2016

Daylight Glare Evaluation When the Sun is Within the Field of View Through Window Shades

Iason Konstantzos
School of Civil Engineering, Purdue University / Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, ikonsta@purdue.edu

Athanasios Tzempelikos
ttzempel@purdue.edu

Nicole M. Murchison
Psychological Sciences, Purdue University, nicole.murchison@gmail.com

Robert W. Proctor
Psychological Sciences, Purdue University, rproctor@purdue.edu

Daylight Glare Evaluation when the Sun is Within the Field of View Through Window Shades

Iason KONSTANTZOS[1,2]*, Athanasios TZEMPELIKOS[1,2], Nicole MURCHISON[3], Robert PROCTOR[3]

[1]Lyles School of Civil Engineering, Purdue University
West Lafayette, Indiana 47907 USA, (ikonsta@purdue.edu)

[2]Center for High Performance Buildings, Ray W. Herrick Laboratories, Purdue University
West Lafayette, Indiana 47907 USA

[3]Department of Psychological Sciences, Purdue University
West Lafayette, Indiana 47907, USA

* Corresponding Author

ABSTRACT

Shading fabrics have the ability to reduce daylight glare and provide privacy when needed. Recent studies have shown that glare indices such as DGP and its simplified version can be used to predict daylight glare through shades when the sun is not within the field of view. However, there are no comprehensive studies on glare sensation with the sun visible through the fabric – a situation that happens in office buildings – and therefore the applicability of glare indices for such conditions is uncertain. Shades with very low openness factors transmit only a small amount of direct sunlight due to their weave density; nevertheless, existing glare metrics may show intolerable conditions for these cases, while specific studies with human subjects are nearly non-existent.
This paper presents an experimental study on daylight glare evaluation for the case of shading fabrics with the sun within the field of view. 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). The measured variables and survey results were used to: (i) associate discomfort glare with measured and modeled parameters for these cases (ii) evaluate the robustness of existing glare indices for these cases (iii) examine recently suggested alternate (direct and total vertical illuminance) criteria for glare assessment through fabrics, extract discomfort thresholds and suggest a new related index and (iv) propose corrections in the DGP equation when the sun is visible through the shades, which could be generalized for other systems following a similar approach. 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. The new results can be inversely used as thresholds for selecting optical properties of shades to ensure glare protection, as well as for the development of glare-based shading controls.

1. INTRODUCTION

Visual comfort is one of the main concerns in a human-centered design of interior spaces and is mostly associated with effective control of daylight glare. Several indices developed to quantify glare, given its subjective nature and the several factors involved with its evaluation (Clear, 2013, Kent *et al.*, 2015). Examples include DGI (Hopkinson, 1972), originally proposed to describe glare from a large source as a window, and UGR (CIE, 1992), 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 (Van Den Wymelenberg and Inanici, 2014, Karlsen *et al.*, 2015), outperforming more complex metrics, while other studies support luminance-based metrics. The Daylight Glare Probability or DGP (Wienold and Christoffersen, 2006) is considered a realistic 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.

$$DGP = 5.87\times10^{-5} E_v + 9.18\times10^{-2}\cdot\log_{10}(1+\sum_{i=1}^{n}\frac{L_{s,i}^2\omega_{s,i}}{E_v^{1.87}p_i^2}) + 0.16 \quad (1)$$

$$DGPs = 6.22\times10^{-5} E_v + 0.184 \quad (2)$$

, where Ev is the total vertical illuminance, Ls, ωs and, P are the luminance, the solid angle and the position index for each identified glare source respectively and Lb the background average luminance.
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 transmittance (Tv); 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 (Konstantzos *et al.*, 2015a). Literature focusing on the impact of roller shades on visual comfort is scarce and mostly consists of simulation studies; moreover, studies investigating the glare under the presence of sunlight, with or without shades, are certainly needed (Rodriguez *et al.*, 2015). Wienold (2009) used roller shades among other shading systems to present the simplified and enhanced simplified approaches of DGP and investigate the applicability of DGPs, the simplified version of DGP (Eq. 2) as developed by Wienold (2007), for low-openness fabrics, while Van den Wymelenberg and Inanici (2014) 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 (2015) concluded that more than one metric is required for quantifying glare if direct sunlight is present.
Konstantzos *et al.* (2015) 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, it is still not clear whether the full DGP index is applicable for the cases when the sun is visible through shading fabrics (Konstantzos *et al.* 2015b). Due to the extreme values of the solar corona's luminance, the luminance term of DGP is inflated, predicting discomfort levels that are rather incompatible with everyday practice, especially for the cases of low openness fabrics.
To account for that inconsistency, Chan *et al.* (2015) 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, excluding the effect of sunlight. The proposed threshold values were 2760 lux for the total vertical illuminance (equal to DGPs=0.35) and 1000 lux for the direct vertical illuminance, as a modification of IES Standard LM-83-12 (2012). 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.* (2015) 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 Tv = 5% should be used on south-facing facades.
Fewer studies have included human subjects assessing glare through roller shades (Konis, 2013; Hirning *et al.*, 2014; Sadeghi *et al.*, 2016). 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 index 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 and Instrumentation

The experiments were conducted in the Architectural Engineering Laboratories of Purdue University in West Lafayette, Indiana. Two identical, side-by-side office spaces with reconfigurable south-facing facades, specifically designed for quantifying the impact of facade design options and related controls on indoor environmental conditions and energy use, 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: τ_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. 1 shows a typical experimental setting for each office space, separated in three workstations (6 total).

Figure 1: Experimental layout of one of the two identical offices used for the study with three partitioned workstations, each equipped with a different shade.

Several LI-COR calibrated photometers were used to measure illuminance levels during the experiments, for data acquisition and validation purposes. Illuminance sensors have a cosine correction for incidence angles up to 80°, a response time of 0.01 ms and an absolute error of 3%. Exterior sensors (mounted on the roof and south wall) measured the exterior horizontal and vertical illuminance. An illuminance sensor mounted on the interior of the glass measured the transmitted vertical illuminance through the window. The total vertical illuminance on the eye of the subjects was measured with vertical photometers mounted next to the subjects' head (visible in Fig. 1), as well with a handheld Konica T-10s illuminance meter and a calibrated Canon T2i HDR camera. 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). All sensors are 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, visual comfort and energy use.

Table 1: Fabric codes and respective 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
Tv (%)	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

A careful selection of 14 different fabrics was made for the tests. Their properties covered a wide range of OF and Tv values, and shades of white, black and grey. The selected combinations capture the entire space of interested with no specific pattern/relationship between the properties, given realistic limitations. 12 of the fabrics were in the lower range of openness factor (0.7% to 4.3%), while two of them were selected to be very open (OF~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 selected fabrics were measured in detail in terms of their basic properties (openness factor and visible transmittance) 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 (LBNL, 2009). 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.* (2009). The latter is further discussed in detail and validated using integrated sphere measurements and full-scale experiments (Tzempelikos and Chan, 2016). 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 incidence OF and Tv properties, provided by manufacturers. In summary, the angular beam-beam shade transmittance (τ_{bb}) is calculated from:

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

, where θ is the solar incidence angle, $\tau_{bb}(0)$ 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 $\tau_{bb}(0)$, as explained in Kotey *et al.* (2009). The angular beam-total transmittance (τ_{bt}) is calculated from:

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

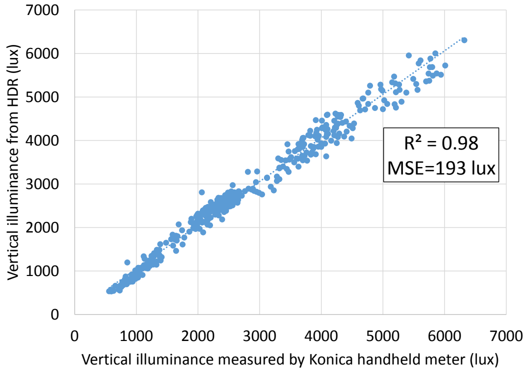
, where $\tau_{bt}(0)$ is the beam-total transmittance at normal incidence (total visible transmittance provided by manufacturers) and d is a parameter that depends on openness factor and total visible transmittance. The cut-off angle should not be applied to light-colored fabrics, to account for direct light scattering at higher angles, while small corrections might be needed for dark-colored fabrics (Tzempelikos and Chan, 2016). The beam-diffuse transmittance, necessary for accurate modeling of light transfer through shades, is then equal to $\tau_{bt} - \tau_{bb}$ 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 on the eye, which is directly measured, there is no standard way to measure direct vertical illuminance on the eye of the observer (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 any 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. To compensate for the dark conditions created by the filer, 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 Color checker color chart 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, cropping and resizing appropriately and then running Evalglare (Wienold, 2012) to calculate the metrics of interest such as DGP. As 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 (as the task area including part of the window or not, etc.), a fixed glare identification threshold approach was followed instead in Evalglare, using the threshold of 2000 cd/m^2. As validating the readings would require an instrument with luminance measuring range exceeding the order of 10^7

cd/m², a validation in terms of vertical illuminance (Fig. 2) was performed for all of the images. A MSE of 197 lux was calculated and considered satisfactory given the severe conditions (extreme solar corona luminance being partly diffused through the fabric).



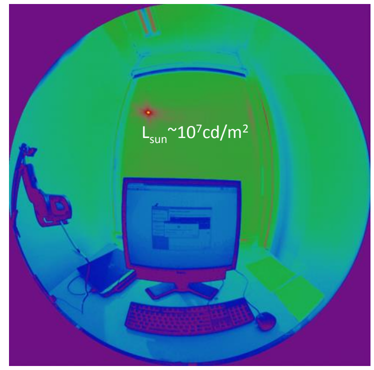


Figure 2: Validation of HDR imaging in terms of vertical illuminance (left); HDR image indicating the luminance of the sun after application of filter and calibration (right)

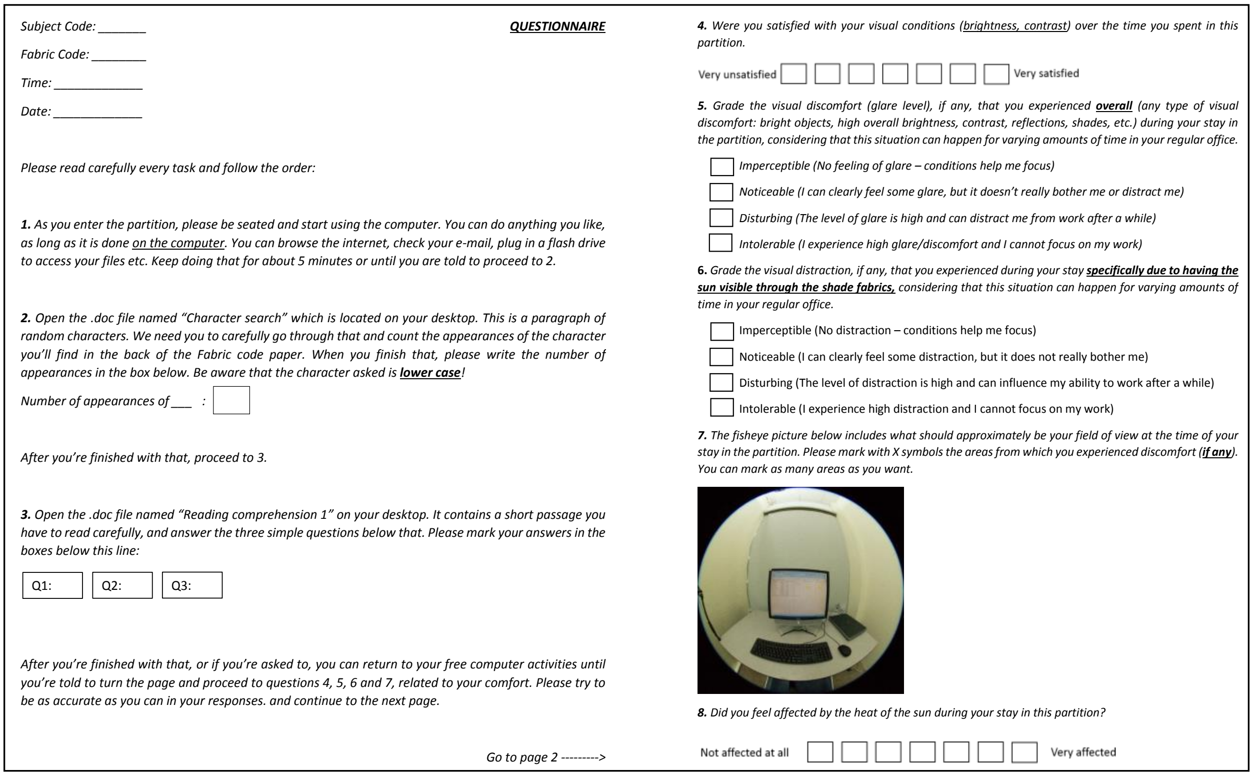
2.5 Experimental procedure, tests, questionnaires and surveys

The experiments were conducted during sunny days from December 2015-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. 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 hours 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 minutes. The 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 15 minutes were split in to 3 main parts, including free web browsing, 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 force the subjects to be focused 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. At the end of the 15 min, the subjects were asked to proceed to the second part of the short questionnaire (Questions 4-8), commenting about their visual comfort sensation. At the same time, illuminance and DGP measurements were acquired for every workstation.

- Question 4 was a 7-point scale satisfaction with the visual conditions (from very unsatisfied to very satisfied)
- Question 5 was a 4-point glare vote (imperceptible to 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 (Wienold and Christoffersen, 2006) 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 imperceptible to 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 not affected at all to 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. After a careful analysis, 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 Tv will always result in uncomfortable conditions.



Subject Code: _______

QUESTIONNAIRE

Fabric Code: ________

Time: ____________

Date: ____________

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 on the computer. 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.

Go to page 2 --------->

***4.** Were you satisfied with your visual conditions (brightness, contrast) 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?*

Not affected at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very affected

Figure 3: Questionnaire used in the study and task-related information

3. RESULTS

3.1 General impact of fabric properties on glare

As expected, the impact of fabric properties in glare sensation is apparent. A general overview of the effect of fabrics on glare through the responses of Questions 5 is shown in Figure 4, with the fabrics appearing in order of increasing openness factor. The yellow dots indicate the averaged responses, while the boxplots effectively illustrate the distribution of the results.

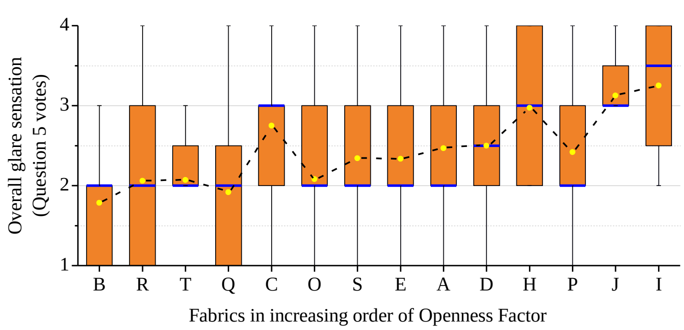


Figure 4: Distribution of responses for Question 5 – overall glare sensation.

The two fabrics of high openness factor, I and J, are the only ones with averaged responses that always lie within the discomfort zone for glare sensation, 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.

3.2 Vertical illuminance, DGP and respective comfort ranges

As described in chapter 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 (2006) 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.

Figure 5 shows the association of the three measured metrics with visual discomfort according to the responses of Question 5. Note from the results that 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 120-2228 lux; total vertical illuminance varied between 588-5940 lux; and DGP ranged between 0.26-0.62. 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. 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 data groups of 211 and 144 points respectively, with distributions that approach normality in the case of all three metrics. The results are shown in Fig. 6. Table 2 shows the descriptive statistics for these dichotomous votes, including the 95% upper bound confidence interval for the comfort group and the 95% lower bound confidence interval for the discomfort group, which indicate the corresponding thresholds for the border of discomfort.

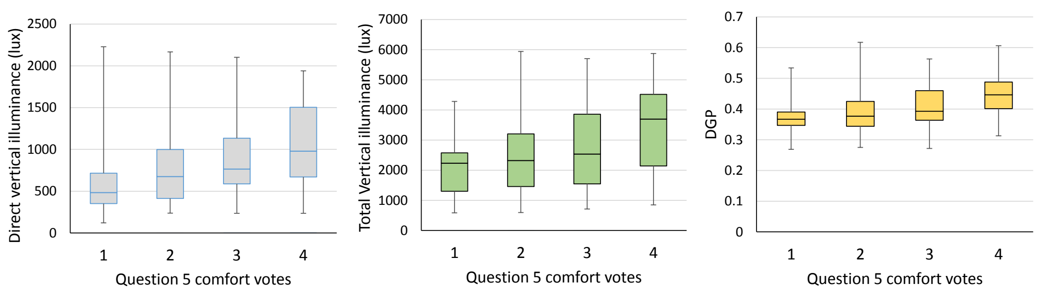


Figure 5: Boxplots associating the responses of Question 5 with direct vertical illuminance, total vertical illuminance and DGP respectively for four-point responses

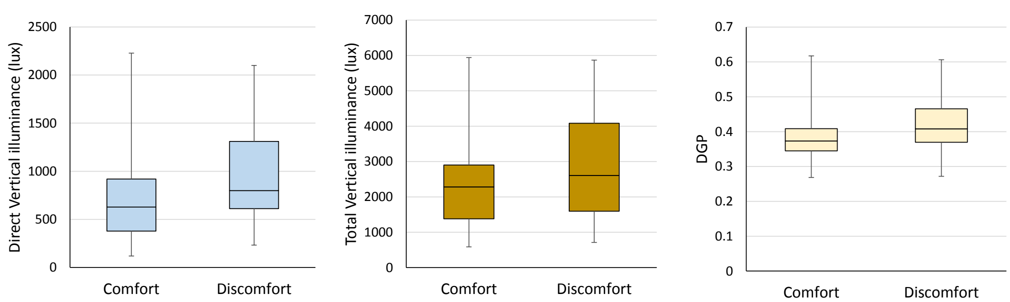


Figure 6: Boxplots associating the responses of Question 5 with direct vertical illuminance, total vertical illuminance and DGP respectively using dichotomous approach

The results show that the 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 illuminance, as recent studies attempt to use a discomfort threshold of around 1000 lux (Chan *et al.*, 2015, Jakubiec and Reinhart, 2015) based on recommendations for direct illuminance on the work plane found in with IES LM-83-12 (IESNA, 2012). The threshold cannot be generalized however for other types of shading or daylighting devices without conducting similar studies with these systems.

Table 2: Descriptive statistics and thresholds extraction for dichotomous approach

	Comfort			**Discomfort**		
	Evdir	Evtot	DGP	Evdir	Evtot	DGP
Mean	741.95	2410.39	0.39	947.28	2896.14	0.42
St.Deviation	470.42	1195.53	0.07	490.36	1420.34	0.07
n	211	211	211	144	144	144
CI (UP/LB)	63.47	161.31	0.01	80.09	231.99	0.01
Threshold	805	2572	0.40	**867**	2664	0.41

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 DGPs (~2800 lux), while the discomfort threshold for DGP was found to be at the level stated by Wienold's original DGP study (~0.4). For reference, there are three (and recent) published studies that propose total vertical illuminance discomfort thresholds: Karlsen *et al.* (2015) suggested 1700 lux; Van Den Wymelenberg and Inanici (2014) proposed 1250 lux and Konis (2014) suggested 1600 lux. However, these 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.
Note that due to the high deviation, as expected, none of the three presented metrics is considered an appropriate comfort/discomfort predictor by itself, for the studied case of roller shades with the sun present. Therefore, 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 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 (2006) splits the total 349 data points into 12 groups of 29 points per group. Hirning (2014) 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.* (2015) who presented both grouping approaches and found differences in the results. 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 for each group a relatively low deviation around the mean would be observed for all metrics of interest. 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 (1^{st} and 12^{th}) 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 of the visual field, DGP and DGI with different thresholds of glare sources identification. The results are shown in Table 3.

Table 3: Evaluation of the fit of some existing illuminance- and luminance-based metrics

	No glare sources			**Threshold: 2000 cd/m^2**		
Metric	Evdir	Evtot or DGPs	Lave	DGP	DGI	UGR
R^2	0.43	0.49	0.36	0.65	0.79	0.82

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 well in the study of Hirning *et al.* (2014) and DGI, which was not found to be an adequate metric in related studies (Van Den Wymelenberg and Inanici, 2014) are both performing better than DGP. Table 3 shows the coefficient of determination results for the evaluated metrics.

3.4 Modification of the DGP equation for cases with the sun visible 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, and can be applied to roller shades (Konstantzos *et al.*, 2015b). 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. 7 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), it was investigated whether the same form of equation could describe the current data set with a 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 'cluster-like' 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 2000cd/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 3. The resulting new equation with the modified coefficients is shown in Eq. 5.

$$DGP_{\mathrm{mod}} = 8.40 \cdot 10^{-5} \cdot Ev + 11.97 \cdot 10^{-2} \cdot \log(1 + \sum \frac{L_{s,i}^2 \cdot \omega}{\mathrm{E}v^{2.12} \cdot P^2}) + 0.16 \tag{5}$$

Figure 7 (left) shows the correlation between DGP for each group and respective percentage of discomfort for the original equation and for the modified one, with obvious improvements. In addition, Figure 7 (left) shows the extracted discomfort threshold based on the techniques used in section 3.2, 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.

3.5 Formulation of a new illuminance-based metric for predicting discomfort glare cases with the sun visible 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. 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 (Konstantzos *et al.*, 2015, Chan *et al.*, 2015, Xiong *et al.*, 2016), 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.* (2015), total vertical illuminance or DGPs 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 on eye illuminance) and another that captures the overall sensation of brightness (total vertical on eye illuminance) 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). So the algorithm presented for the modified DGP equation 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 equation that would predict discomfort glare based on these two metrics. The two independent variables were chosen to be (i) the direct part of vertical illuminance, to capture the visible sun's impact (capturing also the position of the sun, as function of the incidence angle) and (ii) a fraction of the total and the direct part of vertical illuminance in order to capture this interdependence between the color of a 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 was found for the following equation:

$$Glare(Ev) = 0.13 \cdot Evdir^{0.27} + 0.04 \cdot \left(\frac{Evtot}{Evdir}\right)^{0.84} - 0.48 \tag{6}$$

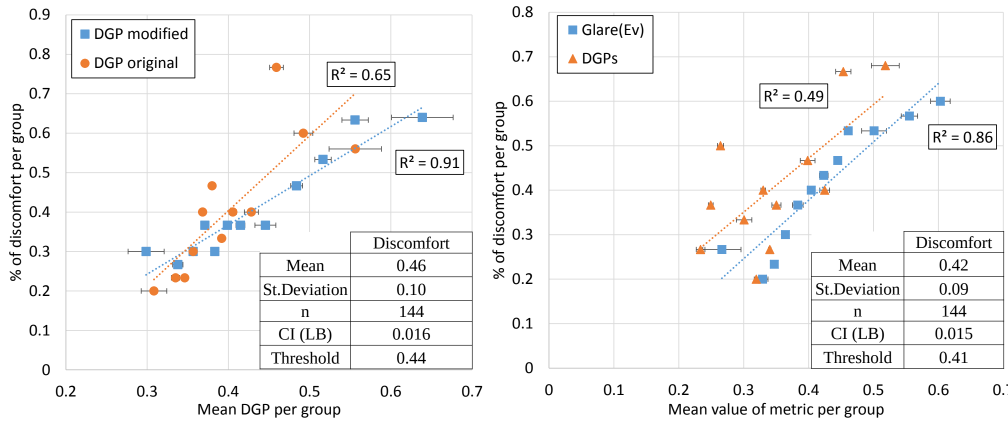


Figure 7: Improvement of fit for the modified DGP compared to original (left) and for the new illuminance-based metric compared to DGPs (right)

Figure 7 (right) shows the satisfactory fit of equation 6 ($R^2 = 0.86$) when regressed with the fluctuation of discomfort in ordered groups, as well as the improvement compared to the standard metric -DGPs or total vertical illuminance - for the entire usable data set of this study.

One of the indications of the effective behavior of a metric is the normality observed in the respective comfort and discomfort groups, a fact that allows the direct extraction of a discomfort threshold equal to 0.41 (Fig. 7 right). Although the fit is poorer compared to the modified DGP equation, 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 can be much more effective than the only other existing illuminance based glare metric (Evtot or DGPs) for cases with direct sunlight through fabrics. Therefore, the authors want to clarify that an index in the form of equation 6 is not proposed as a successor to any of the luminance-based glare metrics, but only as one (the only one for the cases studied here) alternative to vertical illuminance or DGPs, to be used for simpler calculation for cases of direct sunlight through fabrics and for practical applications. Considering that the fabric OF relates to direct vertical illuminance and the fabric Tv 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.* (2015).

4. CONCLUSION

This paper provides new insights on daylight glare evaluation for the case of shading fabrics with the sun within the field of view. 41 human subjects were tested while performing office activities near a south facing façade equipped with 14 different shade products of different openness factors and visible transmittance values. The experimental data was used to extract discomfort glare thresholds for direct vertical illuminance (870 lux), total vertical illuminance (2800 lux) and DGP (0.4). As none of these metrics was proven to be entirely adequate to be a discomfort predictor for the studied case, a modified version of DGP was proposed, using optimized coefficients for this specific conditions. The new modified index allows utilization of the same fundamental index as a dual function with different coefficients for the case with and without direct sunlight on the occupant through shades. To further explore other opportunities, the correlation of discomfort sensation with an illuminance based metric was investigated, aimed to predict discomfort using only the direct and total portions of vertical illuminance on the eye. An index on the basis of equation 6 shows a very improved fit, compared to the only available illuminance based glare predictor (DGPs). Such an index can simplify annual simulations, eliminating the need for a detailed luminance mapping of the interior, and can directly associated with fabric optical properties for development of design guidelines. Note that 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.

5. ACKNOWLEDGEMENTS

This work is supported by Alcoa Foundation and Lutron Electronics Co Inc.

6. REFERENCES

Chan Y.-C., Tzempelikos A., Konstantzos I. (2015). A systematic method for selecting roller shade properties for glare protection. *Energy and Buildings 92*, 81-94.

CIE (1992) Discomfort Glare in the Interior Lighting, Comission Internationale de l'Eclarage (CIE), Technical committee TC-3.13, Division 4, Interior Environment and Lighting Design, Vienna, Austria.

Clear R.D. (2013). Discomfort glare: what do we actually know? *Lighting Research and Technology 45*, 141-158.

Hirning M., Isoardi G., Cowling I. (2014). Discomfort glare in open plan green buildings. *Energy and Buildings 70*, 427-440.

Hopkinson, R.G. (1972). Glare from daylighting in buildings. *Applied Ergonomics 3*(4), 206-214.

IESNA: IES Standard LM-83-12 (2012). Approved method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York.

Jakubiec J.A., Reinhart C.F. (2015). A concept for predicting occupants' long term visual comfort within daylit spaces. *Leukos 2724*, 1-18.

Karlsen L., Heiselberg P., Bryn I., Johra H. (2015). Verification of simple illuminance based measures for indication of discomfort glare from windows. *Building and Environment 92*, 615-626.

Kent M.G., Altomonte S., Tregenza P.R., Wilson R. (2015). Temporal variables and personal factors in glare sensation, *Lighting Research and Technology*, 0: 1-22. 10.1177/1477153515578310

Konis K. (2013). Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California. *Building and Environment 59*, 662-677.

Konis, K. (2014). Predicting visual comfort in side-lit open-plan core zones: results of a field study pairing high dynamic range images with subjective responses, *Energy and Buildings* 77, 67-79.

Konstantzos I., Chan Y-C., Seibold J., Tzempelikos A., Proctor R.W., Protzman B. (2015a). View Clarity Index: a new metric to evaluate clarity of view through window shades. *Building and Environment 90*, 206-214.

Konstantzos I., Tzempelikos A., Chan Y-C. (2015b). Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades. *Building and Environment 87*, 244-254.

Kotey N.A., Wright J., Collins, M.R. (2009). Determining off-normal solar optical properties of roller blinds. *ASHRAE Transactions 117* (1), 10 pages.

LBNL (2013). WINDOW 7 simulation manual. Lawrence Berkeley National Laboratory. http://windows.lbl.gov/software/window/7/

Rodriguez RG, Yamı´n Garreto´ JA, Pattini AE (2015). Glare and cognitive performance in screen work in the presence of sunlight. *Lighting Research and Technology* 0:1-18. 10.1177/1477153515577851

Sadeghi, S.A., Karava, P., Konstantzos, I., Tzempelikos, A. (2015). Occupant interactions with shading and lighting systems using different control interfaces: A pilot study. *Building and Environment 97*, 177-195.

Tzempelikos A., Chan Y-C., (2016). Estimating detailed optical properties of window roller shades from basic available data and modeling implications on daylighting and visual comfort. Energy and Buildings, in press.

Van Den Wymelenberg K., Inanici M. (2014). A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight. *Leukos 10*(3), 145-164.

Wienold J., Christoffersen J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings 38*(7), 743-757.

Wienold J. (2007). Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. *Proc. of IBPSA 2007 Conference*, Beijing, 1197-1204.

Wienold J. (2009). Dynamic daylight glare evaluation. *Proceedings of IBPSA 2009 conference*, Glascow, Scotland, 944-951.

Wienold J. (2012). EvalGlare Version 1.0. Fraunhofer Institute for Solar Energy Systems, Freiburg.

Xiong J., Tzempelikos A. (2016). Model-based shading and lighting controls considering visual comfort and energy use. Solar Energy, in press.