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Daylight glare evaluation with the sun in the field of view through window shades

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ABSTRACT

This paper provides new insights on daylight glare evaluation for cases with the sun in the field of view through window shades. 41 human subjects ($n = 41$) were tested while performing specific office activities, with 14 shade products of different openness factors and visible transmittance values (direct and total light transmission characteristics) installed on the windows. The measured variables and survey results were used to: (i) associate discomfort glare with measured and modeled parameters (ii) evaluate the robustness of existing glare indices for these cases (iii) examine alternate illuminance-based criteria for glare assessment through fabrics, extract discomfort thresholds and suggest a new related index and (iv) propose corrections in the DGP equation coefficients when the sun is visible through the shades. The modified DGP equation resulted in the best fit; the findings show that the general form of the DGP equation is reasonable and can be adjusted to account for different cases, by clustering different sets of coefficients for different environmental conditions or fenestration systems. The new alternate glare discomfort index developed in this study, based on direct and total-to-direct vertical illuminance on the eye, captures the impact of sunlight as well as the interdependence between the fabric color, overall brightness, and the apparent intensity of the visible sun. It can simplify annual simulations, eliminating the need for detailed luminance mapping of the interior, and can be directly associated with fabric optical properties for development of design guidelines and glare-based shading controls.

1. Introduction

Visual comfort is one of the main concerns in human-centered design of interior spaces and is mostly associated with effective control of daylight glare. Several indices have been developed to quantify glare, given its subjective nature and the several factors involved with its evaluation [1,2]. Examples include DGI [3], originally proposed to describe glare from a large source as a window, and UGR [4], originally developed to describe glare from artificial sources. Vertical illuminance on the eye has been found to be the most significant factor in some studies [5,6], sometimes even outperforming more complex metrics, while other studies support luminance-based metrics. The Daylight Glare Probability or DGP [7] is considered a reasonable metric to assess daylight discomfort glare, as it simultaneously considers the overall brightness of the visual field as well as the impact of glare sources and contrast (Eq. (1)), extracted from experiments with human subjects:

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

where E_v is the total vertical illuminance, and L_s, ω_s and P are the luminance, solid angle and position index for each identified glare source respectively. The current knowledge gaps in discomfort glare analysis and remaining challenges summarized by Van Den Wymelenberg [8] show the complexity of the topic.

Shading fabrics are widely used in office spaces to improve visual and thermal comfort, control solar gains and also induce privacy when necessary. They are available in a variety of different colors, materials and weave densities and they can be manually or automatically controlled. The main optical properties that characterize shading fabrics are the openness factor (*OF*) and the visible

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transmittance (T_v); the first is an indicator of the weave density and the direct light transmission, whereas the latter indicates the portion of the visible light transmitted through the fabric, characterizing also the fabric's color [9]. Literature focusing on the impact of roller shades on visual comfort is limited and mostly consists of simulation studies; moreover, studies investigating the glare under the presence of sunlight [10], with or without shades, are certainly scarce and needed. Wienold [11] used roller shades among other shading systems to investigate DGP and DGPs, a simplified index approximating discomfort using only the total vertical illuminance as a variable (Eq. (2)) through simulation, while Van den Wymelenberg and Inanici [12] noted that direct sunlight on the work plane can increase task area luminance and result in misleading use of glare sources when following the standard DGP calculation approach. Jakubiec and Reinhart [13] concluded that more than one metric is required for quantifying glare if direct sunlight is present.

$$DGPs = 6.22 \times 10^{-5} E_v + 0.184 \quad (2)$$

Konstantzos et al. [14] presented a comprehensive analysis of DGP for roller shades, and concluded that, for all instances when the sun is not visible by the occupant, DGPs can be used to approximate daylight glare, including cases with sunlight on various surfaces in the space, for any fabric openness and control type. However, the study showed that it is still not clear whether the full DGP index is applicable for the cases when the sun is visible through shading fabrics. Due to the extreme values of the solar corona's luminance, the luminance term of DGP is inflated, predicting discomfort levels that are sometimes incompatible with everyday practice, especially for the cases of low openness fabrics.

To overcome this potential problem, Chan et al. [15] suggested an alternative dual visual discomfort criterion for roller shades based on direct and total vertical illuminance on the eye. The reasoning behind the dual criterion is that (i) a threshold for direct eye illuminance could be used to capture the effect of sunlight (or contrast), potentially substituting the luminance terms, and (ii) the total vertical eye illuminance would still be used for the overall brightness term. The proposed threshold values were 2760 lux for the total vertical illuminance (equal to $DGP_s = 0.35$) and 1000 lux for the direct vertical illuminance, as a modification of IES Standard LM-83-12 [16]. In this way, the fabric openness factor is directly associated with direct illuminance and the fabric visible transmittance is directly associated with the total vertical illuminance −therefore guidelines for selecting shade optical properties based on glare protection may be developed. Chan et al. [15] used this approach and identified the appropriate ranges of fabric properties in order to mitigate glare for different orientations, locations, glazing properties and distances from the window. For instance, it was found that, to entirely eliminate glare when seated close to the window, a fabric of maximum $OF = 2\%$ and maximum $T_v = 5\%$ should be used on south-facing facades, depending on the building location.

Fewer studies have included human subjects assessing glare through roller shades [17–19]. However, there are no studies with human subjects, either evaluating glare using different shade fabrics, focused on the actual impact of their properties to the sensation of glare with the sun within the visual field, or exploring the applicability of known metrics in such cases.

This paper analyzes daylight glare through shading fabrics with the sun within the field of view (through the shades). Fourteen shading fabrics with different light transmission characteristics were evaluated by 41 human subjects. The measured and survey results were used to associate discomfort glare with measured and modeled parameters, test the usability of existing glare indices, examine the efficiency of alternate illuminance-based criteria, and propose corrections in the DGP coefficients for the cases when the sun is visible through the shades. These results can be used for overall glare assessment through roller shades, as well as thresholds for selecting optical properties of shades to ensure glare protection.

2. Methodology

2.1. Experimental setting, measurements and instrumentation

The experiments were conducted in two identical, side-by-side office spaces with reconfigurable south-facing facades located in West Lafayette, Indiana. These are designed for quantifying the impact of facade design options and related controls on indoor environmental conditions and energy use, and were modified in order to host six isolated workstations for testing different fabrics, all facing the exterior façade from a distance of 1.30 m. The placement of the workstations was decided in order to capture the "worst case" scenario for daylight glare in office spaces (view direction), while also providing an adequate time frame of view of the sun through the fabric (distance from window) for each measuring day. All façade sections were equipped with a SB70XL-clear high performance glazing unit (60% window-to-wall ratio) with a selective low-emissivity coating (visible transmittance: $\tau_v = 65\%$ at normal incidence). The partitions were approximately 1.70×2.40 m, separated by fully opaque dividers having the same color as the walls of the facility. Fig. 1a shows a typical experimental setting for each office space, separated in three workstations (6 total), while Fig. 1b shows a detailed geometry for each partition.

Several LI-COR calibrated photometers were used to measure illuminance levels during the experiments, for data acquisition and validation purposes. The latter were used in the exterior (mounted on the roof and south wall) measuring the external horizontal and vertical illuminance, on the interior of the glass, measuring the transmitted vertical illuminance through the window, and in a small distance next to the subjects' heads, measuring the total vertical illuminance on their eye level. (visible in Fig. 1a). For the latter, a Konica T-10s illuminance meter was also utilized as a secondary sensor for reasons of validation, taking a single reading for each measured data point from the exact position of the subject's head. This addition was essential as it could (i) indicate erroneous readings of the Licor sensor due to accidental misplacement to the side etc., (ii) correct the readings of the Licor sensors in some cases of morning or late afternoon measurements and (iii) evaluate the validity of the HDR images through comparison of the extracted vertical illuminance. The latter were obtained by a calibrated Canon T2i HDR camera, and were used to map the luminance distribution of the visual field (see section 2.4). Direct and diffuse portions of incident solar radiation on the façade were also measured with a SPN-1 solar pyranometer, mounted vertically on the exterior south wall. These readings were used to calculate the direct portion of vertical illuminance on the eye, after also correcting for the angular properties of the glass and each fabric (see section 2.3). The sensors were connected to a data acquisition and control system (HP Agilent and Labview), accessible through remote access in order to run experiments without interfering with indoor lighting conditions.

2.2. Shading fabrics

The purpose of this experiment was to evaluate glare sensation with the sun visible through roller shades (fabrics), therefore the selection of fabric types and properties was critical in order to be able to produce results that cover a wide range of products/optical properties, to generalize the study findings. Roller shades consist of different fabric materials with varying degrees of openness and transmission characteristics, both affecting direct and diffuse light transmission, which in turn have an impact on daylight provision,

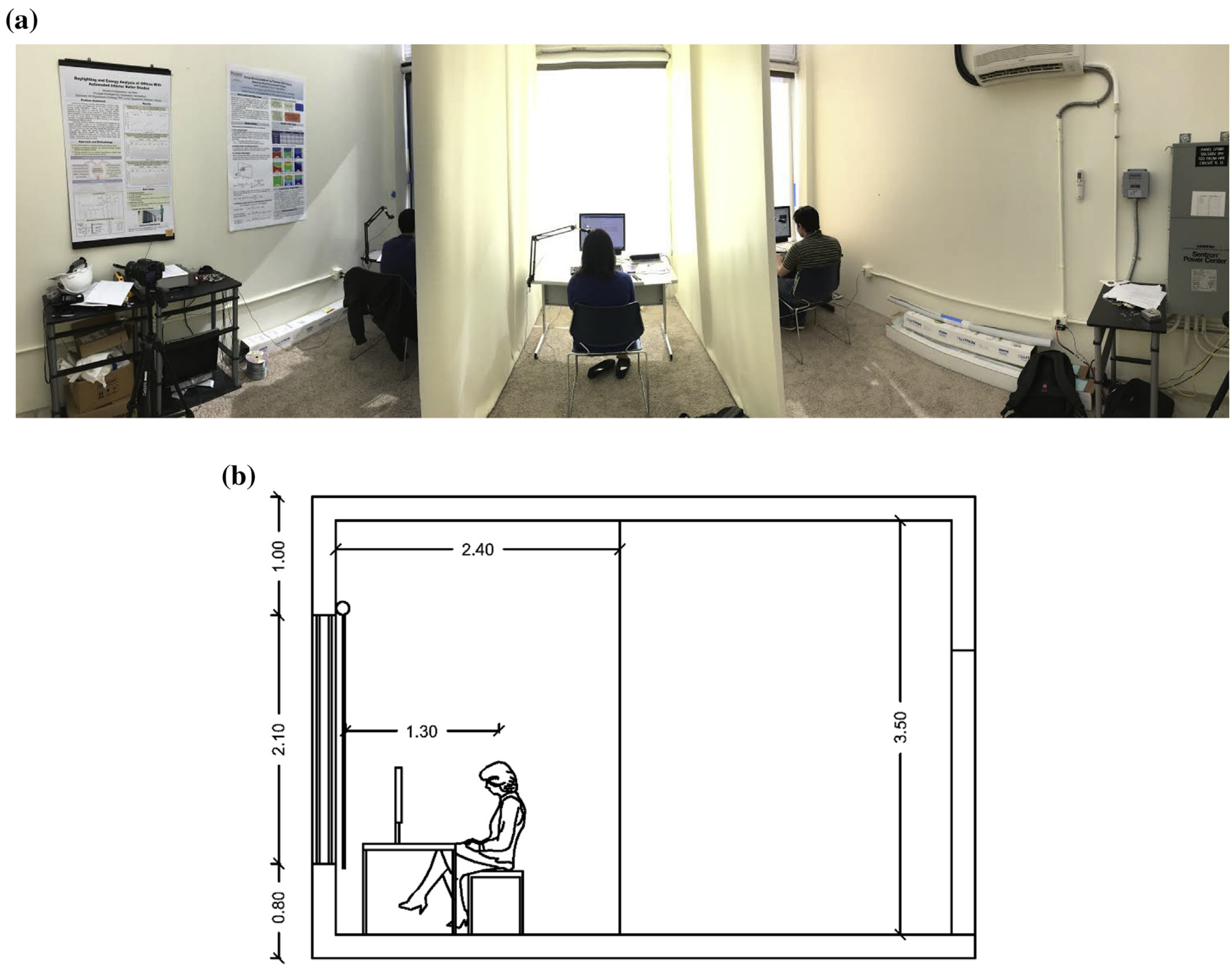


Fig. 1. a: Experimental layout of one of the two identical offices used for the study with three partitioned workstations, each equipped with a different shade. b: Cross section of each of the partitions of the experimental setting; distances of subjects from the glass, depth of partition in the room, and total window and room height (in meters).

visual comfort and energy use.

A careful selection of 14 different fabrics was made for the tests. Their properties covered a wide range of *OF* and T_v values, and shades of white, black and grey. The selected combinations capture the entire range of interest with no specific pattern/relationship between the properties, given realistic limitations. 12 of the fabrics were in the low and middle range of openness factor (0.7%–4.3%), while two of them had high openness ($OF \approx 7\%$). The reasoning behind this selection was to confirm that fabrics of high openness would always lead to conditions of glare, and essentially focus on the lower end of the spectrum to closely observe patterns and thresholds. The basic optical properties of the selected fabrics (openness factor and visible transmittance) were measured in detail using an integrated sphere. They were codenamed using letters for reasons of procedural flexibility. Their basic properties are listed in Table 1.

2.3. Angular fabric transmission properties and direct vertical illuminance on the eye

The angular optical properties of the glazing system were calculated by WINDOW 7.0 software [20]. Shades also have angular light transmission characteristics, which can be modeled either using detailed BSDF data or the semi-empirical model originally proposed by Kotey et al. [21]. The latter is discussed in detail and further validated using integrated sphere measurements and full-scale experiments by Tzempelikos and Chan [22]. This model, which proved to be accurate and reliable for several types of standard (PVC-coated and vinyl) fabrics, calculates the beam-beam and beam-total visible transmittance angular variation as a function of the incidence angle and the normal *OF* and T_v properties, provided by manufacturers. The latest version of EnergyPlus [23] includes this angular model in the “window thermal calculation module”, as part of the new “equivalent layer fenestration model”. In summary, the angular beam-beam shade transmittance (τ_{bb}) is calculated from:

$$\tau_{bb}(\theta) = \tau_{bb}(0) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \frac{\theta}{\theta_{cut-off}} \right) \right)^b \tag{3}$$

where θ is the solar incidence angle, τ_{bb} (0) is the beam-beam transmittance at normal incidence, assumed equal to the *OF* of the fabric (provided by manufacturers), and b and $\theta_{cut\text{-}off}$ are parameters that depend on τ_{bb} (0), as explained in Kotey et al. [21].

Table 1
Fabric codes and respective measured optical properties.

Code	A	B	C	D	E	H	I	J	O	P	Q	R	S	T
OF (%)	2.6	0.7	1.6	3.7	2.3	3.9	7	6.7	1.65	4.36	1.15	0.85	1.87	0.95
T_v (%)	2.8	6.4	13.7	4.1	6.6	15.9	7.5	13	7.63	8.57	1.43	12.29	2.18	6.62

The angular beam-total transmittance (τ_{bt}) is calculated from:

$$\tau_{bt}(\theta) = \tau_{bt}(0)\cdot(\cos\theta)^d, \ \left\{\theta < \theta_{cut-off}\right\} \tag{4}$$

where τ_{bt} (0) is the beam-total transmittance at normal incidence (total visible transmittance provided by manufacturers) and d is a parameter that depends on openness factor and total visible transmittance. The cut-off angle should not be applied to light-colored fabrics, to account for direct light scattering at higher angles, while small corrections might be needed for dark-colored fabrics [22]. The beam-diffuse transmittance, necessary for accurate modeling of light transfer through shades, is then equal to τ_{bt} -τ_{bb} for each angle. Finally, integrating τ_{bt} over the hemisphere yields the diffuse-diffuse shade transmittance (τ_{dd}), which cannot be measured or calculated otherwise.

In contrast with total vertical illuminance, which is directly measured, there is no standard way to measure direct vertical illuminance on the eye of the observer (induced by the sun through the glazing and shading) without interfering with the experiment. Instead, the measured transmitted illuminance through the glazing was separated into direct and diffuse parts using the direct/diffuse ratio obtained by the SPN1 pyranometer, while the incidence angle θ was computed for each respective measured data point. The shade angular transmission model, described above, was then used to calculate the direct and diffuse illuminance through each fabric at each measurement time. In this way, we achieved a reliable estimation of the direct portion of vertical illuminance on the eye with each of the tested fabrics, for the selected position and view direction of the observers. This measurement is needed to evaluate vertical illuminance thresholds and alternate glare criteria when the sun is within the field of view.

2.4. HDR imaging

For the calculation of the luminance-based metrics, the overall luminance mapping of the visual field of the subjects was measured once for each case of subject and partition (355 images in total). A Canon Rebel T2i camera was used, equipped with a Sigma 4.5 Fisheye lens. Due to the main objective of this study, all measurements were taken with the sun being included within the visual field, leading to severe overexposure problems. To overcome the latter, a Wratten ND 3.0 neutral density filter was used, mounted between the fisheye lens and the CCD sensor of the camera as suggested by Stumpfel et al. [26]. To compensate for the dark conditions created by the filter, a strategy of slower exposures (9 in total) was selected for creating the HDR images. A Konica LS110 luminance sensor, a calibrated LMK Canon 550 HDR measurement system and a Macbeth Color Checker Test target were used for obtaining the camera's response curve. A script was created in order to automatically perform all the stages of HDR imaging, from creating the images from the pictures based on the extracted response function, to cropping and resizing appropriately and then running Evalglare [27] to calculate the metrics of interest such as DGP.

Since for each measuring point the camera had be to set up at the exact same point with the occupant's head, each case showed slight differences in terms of absolute camera position (due to height differences of the subjects, minor differences in the distance from the screen each subject was choosing, etc.). For that reason, and to avoid inconsistencies between observations due to assuming a fixed uniform task area for all DGP calculations, a fixed glare identification threshold approach was followed instead in Evalglare, using the threshold of 2000 cd/m^2, which has been found to correlate well with human responses [12]. The selection of the specific threshold was to some extent validated by the responses of the subjects for question 7 of the questionnaire, where they were asked to point out any sources of discomfort within the visual field; assuming lower thresholds (for example 500 or 1000 cd/m^2) would most of the times identify as glare sources several parts within the visual field that subjects would not consider as sources of distraction whatsoever. As validating the readings would require an instrument with luminance measuring range exceeding the order of 10^7 cd/m^2, a validation in terms of vertical illuminance (Fig. 2) was

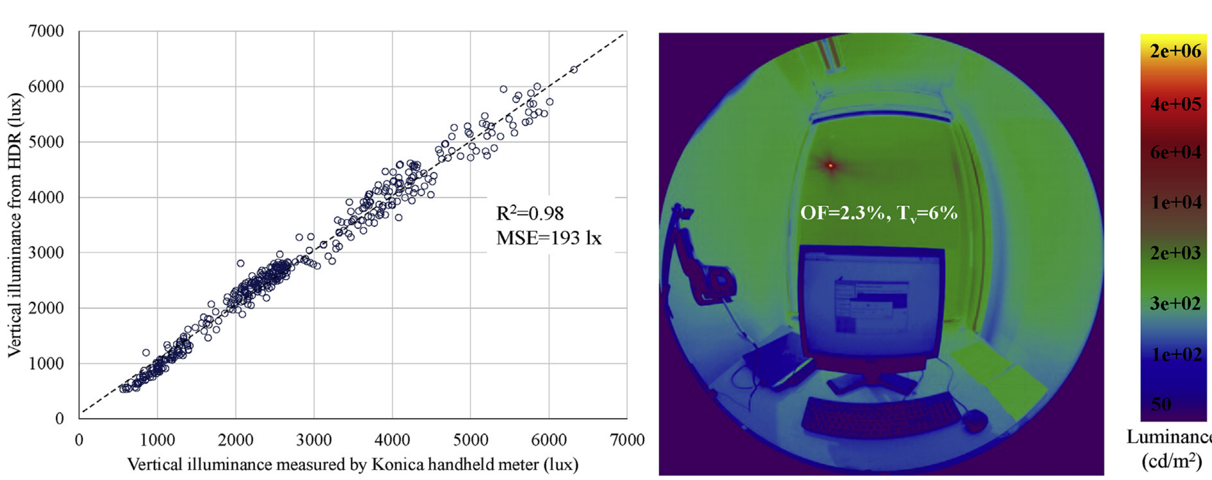


Fig. 2. Validation of HDR imaging in terms of vertical illuminance (left); HDR image of a partition with fabric E indicating the luminance distribution including the sun visible through the fabric (right).

performed for all of the images. A MSE of 193 lux was calculated and considered satisfactory given the severe conditions (extreme solar corona luminance being partly diffused through the fabric) and the high values of vertical illuminance measured throughout the study.

2.5. Experimental procedure, tests and surveys

The experiments were conducted during sunny days from December 2015 until March 2016. Winter conditions were selected to utilize low sun angles, so that the sun is visible through the fabric during the entire test periods, in order to evaluate glare sensation under the worst case scenario situations (exterior vertical illuminance on the window was above 70,000 lux). An IRB approval (#1410015323) was obtained in order to recruit human subjects to participate in the study. In total, 41 different subjects participated in the experiment, 25 male and 16 female, all graduate students, while care was taken to achieve the maximum possible diversity in terms of ethnicity. On each test day, the experiments lasted 2–4 h depending on the number of test subjects and variability in the sky conditions (stable clear sky conditions were necessary for these tests). The test subjects evaluated 6–14 fabrics during each measurement day. The shades were randomly deployed in each workstation every day, although care was taken to ensure a complete range of fabric properties to be present in each measuring day, diminishing the possibility of bias as much as possible.

Each subject was initially assigned to a workstation/partition, in which they would spent 15–20 min. This duration should satisfy the need for proper adaptation to the conditions while also providing adequate time to perform specific tasks. The objective was to simulate regular office activities, including free and time-sensitive tasks. For that reason, the time was split into 3 main parts, including free web browsing period, a character count test and a reading comprehension task, in which subjects had to complete a short questionnaire (Fig. 3). As the main reason for including the specific tasks was to make the subjects focus on their screens (performing computer-related activities while the sun is within the field of view through the fabric), the task performance of the subjects is outside of the scope of this study. Towards the end of the session, each subject was asked to lean aside in order for the investigator to place the camera and the handheld sensor in the exact position of the subject's head and shoot the 9 used exposures while also taking a reading with the handheld illuminance sensor. In this way, the luminance distribution of the visual field plus a total vertical illuminance reading were acquired for each combination of subject and fabric. As the conditions were assumed to remain constant throughout the 15–20 min of the evaluation (due to the clear sky, only negligible fluctuation was observed in the exterior and transmitted illuminances), the readings of the camera and the handheld sensor were assumed to capture the conditions of the entire stay in the partition. At the end of the test period, the subjects were asked to proceed to the second part of the short questionnaire (Questions 4–8), commenting about their visual comfort sensation.

- Question 4 was a 7-point scale satisfaction with the visual conditions (from 1- very unsatisfied to 7- very satisfied)
- Question 5 was a 4-point glare vote (from 1- imperceptible to 4- intolerable) about their overall perception of glare (including any possible source of it, the sun, the fabric, reflections on the desk or within the room, etc.). Keeping the same scale as in the original DGP study [7] allows a systematic comparison with previous results.
- Question 6 asked about the level of distraction because of the presence of the solar disc within the visual field. (4-point scale from 1- imperceptible to 4- intolerable)
- Question 7 requested the subjects to indicate the sources of visual discomfort, if any, on a photo of their workstation, and
- Question 8 asked about whether the subjects felt they were affected by the heat from the sun during their stay in the partition (7-point scale from 1- not affected at all to 7- very affected). The contents are out of the scope of this study, but may be useful in future for thermal comfort evaluation near roller shades.

In total, 425 data points were recorded, with each point being a subject evaluating a fabric. Among these, 355 observations were considered reliable and were used for the main part of the glare evaluation results. The rest were not used, mainly due to (i) subjects that appeared to be entirely insensitive to any change of conditions (ii) data with Fabrics I and J in Table 1 that were used just to confirm that high *OF* or T_v will always result in uncomfortable conditions.

3. Results

3.1. General impact of fabric properties on glare

In order to investigate in more detail the extent to which the two main fabric properties affect glare sensation, Fig. 4 shows the behavior of all tested fabrics in terms of the votes obtained by Question 5 (4-point scale overall glare), with the fabrics appearing in order of increasing openness factor. The yellow dots indicate the averaged responses with the median noted by the blue line, while the boxes illustrate the distribution of the results. The two fabrics of high openness factor, I and J, are the only ones with averaged responses that always lie within the discomfort zone, while their distribution is clearly distinguished from the rest of the fabrics. In addition, it has to be mentioned that, while all other 12 fabrics produce a relatively continuous range of direct illuminance, from 119 to 2228 lux, the latter two produce values that lie on an entirely different range (from 2940 to 3558 lux). This inconsistency in terms of ranges, combined with the clear discomfort responses obtained for the two fabrics led to their elimination when it came to the calculation of thresholds or other quantification attempts presented in the next sections.

In order to evaluate the validity of the experimental approach, an analysis of variance was conducted, where the subjects were used as a blocking factor with random effect. However, as described in section 2.5, the logistic complexities of the study, due to the random sequence of days with clear sky prevented the approach of a complete within-subject design, where every subject would end up having evaluated every fabric on the same day. For that reason, care has been taken for each subject to encounter a complete range of visual conditions, with respect to direct and total vertical illuminance (which in terms of fabrics can be translated to openness factor and visible transmittance). Within that scope, for the needs of the analysis of variance, the treatments were considered to be four different classes of openness factor and visible transmittance, as shown in Table 2, as well as the interaction between them.

Table 3 shows the ANOVA results for the two overall comfort related questions and for a confidence level of 95%. As expected, the blocking factor (subjects) appears to be significant at all cases, pointing the differences between individual subjects and the fact that due to the low resolution of the responses (seven points for question 4 and four points for Question 5), it is expected that for a given condition, the responses will be distributed among more than one votes. For both questions 4 and 5 (overall satisfaction/glare perception), both independent variables (classes of *OF* and T_v)

Subject Code: _______

Fabric Code: ________

Time: _____________

Date: _____________

QUESTIONNAIRE

Please read carefully every task and follow the order:

***1.** As you enter the partition, please be seated and start using the computer. You can do anything you like, as long as it is done <u>on the computer</u>. You can browse the internet, check your e-mail, plug in a flash drive to access your files etc. Keep doing that for about 5 minutes or until you are told to proceed to 2.*

***2.** Open the .doc file named "Character search" which is located on your desktop. This is a paragraph of random characters. We need you to carefully go through that and count the appearances of the character you'll find in the back of the Fabric code paper. When you finish that, please write the number of appearances in the box below. Be aware that the character asked is **lower case**!*

Number of appearances of ___ : ☐

After you're finished with that, proceed to 3.

***3.** Open the .doc file named "Reading comprehension 1" on your desktop. It contains a short passage you have to read carefully, and answer the three simple questions below that. Please mark your answers in the boxes below this line:*

Q1:	Q2:	Q3:

After you're finished with that, or if you're asked to, you can return to your free computer activities until you're told to turn the page and proceed to questions 4, 5, 6 and 7, related to your comfort. Please try to be as accurate as you can in your responses. and continue to the next page.

***4.** Were you satisfied with your visual conditions (<u>brightness, contrast</u>) over the time you spent in this partition.*

Very unsatisfied ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very satisfied

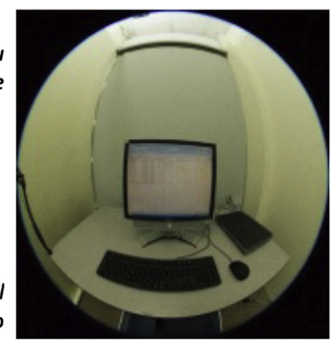
***5.** Grade the visual discomfort (glare level), if any, that you experienced **overall** (any type of visual discomfort: bright objects, high overall brightness, contrast, reflections, shades, etc.) during your stay in the partition, considering that this situation can happen for varying amounts of time in your regular office.*

- ☐ *Imperceptible (No feeling of glare – conditions help me focus)*
- ☐ *Noticeable (I can clearly feel some glare, but it doesn't really bother me or distract me)*
- ☐ *Disturbing (The level of glare is high and can distract me from work after a while)*
- ☐ *Intolerable (I experience high glare/discomfort and I cannot focus on my work)*

***6.** Grade the visual distraction, if any, that you experienced during your stay **specifically due to having the sun visible through the shade fabrics,** considering that this situation can happen for varying amounts of time in your regular office.*

- ☐ Imperceptible (No distraction – conditions help me focus)
- ☐ Noticeable (I can clearly feel some distraction, but it does not really bother me)
- ☐ Disturbing (The level of distraction is high and can influence my ability to work after a while)
- ☐ Intolerable (I experience high distraction and I cannot focus on my work)

***7.** The fisheye picture below includes what should approximately be your field of view at the time of your stay in the partition. Please mark with X symbols the areas from which you experienced discomfort (**if any**). You can mark as many areas as you want.*



***8.** Did you feel affected by the heat of the sun during your stay in this partition?*

Go to page 2 ---------> Not affected at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very affected

Fig. 3. Questionnaire used in the study and task-related information.

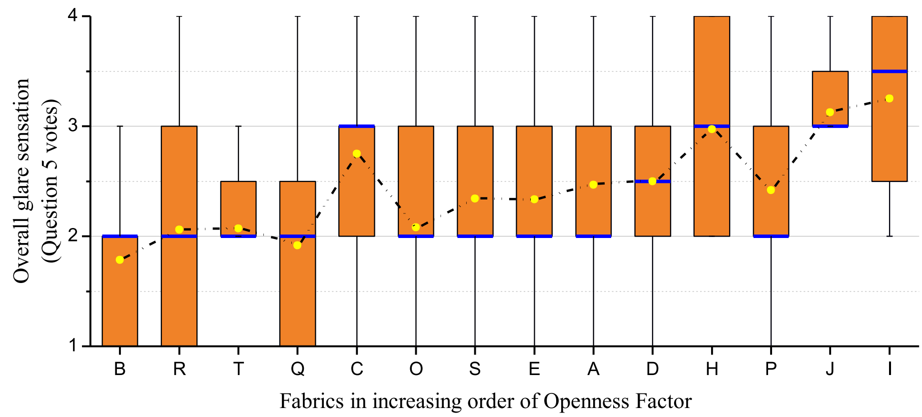


Fig. 4. Distribution of responses for Question 5– overall glare sensation (fabrics listed in order of increasing openness factor).

Table 2
Classes of fabric properties used in ANOVA.

Class	OF (%)	Tv (%)
1	0–1.1	0–5
2	1.1–2.2	5–10
3	2.2–3.3	10–15
4	3.3–4.4	15–20

Table 3
ANOVA results.

	Variable	df	Sum of sq.	Mean square	F Value	p-value
Question 4	*Subject*	35	257.827	7.366	3.29	<0.0001
	OF	3	74.500	24.833	11.08	<0.0001
	Tv	3	33.454	11.151	4.98	0.0022
	OF x Tv	3	14.037	4.679	2.09	0.1018
Question 5	*Subject*	35	50.138	1.433	2.44	<0.0001
	OF	3	19.449	6.483	11.02	<0.0001
	Tv	3	12.956	4.319	7.34	<0.0001
	OF x Tv	3	2.148	0.716	1.22	0.3034

appear to be statistically significant, thus having a strong impact on both visual satisfaction or the overall perception of glare. This result underlines the need for the inclusion of both parameters (in the current or an equivalent form, such as direct and total illuminance) for any discomfort predictor, something that is followed in the next sections of this study. Their interaction, however is not significant, demonstrating the reality of different combinations of *OF* and T_v potentially leading to similar levels of glare sensation (for example a very dense fabric of very high transmittance or a very open black fabric).

3.2. Vertical illuminance, DGP and respective comfort ranges

As described in section 2.5, there were three questions including classic comfort votes, one from a positive aspect (visual satisfaction) and two from a negative aspect (glare and visual distraction). The authors consider the four - point glare scale as defined by Wienold and Christoffersen [7] to be an effective way to assess discomfort. This, combined with the fact that one of the metrics of interest was DGP, led to a 4-point range extraction for the three main metrics investigated (total vertical eye illuminance, direct vertical eye illuminance and DGP) –and their combinations, as shown later. As the objective was to associate the overall sensation of glare with measurable metrics, Question 5 was considered to be most suitable. This decision was corroborated by the fact that, as expected, there was a strong correlation between the responses of Questions 5 and 6 ($R^2 = 0.74$) and Questions 4 and 5 ($R^2 = -0.75$).

Fig. 5 shows the association of the three measured metrics with visual discomfort according to the responses of Question 5. The selected fabrics indeed resulted in a wide variation for all metrics, which was important for the analysis. More specifically, direct vertical illuminance ranged between 119 and 2228 lux; total vertical illuminance varied between 588 and 5940 lux; and DGP ranged between 0.26 and 0.62 (note again here that exterior vertical illuminance on the windows was in the order of 80,000–100,000 lux). The standard way to extract thresholds based on the four-point scale requires the mean, standard deviation and upper and lower bound confidence intervals need to be calculated for each vote and for each metric. Although there are clear differences between the different votes, the distribution of the data for each vote did not always approach normality at the desired level, while for the cases of votes 1 and 4, the number of points was significantly lower (Fig. 6 – left). Therefore it was preferred to follow a dichotomous approach (grouping the votes into two groups – comfort for votes 1 and 2 and discomfort for votes 3 and 4), which gives two more equivalent data groups of 211 and 144 points respectively (Fig. 6 – right).

The results are shown in Fig. 7. Table 4 shows the descriptive statistics for these dichotomous votes and the lower bound 95% confidence interval for the discomfort group, which indicate the corresponding thresholds for the border of discomfort. The results show that the direct vertical illuminance discomfort threshold for the cases of roller shades and the sun present is around 870 lux. This result provides a first validated insight about the acceptable ranges of direct vertical (sun) illuminance, as recent studies attempt to use a discomfort threshold of around 1000 lux [15,24] based on recommendations for direct illuminance on the work plane found in IES LM-83-12 [16]. The threshold cannot be generalized however for other types of shading or daylighting devices without conducting similar studies with these systems. As discussed later, none of the three metrics proves to be appropriate to capture the fluctuation of discomfort by itself, therefore none should be acting as an individual predictor for this special case of conditions.

For the other two metrics, the results show a noticeable agreement with some previous studies; the discomfort threshold for total vertical illuminance lies in the order of the discomfort threshold for DGP_s (~2800 lux), while the discomfort threshold for DGP was found to be at the level stated in the original DGP study (~0.4). For reference, there are three published studies that propose total vertical illuminance discomfort thresholds: Karlsen et al. [6] suggested 1700 lux; Van Den Wymelenberg and Inanici [5] proposed 1250 lux and Konis [25] suggested 1600 lux. However, these

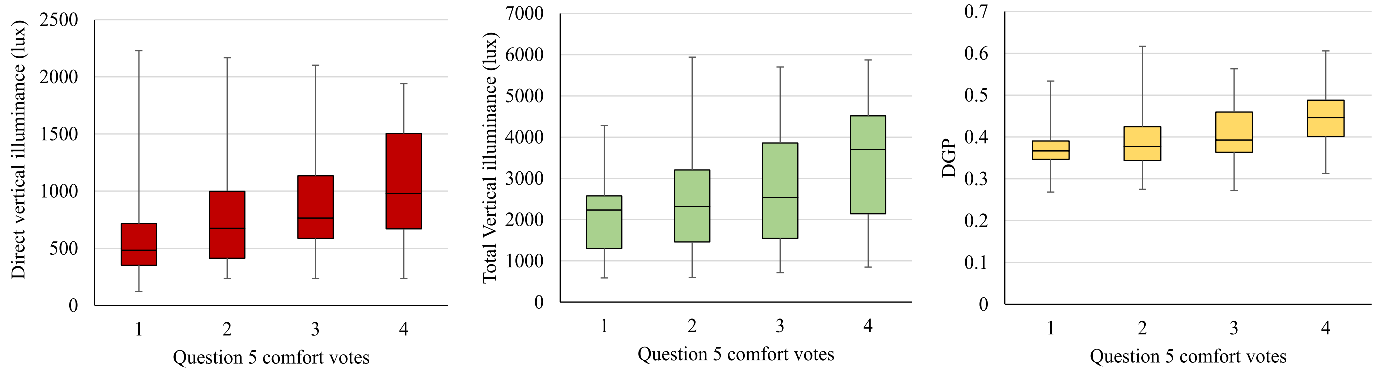


Fig. 5. Boxplots associating the responses of Question 5 with direct vertical illuminance, total vertical illuminance and DGP respectively for four-point responses.

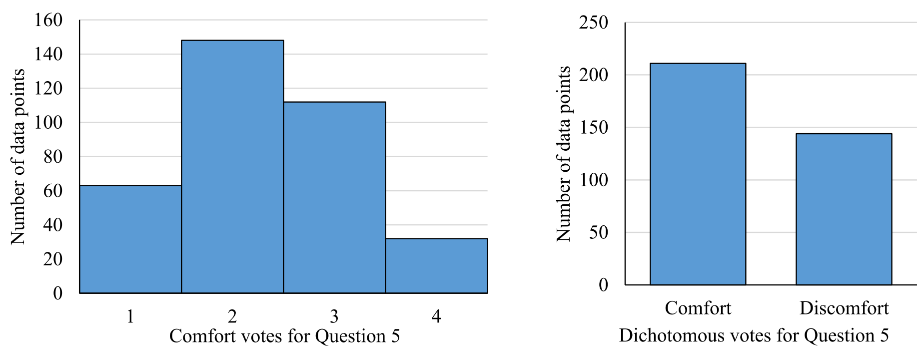


Fig. 6. Distribution of votes for Question 5 in original form (left) and dichotomous approach (right).

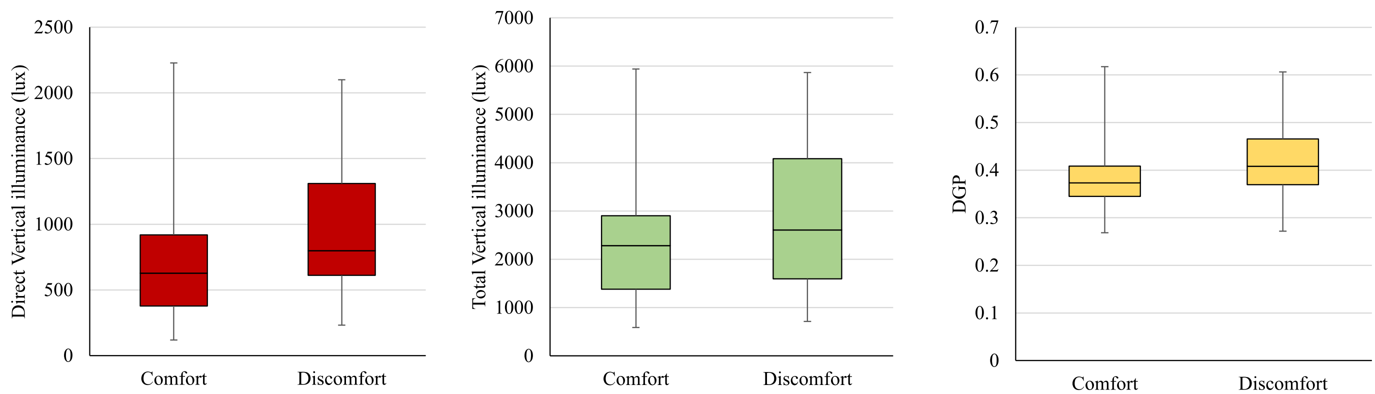


Fig. 7. Boxplots associating the responses of Question 5 with direct vertical illuminance, total vertical illuminance and DGP respectively using a dichotomous approach.

Table 4
Descriptive statistics and thresholds extraction for dichotomous approach.

	Discomfort		
	$E_{v,dir}$	E_v	DGP
Mean	947	2896	0.42
Standard Deviation	490	1420	0.07
Number of points	144	144	144
Confidence Interval (Lower bound)	80	231	0.01
Threshold	867	2664	0.41

studies used different shading systems and different discomfort scales, the presence of the sun was not consistent and the vertical illuminance ranges were not similar. This shows the need for more related studies with different fenestration systems under variable conditions.

Due to the high deviation, none of the three presented metrics is considered a reliable comfort/discomfort predictor by itself, for the studied case of roller shades with the sun present. The work presented in the next sections aims to bridge this gap.

3.3. Correlation of discomfort sensation with existing illuminance- and luminance-based metrics

The results presented in 3.2 indicate the extracted thresholds from this study's dataset. However, to effectively evaluate the extent to which a metric can capture the fluctuation of discomfort sensation, the method of ordered grouping of the data points is used. According to that, the data set is first sorted into increasing order of the metric of interest, grouped in n groups of m points per group, and then the correlation of the ordered averages of the groups and the percentage of discomfort per group is evaluated. There is some ambiguity in related literature about the correct approach for creating groups in that sense. Wienold and Christoffersen [7] split the total 349 data points into 12 groups of 29 points per group. Hirning [18] states that if the number of groups exceeds the number of data points per group, the system will be underdetermined, leading to lower correlation results, while for number of data points per group exceeding the number of groups, over-determination will occur. This topic was discussed by Karlsen et al. [6] who presented both grouping approaches and found differences in the results.

Indeed, for the data set of this study, Fig. 8 shows the “inconsistency” in terms of fit for two different group splitting logics: Allocation 1 shows an approximation of the *n* x *n* rule; as dividing the 355 points data set in *n* groups of *n* points was impossible without missing valuable data points, 19 groups were used (18 groups of 19 points and a last group with the remaining 13 points). Allocation 2 shows a split in fewer groups (12) with more points (therefore added reliability) per group (30 points for 11 groups and remaining 25 points for the 12th). Confirming the points made by Hirning et al. [18], Allocation 1 shows a considerably lower fit of the mean value of metric of each group with the percentage of discomfort ($R^2 = 0.52$) compared to Allocation 2 ($R^2 = 0.65$).

The authors of the present study consider that an increased number of data points per group would improve the validity of the results as long as a relatively low deviation around the mean would be observed for all metrics of interest for each group. Also, the same approach should be followed for the evaluation of all existing and newly developed metrics for reasons of fair comparison among them. Within that scope, the 355 total data points were split into 12 groups in total, divided to 11 groups of 30 points and 1 group of 25 points. The deviation was only slightly increased in the boundary points (1st and 12th) with that being a result of the continuity of the data set and the fabrics selection (discrete properties).

A script was created in order to sort all data points (for each metric of interest) from lowest to highest, along with the respective comfort votes, transform the four votes to a binary approach of comfort and discomfort, split the groups according to the approach described above, calculate the averages and standard deviation for each group, along with the percentage of discomfort, and then produce the respective coefficient of determination for each case. Several metrics were evaluated, including vertical illuminance (total and direct), average luminance in the visual field, DGP, UGR and DGI with different thresholds of glare sources identification. The results are shown in Table 5, while Fig. 9 shows the fit of four of the metrics of interest.

As expected, metrics that were not able to describe the influence of the peak luminance of the solar disc did not manage to behave satisfactory. Similar poor results were observed for metrics that could describe the influence of the sun but not the overall brightness (such as the vertical illuminance). UGR, which was found to perform relatively well in the study of Hirning et al. [18] and DGI, which was not found to be an adequate metric in related studies [5] showed better fits than DGP. Table 3 shows the coefficient of determination results for the evaluated metrics.

3.4. Modification of the DGP coefficients for cases with the sun in the field of view through roller shades

DGP is considered a generalizable glare index, as it simultaneously takes into account the overall brightness of the scene, expressed with the vertical illuminance term, as well as the individual glare sources using the luminance term. The overall brightness is important when it comes to cases of high vertical illuminance conditions with limited glare sources (such a fully open window inflating the task area luminance). However, the results of Fig. 8 and Table 5 show a relatively poor fit of the existing DGP index for the studied cases.

For that reason, and assuming that this inconsistency might be a consequence of the specific cases met in this study (glare through fabrics with the sun visible), we investigated whether the same form of equation could describe the current data set with a

Table 5
Evaluation of the fit of some existing illuminance- and luminance-based metrics.

	No glare sources			Threshold: 2000 cd/m^2		
Metric	$E_{v,dir}$	E_v or DGP_s	L_{avg}	DGP	DGI	UGR
R^2	0.43	0.49	0.36	0.65	0.79	0.82

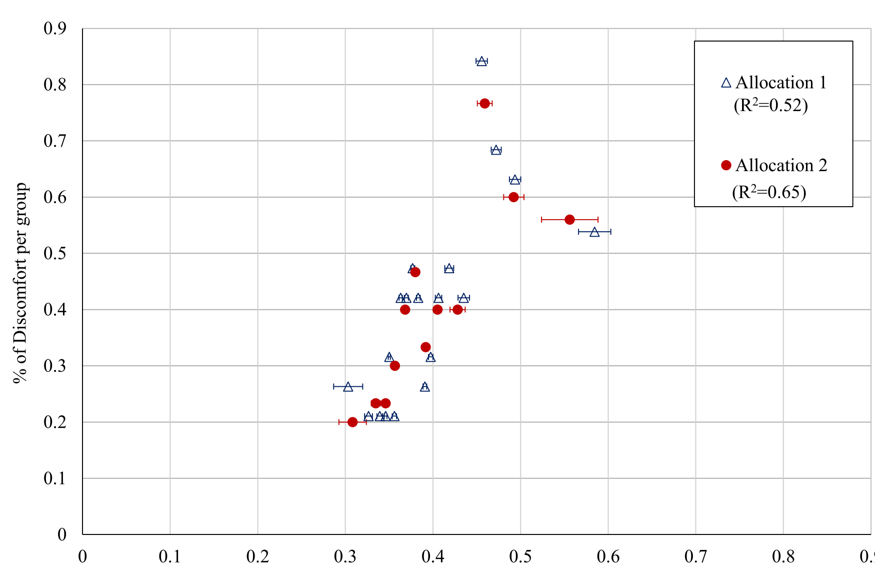


Fig. 8. Comparison of fits for DGP (2000 cd/m^2 threshold) using two different grouping approaches; Allocation 1 (similar number of groups and points per group) and Allocation 2 (low number of groups with an increased number of points per group).

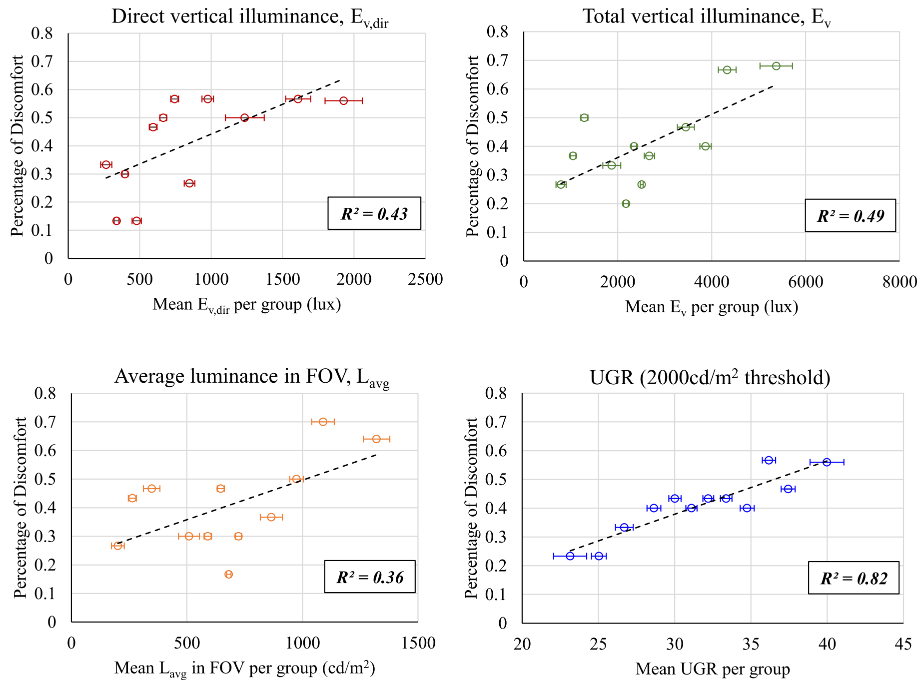


Fig. 9. Fit of different candidate discomfort predictors with the fluctuation of percentage of discomfort.

modification of its four coefficients. The number of data points was equivalent to the one in the original DGP study (355 compared to 349), therefore such an investigation would show whether indices should be fixed or if a clustering approach should be followed, having different sets of coefficients for fundamentally different kinds of environmental conditions.

An optimization algorithm was created, reading the detailed output of Evalglare, using a 2000 cd/m^2 identification threshold and applying the genetic algorithm approach, with objective to maximize the coefficient of determination for the ordered groups of the modified DGP and the corresponding percentages of discomfort. This investigation showed that the four DGP coefficients can be indeed modified in order to describe our dataset better than any of the metrics evaluated in Table 5. The resulting equation with the modified coefficients is shown in Eq. (5). Note that this equation applies to the conditions studied for this experiment. Fabrics of high openness could result to luminances of higher orders of magnitude and therefore severe disability glare, something that was not met during the experiment.

$$DGP_{mod} = 8.40 \cdot 10^{-5} \cdot E_v + 11.97 \cdot 10^{-2} \cdot log\left(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{2.12} \cdot p_i^2}\right) + 0.16 \quad (5)$$

Fig. 10 shows the correlation between DGP for each group and respective percentage of discomfort for the original and modified equation coefficients, with obvious improvements. In addition, the extracted discomfort threshold based on the techniques used in section 3.2 is calculated equal to 0.44, slightly higher than the discomfort threshold assumed for the original DGP (0.40). This structure allows utilizing the same fundamental index for cases with and without direct sunlight on the occupant, as a dual function with different coefficients. The authors believe that the general form of the DGP equation is reasonable and adequate, and can be adjusted to account for different cases. Similar approaches may be followed for other shading or daylighting systems and further studies with human subjects are needed for that purpose.

While Eq. (5) shows an obvious improvement in terms of describing this study's dataset over the original DGP equation, it cannot be safely assumed that it will demonstrate the same effectiveness in other studies with slightly different setups. This is an inevitable characteristic of comfort related regression approaches, as hidden factors can affect the results, causing a metric to over- or underperform in different attempts. Although care has been taken in order for the sample to be as random as possible, potential overfitting could never be entirely eliminated in such experiments with finite resources, in terms of recruited subjects and available time. This proves the necessity of a more generalized approach with specific ways of extracting and handling data in order to be possible to even combine different data sets, as discussed by Van den Wymelenberg [8]. That is also the reason why, while a similar approach was investigated for the other two main luminance-based indices (UGR and DGI), their fair fit with the data set in their current form made the formulation of a new modified index vague, as minor improvements in the fit are not necessarily generalizable in any other data sets in order to constitute an improvement.

3.5. Formulation of a new illuminance-based metric for assessing daylight glare with the sun in the field of view through roller shades

The final part of this study attempts to assess the efficiency and applicability of a new metric for discomfort glare evaluation, for the cases studied here, based only on vertical illuminance on the eye of the observer. While DGP (especially in its modified aspect presented above) can adequately describe discomfort with roller shades, it requires both extensive field measurements and complicated procedures (calibrated cameras with filters, automation, processing etc.), or, in the case of simulations, heavy computational load for accurate luminance mapping. Although recent computational efforts made it possible for fast calculations of luminance and DGP [14,15] with implementation of real-time,

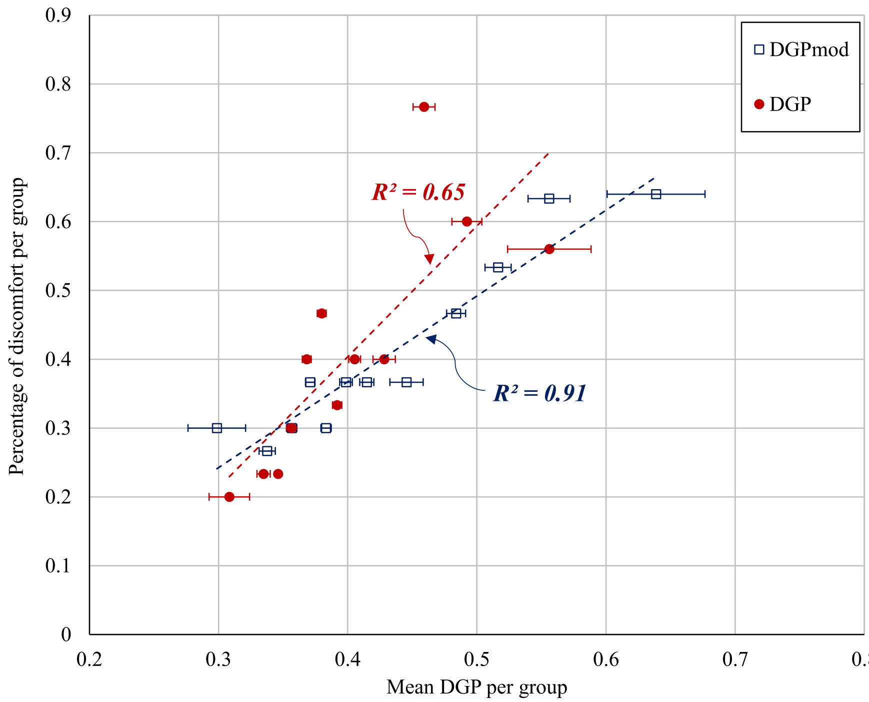


Fig. 10. Improvement of the fit of DGP using modified coefficients for the current dataset (roller shades and sun within FOV through fabrics).

model-based controls [28], illuminance-based metrics would allow faster and simpler calculations and can be directly associated to shade optical properties for development of design guidelines.

As shown in section 3.3 and in Konstantzos et al. [14], total vertical illuminance or DGP_s are not applicable in cases like the focus of this study. However, a combination of a metric that solely describes the effect of the sun (direct vertical illuminance on eye) and another that captures the overall sensation of brightness (total vertical illuminance on eye) was hypothesized to adequately capture cases including the sun in the visual field but not directly looking at it (as that case would have to be assessed as disability glare). Although the presence of possible minor specular reflections within the room cannot be captured without a detailed luminance distribution, the authors believe that in the case of fully applied shading fabrics of relatively low openness, the impact of the latter on the direct vertical illuminance on the eye is negligible compared to the part directly induced by the solar disc being in the field of view. This, combined with the fact that no highly specular surfaces were present in the experiment, led to the assumption that the impact of projected direct light (on the desk or on the side walls) could be entirely captured by the term of the total vertical illuminance. This can be corroborated by [14], where for the case of direct light projected on the interior surfaces, DGP_s (equivalent to total vertical illuminance) was proven to have a very good fit with DGP (extracted by the accurate luminance distribution). The algorithm presented previously for the modified DGP coefficients was used to associate the direct and total parts of vertical illuminance with their corresponding comfort votes of question 5, in order to find an

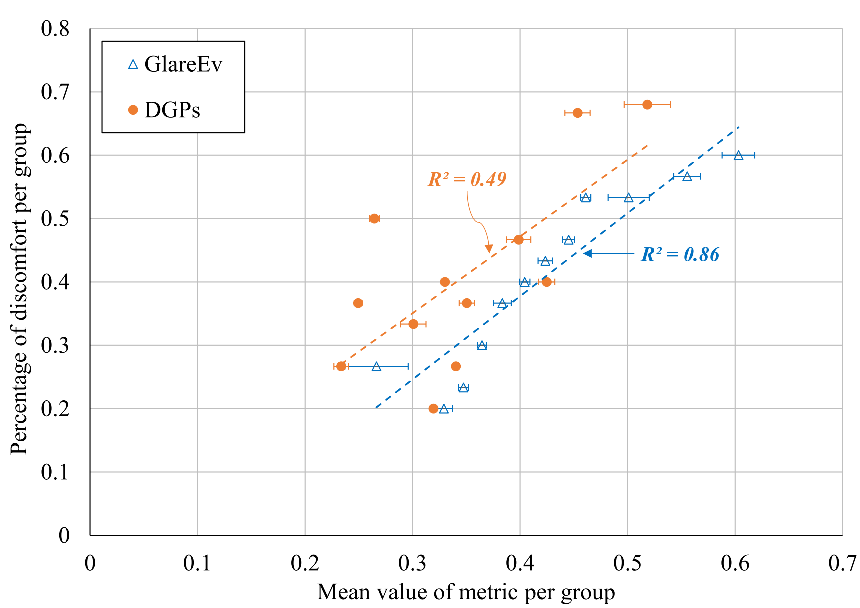


Fig. 11. Performance of new illuminance-based glare metric compared to DGP_s.

equation that would predict discomfort glare based on these two metrics. The two independent variables were chosen to be (i) the calculated direct (sun) part of vertical illuminance, $E_{v,dir(sun)}$, to capture the sun impact, (capturing also the position of the sun as a function of the incidence angle), and (ii) the fraction of the total (E_v) to the direct part ($E_{v,dir(sun)}$) of vertical illuminance in order to capture this interdependence between the color of the fabric, overall brightness, and the apparent intensity of the visible sun. Other combinations of direct and total vertical illuminance were also tried without satisfactory results. The best fit ($R^2 = 0.86$) for the new illuminance-based metric, called here Glare_{Ev}, is expressed by Eq. (6). Fig. 11 shows the overall regression with the fluctuation of discomfort in ordered groups, as well as the improvement compared to standard illuminance-based metrics −total vertical illuminance or $\mathrm{DGP_s}$.

$$Glare_{Ev} = 0.13 \cdot E_{v,dir(sun)}^{0.27} + 0.04 \cdot \left(\frac{E_v}{E_{v,dir(sun)}}\right)^{0.84} - 0.48\,,\ for\ 119 < E_{vdir(sun)} < 2228\,lx\ and\ 588 < E_v < 5940\,lx \tag{6}$$

The normality observed in the respective comfort and discomfort groups, allowed the use of the 95% lower bound confidence interval of discomfort for the direct extraction of a discomfort threshold equal to 0.41. Although the fit is not as good compared to the modified DGP coefficients, an illuminance metric on the basis of Eq. (6) would simplify annual simulations, eliminating the need for a detailed luminance mapping of the interior, compensating the slight compromise in terms of fit with increased convenience of use. At the same time, it is much more effective than the only other existing illuminance-based glare metric (E_v or $\mathrm{DGP_s}$) for cases with direct sunlight through fabrics.

Consequently, an index in the form of equation (6) is not proposed as a successor to any of the luminance-based glare metrics -or the modified DGP equation that proved to be the best for the studied cases- but only as one (the only one for the cases studied here) alternative to vertical illuminance or $\mathrm{DGP_s}$, that may be used for simpler calculation in cases with direct sunlight through fabrics and relevant practical applications. Considering that the fabric *OF* relates to direct vertical illuminance and the fabric T_v relates to total vertical illuminance, the discomfort glare thresholds can be directly used to provide design guidelines for selecting fabric properties, as suggested by Chan et al. [15].

It has to be noted here that Eq. (6) was extracted by calculating the direct (sun) part of vertical illuminance specifically induced by the solar disc being within the visual field, and using the validated model described in section 2.3, utilizing as inputs real measured values for the transmitted vertical illuminance through the glazing. The authors propose this variable for Eq. (6) in order to eliminate the need for heavy calculations (in case of simulations) or extensive calibrations and image processing (when it comes to field measurements), steps required for the extraction of an accurate luminance distribution). Therefore, any future use of Eq. (6) should be based on the assumptions discussed above, as it cannot be generalized for other methods of obtaining the overall direct part of vertical illuminance (as Evalglare does, including the impact of all identified glare sources).

4. Conclusion

This paper provides new insights on daylight glare evaluation for cases with the sun in the field of view through window shades. 41 human subjects were tested while performing specific office activities near a south-facing façade equipped with 14 shade products of different openness factors and visible transmittance values (direct and total light transmission characteristics). The fabrics were carefully selected to cover a wide range of properties (*OF* and T_v), resulting in a large variation of vertical illuminance values on the eye and DGP ranges, to study worst case scenario situations in order to establish discomfort thresholds.

The measured variables and survey results were first used to associate discomfort glare (based on a 4-point scale) with measured direct and total vertical illuminance on the eye and with DGP. Although clear differences exist between the votes, a large deviation was observed and it was preferred to follow a dichotomous approach (comfort for votes 1 and 2 and discomfort for votes 3 and 4). This allowed the extraction of glare discomfort thresholds for direct vertical illuminance (870 lx), total vertical illuminance (2800 lux) and DGP (0.4). While these can be used as rough estimates, none of the three individual metrics is considered entirely adequate to be a sole discomfort predictor for the studied case of roller shades with the sun present. That was also confirmed by a statistical analysis, following the method of ordered grouping. Existing metrics which are only luminance-based or only illuminance-based showed a poor performance in that regard, while DGI and UGR showed better results.

To further investigate other options for improved glare assessment metrics for the studied cases, a modified DGP equation was developed, using optimized coefficients, based on the ordered groups of the current dataset. The new equation showed the best agreement with the discomfort votes and this allows utilization of the same fundamental index for cases with and without direct sunlight on the occupant through shades, as a dual function of DGP with different coefficients. Moreover, the authors believe that the general form of the DGP equation is reasonable and adequate, and can be adjusted to account for different cases, by clustering different sets of coefficients for different environmental conditions or fenestration systems.

Finally, a new glare discomfort index was developed for the studied cases with fabrics and the sun visible through them, based on direct and total-to-direct vertical illuminance on the eye. The direct illuminance captures the impact of sunlight whereas the second variable captures the interdependence between the color of a fabric, overall brightness, and the apparent intensity of the visible sun. The new index can simplify annual simulations, eliminating the need for a detailed luminance mapping of the interior, and can be directly associated with fabric optical properties for development of design guidelines.

The results presented in this paper are only applicable to roller shades. Combining illuminance-based metrics and existing glare indices can result in a more realistic glare evaluation covering all cases with and without the sun through shading fabrics, and potentially through other systems. Further similar human subject studies with different datasets and similar or higher numbers of observations are needed to apply the new equations and metrics, further validate the respective discomfort thresholds and hopefully extend the present findings.

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References

[1] R.D. Clear, Discomfort glare: what do we actually know? Light. Res. Technol. 45 (2013) 141–158.
[2] M.G. Kent, S. Altomonte, P.R. Tregenza, R. Wilson, Temporal Variables and

Personal Factors in Glare Sensation. Lighting Research and Technology, 2015, http://dx.doi.org/10.1177/1477153515578310.
[3] R.G. Hopkinson, Glare from daylighting in buildings, Appl. Ergon. 3 (4) (1972) 206–214.
[4] CIE, Discomfort Glare in the Interior Lighting, Commission Internationale de l'Eclairage, in: Technical Committee TC-3.13, Division 4, Interior Environment and Lighting Design, Vienna, Austria, 1992.
[5] K. Van Den Wymelenberg, M. Inanici, A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight, Leukos 10 (3) (2014) 145–164.
[6] L. Karlsen, P. Heiselberg, I. Bryn, H. Johra, Verification of simple illuminance based measures for indication of discomfort glare from windows, Build. Environ. 92 (2015) 615–626.
[7] J. Wienold, J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy Build. 38 (7) (2006) 743–757.
[8] K. Van Den Wymelenberg, Visual comfort, discomfort glare and occupant fenestration control: developing a research agenda, Leukos 10 (2014) 207–221.
[9] I. Konstantzos, Y.-C. Chan, J. Seibold, A. Tzempelikos, R.W. Proctor, B. Protzman, View Clarity Index: a new metric to evaluate clarity of view through window shades, Build. Environ. 90 (2015) 206–214.
[10] R.G. Rodriguez, J.A. Yamín Garreto', A.E. Pattini, Glare and Cognitive Performance in Screen Work in the Presence of Sunlight, Lighting Research and Technology, 2015, http://dx.doi.org/10.1177/1477153515577851.
[11] J. Wienold, Dynamic daylight glare evaluation, in: Proceedings of IBPSA Conference, Glasgow, Scotland, 2009, pp. 944–951.
[12] K. Van Den Wymelenberg, M. Inanici, P. Johnson, The effect of luminance distribution patterns on occupant preference in a daylit office environment, Leukos 7 (2) (2010) 103–122.
[13] J.A. Jakubiec, C.F. Reinhart, A concept for predicting occupants' long term visual comfort within daylit spaces, Leukos (2015), http://dx.doi.org/10.1080/15502724.2015.1090880.
[14] I. Konstantzos, A. Tzempelikos, Y.-C. Chan, Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades, Build. Environ. 87 (2015) 244–254.
[15] Y.-C. Chan, A. Tzempelikos, I. Konstantzos, A systematic method for selecting roller shade properties for glare protection, Energy Build. 92 (2015) 81–94.
[16] IESNA. IES Standard LM-83–12 Approved method, IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE), Illuminating Engineering Society of North America, New York, 2012.
[17] K. Konis, Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California, Build. Environ. 59 (2013) 662–677.
[18] M. Hirning, G. Isoardi, I. Cowling, Discomfort glare in open plan green buildings, Energy Build. 70 (2014) 427–440.
[19] S.A. Sadeghi, P. Karava, I. Konstantzos, A. Tzempelikos, Occupant interactions with shading and lighting systems using different control interfaces: a pilot study, Build. Environ. 97 (2015) 177–195.
[20] LBNL. WINDOW 7 simulation Manual, Lawrence Berkeley National Laboratory, 2013. http://windows.lbl.gov/software/window/7/.
[21] N.A. Kotey, J. Wright, M.R. Collins, Determining off-normal solar optical properties of roller blinds, ASHRAE Trans. (1) (2009) 117.
[22] A. Tzempelikos, Y.-C. Chan, Estimating detailed optical properties of window roller shades from basic available data and modeling implications on daylighting and visual comfort, Energy Build. 126 (2016) 396–407.
[23] US Department of Energy, Energyplus Engineering Reference. The Reference to EnergyPlus Calculations, Lawrence Berkeley National Laboratory, 2015.
[24] J.A. Jakubiec, C.F. Reinhart, The "adaptive zone" – a concept for assessing discomfort glare throughout daylit spaces, Light. Res. Technol. 44 (2) (2012) 149–170.
[25] K. Konis, Predicting visual comfort in side-lit open-plan core zones: results of a field study pairing high dynamic range images with subjective responses, Energy Build. 77 (2014) 67–79.
[26] J. Stumpfel, A. Jones, A. Wenger, P. Debevec, Direct HDR capture of the sun and sky, in: Proceedings of 3rd International Conference on Virtual Reality, Computer Graphics, Visualization and Interaction in Africa, Cape Town, South Africa, 2004.
[27] J. Wienold, EvalGlare Version 1.0, Fraunhofer Institute for Solar Energy Systems, Freiburg, 2012.
[28] J. Xiong, A. Tzempelikos, Model-based shading and lighting controls considering visual comfort and energy use, Sol. Energy 134 (2016) 416–428.