the subjective point of view of the office workers, and, in this way, understand which metric best evaluates glare sensation. The selected metrics were: luminance and illuminance levels, luminance ratios, luminance distribution, which are divided into two categories: "absolute glare values" and “relative glare values” following the study by Suk et al. (2016).

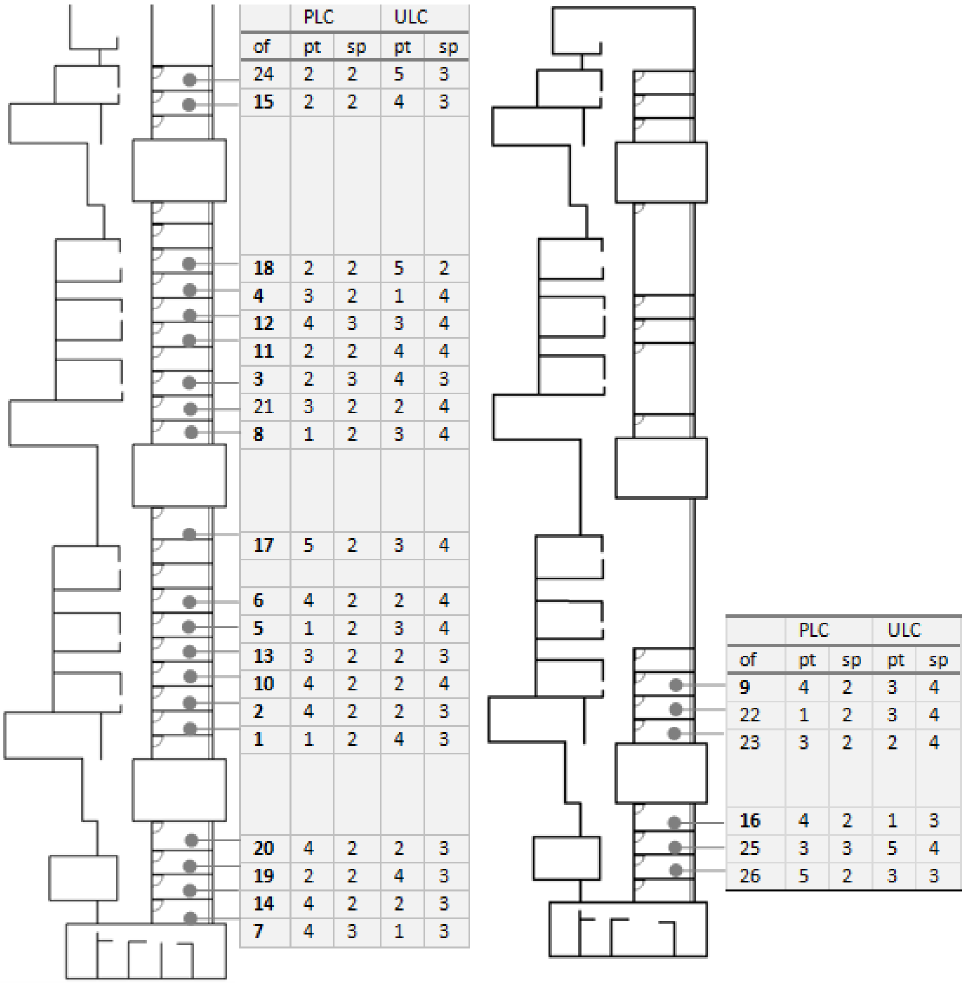
2 Methodology

A field-based research was carried out, where a total of 26 participants were evaluated in two lighting conditions, obtaining a total of 52 tests. This sample size is recommended by IEA [27], in order to obtain any significant conclusion from post-occupational studies. Participants were all postgraduate students, 7 male and 19 female, the mean age was 27.00 (SD= 3.01) and only 8 subjects wore glasses.

The offices were located in the scientific and technological center, CCT-Mendoza, Argentina, on the ground and first floor oriented towards the east (Figure 1). The total area of each office is 4.62x2.32m, with a window bay of 1.56x1.8m, composed of three panels of glass (Figure 2). The solar shading devices in all of the offices were horizontal movable exterior sun shades (Louver 12 cm, white color, reflectance r=0.85) (Figure 3 and 4), and the shading device element that varies in each office were the curtains which cover the first pane of glass. Curtains were fully open in all offices during the experiment period.

The investigation was done between 8:30 and 11.00 in the morning during the month of September and October 2017. In this period of time the highest income of sunspot was registered. Each participant was asked to perform the experimental task at the VDT (Visual Display Terminal), and afterward to answer a brief survey. In the meantime, photometric measurements were taken by the researchers (table 1).

These offices were evaluated under clear sky conditions, which were characterized by the presence of direct sunlight in the working environment and the only light source was the window. Participants had to evaluate two lighting conditions under different shading setting: 1) Preferred lighting condition (PLC), where blinds were adjusted to the subject's own preferences and 2) Unfavorable lighting condition (ULC), where the blind were adjusted to achieve the highest glare level. The highest glare level reported was in a short period of time due to the dynamism of the daylight sources. The order of exposure to the two lighting conditions was switched in order to avoid order effect.



	PLC		ULC	
of	pt	sp	pt	sp
24	2	2	5	3
15	2	2	4	3
18	2	2	5	2
4	3	2	1	4
12	4	3	3	4
11	2	2	4	4
3	2	3	4	3
21	3	2	2	4
8	1	2	3	4
17	5	2	3	4
6	4	2	2	4
5	1	2	3	4
13	3	2	2	3
10	4	2	2	4
2	4	2	2	3
1	1	2	4	3
20	4	2	2	3
19	2	2	4	3
14	4	2	2	3
7	4	3	1	3

	PLC		ULC	
of	pt	sp	pt	sp
9	4	2	3	4
22	1	2	3	4
23	3	2	2	4
16	4	2	1	3
25	3	3	5	4
26	5	2	3	3

Figure 1: Location of offices in the building plan: (of) office number, (pt) period of time in which each office was measured: 1 (8:30-9:00), 2 (9:00-9:30), 3 (9:30-10:00) 4 (10:00-10:30) 5 (10:30-11:00), and (sp) slats position : 1 (0º), 2 (15º), 3 (45º), 4 (90º).

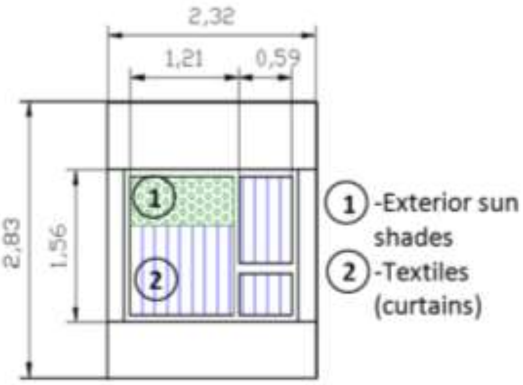


Figure 2: Interior view of windows.

Figure 3: Office facade.

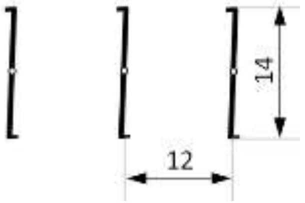


Figure 4: dimension of the sun shades.

2.1 Experimental procedure

Table 1 described the sequence of activities developed during the experiment, as well as the approximate time each stage required.

Stage	Tasks of the researchers	Tasks of the volunteers	time
1	Explain experimental procedure		5min
2	Register photometric data (HDR, Luminances, illuminance, temperature, humidity)	Complete personal data (demographic, personal factors)	5 min
3		Reading task	10 min
4		Survey (Glare assessment and additional question)	5 min

Table 1: Experimental procedure.

After the participants complete their personal data, they performed a reading task, the text was typed in 12pt, Arial, double-spaced and color black; and the background was white.

2.2 Subjective Assessments

The assessment methods selected for visual comfort were semantic differentials and multiple choice questions. Some questions of the survey were based on the procedure described by Christoffersen and Wienold [28]. Four relevant questions focused on glare and uniformity was asked for this study:

Q1 seeks to measure the level of perceived glare. It was measured with GSV (Glare sensation vote) scale [29]. This method originates from the work of Hopkinson [30]. GSV scale is an ordinal scale of four points: 1-imperceptible, 2- noticeable, 3- disturbing and 4-intolerable. The participants must associate the degree of perceived glare with this four points scale. Participants should evaluate the total level of perceived glare, including glare from windows, from direct sunlight as well as reflections from the screen. The survey included a definition for each point on the scale, where the four glare categories were linked to an approximate period of time that a given source of glare would be tolerated. Q2 asks participants the level of comfort associated with the magnitude of perceived glare. Q3 asks participants to be aware of the presence of the sunspots at their work space and the lack of uniformity and Q4 to the association of this lack of uniformity.

Q1: What is the degree of glare experienced while reading the screen?
Imperceptible /noticeable/disturbing/intolerable

Q2: How do you assess the perceived glare?

Very uncomfortable / very comfortable (Five point scale)

Q3: Which factors influence the assessment of your luminous environment?

Spots of direct sunlight / insufficient illumination / Shadows / Lack of uniformity (yes/no)

Q4: How do you assess the lack of uniformity?

Very uncomfortable / very comfortable (Five point scale)

2.3 Objective Measurements

2.3.1 Temperature and Humidity: The temperature and humidity were monitored during the field-based research by means of an LMT 8000 environmental measurement device.

2.3.2 Predictive Glare Models: DGP index was calculated with Evalglare software [15]. This program is able to calculate the mean luminance of the scene, the source luminance, the position of each glare source and the solid angle subtended by the source from the HDRI (high dynamic range images). Luminance mappings were obtained from HDR images, and these images were the basis for calculating glare. First, the LDRI (low dynamic range images) were obtained with a “Nikon Coolpix 5400” camera with a fish-eye lens (Nikon FC-E9). Each LDRI was taken at eye position, facing to the center of the VDT. In addition, the exposure variations of the LDRI images were achieved with a fixed aperture size (f/4.0), varying only exposure time (1 s to 1/2000 s) and with the ISO sensitivity fixed at 400 [31]. Each image was processed with the “Photosphere” software for Mac. No vignetting correction was performed; however, each image was calibrated with a “Minolta LS100” luminancemeter. It is important to highlight that the “task luminance criterion” was the method selected for glare source detection (with a threshold value of 5 times the mean task luminance) [32]. The cut-off-points for the DGP model are: Imperceptible (DGP < 0.35), Noticeable (0.4 < DGP <=0.35), Disturbing (0.45 < DGP <= 0.4), Intolerable (DGP > =0.45)

2.3.3 Absolute glare value:

2.3.3.1 Illuminances: vertical eye illuminance values were measured with a luximeter (model LMT Lux 2) with an illuminance sensor (in a range of 0.1 to 120000 lux) and with cosine corrector and v lambda filter. A vertical illuminance sensor was placed on a tripod at the approximate eye level facing to the center of the VDT, directly above the camera with a fish-eye lens. Vertical eye illuminance values were selected because they have a high correlation with glare sensation [33].

2.3.3.2 Luminance: Luminance values were calculated with an open source software called HDRscope (version 1.0) [34]. This program allows the user to select the portion of pixels from the HDR image with different selection tools (i.e. rectangle, circle, polygon). The polygon tool was used in this research because it allows the user a more precise selection of complex surfaces.

The indicators selected were:

-Task mean luminance, task maximum luminance, task minimum luminance, source mean luminance, source maximum luminance, source minimum luminance. The task (Figure 5a) and source (Figure 5b) areas were determined by two masks located within the field of view (FOV).

-Percentage of pixels in the selected region greater than 2000cd / m^2: The selected regions were 1- Central and near FOV: It is the area covered by the task and the adjacent surfaces. To define these areas, a 180º mask was used considering the amplitude of the total FOV. The task was defined with a 30º mask considering the amplitude of the central FOV. The adjacent surfaces were defined with a 60º mask considering the amplitude of the near FOV (figure 5c). and 2- Far FOV: this surfaces were defined with a 90º mask considering the remaining FOV (Figure 5d).

Figure 5a: Task mask

Figure 5b: Source task

Figure 5c: Central and near FOV mask

Figure 5d: Far FOV mask

2.3.4 Relative and contrast values: they were measured from the relation between the luminance of the source and the luminance of the task. The recommended values of luminance ratios are 1:10 (task: adjacent surfaces); 1:20 (task: remote surfaces) [21].

2.3.5 Uniformity: The illuminance uniformity on the work plane was calculated as a ratio of the minimum illuminance to the average illuminance, according to Eq. (1):

$$\text{Uniformity ratio}=Eh_{min}/Eh_{avg} \quad (1)$$

Where Eh_{min} is minimum desk illuminance; and Eh_{avg} is average desk illuminance.

The CIBSE guidelines recommend a minimum uniformity ratio of 0.8 [35]. The horizontal illuminance values on the workstation were calculated from five measuring points which were located at regular distances. These points formed a grid at 0.85 m from the floor. One sensor was located in the center of the keyboard and the other four were equidistant to this central sensor (approximate distance between sensors 30cm).

2.3.6 *Brightness:* The brightness ratio between the screen and the surroundings was calculated in order to know if the brightness affects the glare perception. The brightness-luminance relationship was calculated with Bodmann and La toisson model [36,37] according to Eq. (2):

$$B = \; ct \; [L_t^n - \; S_1 \; (\emptyset) L_b] \quad (2)$$

Were B is brightness, Lt is task luminance, Lb is background luminance, $\emptyset$ is the angular subtense of the test field and ct and s1 were model coefficients ($\emptyset$ =10º, ct = 30.74 and s1 = 0.27)

3 Results

The 52 lighting condition were classified using the GSV scale (Glare Sensation Vote) in scenarios defined as: imperceptible, noticeable, disturbing and intolerable. This classification is used in most of the results presented. The indoor temperature recorded in the experiment was within the thermal comfort ranges (19ºC – 26º).

Figure 6 shows luminance mappings of some of the offices evaluated according to their GSV, it also shows the location of the glare sources as well as their intensity variation.

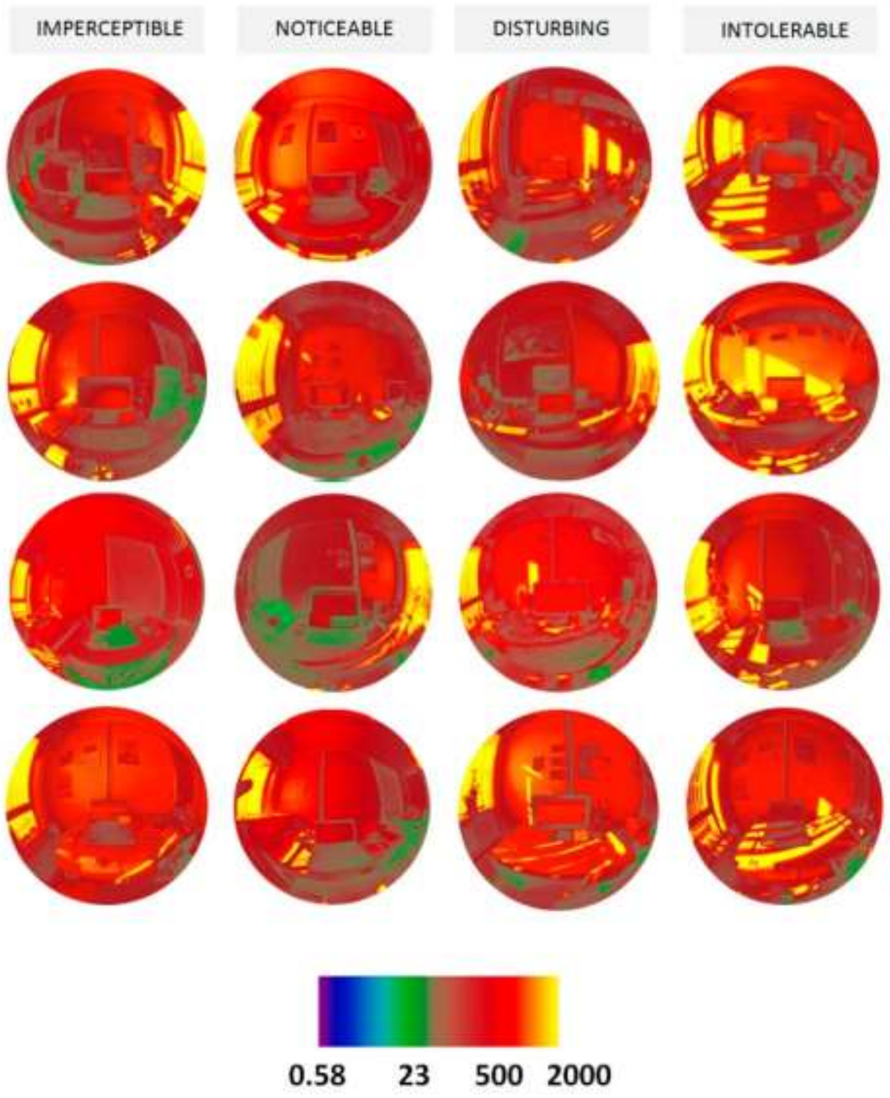


Figure 6: HDR with luminance mappings

3.1 Illuminance uniformity

The calculated uniformity values were compared with those perceived by the participants through percent agreement method, in order to assess the consistency and accuracy of this metric [38]. This method was used because the uniformity values were treated as dichotomous variables (perceived uniformity: yes/no, calculated uniformity: uniform/non-uniform). The overall percentage agreement was 71%. Although the cut-off-point is 75%, the percentage agreement scores could be considered adequate, since only 13 of the 52 scores differed between the two groups. In addition, the percentage agreement of the “imperceptible”, “noticeable” and “intolerable” scenarios was around 75% (table 2). Meanwhile, the percentage agreement of the “disturbing” scenario was 58%.

In order to evaluate qualitatively the uniformity values, mode values were obtained. Mode values (table 2) showed that the non-uniform offices of the "imperceptible" scenario were evaluated as "comfortable", while the non-uniform offices of the other three scenarios were assessed as “uncomfortable”. These results showed that the lack of uniformity was considered as comfortable when glare was imperceptible. These results need further validation studies because the sample was not large enough.

	Calculated uniformity (Percentage of response)		Perceived uniformity (Percentage of response)		% of agreement by scenario	Mode Q3	
	Uniform	No-uniform	Uniform	Non-uniform		Uniform	Non-uniform
Imperceptible	55%	45%	78.6%	21%	74%	1-2	2
Noticeable	33.3%	66.6%	58.33%	41.66%	75%	3-4	4
Disturbing	16.6%	83.3%	25%	75%	58%	4	4
Intolerable	42.9%	57%	35.7%	64%	78%	3-4	4

Table 2: Percent Agreement between perceived and calculated uniformity values and mode values of Q3 question (uniformity assessment): (5) Very uncomfortable (4) Uncomfortable (3) neutral (2) Comfortable (1) Very comfortable.

3.2 Glare

The first part of the experiment consisted of adjusting the blinds. When participants achieve their preferred lighting conditions (PLC), they chose “imperceptible” glare values (56%) and “noticeable” glare values (46%) (Noticeable glare levels were considered as comfortable). Moreover, when participant achieve their unfavorable lighting condition (ULC), they allowed “disturbing” glare values (46%) and “intolerable” glare values (56%). Q2 question (comfort level) allows us to confirm that the “imperceptible” and “noticeable” scenarios were considered as comfortable and very comfortable and the “disturbing” and “intolerable” scenarios as uncomfortable and very uncomfortable.

Table 3 provides mean and standard deviation values of calculated glare (DGP model, absolute and relative glare metrics) and its correlation with perceived glare (GSV scale). The mean and standard deviation values were calculated for the four categories of glare (Imperceptible, Noticeable, Disturbing and Intolerable).

		PLC				ULC				GSV
		Imperceptible		Noticeable		Disturbing		Intolerable		
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	r
Absolute glare	DGP	21.92	3.04	24.08	3.80	40.08	20.79	63.21	31.89	0.61
	E-eye	610.30	216.02	1286.15	732.69	5102.46	3778.84	19630.9	10856.5	0.55
	L_s_min	451.33	210.08	673.07	150.52	1439.08	647.75	1893.65	1207.57	0.63
	L_s_max	12283.3	6656.5	14808.2	13169.8	18115.8	16125.8	38247.1	37039.1	0.37
	L_s_mean	3201.11	1546.6	3124.65	1431.17	5005.45	3274.53	4049.92	1993.60	0.22
	L_s_%2000_C	0.33	0.34	1.11	0.33	3.51	2.14	7.53	4.21	0.71
	L_s_%2000_F	3.10	1.70	3.38	1.77	3.39	1.49	5.97	3.74	0.37
Relative glare	Ls_mean/Lt_ min	325.14	311.51	220.86	151.80	291.62	204.01	297.19	208.61	-0.1
	Ls_mean/Lt_ max	15.74	8.31	8.52	3.94	18.24	10.76	4.99	3.95	-0.3
	Ls_min/Lt_mean	27.22	11.14	26.75	19.26	72.14	77.18	56.56	68.98	-0.05
	Ls_min/Lt_max	2.80	1.62	2.12	1.57	8.42	12.73	1.99	1.31	0.36
	Ls_min/Lt_min	56.13	52.23	51.92	54.82	106.62	98.37	120.76	93.12	0.41
	Ls_mean/Lt_mean	3.7	2.02	9.09	3.51	25.13	14.12	45.18	32.98	0.66

Table 3: Glare metrics (mean standard deviation and Pearson correlation coefficient). E-eye (illuminance at the eye),L_s_min (minimum source luminance), L_s_max (maximum source luminance), L_s_mean (mean source luminance), L_s_%2000_C (percentage of central and near FOV with 2000cd/m2), L_s_%2000_F (percentage of far FOV with 2000cd/m2).

	PLC		ULC			PLC		ULC	
p	E-eye	E-window	E-eye	E-window	p	E-eye	E-window	E-eye	E-window
1	300	51000	5455	65232	14	900	88130	12488	71500
2	750	75000	16000	55102	15	850	25690	1850	39850
3	835	22000	8000	59630	16	1150	41260	2725	68455
4	850	73210	10589	61210	17	920	67195	9000	42590
5	700	58025	8952	89130	18	840	81456	1201	79123
6	800	75120	24545	61250	19	600	30990	8000	45568
7	550	74520	25045	43200	20	1100	81280	11000	80233
8	850	44500	14589	68000	21	1200	88570	1850	69800
9	200	81260	35869	71400	22	600	15230	7000	29450
10	340	71450	70624	58690	23	2600	45620	3562	38000
11	644	54000	6523	78560	24	1360	68955	2430	76523
12	689	79560	14589	67900	25	3000	67850	5563	78025
13	596	68600	11565	45790	26	1600	69450	7896	65000

Table 4: Vertical eye illuminance values and exterior vertical illuminance values (at the window level) of each participant.

The calculated glare following the DGP model shows a value less than 0.35 for “imperceptible” and “noticeable” scenarios, which is equivalent to an “imperceptible” value. The data shows that the threshold between “imperceptible” and “noticeable” is not near 0.35. However, it should be remembered this figure is an estimate and in order to move the thresholds of the scale, a greater number of cases as well as more validation studies are needed. For "disturbing" and "intolerable" scenario the calculated glare coincides with the perceived glare, however the correlation between DGP and GSV was moderate ($r=0.59$; $p=0.04$). Because of this, it can be concluded that DGP model is not enough to predict glare when direct sunlight is present in the work area. For this reason, the metrics listed in table 3 were evaluated to develop a suitable glare model.

Pearson correlation coefficient was calculated in order to know the association level between the selected metrics and the glare sensation. Regarding absolute glare metrics, the metrics that showed a significant correlation with glare sensation (GSV) were "Ls_min", with a moderate correlation values ($r > 0.6$), and "Ls_%2000_C", with a high correlation values ($r > 0.7$). With respect to luminance ratios, the only one metric that showed a better correlation with the subjective response was "Ls_mean/Lt_mean", with a moderate correlation level ($r > 0.6$). These values are in accord with the statistical benchmark that considers correlation coefficients above 0.7 as high and coefficients higher than 0.4 as moderate [39].

After the correlation analysis, a linear regression was performed for each of the three selected metrics: the minimum luminance of the source (Ls_min), the percentage of central and near FOV with luminance greater than 2000cd/m^2 (Ls_%2000_C) and luminance ratios between source mean luminance and task mean luminance (Ls_mean/Lt_mean) (table 5).

	CI	F	*p*	R	R^2
(Ls_min)	95%	33.7	0.001	0.63	0.40
(Ls_%2000_C)	95%	52.5	0.001	0.71	0.51
(Ls_mean/Lt_mean)	95%	39.36	0.001	0.66	0.44

Table 5: Simple regression model.

The R^2 values showed in table 5 indicate that 50% of the total variation in glare sensation can be explained by "Ls_%2000_C" metric, 44% by "Ls_mean/Lt_mean" and 40% by "Ls_min". These three metrics alone contribute effectively to the prediction of glare ($p<0.001$), however, for a better prediction of the dependent variable (GSV), two multiple regression models were used in later analysis.

Before testing the multiple regression models, Tukey post hoc tests (From ANOVA analysis) were calculated (Table 6). Tukey test determine if there were significant differences among the four glare categories (imperceptible, noticeable, disturbing and intolerable) for selected absolute glare metrics (Ls_min, Ls_%2000_C) and relative glare metric (Ls_mean/Lt_mean).

(I) GSV	(II) GSV	*p*		
		Ls-min	Ls-%2000-C	Ls-min/Lt-mean
Imperceptible	Noticeable	0.821	0.052	0.923
	Disturbing	0.003	0.020	0.002
	Intolerable	0.000	0.000	0.000
Noticeable	Disturbing	0.034	0.010	0.012
	Intolerable	0.002	0.000	0.003
Disturbing	Intolerable	0.695	0.003	0.956

Table 6: p values of Tukey post hoc tests

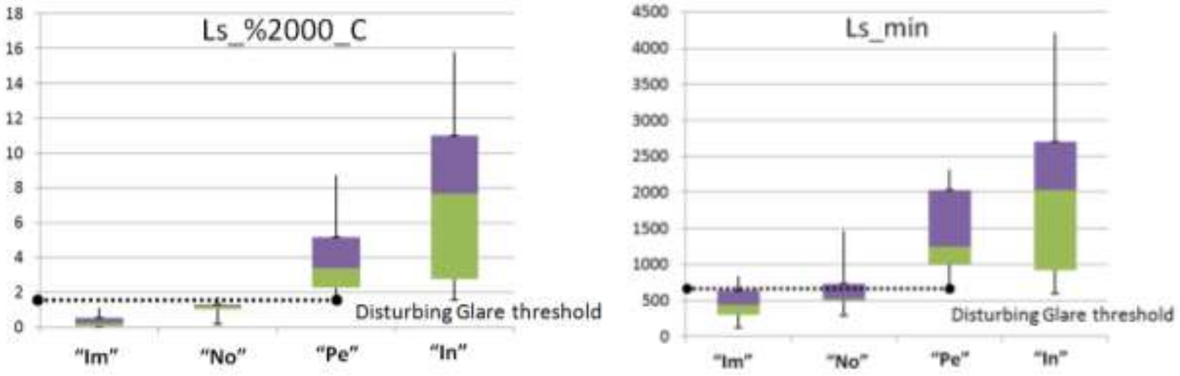
Tukey post hoc test reveals that glare sensation vote was statistically significantly different between the four scenarios for (Ls_%2000_C) metric. On the contrary, there were not significant differences between “imperceptible” and “noticeable” scenario and between “disturbing” and “intolerable” scenario for “Ls_min” and “Ls_mean/Lt_mean” metrics.

Figures 7 a-b-c show box-plot graphs for the three selected glare metrics: Absolute glare metrics (Ls _%2000_C and Ls_min) and relative glare metric (Ls_mean / Lt_mean). The box-plot graphs reflect minimum, 25th, 50th, 75th percentiles, and maximum glare values for each range of glare (imperceptible, noticeable, disturbing and intolerable). Also, the interval plot show the glare ranges for different glare categories and the threshold value for avoiding “disturbing” glare (the borderline between comfort and discomfort glare). The threshold values found were:

-Ls-%2000-I: less than 1.9% of the central and near FOV with 2000 cd/m2.

-Ls-min: less than 626 cd/m2 of minimum source luminance

-Ls mean /Lt mean: Glare ratio between task and glare source below 1:15.



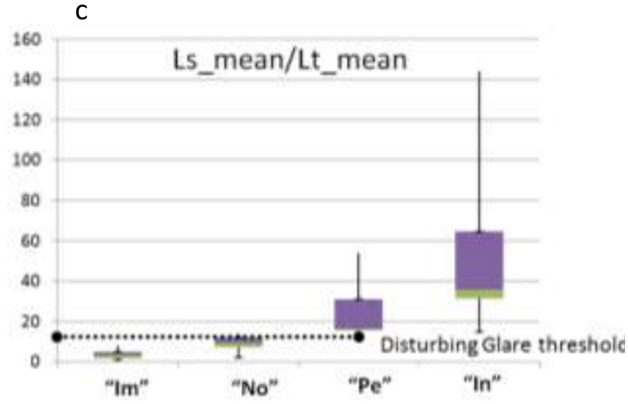


Figure 7-a-b-c: Selected glare metrics (y-axis) and perceived glare through GSV scale (x-axis).

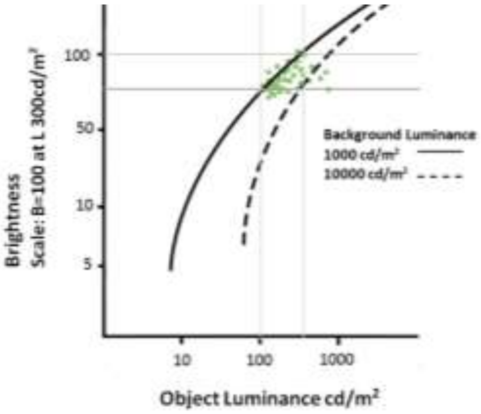


Figure 8: Brightness as a function of task luminance and background luminance.

Finally, two multiple regression models, Model 1 and Model 2, were tested to improve the prediction of the dependent variable (GSV) (Table 7). The first independent variable introduced into Model 1 was "Ls_min", which represents the absolute glare factor, and the second independent variable introduced was "Ls_mean/Lt_mean", which represents the relative glare factor. This first model includes the variables proposed by Suk et al. [22] and both variables showed an acceptable R^2-values. Furthermore, the first independent variable introduced into Model 2 was "Ls_%2000_C", which represents the absolute glare factor, and the second independent variable introduced was "Ls_mean/Lt_mean", which represents the relative glare factor. This second model was proposed in this study because "Ls_%2000_C" showed a high R^2-value (Figure 9) and their mean values were statistically significantly different between the four scenarios.

An absolute glare factor was introduced into the two models as the main independent variable, and a relative glare factor as the second independent variable. While both variables are involved in every glare condition, absolute glare factors are more dominant than relative glare factors [22].

Model	Dependent variable	Independent variable	CI	F	*p*	R	R^2
1	GSV	(Ls_min) (Ls_mean/Lt_mean)	95%	34.71	0.001	0.76	0.58
2	GSV	(Ls_%2000_C) (Ls_mean/Lt_mean)	95%	42.11	0.001	0.79	0.63

Table 7: Multiple regression models

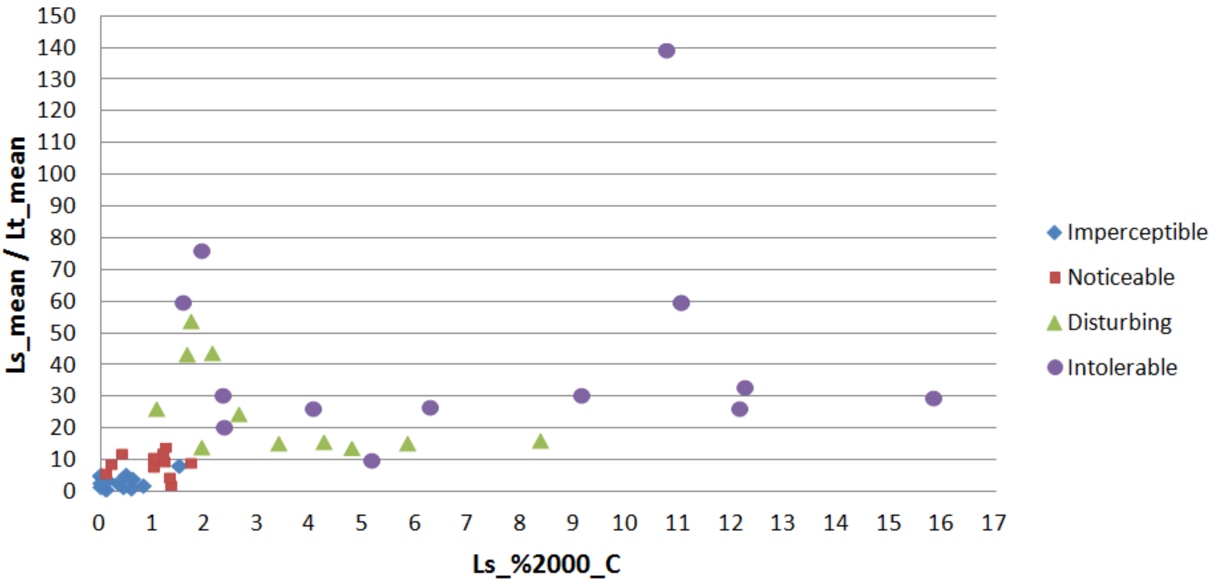


Figure 9: Relationships between absolute and relative glare for each participant.

The following regression equation (3) was obtained from the multiple regression analysis (model 2).

$$GSV = 1.61 + 0.152 * Ls\%2000C + 0.019 * \text{Ls\_mean/Lt\_mean} \qquad (3)$$

Where $Ls\%2000C$ is the percentage of central and near FOV with 2000cd/m^2, and Ls_mean/Lt_mean is luminance ratio between the luminance of the source and the luminance of the task.

This model tries to simplify the evaluation of the glare, specifically when direct sunlight is present in the work area in central and near FOV. However, this model needs more validation studies, and needs to be tested in more controlled laboratory situations.

4 Conclusions

In the present paper, a field-based research over 26 offices is described. The 26 offices were evaluated based on absolute and relative glare metrics and uniformity values. The primary advantage of field-based research is that occupants are performing real work tasks under dynamic lighting conditions and they are not influenced by the ‘Hawthorne effect’[40].

The main results of this work showed that DGP model had a moderate correlation with the subjective responses (r=0.59). For this reason, that model should not be considered as completely appropriate when applied to work places with the presence of direct sunlight. Regarding uniformity values, the level of comfort related to the illuminance uniformity was closely linked to the perceived glare. The non-uniformity was considered as pleasant for "imperceptible" glare, while for the other three scenarios was considered as pleasant.

The focus of this article was the glare metrics. The most promising metric to evaluate glare was Ls_%2000_C. This metric highlights the importance of the location of the glare source in the observer's FOV. Glare sources that are closer to the work area have greater weight on glare sensation, while the influence of the glare sources in the distant surroundings is much less. The other two metrics suitable for evaluating glare were those proposed by Suk [22]: Ls-min as absolute glare value and Ls_mean / Lt_mean as relative glare value. These two metrics showed a good fit with the responses of people in real spaces.

Finally, in this study a regression equation is proposed to simplify the evaluation of the glare. This equation includes the percentage of central and near FOV over 2000cd/m^2 and a contrast value. This model is recommended to be used specifically when direct sunlight is present in the work area. However, it is important to point out that the proposed model needs more validation studies under controlled laboratory conditions.

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