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Comparative analysis of simplified daylight glare methods and proposal of a new method based on the cylindrical illuminance

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Abstract

This paper analyzed the accuracy of simplified glare analysis methods compared to the Daylight Glare Probability (DGP) through a parametric study. It consisted of glare calculations in a sample office room, with varying façade layout and orientation. Calculations were performed with Radiance, obtaining the simplified and full glare indices for each case. The different options were compared for discrete daylight conditions as well as for complete annual simulations. As a final output of the research, a new metric is proposed based on the cylindrical illuminance. This has the advantage of retaining the vertical component of illuminance, while being view independent.

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1. Introduction

The assessment of discomfort glare in buildings is a crucial parameter to verify for an accurate and conscious daylighting design. Nevertheless, this analysis is rarely carried out by a design team, due to the inherent uncertainties concerned with the nature of this phenomenon: the perception of glare actually depends on luminance distribution within a user's field of view, as a function of the user's position and direction of view while performing a task. Furthermore, in the case of natural lighting conditions, glare also depends on the luminance distribution of the sky, which is dynamically changing over time. For the same room lay-out (position of the desks, main directions of view for users), the amount of daylight in the visual field may change significantly.

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A number of different glare indices have been proposed in the past to quantify the discomfort glare potentially perceived by building occupants, each of them valid for a limited set of conditions [1]. Recently, the study of discomfort glare has been advanced and a new index, the Daylight Glare Probability (DGP) has been introduced and validated [2]. This is based on the analysis of glare sources and on the vertical illuminance at eye level (rather than the luminance perceived at the eye due to the observed scene). Although this method is far more precise, it requires a higher level of input detail to determine view positions and directions. In order to reduce the inherently long computation time for annual calculations, a simplified version of the DGP was proposed by Wienold et al. based solely on the vertical illuminance at eye's level [3]. This method was found to be relatively accurate for situations when direct sunlight or highlight reflections are not present.

To account for users' tendency to adapt themselves to reduce the discomfort perceived, Jakubiek and Reinhart introduced the concept of 'adaptive zone' [1], which "accounts for occupant freedom to change position and view direction to predict occupant behavior under daylight conditions in response to discomfort glare and to assess the overall glare sensation throughout a space". In this study, a remarkable reduction in occurrence of intolerable occupied hours during the course of a year and an increase in the mean daylight availability were observed.

At the same time, the assessment of daylighting in buildings has been evolving towards climate based daylighting modeling (CBDM), superseding the standard approach based on the average daylight factor concept. Rather than analyzing only the worst case scenario concerned with an overcast sky, CBDM considers annual dynamic daylight conditions (both sunlight and skylight), and the incidence of glare that limits excessive daylighting levels. This methodology relies on the use of new climate-based daylight metrics, several of which have been proposed for different applications [4-6]. Most of these metrics use horizontal illuminance alone to evaluate the characteristics of daylighting in spaces, including visual discomfort. This presents several advantages due to the simplicity of the method and the possibility of comparing design options, especially at the initial stages, when interior layouts are not yet defined but decisions affecting daylight are most important. This is the case of two metrics such as the maximum Daylight Autonomy DA_{max} [4] and the Useful Daylight Illuminance [7]: both metrics set a threshold horizontal illuminance (ten times the average target illuminance over the working plane for the case of DA_{max} , a flat value of 3000 lux for the UDI, which is the most up-to-date value, as explained in [6]) over which a condition of potential glare is assumed. Within this context, this paper analyzed the relative accuracy of simplified glare analysis methods compared to the DGP through a parametric study. Four simplified glare assessment methods were compared to DGP:

- horizontal illuminance (E_{hor}), consistently with the UDI concept (potential glare for $E > 3000lx$) (Fig. 1b)
- vertical illuminance (E_{vert}): this is the illuminance calculated, for the purpose of this study, at the eyes' level of a sitting person (1.10 m above the floor) and depends on the direction of view of the observer (Fig. 1a)
- vertical illuminance vector ($E_{v,vector}$): this is based on the concept of illuminance vector, which is defined by obtaining the illuminance in three pairs of opposed directions corresponding to the three Cartesian coordinates. The difference between opposing directions conforms each component of the vector. The $E_{v,vector}$ considers only the components for the horizontal directions, which correspond to vertical illuminances in four directions, and it represents the level of contrast in the vertical plane (Fig. 1d)
- cylindrical illuminance (E_{cyl}): this is defined as "the total luminous flux falling on the curved surface of a very small cylinder located at a specified point, divided by the curved surface area of the cylinder", and it represents the average of all vertical illuminances in all directions around the considered point [8] (Fig. 1e).

It is worth stressing that, except for the case of E_{hor} , the other illuminance-based simplified methods do not have any prescription as for the threshold illuminance value over which a condition of glare discomfort is determined.

The parametric study consisted of annual simulations of a sample office room, with varying façade design and orientation. Glare indices were calculated with Radiance. The work was aimed at:

- defining illuminance threshold values for each simplified glare index
- comparing the simplified glare methods to the validated DGP so as to highlight which ones perform the most consistent results
- proposing a new metric, based on the cylindrical illuminance, also testing its degree of accuracy with respect to other metrics and the DGP.

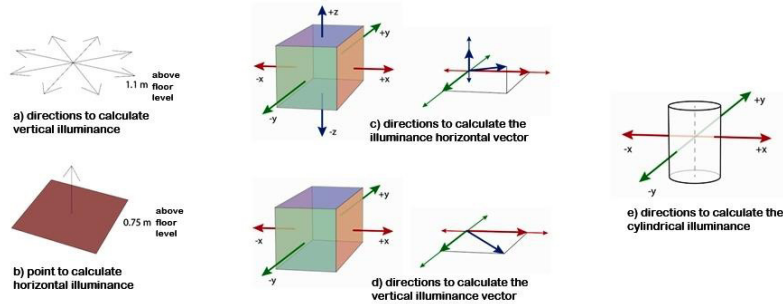


Fig. 1. Visualization of points and directions used to calculate the simplified indexes investigated.

2. Method

The parametric study was carried out through two stages:

- 1) in a first stage, different façade designs were simulated under a series of simplified sky conditions. Two different types of façades (Fig. 2) were considered, with two different ceiling heights. One additional case had only a skylight and no windows, totaling five options. Each of these options was simulated under a series of clear skies with varying solar altitude and azimuth, giving fifty-four different sun positions (Fig. 3). A grid of nine points was defined inside the room at distances between 1m and 3m from the façade. E_{hor} was calculated at each point, at a height of 0.75m above the floor. E_{vert} was calculated in eight directions, at 1.10m high. Finally, hemispherical images were produced in each of the eight directions and DGP was calculated from them. The highest DGP result for each point was compared to the different simplified glare methods. The final aim of this stage was to identify for each simplified glare metric the illuminance threshold corresponding to the validated DGP threshold value of 0.45 for discomfort glare [7].

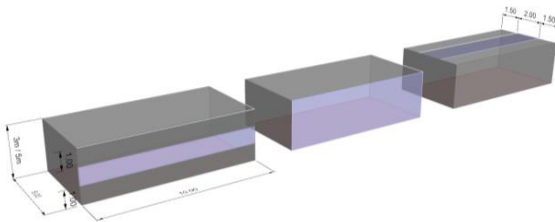


Fig. 2. Façade typologies analyzed in the first stage of the study.

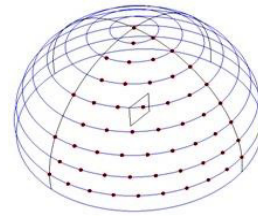


Fig. 3. Sun positions for clear skies used in stage 1 of the study.

- 2) in a second stage, one façade was tested under full annual weather conditions, in two orientations, using the same comparison between DGP and simplified methods. The findings of stage 1, described in detail in the following section ‘Results’, suggested that the simplified methods that include a vertical component of the illuminance predict glare with higher accuracy than methods based on horizontal illuminance. In order to verify this, a second round of simulations was produced using full annual weather data corresponding to London. In this case, only one façade type was considered with two orientations, facing South and East. In order to reduce the number of calculations required, only one point was considered, 1 m inside from the centre of the facade. All other calculations remained the same, with E_{hor} , E_{vert} , E_{cyl} , $E_{v, vector}$ and DGP in eight directions being calculated for each daylight hour, that is to say from sunrise to sunset throughout a year.

3. Results and discussion

3.1. Identification of the illuminance threshold values for each simplified glare metric

For the analysis and to identify the threshold illuminance values corresponding to the DGP threshold value of 0.45, the following check was adopted for each configuration, resulting in one of the following labels:

- ‘true positive’ TP: $DGP > 0.45$ and illuminance over the threshold value adopted for the considered metric. This proves a correspondence between DGP and the considered glare metric in identifying a glare condition
- ‘true negative’ TN: $DGP < 0.45$ and illuminance below the threshold value adopted for the considered metric. This proves a correspondence between DGP and the considered metric in identifying a non-glare condition
- ‘false positive’ FP or ‘false negative’ FN: these two conditions do not show a correspondence between the DGP and the considered metric, showing a DGP over its threshold and an illuminance below its threshold (‘false negative’) or vice versa (‘false positive’).

Following this approach, Fig. 4 shows how the E thresholds values corresponding to the DGP threshold value of 0.45 were identified for the simplified methods used in stage 1. The E value yielding the highest percentage of TP+TN results was selected as threshold for this stage, resulting in the following values: 2700 lx for E_{hor} ; 5000 lx for E_{vert} ; 3000 lx for E_{cyl} ; 3700 lx for $E_{v, vector}$. Despite the simulation results, it was decided to use for the E_{hor} according to the UDI metric the threshold value of 3000 lx rather than the value which was found (2700 lx), so as to remain consistent with the definition of the UDI metric [6]; however, the relative difference is negligible (around 2%). The same methodology was followed with the results from the second stage, which produced a different set of thresholds (Fig. 5). The difference suggests that the proportion of cases with direct sunlight affects the effectiveness of the different methods. Further analysis using different climatic conditions and different orientations will be required in order to better understand this effect.

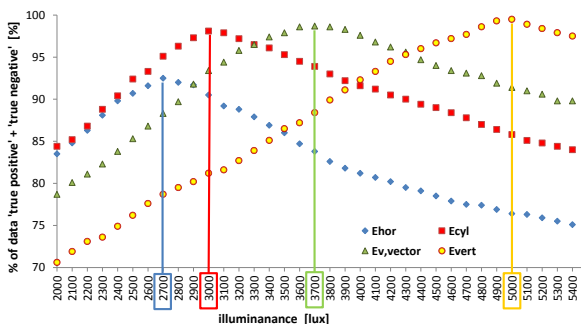


Fig. 4. Identification of the E thresholds values corresponding to the DGP threshold value of 0.45 for stage 1. The E value yielding the highest percentage of TP+TN results was selected as threshold.

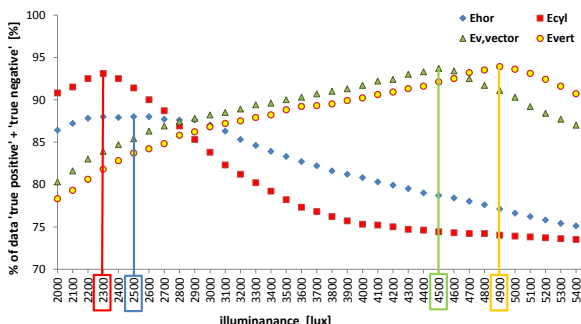


Fig. 5. Identification of the E thresholds values for the second stage corresponding to the DGP threshold value of 0.45 in stage 2. The E value yielding the highest percentage of TP+TN results was selected as threshold.

3.2. Comparison of simplified methods with DGP

The different methods were assessed by considering the number of accurate glare predictions vs. errors. This is consistent with the usual application of glare assessment methods within simulations. Figures 6 and 7 show the results which were found in stage 1 and 2, respectively. In both figures, the values found through each simplified glare method are plotted versus the corresponding DGP values for all configurations. Using the DGP threshold and the corresponding illuminance threshold found for each simplified method, four sectors were identified for each set of data, representing the TP, TN, FP and FN results. The correct glare predictions were therefore found summing TP and TN data.

As shown in Fig. 6, it appears clear that the method based on the horizontal illuminance yields the least accurate predictions, while the methods based on vertical vector and cylindrical illuminance provide predictions with comparable accuracy, with a slight better result for the method based on E_{cyl} . The results for E_{vert} are very similar to DGP, as both correspond to the direction of the maximum glare, thus being view dependent and less practical for annual calculations. However, the approach based on the E_{cyl} has the merit to yield comparable results to the DGP-based approach, with reduced computation times and the advantage of making the glare analysis view-independent.

In Fig. 7, results obtained using the E thresholds found in stage 1 are also shown: the differences show the importance of defining appropriate thresholds.

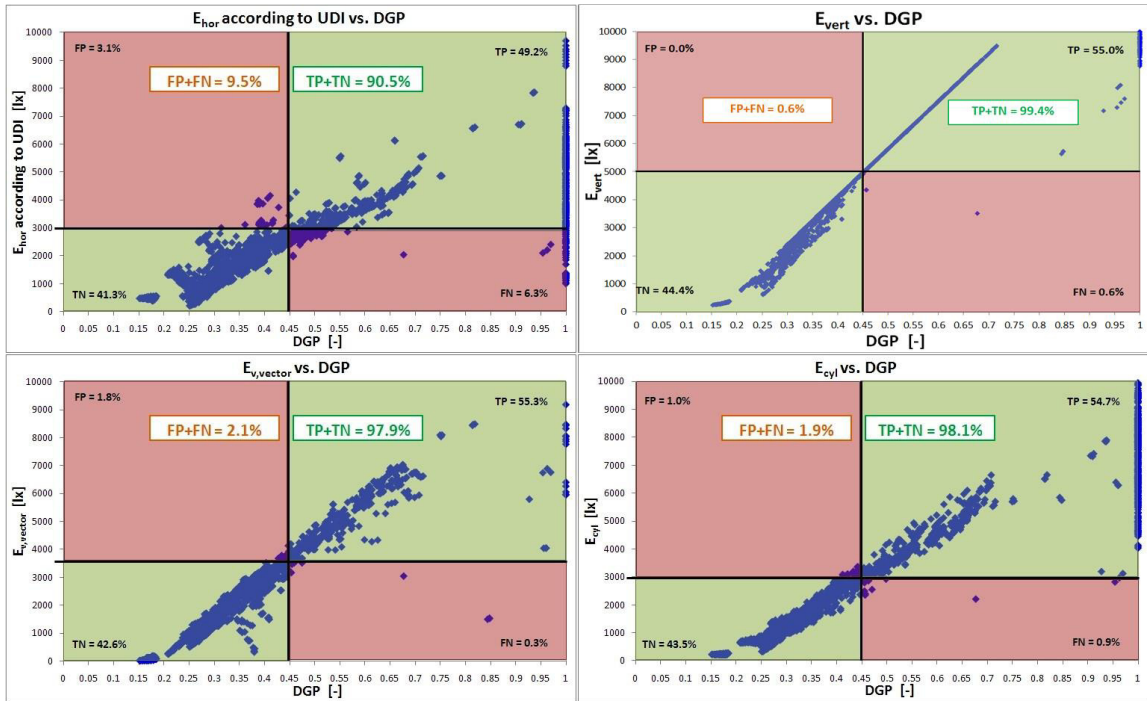


Fig. 6. Results from stage 1: glare values according to simplified methods vs. DGP values.

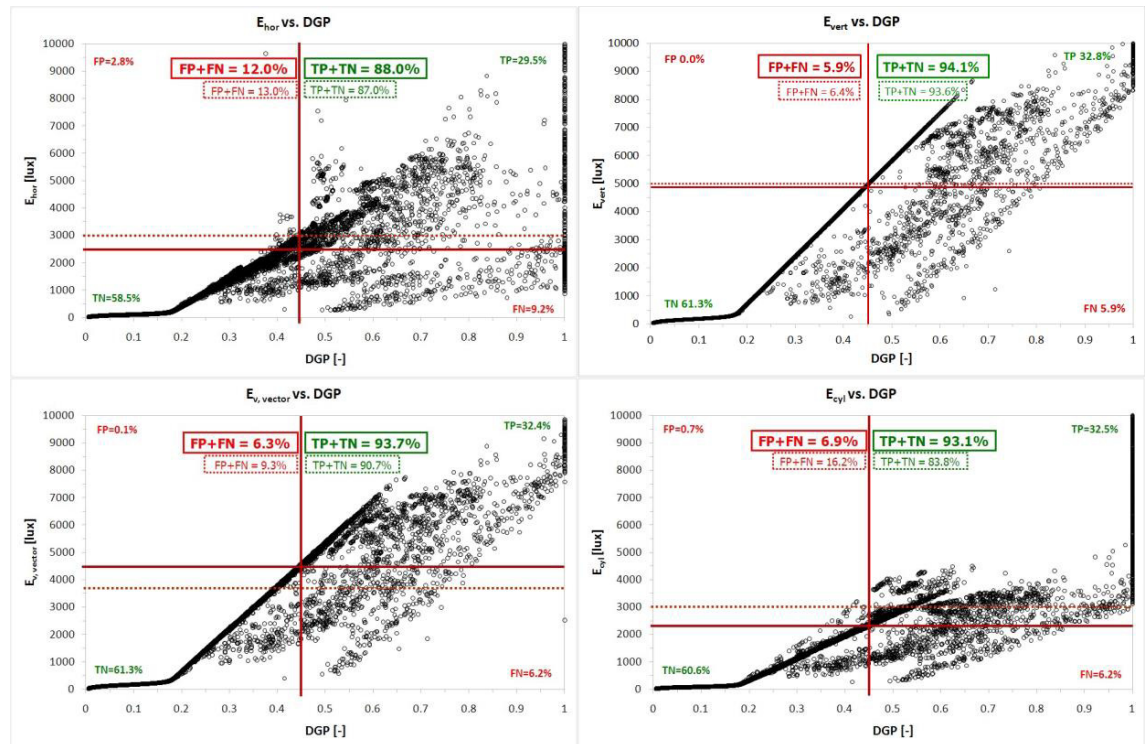


Fig. 7. Results from stage 2: glare values according to simplified methods vs. DGP values. Results in dotted box refer to the E thresholds calculated in stage 1.

It is important to note that it is very difficult to understand the effectiveness of the different methods by annual cumulative results alone. If the glare estimates will be used to inform design decisions, the time of occurrence of the detected glare cases is as important as the number of correct predictions. To illustrate this, the predicted glare cases for the East-facing façade were mapped onto the sun-path diagram according to the sun's position at the time (Fig. 8). This could be used, for example, to approximate the geometry of an external shading. As shown in the figure, most of the cases not predicted by E_{hor} correspond to solar positions below 20 degrees, especially towards the direction of the façade. Although this is to be expected due to the method, it produces a distortion more pronounced than what the annual statistics would suggest. On the contrary, methods that preserve the vertical component do not present this problem.

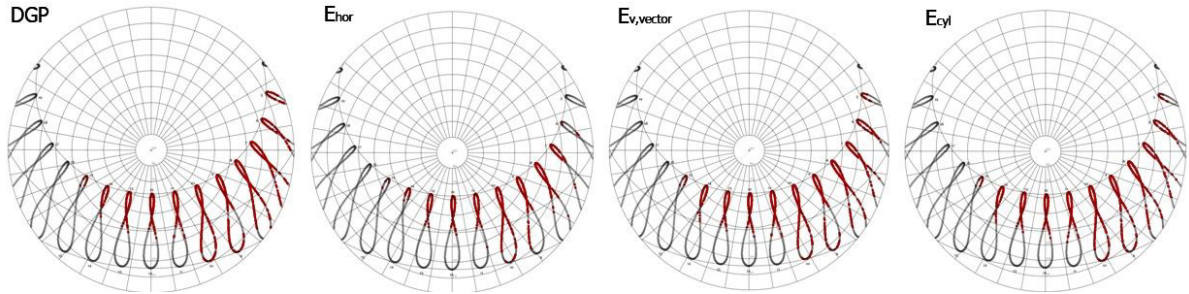


Fig. 8. Glare cases mapped onto the sunpath diagram for DGP, E_{hor} , E_{cyl} and $E_{v, vect}$. Parts in red visualize the errors in estimates.

4. Conclusions and future work

A parametric study was carried out to analyze the reliability of some simplified glare predicting methods with respect to DGP. For office buildings, this latter is the most accurate metric to quantify the potential discomfort glare for occupants, but it implies long simulation times to calculate the necessary view positions and directions for each time-step throughout a year, even when the simplified DGPs is used. In the study, E_{hor} (according to the UDI concept), E_{vert} , $E_{v, vector}$ and E_{cyl} at the eyes were compared to the DGP values. The results show that simplified methods based on E_{hor} predict glare with less accuracy than methods where the vertical aspect is considered. E_{vert} is very similar to DGP for the same view direction when it corresponds to the worst glare perceived.

As a final output of the research, a new metric is proposed based on the cylindrical illuminance. This has the advantage of retaining the vertical illuminance aspect, while being view independent. Furthermore, it is an existing measure that is already calculated by most lighting software. It was found that the new metric produces results with accuracy similar to the more detailed methods, although being easier to implement.

The work is not considered accomplished, but is still on-going: with particular regard to the stage 2 of the research, annual simulations will be carried out for locations other than London, so as to gather more information on the magnitude of the dispersion of results based on the simplified method and on the DGP for other climates.

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