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A novel methodology to spatially evaluate DGP classes by means of vertical illuminances. Preliminary results.

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ABSTRACT
A novel methodology to overcome the main limit of the Daylight Glare Probability DGP (i.e. the heavy computational time for an annual analysis of the DGP profile in one point) is presented. This uses a proxy based on the vertical illuminance (E_v) at the eye level. To do so, the most suitable value of E_v, to substitute DGP, is found by means of a comparison to the corresponding DGP value through a fault-detection diagnosis technique.
The methodology was applied to a representative enclosed office with one South-facing window (Window-to-Wall Ratio of 50%) located in Turin. The glazing was assumed to have different transmission properties (specular and scattering) with different visible transmittances (in the range 3%-66%). The error in the estimation of the DGP classes calculated through the eye vertical illuminance was evaluated, for an analysis period of a whole year.
The main advantages of the methodology proposed lie (i) in a significant reduction of the computational time required for its application and (ii) in the possibility of evaluating glare conditions not only for one or few points, but for a grid of points across a considered space. Its main limitation lies on its inability to quantify the exact DGP value, returning instead, at every time-step, the DGP class of performance.

KEYWORDS
Daylight simulation; Daylight Glare; DGP spatial resolution.

INTRODUCTION

Glare sensation is one of the most important aspects to control when dealing with visual comfort related to daylight. Daylight Glare can be caused either by a too high solar radiation in the occupants' visual field or by the presence of objects whose luminance is considerably higher than the background average luminance. Currently, the most widespread and validated metric to numerically assess daylight glare condition is the Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006), which expresses the percentage of people dissatisfied with the visual environment. The DGP is view-dependant, which means that its validity applies only to a specific point in the space and to a specific direction of observation. Moreover, due to its calculation algorithm, evaluating DGP on a yearly basis requires a heavy and time-consuming computation (Carlucci et al., 2015).
An attempt to simplify the DGP algorithm was made by Wienold (2007) to reduce the computation time required, by devising a simplified algorithm accounting for vertical illuminance (E_v) hitting the eye only. This metric, called DGPs (simplified DGP) showed a strong correlation to DGP for situations in which no direct sunlight hits the eye only, making thus its application unsuitable for a wide range of situations.
Kleindienst and Andersen (2012) developed a different simplified algorithm to evaluate DGP, the DGPm: this considers the apertures (windows, skylights, etc…) as the only luminance

sources in the scene, not accounting thus for the light reflected by internal surfaces. Despite its advantages (a more efficient computation algorithm than DGP, a better correlation to DGP than DGPs, possibility of a spatial glare evaluation), the application of DGPm remained limited as it was implemented on a non Radiance-based simulation software only. Another attempt to simplify the evaluation of DGP was made by Torres and Lo Verso (2015): they correlated the DGP to the cylindrical illuminance in the same point. Even though they obtained a good correlation to DGP, their approach is limited to the specific calculation point. In this framework, the paper presents a novel methodology to assess DGP by means of a proxy based on vertical illuminance values measured at eye level only. Such a methodology is able to significantly reduce the computation time, as the annual DGP profile for one point only needs to be calculated. Moreover, it allows the glare sensation to be assessed not only for a point in the space, but for the whole space analysed.

STEP-BY STEP DESCRIPTION OF THE NOVEL METHODOLOGY

The novel methodology proposed is presented for a representative case-study, which is an enclosed office located in Turin (45.06°N, 7.68°E), 3.6 m large, 4.5 m deep and 2.7 m high. A 3.3 m large and 1.5 m high window (Window-to-Wall Ratio = 50%) is located in one of the short walls, oriented South. The window was assumed to be alternatively equipped with 13 different glazing types, each with a specific transmission property (specular or scattering) and different visible transmittance (T_{vis}). The glazing features are summarised in Table 1.

Table 1. Glazing types considered in the study.

	Scattering glazing						Specular glazing							
$T_{vis, diffuse}$	12%	15%	23%	34%	45%	$T_{vis, specular}$	3%	12%	15%	23%	34%	45%	55%	66%

Three points in the office were identified to be representative of the different glare conditions occurring in the different parts of the room. They are all located 1.2 m above the floor, i.e. the height of the eyes of a seated person. For all the points, the observation direction was assumed perpendicular to the window, so as to evaluate the worst-case scenario (see Fig. 1).

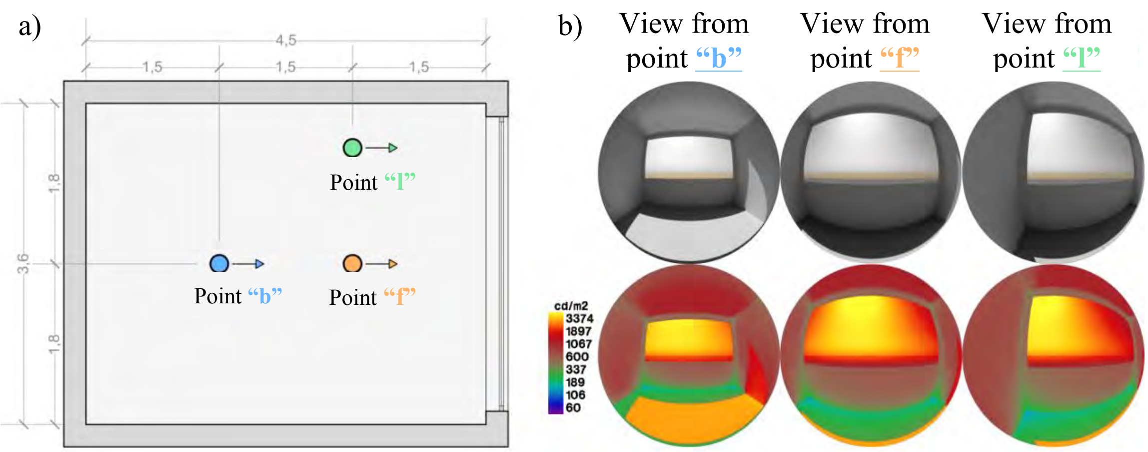

Figure 1. a) office plan with the locations and observation directions of the three points selected, b) example images and luminance images illustrating the view from each point.

For each point, DGP and E_v values at eyes were calculated through DAYSIM simulations during the course of a year (time-step: 1 hour) whenever daylight was present (night hours were not considered). This operation was repeated for each glazing type. As a result, an annual database for each glazing type was built, containing a pair of values for each time-step: a DGP value and an E_v value. The procedure is then structured in three steps.

Step 1. The goal of this phase was to define the most suitable E_v values to be used as threshold for each DGP comfort class, defined by Wienold (2009). Table 2 summarises the DGP classes with the relative DGP thresholds (DGP_{thr}).

Table 2. Daylight glare comfort classes with relative DGP threshold values.

Daylight glare comfort class	DGP thresholds
Imperceptible	DGP < 35%
Perceptible	35% ≤ DGP < 40%
Disturbing	40% ≤ DGP < 45%
Intolerable	DGP ≥ 45%

Practically speaking, E_v and DGP were compared for each time-step as metrics to identify a glare/non glare condition, using the DGP thresholds as validation reference. For each DGP threshold (DGP_{thr}), the optimal E_v threshold ($E_{v,thr}$) was found by means of a fault-detection diagnosis technique. Four sceneries were possible:

- True Positive (TP): a condition in which $E_v > E_{v,thr}$ is associated to $DGP > DGP_{thr}$
- True Negative (TN): a condition in which $E_v < E_{v,thr}$ is associated $DGP < DGP_{the}$
- False Positive (FP): a condition in which $E_v > E_{v,thr}$ associated to $DGP < DGP_{thr}$
- False Negative (FN): a condition in which $E_v < E_{v,thr}$ is associated to $DGP > DGP_{thr}$.

The fault-detection diagnosis technique was applied to every annual database previously determined (each relative to a specific glazing type and a single point). Being the *faults* represented by FP and FN cases, the E_v value minimising the FP+FN value was assumed as threshold for each DGP class. The result of this analysis was a triplet of $E_{v,thr}$ (one for each DGP_{thr}) for each of the three points in the space selected and for every glazing type. A total number of 39 $E_{v,thr}$ triplets was obtained in this phase.

Step 2. The calculation of the annual DGP for a single point in the room is a necessary assumption to reduce the computational time. Therefore, to be able to perform a simplified spatial evaluation of glare throughout the room, the $E_{v,thr}$ triplet for one point in the space was used as thresholds to assess glare for the other points. This needs to be repeated for each point of the room, i.e. applying its specific triplet of $E_{v,thr}$ as thresholds for all the other point. The goal of this phase is to determine the errors that are committed when applying this procedure. The error committed in the estimation of DGP was quantified again in terms of FP+FN. This was evaluated for every $E_{v,thr}$ and for every glazing type considered. Output of this phase are, for every glazing type, three triplets of errors for each point selected (one for DGP_{thr} of 35%, one for DGP_{thr} of 40% and one for DGP_{thr} of 45%).

Step 3. Aim of this phase is to identify the most suitable point in the space, among the three considered, to be used to determine the only annual DGP profile and hence the $E_{v,thr}$ values. To do so, for every point, the average error committed for all the glazing types was calculated for each DGP_{thr}. The optimal $E_{v,thr}$ triplet was eventually found to be the one minimising the average error committed.

RESULTS

The results of each of the three steps exposed above are shown in the following sub-sections.

Step 1. Figure 2 shows the results relative to Step 1, i.e. the $E_{v,thr}$ values obtained in correspondence of the DGP_{thr} values for every glazing type and for each of the three points in the room. As one could expect, the results show that the $E_{v,thr}$ values obtained for a DGP_{thr} of 35% are nearly always lower than the ones obtained for a DGP_{thr} of 40%, which are in turn lower than those obtained for a DGP_{thr} of 45%. It is also possible to observe a common trend for the three DGP_{thr}: $E_{v,thr}$ values tend to grow as T_{vis} increases, either for specular or scattering glazing types, up to a maximum T_{vis} value (which varies depending on the DGP_{thr} considered). Over this T_{vis}, the $E_{v,thr}$ values fluctuate around nearly the same value. For all the DGP_{thr}, a huge difference in the $E_{v,thr}$ values was observed for the three calculation points for lower T_{vis} values (considering the same glazing), while as T_{vis} grows, this difference becomes almost negligible. The error committed when assessing glare with the $E_{v,thr}$ values found, calculated as FP+FN, is in the range 0.33% - 7.24% for DGP_{thr} of 35%, 0.33% - 6.50% for DGP_{thr} of 40% and 0.29% - 5.01% for DGP_{thr} of 45%.

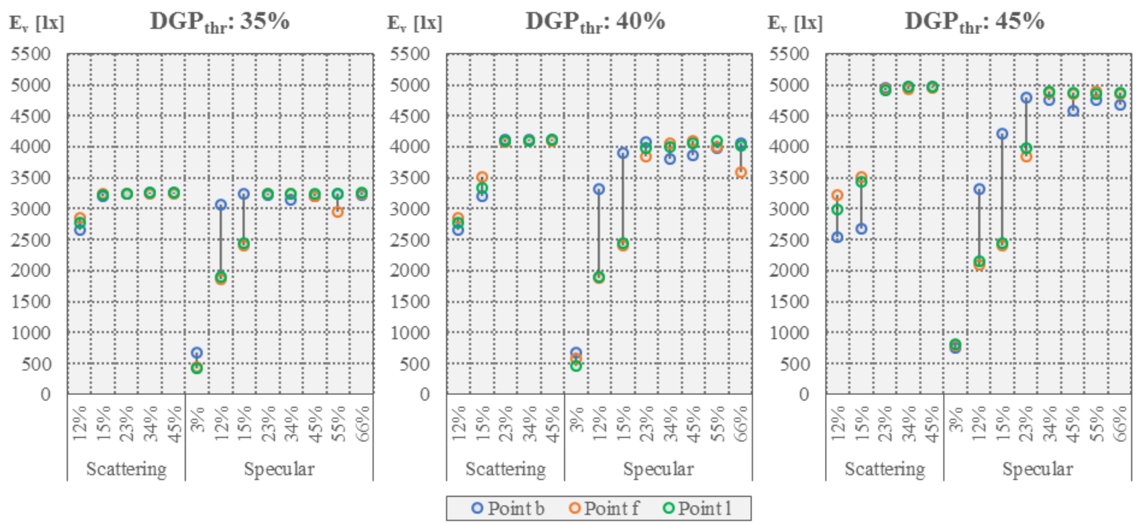

Figure 2. $E_{v,thr}$ values obtained, for every glazing type considered, for each DGP threshold

Step 2. Figure 3 shows the results relative to Step 2, i.e. the error committed when estimating the DGP class (error computed as FP+FN) by using the $E_{v,th}$ values found for a given point for all the three points. The results show that, for each DGP threshold and for every point, higher errors are committed for glazing, either specular or scattering, with lower T_{vis}. As T_{vis} grows, lower errors are committed. Analysing then the errors committed for the three calculation points, it is possible to observe that point b (located in the back part of the room) shows the most cases with higher errors. For most of the other cases instead, the errors obtained for the three points are similar.

Step 3. Figure 4 shows the average error committed for all the glazing types when estimating DGP by means of the $E_{v,thr}$ obtained for each of the 3 points in the room. For every DGP_{thr}, the results confirm that the average error committed when assessing glare by means of $E_{v,th}$ triplets relative to point b are higher than the ones relative to the other points. Similar average errors were instead obtained for point f and point l. In more detail, it is possible to observe that average errors committed for DGP_{thr} of 35% and 40% are lower for point l, while the average error relative to DGP_{thr} of 45% is lower for point f.

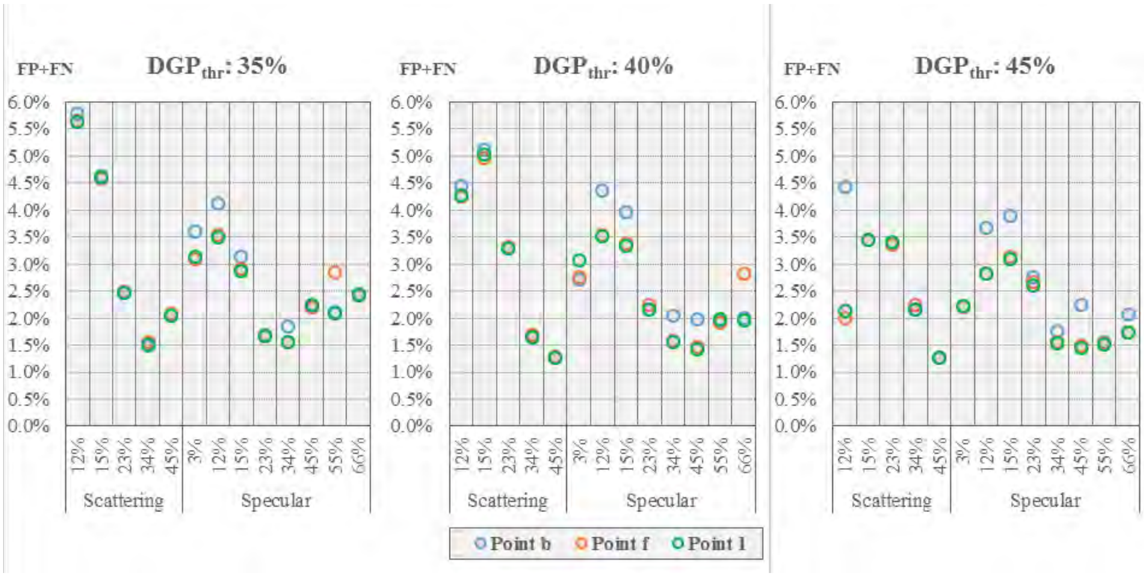

Figure 3. Error committed in the estimation of the DGP classes, for every glazing type, using the $E_{v,thr}$ values relative to each point in the room.

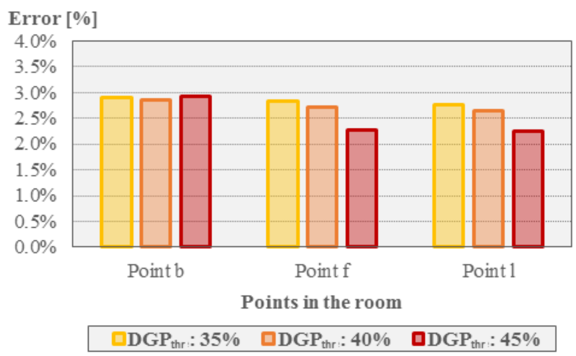

Figure 4. Average error committed, for every point, for each DGP$_{thr}$.

DISCUSSION

The novel methodology proposed allows the DGP to be assessed in a simplified way by means of a proxy based on vertical illuminance hitting the eye. Being a simplified methodology, it only allows the glare comfort class for DGP, and not the exact value, to be determined for a given E_v value.

Using a proxy based on vertical illuminance implies an average error in the estimation of the glare comfort class, which was quantified to be, for every DGP$_{thr}$, lower than 3% of the cases analysed. Such a value is considered acceptable by the Authors. The advantage of the present methodology lies in the reduction of the computation time necessary for the calculation of the annual DGP values in a grid of points across a space. In fact, the DGP for all the points in the space is assessed by means of one annual DGP computation for a single point in the room; for this point the triplet of $E_{v,thr}$ corresponding to the three DGP$_{thr}$ is calculated and used to estimate DGP for all the space. As an example, for an office such as the case-study used in this study, the computation of spatial DGP for a grid of points with a mesh of 0.5m x 0.5m (48 points) would require a computational time 48 times higher than that necessary to apply the novel methodology presented. Assuming to use an i7 processor (8 cores), the evaluation of full DGP would require 12 hours, against the 15 minutes necessary for the proposed methodology. The difference in the computation time would of course even grow as the size of the room (and the number of calculation points) increases.

CONCLUSIONS

The paper presented a novel methodology for the estimation of DGP across a space by means of a proxy based on vertical illuminance hitting the eye appears. The methodology proved to be robust, with an average error committed below 3% for all the cases considered. Its main advantage consists in its ability to significantly reduce the computation time required for the calculation of DGP for a whole space. It may therefore be used to improve the visual comfort assessment, evaluating glare sensation not only for a few points in a space, which is currently the common practice, but for a grid of points across the whole space considered.

Future work consists in an extensive validation of the proposed methodology for different directions of observation, different geometrical features of the space analysed (depth, width, Window-to-Wall Ratio, etc...) and different orientations and climates.

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