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ABSTRACT

Daylight glare evaluation has been the recent focus of research on visual comfort since newer office buildings have large glass facades offering daylight provision and outdoor views. Available glare indices are related to source luminance size and location, view direction and background luminance. The Daylight Glare Probability index that considers vertical illuminance at the eye level, has been identified as one of the reliable metrics, since it was based on experiments with real human subjects. In this study, extensive experiments were conducted in a full-scale private office environment with dynamic shading controls, to measure interior luminance and illuminance conditions under variable sky conditions and shading control strategies. A high dynamic range camera with a fish eye lens was used to capture the luminance in the field of view, while horizontal and vertical illuminance was measured at different positions. The images were processed for calculating DGP values based on the "evalglare" method. The results are used to evaluate the efficiency of control strategies in terms of glare probability, while correlations between indoor illuminances, sky conditions and DGP may lead to simplified criteria and guidelines for controlling daylight glare in office spaces. Finally, the experimental results can be used for daylight model validation for spaces with dynamic facades.

1. INTRODUCTION

The utilization of large glass areas following the architectural trends of the 20th century has increased daylight availability in office spaces, leading thus to significant advantages in terms of energy savings and occupant satisfaction However, more daylight is accompanied by increased solar gains and visual discomfort (glare). Glare, defined as the contrast lowering effect within a visual field due to the presence of bright light sources, has been studied for the past decades from various scopes and has been quantified using several indices. Daylight Glare Probability or DGP (Wienold and Christoffersen, 2006) is the most recent index used to evaluate glare from daylight, and it was extracted by experimental data in private office spaces involving human test subjects. DGP is considered part of the main climate-based daylight metrics for assessing daylight quality (Cantin and Dubois, 2011) and establishing adaptive zones (Jakubiec and Reinhart, 2012), although more research is needed to establish appropriate criteria for acceptable luminance ratios. There has been an extensive amount of literature involving glare, with the majority of studies related to simulation, usually utilizing Radiance renderings to simulate the visual field. A computational analysis of DGP and its simplified versions (Kleindienst and Andersen, 2009), with discussion on vertical illuminance and contrast-based terms, showed that the contrast terms need more detailed analysis, especially under low illuminance conditions. Mardaljevic *et al.* (2012) conducted an initial study to relate DGP with a daylight metric such as the useful daylight illuminances (Nabil and Mardaljevic, 2006), while Araji and Boubekri (2008) linked window size with vertical illuminance and glare. Fewer studies actually involved experimental glare measurements, investigating the impact of large area sources (Rodriguez and Pattini, 2014), luminance variation (Kim and Kim, 2012), non-uniform luminance distributions (Kim and Kim, 2011), identifying modifications in existing glare indices (Fisekis *et al*., 2003, Nazzal, 2005), or performing case studies using translucent facades (Matusiak, 2013), anidolic daylighting systems with electric lighting operation (Borisuit *et al*., 2010) or photovoltaic windows (Cannavalle *et al*., 2013, Piccolo and Simone, 2009). The potential effect of different window views on the subjective assessment of discomfort glare can be significant (Yun *et al*., 2011, Tuaycharoen and Tregenza, 2007, Shin *et al.*, 2012, Aries *et al.*, 2010). Post-

occupancy studies with measurements and surveys under different sky conditions and façade configurations emphasize the complexity of assessing glare including occupant preferences (Konis, 2013). As stated by Clear (2013), more research is needed since evaluating glare in complex scenes may require fundamental changes to the form of the glare models.
The initial DGP study (Wienold and Christoffersen, 2006) compared discomfort opinions from subjects with measurements using a CCD luminance camera, recording their field of view in order to extract the DGP index. In a recent study (Suk and Schiler, 2012), experiments were combined with Radiance simulations in order to investigate the validation of simulated DGP and illuminance results to the actual measured quantities using an HDR camera, and to compare different glare indices. Suk *et al* (2013) also utilized HDR camera measurements to investigate and support their introduction of the terms of absolute and relative glare factors. Van Den Wymelenberg *et al*. (2010) performed a study involving HDR imaging and a survey to investigate details as the appropriate luminance threshold selection and the correlation of observations to DGP and DGI. Hirning *et al.* (2014) provided a detailed glare measurement methodology aiming to explore the differences among glare indexes, in the first large scale survey performed in an open plan office using camera measurements. Reinhart *et al.* (2012) provided enlightening methodology details for glare evaluation using cameras. Inanici and Galvin (2004) and Inanici (2006) extensively studied luminance extraction from HDR cameras, analyzing related terms as the camera response curve, the vignetting effect and the point spread functions and evaluated the use of HDR imaging as luminance measurement. HDR photogrammetry protocols are also discussed by Cai (2013), along with the impact of settings and vignetting effects.
This study presents DGP experimental measurements in full-scale test offices using a HDR camera, including measurement procedures and HDR image creation and processing. Experimental data were used to develop correlations between indoor illuminances and DGP parameters, for different shading control strategies. The effects of the contrast term and vertical illuminance are discussed in this context. Finally, validated models are presented to assist in model-based glare and luminance mapping, for different façade controls.

2. EXPERIMENTAL METHODOLOGY

2.1 Experimental Facilities description

The experiments were conducted in the facade engineering laboratories of Purdue University in West Lafayette, Indiana. This research facility was particularly designed for quantifying the impact of façade design options and related controls on indoor environmental conditions and energy use. Two identical, side-by-side test office spaces with reconfigurable facades (Fig. 1a) are used to compare between different glazing, shading and control options under real weather conditions. The dimensions of each room are 5m wide by 5.2m deep by 3.4m high, with a glass façade (60% window-to-wall ratio) facing south.

A Solaban70XL-clear, a high performance glazing unit with a selective low-e coating (τ_v=65%) was used for the measurements. The façade is equipped with motorized grey roller shades, with 5% total visible transmittance (beam-beam transmittance =4.2%), 74.5% exterior reflectance and 28% interior reflectance. The shading system can be controlled automatically (through customized software) and manually, and is connected to the lighting control system and to the data acquisition and monitoring system. This way shading operation and shade position at any time is fully monitored. Several photometers (Fig.1b) are used to measure light levels, both exterior (horizontal and vertical illuminance) and interior (transmitted through window, horizontal work plane illuminance at 6 points in each room, and at variable positions at the observer's eye height level for vertical illuminance measurements). A vertical exterior solar pyranometer provides information about the direct and diffuse portions of solar radiation and illuminance. All sensors are connected to a data acquisition and control system, controllable through remote access in order to run experiments without interfering with human presence. In this way, we can conduct comparative experiments using custom shading and lighting controls and study the impact on daylighting conditions, energy use, and visual comfort. Illuminance, solar radiation, electric light levels and shading operation were recorded every 1 minute for different measurement periods of March and April 2014 for the needs of this study.

2.2 Experimental Setup for Glare Measurements

A calibrated Canon 550D camera, equipped with a Sigma 4.5mm fisheye lens was used for luminance mapping and glare measurements. The fisheye lens is recommended since it better resembles the human visual field. Hirning *et al.* (2014) suggests a modified human visual field according to the total field of Guth (1966), which is also an option in evalglare since version 1.0 (Wienold, 2012). Although this approach is reasonable for human involved studies, due to the fact that this study is purely experimental, and includes correlations with measurements extracted by photometers having 180^{o} field of view, the original 180^{o} wide visual field was assumed. The camera was mounted on a tripod at

1.20m height, simulating an average seated occupant's eye level, and was facing a laptop screen running typical office to maintain the screen luminous exittance at normal office levels (Fig. 1c).

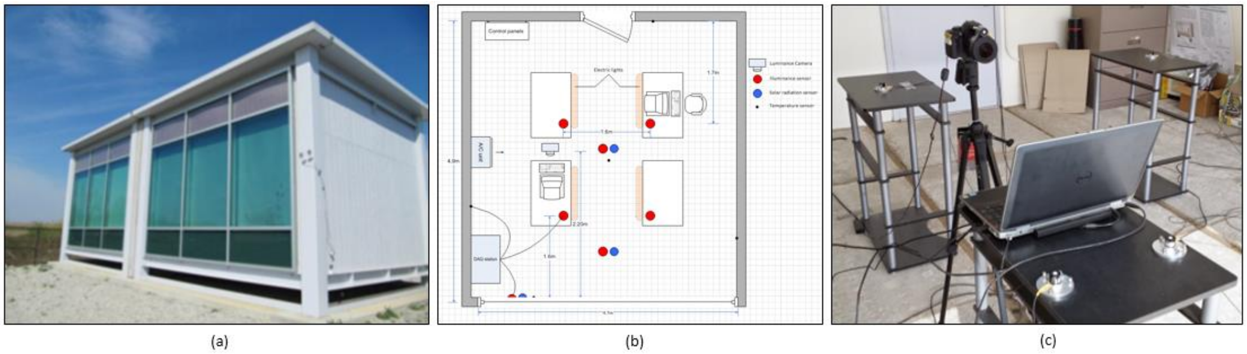


Figure 1: (a) Exterior view of the twin labs – (b) Sensors placement in the experimental room – (c) Interior view

The placement of the camera is of great importance, as both of the dynamic parts of the DGP equation can be influenced by it: The first term based on vertical illuminance (E_v) can be significantly smaller when a table and/or a computer screen are present, either blocking part of the view and the projected light on the floor/other surfaces, or adding a relatively constant amount of light (and luminance) in the case of a screen; the second term that considers contrast is also directly influenced by the luminous exittance of the area of focus. A photometer was vertically mounted on the camera, to validate the vertical illuminance results extracted by camera measurements. Alternatively, the sensor can be also used for overriding the E_v values extracted from the photographs, providing more accurate DGP results, as suggested by Evalglare (Wienold, 2012).

For the creation of HDR photographs, the typical approach described in related literature of "Evalglare" (Wienold, 2012) was followed: The camera is set to shoot for every measured instance three pictures of different exposures. The exposure of a photograph describes the quantity of light reaching the digital sensor; it is influenced by three different factors set directly on the camera: the aperture, the shutter speed, and the ISO level. The aperture setting modulates the amount of light let into the lens by modifying the area of the shutter opening; the shutter speed is defined as the time duration of open shutter; and the ISO is the light sensitivity of the sensor. These three factors influence the results, therefore an acceptable combination for reliable measurements is required. Both over- and under-exposed photographs will result in poor luminance mapping, as part of the information will be either "burnt" or dark. Smaller apertures usually lead to less bright images but with greater depth of field (amount of visual field that is on focus), and are preferred for many reasons, such as the more limited effect of vignetting distortion (Inanici and Galvin 2004). To balance the light cost due to the higher aperture, a slower baseline shutter speed needs to be selected. The ISO level should be always set in the baseline setting of 100, as a possible sensitivity increase of the sensor could alternate the results. A representative set of the settings used were aperture of f/11, shutter speed of 1/100-1/200 and ISO 100.

In winter time, when the sun is low and clearly visible through the window, many of the photographs were "overdriven". This is a term used by the camera's software to describe overexposed images, where what should be discrete mapping is transformed to a uniform white blob, or where there is a luminance part of the photograph so high, that it is impossible for the sensor to handle such an extreme contrast correctly. The overexposed images can be unpredictable in terms of measuring; while they usually overestimate luminance in certain areas, lower values may appear when it comes to contrast glare. A symptom of this problem can be found in literature (Suk and Schiler, 2012) where, in case of direct sun within the field of view, DGP is significantly underestimated compared to similar RADIANCE simulations. Usually, this kind of problems is solved by adding specific ND filters on the lens and of course repeating the calibration process for the new setup. However, due to the fisheye lens geometry, an addition of such filters would lead to a severe narrowing of the visual field, as well as a significant increase of vignetting distortion. Therefore, the only possible option is to reduce the base exposure, using significantly faster shutter speeds as a baseline. Nonetheless, the problem remained in several cases. For such cases, a criterion for storing (or rejecting) the measurements was used; if the vertical illuminance calculated by the luminance mapping was in good agreement with the one measured by the vertical photometer, the image was kept; otherwise it was rejected as unreliable. It turned out however that only few of the overdriven images were actually rejected by this filtering process, proving so that the error message appeared even in cases where the issue is negligible.

2.3 HDR image creation and processing

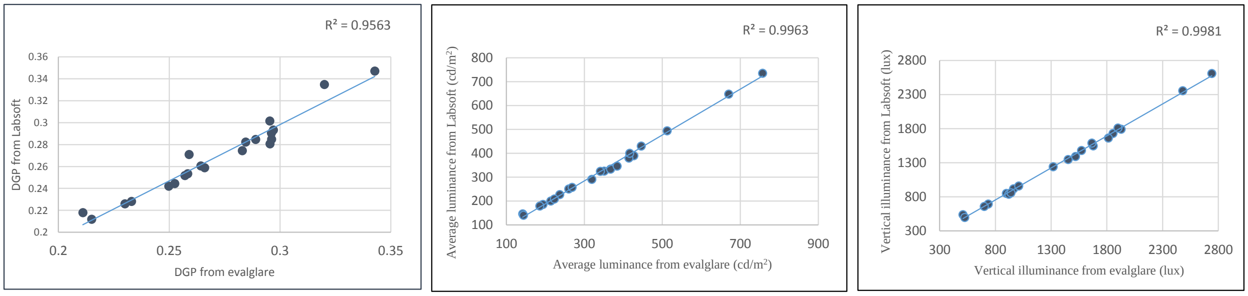
Three different software solutions were investigated for HDR image creation and processing, in order to select the most efficient method. The luminance camera used in this study was custom designed for research use, so it was already calibrated by the manufacturer, with detailed data sets and corrections for response curves, vignetting, point source errors, etc. Therefore the luminance mapping created by the camera's software Labsoft 14.3.6 (Technoteam, 2014) was considered to be the baseline for comparing with other software. The calibration and correction data sets cannot be used by other software, thus for comparison purposes the images had to be calibrated in other ways. The camera's software is capable of calculating DGP, but as Evalglare is the "standard" procedure for this task, a validation was first conducted. The three methods studied for HDR image creation and processing are described below:

- Based on the main trend found in related literature, Photosphere (Ward, 2014) was initially selected to run the process. Photosphere is a Mac OS only freeware program which has the advantages of performing most of the essential steps for glare evaluation under a fairly user friendly graphical interface. However, Photosphere is not able to directly input the Canon's .CR2 RAW files. This was a complication that didn't allow us to follow the planned procedure of using RAW files for maximum accuracy, as using another software to convert the images would slow down the process; however we tried using JPEG files at the least compression possible instead to investigate the results. After the image creation, a calibration data set was created within Photosphere for our current setup. After calibrating the pictures, they were appropriately cropped and resized to meet the Evalglare restrictions and then used in Evalglare for DGP and other calculations. The results from Photosphere were compared with the camera's software readings in terms of average luminance. It has been found that the accuracy of the procedure was very sensitive to the selection of the baseline surface of the calibration. It is suggested for a small grey surface to be chosen, uniform in luminance and neither very dark nor directly lit by sunlight.
- To overcome the .CR2 incompatibility of Photosphere, Adobe Photoshop CC was also used, since it can directly handle Canon RAW data. However, Photoshop did not include a calibration function. Therefore, the "hdrscope" tool (Kumaragurubaran and Inanici, 2013) was used for this task. Hdrscope is a free software created by the University of Washington which implements the complete operation of Evalglare, combined with some convenient tools for luminance statistical analysis. It also implements a similar calibration function with Photosphere, using a "linear" calibration factor created by the measured value of a grey target within the visual field and the respective luminance value of the input HDR image. Sane suggestions for the selection of the calibration surface apply here. After created in Photoshop, images were calibrated in hdrscope and then appropriately formatted for Evalglare. The results were a very good match with our baseline, indicating that this process, although intensive, can be reliable for HDR creation.
- The third software investigated was Labsoft (Technoteam, 2014), the solution that accompanied the luminance camera. The software merges the HDR photographs and does not require any calibration as the calibration data set including all corrections is directly embedded in the software. The images created were extracted to use in evalglare. As mentioned before, the luminance mapping was considered as reliable due to the manufacturer performed calibration, so for this solution a validation of the Evalglare operations was needed (Fig. 2). Overall, very good agreement was observed, and the small differences are assumed to be an effect of resizing the photographs (to 800x800) for use with Evalglare. An issue of Labsoft was that it does not correct the DGP values for low light conditions (Ev<320lux) according to the suggested method of Wienold (2012), resulting to the addition of the 0.16 constant for DGP values below 0.2 for these cases.

The HDR images can also be used to calculate vertical illuminance from the visual field by integrating the total pixels' contribution to the vertical illuminance at eye level, as a product of the pixel's measured luminance multiplied by the respective "configuration" factor. The vertical illuminance values (at the eye level) extracted by the HDR images were compared to measured values using a vertical photometer, demonstrating a good fit (Fig. 3), a fact that proves the reliability of HDR luminance measurements.

To identify the glare sources within the field of view, a rule of 4 times the task luminance was used as suggested in the initial DGP study (Wienold and Christoffersen, 2006). The task area in our case is a circular area contained in the computer screen, based on our assumption that the focus area of importance in an office environment is contained in the screen and not a larger area that contains it. Since there were no people involved in the experiment, this assumption allowed better control of the task area luminance. Evalglare, except for the information mentioned above, can also output a modified image where it marks the task area as a blue circle and the glare sources identified with other colors.

Using this methodology in Labsoft leads to identical glare sources identification (Fig. 4). Based on the above validation, and to avoid extensive image processing and calibrations, Labsoft was selected for HDR processing and glare evaluation. Due to the experimental scope of the study and the need to observe correlations, values of DGP for Ev<320lux were not corrected according to Wienold (2012), neither did values for DGP lower than 0.2. For comfort related studies, these corrections should be applied to comply with occupants' impressions.



(a) (b) (c)

Figure 2: Validation for Labsoft's (a) DGP, (b) average luminance and (c) vertical illuminance using Evalglare as a baseline.

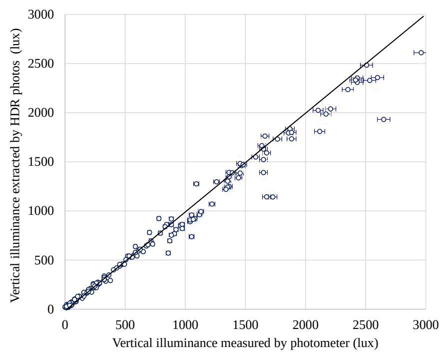


Figure 3: Validation of Labsoft's vertical illuminance using a camera-mounted illuminance meter for the case of controlled shades. (R^2=0.9817)

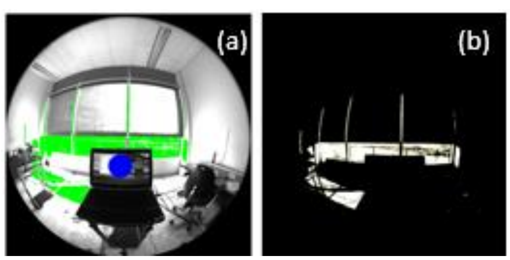


Figure 4: Glare sources identification through (a) Evalglare and (b) Labsoft (sunny conditions, employed shades (DGP=0.23).

2.4 Shading control and operation

The scope of this study includes glare evaluation and correlation with illuminance in spaces with dynamic shading controls. For this purpose, three different control schemes were applied.

- First, a fully closed shades strategy (Case I) was utilized; as closed shades are the most effective method of minimizing glare (with the obvious disadvantages of low daylight availability or view quality), this scheme provides an ideal baseline for comparisons, while it is also a realistic setting in cases of manual shading especially for instances of high direct transmitted illuminance.
- Second, a typical shading control industry standard was utilized, aiming to maximize the use of daylight. In this case (Case II), shades move automatically to a position that just prevents direct sunlight from falling on the work plane assuming a certain distance between the working area and the façade. Therefore shading position at any

time during the day is a function of solar geometry (profile angle) and distance between the seated occupant and the window (Tzempelikos and Shen, 2013).

- Finally, an advanced shading algorithm (Case III) was studied, aiming to protect the work area from direct sunlight, while adjusting the shade height to prevent high illuminances (> 2000 lux) at all times and maximize daylight provision under cloudy sky conditions. Using a window-mounted sensor, the total transmitted “effective” illuminance is defined (Eq. (1))

$$E_{eff} = \frac{\sum_i (E_g \cdot A_g + E_{sh} \cdot A_{sh})}{\sum_i (A_g + A_{sh})} \tag{1}$$

where E_g and E_{sh} are the illuminance transmitted through the unshaded and shaded window parts and A_g and A_{sh} are the areas of the unshaded and shaded window parts[2] respectively. E_{eff} is plotted against work plane illuminance (for the entire year using simulation) to determine a threshold (Tzempelikos and Shen, 2013). If the effective transmitted illuminance is below this threshold (E_{esp}), shading position is determined by the control described in Case II (work plane protection); otherwise, the shades will move to a lower position to avoid excessive amounts of daylight on the work plane. The lowest shade position h_{sh} (portion of unshaded window) to avoid high illuminances is obtained by:

$$E_{sh} \cdot (H - h_{sh}) + E_g \cdot h_{sh} = E_{esp} \cdot H \tag{2}$$

where H is the entire window height. For the experimental facilities described above, the effective illuminance threshold is 7000 lux.

2.5 Real time measurement-aided simulation

Most glare evaluation experiments involve human subjects to record their perception of discomfort. While in the case of private offices the placement of measuring equipment can be configured without problems, for open plan offices (where many different positions are being evaluated), the procedure is getting bottlenecked by the need to use luminance cameras and illuminance meters at different positions on several times. Even without considering financial aspects, there remains the fact that in a real working environment (e.g., an open plan office or a classroom), the placement of numerous sensors for every seating position could distract the subjects, creating bias influences to the results. For that reason, simulation has been used to evaluate possible daylight glare scenarios (Jakubiec and Reinhart 2013). However, uncertainty in typical weather data and sky conditions might cause errors and deviations from real-time perceived visual discomfort. Therefore, in our case, real-time measured transmitted illuminance (sensor not noticeable by occupants) can be used as an input to simulation of interior illuminance and luminance mapping. Real-time measurements allow solar geometry calculations, while an external pyranometer is used to measure direct and diffuse portions of incoming daylight. The shading position is recorded through the building automation and controls system.

The simulation uses a hybrid ray tracing and radiosity model (Chan and Tzempelikos, 2012) for rapid calculations without sacrificing accuracy of results.

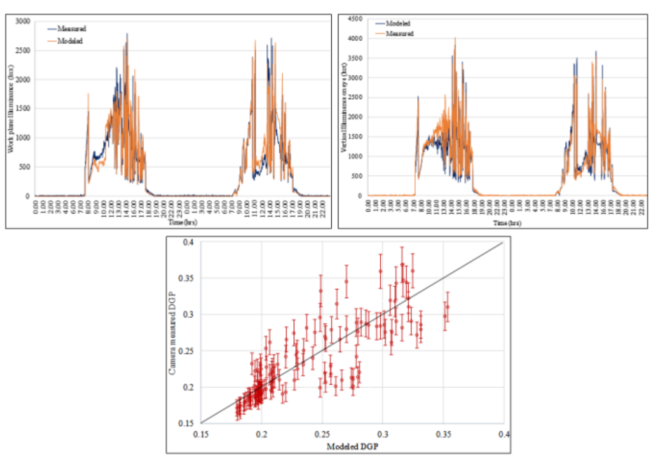


Figure 5: Validation of the model for (a) vertical illuminance; (b) work plane illuminance and (c) DGP (MSE=0.03)

The roller shades properties were modeled using a semi-empirical method (Kotey *et al.,* 2009) in order to simulate their off-normal properties and beam-diffuse transmission. The ray tracing method was used to calculate the sun's projection areas in the interior of the room, the direct light hitting the eye, as well as the direct illuminance distribution on surfaces; this information was used to extract the initial luminous exittance mapping of surfaces, as input to the radiosity method. A dense grid was used for all surfaces, to take into account glare sources due to sun projections, while a coarser grid was used for the floor to create multiple possible positions for the observer within the room, for work plane and vertical illuminance calculation purposes. The model was validated in terms of measured work plane and vertical illuminance in the test offices, and in terms of DGP measured values directly obtained by the luminance camera (Chan *et al.* 2014). Fig. 5 presents sample validation results for two successive days, using the advanced shading control (Case III). Horizontal and vertical illuminance values are in good agreement; DGP values show more dispersion, with MSE=0.03.
This approach also provides flexibility for other evaluations, such as the comparison of two shading control strategies without the need of using two cameras, or processing thousands of pictures to obtain continuous DGP fluctuation.

3. EXPERIMENTAL RESULTS

3.1 General correlations and observations

Experimental measurements in the test offices were performed for several months (different seasons and sky conditions), with all three different shading controls. The camera was placed at a distance of 2.20m from the glass and 1.60m of the right wall, at a height of 1.20m. Each test case was studied for several days, in order to observe the fluctuation of design values such as work plane illuminance compared to restrain factors such as discomfort glare. Horizontal and vertical illuminance values were recorded every minute, while luminance pictures were taken every hour. More frequent glare measurements were not necessary since the purpose of experiments is (i) to validate the models that can be used towards an integrated daylighting and glare module using hybrid ray-tracing and radiosity techniques and (ii) to derive correlations between DGP and interior illuminance using a large enough set of measured data. Having a variety of measured data (transmitted, work plane and vertical illuminance, shade position and luminance mapping) under different conditions and shading controls provides the opportunity to study potential correlations between measured parameters.
An interesting opportunity for creating guidelines would be a correlation between a design value such as work plane illuminance (or a daylight metric, e.g., UDI, as suggested by Mardaljevic *et al*., 2012) and glare probability. Representative experimental results for March and April using the SB70XL glazing are shown in Fig.6a. Work plane illuminance is related to DGP, although the correlation is not strong. This is expected for several reasons, the most important being the direct sunlight entering the space and altering the distribution of work plane illuminance with different controls –in several cases, the window is identified as a potential glare source and DGP can vary depending on window luminance and contrast between the unshaded portion and other surfaces in the field of view (more details in section 3.2). Nevertheless, even with closed shades, there is a fraction of direct light entering the space since the fabrics have a direct-direct component (4.2%) that affects interior illuminances (Kotey *et al*., 2009). Related modeling performed by the authors suggests that the smaller the direct-direct component (more diffusing fabrics), the better the correlation between DGP and vertical or work plane illuminance. However, the current setup was not suitable to prove that. Case II control (work plane protection) results in higher interior illuminance since the shades open for a significant amount of time. A more detailed comparison between the shading control strategies is presented in section 3.3.

3.2 Vertical illuminance and contrast influence on DGP

Vertical illuminance on the eye and DGP (Fig. 6b) have a strong correlation but the relationship is not linear for the reasons mentioned above. By definition, DGP (Eq. 3) is mainly influenced by the vertical illuminance term (Eq. 4), and that was the trigger for introducing DGPs, the simplified glare evaluation measure (Wienold, 2007). However, its relative weight to the equation remains unclear, especially in terms of whether and when it can be possible for the second (contrast) term (Eq. 5) to become significant or even outweigh the vertical illuminance term. This is a discussion that involves many different parameters, such as orientation, time of year for the measurements (solar path), ground reflectance, as well as window and shading properties and controls. The perceived contrast for a person facing a partially shaded window can be significantly higher for dark-colored fabrics if the openness factor is relatively small. In addition, orientations or climates exposed to lower vertical illuminance values are more prone to be directly influenced by contrast with regards to glare, since the first term is reduced and E_v appears in the denominator of the contrast term.

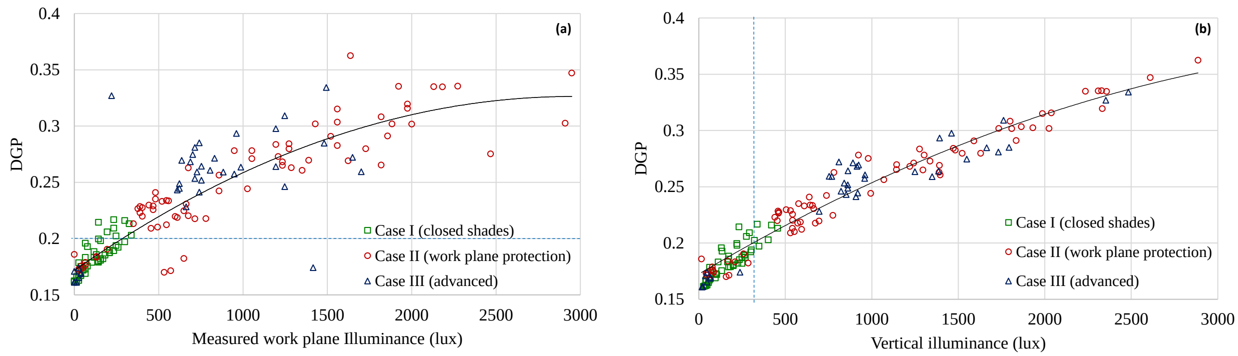


Figure 6: Correlation between measured DGP and (a) work plane illuminance and (b) vertical (eye) illuminance

$$DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_i}{E_v^{1.87} \cdot P_i^2}) + 0.16 \quad (3)$$

$$ET = 5.87 \cdot 10^{-5} \cdot E_v \quad (4)$$

$$CT = 9.18 \cdot 10^{-2} \cdot log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_i}{E_v^{1.87} \cdot P_i^2}) \quad (5)$$

This study's experimental setting involved a relatively dark (grey) fabric, and due to the south orientation, high values of vertical illuminance were present. Therefore this was an opportunity to study the relative effect of each term in more detail. Figures 7a,b,c present the contribution of each term to DGP for each of the three shading controls (variable shade positions and sunlit projections) over the period of three representative days in spring. Note that total DGP also includes a constant term (equal to 0.16) which is not shown in Fig. 7 for simplicity. The resulting measured work plane illuminance reading of the sensor in front of the camera is also shown in Fig. 7d for reference.

Closed shades naturally reduce illuminance levels –in this case to lower than 500 lux since the shade transmittance is small. The contrast term is important for several hours, with this however not providing useful insight, as DGP levels are minimized (Fig. 7a) since light levels are quite low (and for most cases below the DGP definition threshold). Case II control results in peaks of work plane illuminance, since a significant amount of light can enter the space for this type of control, and even though no direct light reaches the work plane, the overall illuminance can be high; therefore the E_v term dominates in terms of DGP contribution (Fig. 7b). The advanced control (Case III) reduces the peaks and the contrast term becomes more significant (Fig. 7c) since E_v is lower (shades move to a lower position).

However, lower vertical illuminance does not necessarily translate to a higher contrast term in the case of controlled shades (variable shade positions and sunlit projections). The luminance of identified glare sources (numerator of contrast term), source sizes and position factors also affect vertical illuminance. Therefore the type of control affects the E_v and the contrast terms in different ways, and their complex interactions are difficult to analyze. This is shown in Fig. 8, where the contrast term for all cases is plotted against vertical illuminance. The small contrast term with closed shades still remains due to some direct-direct transmission even under low illuminances; however, it is not a linear function of E_v. For controlled shades, there is a dispersion of results with only Case III showing higher contrast term trends for vertical illuminances between 800-1000 lux (and not lower or much higher).

As mentioned before, relationships between DGP and simple design (or measurable) parameters are of interest. For relatively high values of vertical illuminance, discomfort glare could be described by an equation based only on vertical illuminance (Wienold, 2007), namely simplified DGP (*DGPs*), introduced by Wienold which was in good agreement with experimental results when there is no direct sunlight in the field of view. Otherwise, errors up to 20% were estimated using modeling (Kleindienst and Andersen, 2009).

$$DGPs = 6.22 \times 10^{-5} \cdot E_v + 0.184 \quad (6)$$

The flexibility of using only vertical illuminance as a glare input is useful, especially for real-time glare-based shading controls using a sensor input. Therefore it is interesting to estimate the validity of *DGPs* in the case of controlled roller shades, with portions of the window unshaded and variable sunlit projections on the floor or on side walls within the field of view. For this reason, measured DGP values were compared to corresponding DGPs values obtained from vertical illuminance measurements (Fig. 9a) for the three cases considered. The correlation is strong but not linear, as equivalently described in Fig. 9b. The differences are due to the contrast term effects (Fig. 7), and differ with variable patterns as briefly explained in the results of Fig. 8.

The relative errors in DGPs distribution should be normally reduced for higher values of vertical illuminance, for all control schemes. This is shown in Fig. 9b, where the DGPs relative error (Eq. 7) is plotted against vertical illuminance.

$$e = \left|\frac{DGPs - DGP}{DGP}\right| \tag{7}$$

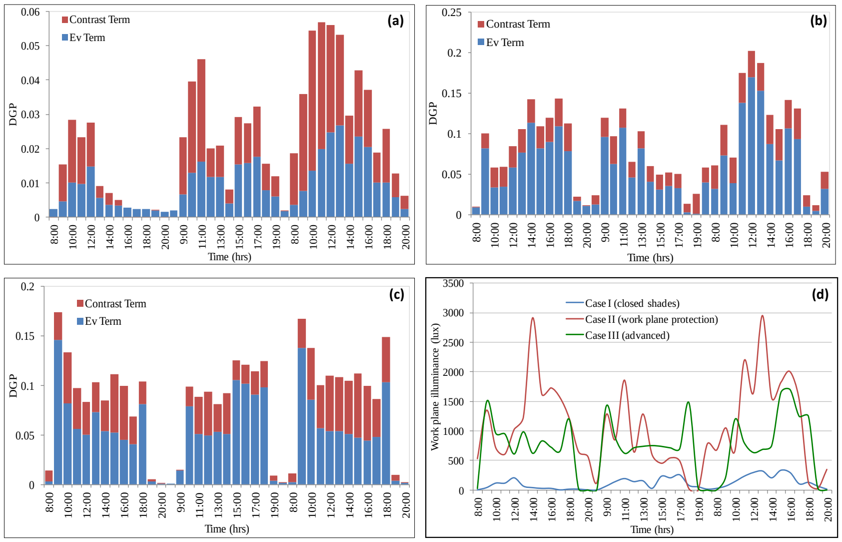


Figure 7: Contribution of vertical illuminance and contrast term for the three control cases: (a) Case I; (b) Case II; (c) Case III and (d) Work plane illuminance using the three shading control strategies for representative days used to study the effect of vertical illuminance and contrast terms.

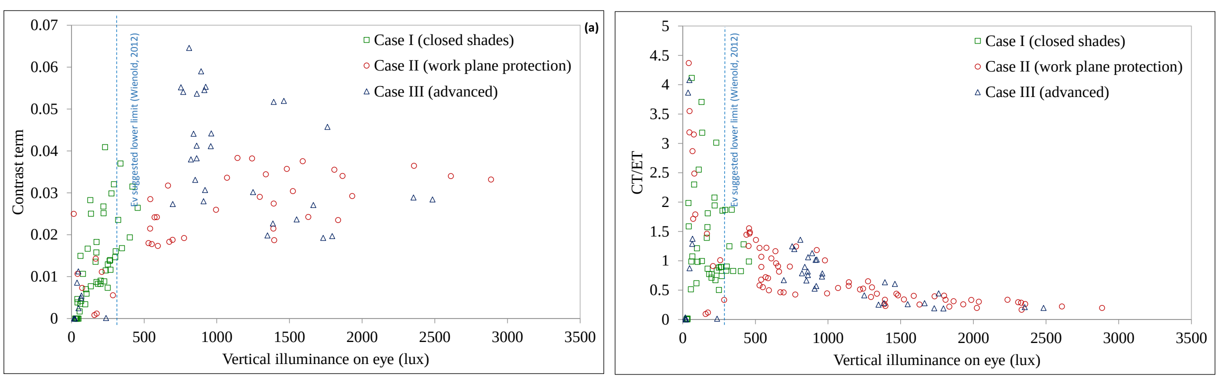


Figure 8: DGP contrast term as a function of vertical illuminance: (a) absolute value – (b) relative value (divided by the vertical illuminance term

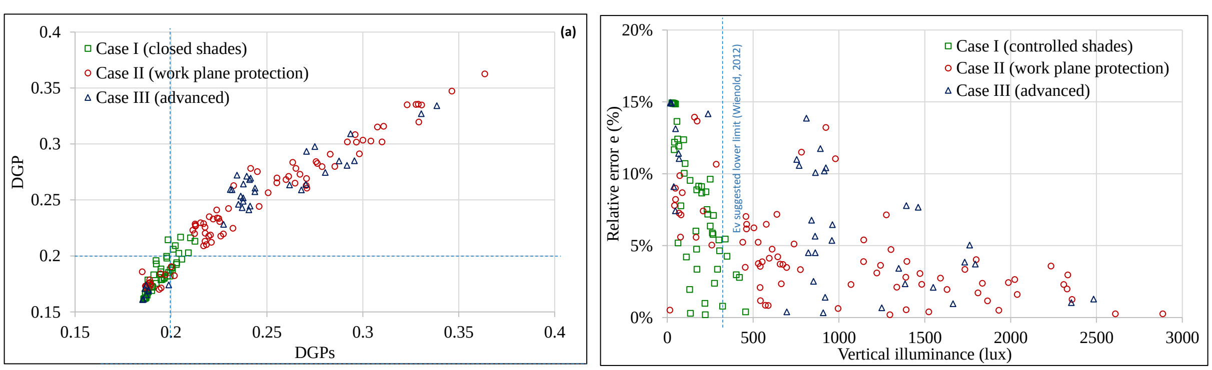
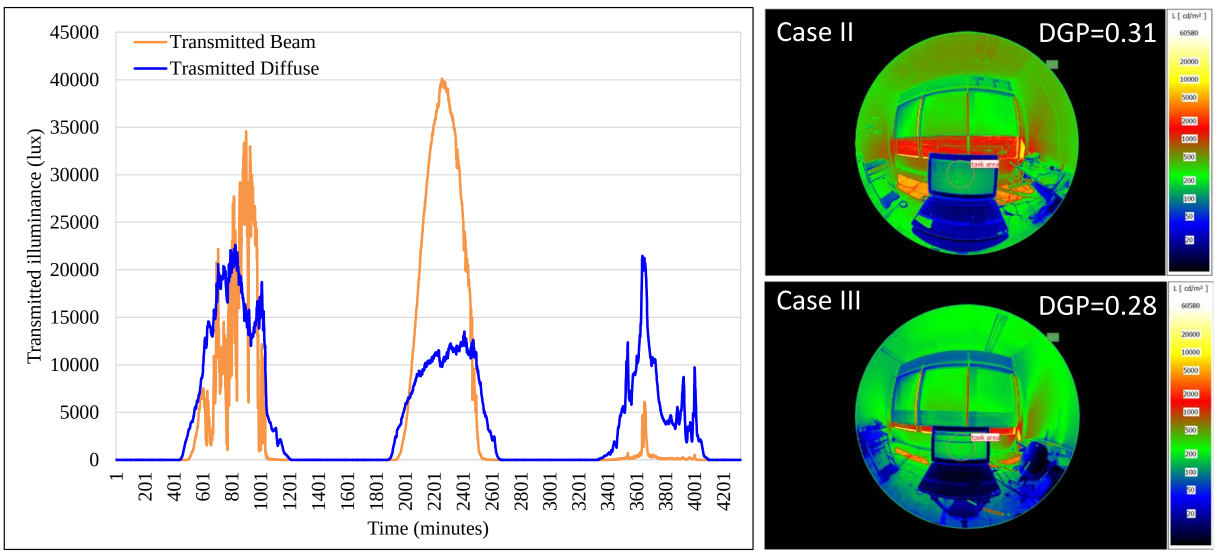


Figure 9: (a) Comparison between DGP and DGPs for all cases considered. – (b) DGPs relative error as a function of vertical illuminance for all studied cases

For closed shades, the scattering is continuous, as no high values of vertical illuminance are met during the experiments. For controlled shades, the relative error is reduced for vertical illuminance higher than 1500 lux, which according to Fig. 6 corresponds to a DGP level below the 0.35 “perceptible” limit (same for lower illuminance values); therefore the contrast term will not cause glare for the studied cases, and *DGPs* might be used to predict glare. Future experimental and modeling studies should further investigate more cases, since the results might be different for other types of shading devices and different direct-diffuse transmission characteristics.

3.3 Shading control performance in terms of glare protection and outside view

The last part of the experimental study included a comparison of shading control strategies with respect to glare performance. Case II shading control was used in one office, while Case III control was used in the second office. The analysis is presented for three successive representative days (March 29-April 1) with variable sky conditions: a mixed first day, a clear second day and a mostly cloudy third day –to ensure capturing as many presentable cases as possible. Direct and diffuse transmitted illuminance through the windows (SolarBan70XL) is shown in Fig. 10a. Shade position was recorded every minute, along with illuminance measurements for certain positions in both rooms. The methodology described above allowed the use of measured values for direct and diffuse transmitted illuminance and shade positions as inputs for the lighting model, generating this way detailed luminance and illuminance and DGP mapping and allowing direct comparison of DGP values and efficiency of shading controls.



(a) (b)

Figure 10: (a) Transmitted direct and diffuse illuminance during the comparative experiments. (b) Sample simultaneous luminance mapping for the two shading control strategies (first day, 4:30pm)

Sample images were also taken with the luminance camera for validating purposes. A snapshot of luminance images with DGP values is presented in Fig. 10b. Case II results in higher vertical illuminance and surface luminance and therefore higher DGP.

The variation of DGP as a function of time is shown in Fig. 11a for both offices. Work plane protection control (Case II) is not efficient in terms of glare protection since the portion of unshaded window allow excessive amounts of daylight into the space, causing E_v to reach high values, consequently affecting DGP. The advanced shading control performs better, since it can protect from glare (DGP>0.35) for most of the daytime. Higher values during early morning and late afternoon (due to the shading operation in order to maximize daylight) are not of concern because during these times the office is not likely to be occupied. An important result is observed for the third (cloudy) day. The shades open to allow enough diffuse daylight into the space (work plane illuminances up to 1500 lux in this case), but this is enough to cause “noticeable” glare –note that although the day is cloudy, it is not heavily overcast. Different shading control algorithms also have an effect of outside view. As shown in Fig. 11b, the advanced control algorithm reduces outside view (even down to 15%) when transmitted illuminance exceeds the pre-defined threshold to protect from high work plane illuminance values and glare. This mostly happens when direct sunlight is present and it is expected that occupants would tend to close the shades at these times. The work plane protection strategy allows at least 40% open view; however this comes with a discomfort penalty and would not be acceptable by occupants.

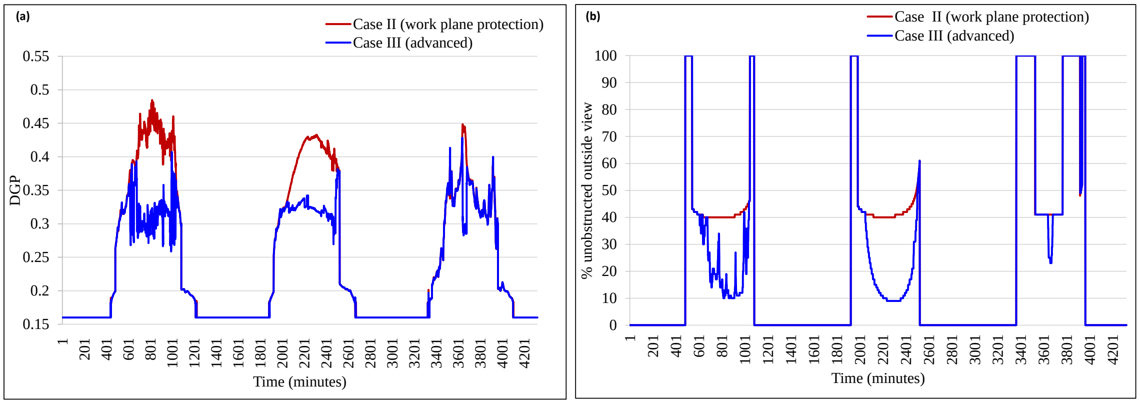


Figure 11: (a) DGP variation during comparative shading control experiments – (b) Percent of unshaded window area (unobstructed outside view during the comparative shading control experiments).

4. CONCLUSIONS – FUTURE WORK

This study was focused on the methodology of obtaining DGP measurements with HDR imaging equipment in a room with automatically controlled roller shades, and presenting correlations between indoor illuminance and DGP that leads to future modeling work about glare and visual comfort. In addition, a new methodology of integrating sensor readings and modeling to calculate interior luminance and illuminance mapping has been presented to demonstrate the flexibility of calculating DGP fluctuation throughout the room and making comparisons of different shading control strategies using limited measured data for exterior conditions. The following conclusions can be summarized from this study.

- HDR photography is found to be a convenient and adequately reliable method of luminance and illuminance mapping measurement. The variety of tools and methodologies available gives researchers plenty of ways to choose from, ranging from free software to expensive integrated hardware and software solutions.
- DGP shows only a fair correlation with the workplane illuminance. The correlation is not strong enough to extract a reliable equation, but it shows the potential of correlating a discomfort factor like DGP with a design factor like workplane illuminance in the future. Modeling work suggests higher correlation for more diffuse fabrics, but this has yet to be validated. For the case of vertical illuminance, the correlation is stronger, still influenced however by the contrast effect, especially for lower values.
- The influence of the contrast related term of the DGP equation has yet to be studied in detail; the results show that for control schemes with higher unshaded fractions, DGP is mostly dominated by the vertical illuminance term, while for controls with more closed positions the contrast term becomes significant. However, for the latter, when the vertical illuminance rises after a certain critical value, the contrast can be also negligible. These results cannot be generalized, as they reflect the specific settings used in the experiment and further modeling and measurements are needed in future studies.
- For vertical illuminance values higher than the critical value described above, the scattering of DGPs in the correlation with DGP minimizes. For the controlled schemes, this minimizing starts to take place at a point which is related to a DGP value well below the 0.35 threshold. This could mean that for higher values of vertical illuminance, but still below the design glare threshold of 0.35, a simplified index would be adequate to evaluate glare. The advantages of a simplified index are obvious considering the difficulties of detailed luminance mapping in real time using adaptive control strategies.
- Among the cases presented, the advanced control (case III) offers better protection from glare, with the cost of reducing the view quality due to the decrease of the unshaded fraction of the window. However the target work plane illuminance continues to satisfy the desired levels (Fig.7d). Shading control strategies need to be carefully designed using annual simulation results taking into account the balance between visual comfort, daylight provision and view. Nevertheless, priority should be always given to protection from glare. Model-based controls that include glare evaluation are possible, however dynamic roller shades are a complex case, even compared to venetian blinds –which can redirect daylight, eliminating some of the problems.

- The integrated simulation and measurements methodology proves to be very useful as it allows detailed mapping for DGP using simple measured inputs. In this way, it is possible to perform experiments in open plan offices without creating obstructions to the subject while maintaining a realistic working environment. Also, parametric or optimization studies with a minimum error are possible, avoiding the expensive and time consuming processes of utilizing luminance cameras.

Future work includes a more detailed modeling oriented investigation of the main conclusions of this study in terms of work plane illuminance correlation and contrast investigation, as well as a full survey with combined experiments in occupied open plan offices, to expand the studied cases and develop generic daylight discomfort guidelines.

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