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# Effects of perceived indoor temperature on daylight glare perception

Julieta Yamin Garretón, Roberto Rodriguez and Andrea Pattini

Laboratorio de Ambiente Humano y Vivienda, INCIHUSA,
Consejo Nacional de Investigaciones Científicas y Técnicas (CCT), Mendoza 5500, Argentina
E-mails: jyamin@mendoza-conicet.gob.ar, rgrodriguez@mendoza-conicet.gob.ar
and apattini@mendoza-conicet.gob.ar

**This research investigates the effects of perceived indoor temperature on glare sensation. A laboratory experiment was carried out where volunteers ($n = 19$) performed an office-like computer task. Three scenarios with sunspots over the desk were evaluated: a cold scenario, a comfort scenario and a hot scenario. All had the same vertical illuminance at the eye and luminance ratios. Discomfort glare was measured with the predictive daylight glare probability (DGP) model; actual perception of glare was assessed with glare sensation vote (GSV) scale; while thermal comfort was evaluated with thermal sensation vote (TSV) scale. In order to know how much the perceived temperature contributes to the model, an ordinal regression was performed. The result showed a Nagelkerke pseudo-$R^2 = 0.52$, $p = 0.001$, indicating that the perceived temperature affected glare predictions. This is an improvement in the understanding of daylight glare, which will allow researchers and practitioners to make informed decisions about sustainable design and occupant comfort. In conclusion, a more comprehensive glare model should include perceived temperature as a variable of the current glare model. Also, the results suggest that DGP should be used only when the person is in thermal comfort.**

**Keywords:** comfort, daylight, glare, natural light, offices, occupant satisfaction, thermal comfort, visual comfort

## Introduction

The perception of comfort is a subjective phenomenon, being almost impossible to satisfy everyone in a given situation. This makes it necessary to design a proper workplace with satisfying environmental conditions for most of the occupants. Achieving thermal and lighting comfort are some of the most important and dominant features in any work situation (Nelson, Nilsson, & Johnson, 1984). For this reason, it is necessary to study them separately as well as their interactions.

### Visual comfort

There is no single approach to achieve a comfortable lighting environment (Boyce, 2003; Veitch & Newsham, 1998), because it involves many different aspects: lighting standards give recommendations for achieving optimal lighting distribution, minimum illuminance levels, acceptable glare levels, appropriate colour temperature, proper lighting uniformity values for different tasks, avoidance of shadows and veiling reflections, and proper luminance ratios. Achieving visual comfort refers primarily to the elimination of visual discomfort (Boyce, 2014). However, the main field of study and the development of prediction models are focused primarily on discomfort glare (Nazzal, 2005). Glare is defined by the Illuminating Engineering Society of North America (IESNA, 2000) as:

> the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility.

After decades of continuous research on the topic, the cause of discomfort glare is yet not well understood. Despite this lack of understanding of the causal mechanisms of glare, four factors are identified that influence the perception of discomfort glare: luminance of the glare source, size of the glare source, position of the source in the field of view and luminance of the background (DiLaura, Houser, Mistrick, & Steffy, 2010).

Glare indices are obtained from mathematical formulas associated with subjective studies. Currently, these glare indices are commonly obtained by means of the high dynamic range imaging (HDRI) technique. Some of the existing glare indices were developed for small area sources such as unified glare rating (UGR), visual comfort probability (VCP) and Cornell glare index (CGI), which are more suitable for artificial lighting. Other glare indices were specifically developed for large area sources and daylighting, prominent among them being the daylight glare index (DGI) and daylight glare probability (DGP). The DGI was developed by Hopkinson (1972) through experiments under controlled conditions using large-area electric light glare sources. Then in order to estimate the precision of the method, it was validated in real life situations. According to Jakubiec and Reinhart (2012), DGI relies only upon visible sky brightness through a window and not on interior specular reflections or direct sources of light.

Instead, DGP introduces a new visual adaptation factor into the usual glare formula. The basis of this model is to compare areas of bright luminance against the total vertical illuminance reaching the eye, which is the photometric variable that best correlates with glare predictions (Wienold, 2009b). The DGP index in defined as follows:

$$\mathrm{DGP} = 5.87 \times 10^{-5} E_y + 9.18 \times 10^{-5} \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_y^{1.87} P_i^2}\right) \quad (1)$$

where $E_y$ is the vertical illuminance at the eye; $L_s$ is the source luminance; $\omega$ is the solid angle; and $P$ is the position index.

The DGP index performs better than DGI in the presence of daylight (Van den Wymelenberg & Inanici, 2014; Yamin, Rodriguez, Ruiz, & Pattini, 2014), especially in very bright scenes and in the presence of direct sunlight (Jakubiec & Reinhart, 2012). When developing the DGP prediction model, the indoor air temperature was maintained in a range between 23 and 25°C (Wienold, 2009a). The authors of this model argue that it would be interesting to study the influence of thermal comfort in the visual perception of office environments, since this relationship was outside the scope of their study.

The glare models described above have a subjective four-point associated scale: just perceptible (JP), just acceptable (JA), just uncomfortable (JU) and just intolerable (JI) (Hopkinson, 1950). Based on the Hopkinson scale, DGP used a slightly modified set of criteria to rate discomfort glare: imperceptible, noticeable, disturbing and intolerable (Christoffersen & Wienold, 2005).

### Thermal comfort

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined thermal comfort as 'the condition of the mind in which satisfaction is expressed with the thermal environment' (ASHRAE, 2003, p. 6). Previously, Fanger (1970) provided an initial definition of thermal comfort:

> Thermal comfort is achieved by balancing the heat losses and gains experienced by the human body, by controlling the environmental conditions (temperature, humidity, etc.). The human body adjusts its functions accordingly (for instance through perspiration) and responds of the dominant environmental conditions.

Several models have been proposed to estimate the thermal comfort. The most usual one used is that proposed by Fanger called predicted mean vote (PMV):

$$\mathrm{PMV} = [0.0300 \exp(-0.036\, M) + 0.028] L \quad (2)$$

where $M$ is the metabolism of the human body related to the activity ($W.m^{-2}$); and L is the thermal load of the human body resulting from its thermal balance with the environment ($W.m^{-2}$).

Fanger's method takes a passive, non-adaptive approach irrespective of the exterior temperature that disregards location and habituation to specific climates. Another important contribution was introduced by de Dear and Brager (1998) who helped to reconcile the two approaches (static and adaptive), demonstrating the existence of different levels of adaptation, which was not recognized before. A more recent definition proposed by Nikolopoulou and Steemers (2003, p. 96) affirms that human thermal adaptation is considered as 'The gradual decrease in body's response to repeated exposure to stimuli received from a specific thermal environment'. The recent literature provides five new ways of thinking, or a paradigm shift, in order to enhance energy savings and comfort, including:

> shifts from centralized to personal control, from still to breezy air movement, from thermal neutrality to delight, from active to passive design, and from system disengagement to improved feedback loops.
>
> (Brager, Zhang, & Arens, 2015, p. 274)

### Relationship between thermal comfort and visual comfort

There are different fields of research that investigate how indoor temperature interacts with lighting. On the one hand, photobiology studies the lighting stimulation and its role in melatonin suppression, activating the operation of the circadian system (Figueiro, Rea, & Bullough, 2006; Rea & Figueiro, 2014). Other studies have shown that different melatonin levels modify body temperature, which influences the thermal preference for an environment (Badia, Myers, Boecker, Culpepper, & Harsh, 1991; Myers & Badia, 1993). A high-temperature environment is preferred when the body temperature is low, and vice versa (Shoemaker & Refinetti, 1996). These studies suggest that lighting stimulation has an indirect role in thermal comfort; the primary effect is the suppression and synthesis of melatonin. Another branch of research studies colour temperature and its influence on thermal comfort. A specific study showed that a thermally comfortable environment is a low colour temperature of 5000°K (Candas & Dufour, 2005).

Other authors have studied the influence of thermal conditions in the perception of the lighting environment; however, those studies did not reach conclusive results. A study conducted by Laurentin, Bermtto, and Fontoynont (2000) showed that environmental temperature significantly affected the perception of light when comparing northern and southern European regions. In other words, when people are in thermal discomfort they will be more likely to experience visual discomfort. This effect was found only in women and under an artificial lighting condition. The same authors showed that this effect was not found in a daylight condition because they had no control over the sky condition, colour temperature, level of fatigue and outside view.

On the other hand, studies of energy simulation state that there is an implicit relationship between thermal and lighting aspects in radiative comfort. Laforgue et al. (1997) showed that discomfort glare due to daylighting anticipates overheating related to solar radiation. More recent studies suggest new metrics and annual graphics to evaluate daylight in a comprehensive manner, including illuminance, glare and solar heat gain data with a focus on time variations (Kleindienst & Andersen, 2012).

Previous research in regions with an arid climate, with high luminance contrasts and great thermal amplitude between winter and summer have shown a low correlation between glare indices (DGP, DGI) and the subjective perception of glare (GSV) (Yamin, Pattini, & Rodriguez, 2014). This low predictive capability of the glare models could be attributed to this seasonal temperature variation. The starting hypothesis of this work is that glare tolerance is related, among others, to thermal comfort; subsequently, there is more tolerance to glare in winter than in summer.

## Material and methods

Three different thermal situations were achieved in an experimental setting, all with the presence of direct sunlight over the desk surface. The lighting situation was planned to have sun spots over the desk surface. This condition is frequently found in rooms with natural lighting in sunny climates (Rodriguez & Pattini, 2010). The vertical illuminance at eye level ranged from 2000 to 3000 lx on every treatment. This range is cannot be differentiated by users according to European standard CEN 12464-1, which states that the ability to differentiate illuminance levels should be greater than 1.5 (CEN, 2002). Each experimental setting had different air temperature: (1) WINTER-13 (cold scenario): during the winter with a mean indoor air temperature around 13°C; (2) WINTER-20 (comfort scenario): during the winter with a mean indoor air temperature around 20°C; and (3) SUMMER-28 (hot scenario): during the summer with a mean indoor air temperature around 28°C. The only situation within the comfort indoor temperature (19–26°C) was the WINTER-20 situation.

The experiment was carried out in the experimental lighting laboratory (Figure 1(a)) at CCT-Mendoza, Argentina (latitude 32°53̂S; longitude 68°52′W). A low-density built area and scarce vegetation surrounding the structure meant there were no obstructions to the window and full access to sunlight. The laboratory has two sections: with white walls (reflectance $r = 0.91$), a black floor ($r = 0.07$) and a black ceiling ($r = 0.06$). Both sections have identical geometrical features (1.75 m wide, 3.4 m deep and 2.7 m high). The first section is the test room, which is equipped with one workstation (a desk, an office chair and a computer) where the participants performed the required tasks with a 15.6 ASUS K53E notebook ($r$ keyboard = 0.327). The measuring equipment was also placed in the test room. The other section is the waiting room, where the experimenters stayed during the trials (Figure 1(b)). In order to achieve a friendlier environment, some decorative elements in the test room were included. The only light source was the window, a 1.2 m wide and 1.14 m high glass area with an apparent size of 1.78 sr. The window was composed of 4-mm single-glazed clear glass with visible transmittance (VT) = 89%. A horizontal opaque white venetian blind was used as a solar shading device (Figure 1(c)).

The laboratory had a rotary mechanism in its base that was used to obtain the same lighting conditions in the three scenarios. This mechanism allows the researchers

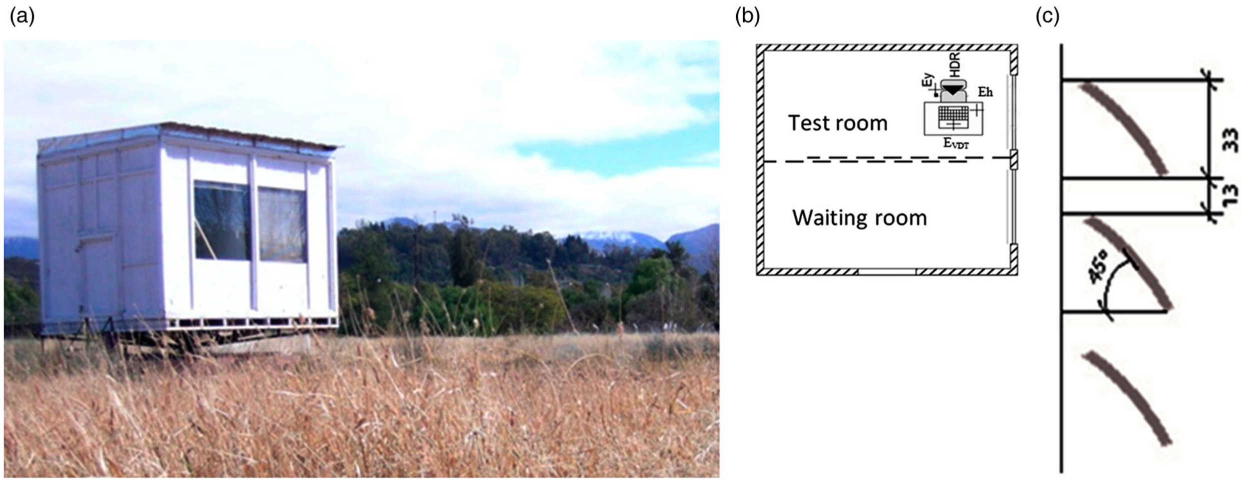


**Figure 1** (a) Exterior of the experimental lighting laboratory; (b) interior plan of the lighting laboratory ($E_y$ = illuminance at the eye, $E_{VDT}$ = VDT illuminance, $E_h$ = horizontal illuminance in the work plane, HDR = high dynamic range); and (c) venetian blind section

to change the orientation of the laboratory facade to the north, south, east or west. Furthermore, the solar shading device used was a horizontal, opaque white venetian blind with VT = 5%, with a fixed opening position of 45°, avoiding a direct view of the sun in either of the experimental treatments. In order to regulate the thermal conditions of the environment and to keep it within the established thermal ranges, the air temperature was conditioned to 28°C in summer and 13 or 20°C in winter, to achieve the three different experimental scenarios.

Figure 2 shows the plan of the experimental lighting laboratory overlapped with a solar chart for each scenario. Each solar chart shows how the sun enters into the three scenarios. The graph on the left corresponds to the WINTER-20 scenario; the middle one to the SUMMER-28 scenario; and that on the right to the WINTER-13 scenario. The solar charts illustrate the sun's path, which is marked between two black dots along with the time at which the data were taken.

### Sample, task and experimental procedure

#### *Sample*

The sample size for this analysis was 19 people, 13 women and six men, aged between 22 and 40 years (mean = 28.15 years). Data collection took 50 days, between July 2013 (winter), January 2014 (summer) and August 2014 (winter).

#### *Task*

The task was presented by means of Psychopy open source software (version 1.74.01). The participants performed a divided attention Stroop task (MacLeod, 1991). This task design includes an essential feature of office work with computers: divided attention

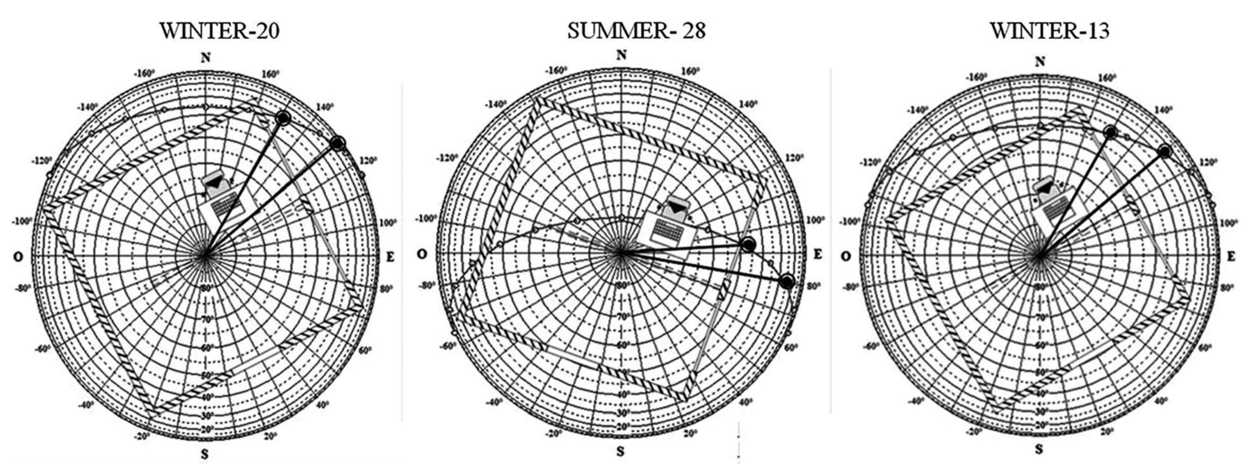


**Figure 2** Plan of the experimental lighting laboratory with a solar chart for each scenario

(Hashizume, Kurosu, & Kaneko, 2007). The Stroop task presents stimuli to participants in which the relationship between meaning and colour is manipulated so that it is congruent (*e.g.* the word RED presented in the colour red) or incongruent (*e.g.* the word BLUE presented in the colour green), resulting in a delay in the colour processing of the word, increasing reaction time and promoting errors. This semantic interference is called the Stroop effect and its magnitude is an indicator of selective attention by requiring participants to respond selectively to a particular type of goal-oriented information while ignoring distraction. Stimuli (RED, GREEN, BLUE) were presented in the centre of the visual displays terminal (VDT), in Arial 16-point font colours (red, green and blue). The amount of congruent and incongruent stimuli was balanced and text/colour combinations were randomly presented. The participants were instructed to report the 'ink' colour in which the stimuli were displayed. The response of the participants was recorded using their right hand (index, middle and ring fingers) and the computer cursor keys (left, down and right keys). The training consisted of four blocks of 12 repetitions, while the experimental trial consisted of eight blocks of 12 repetitions.

### *Experimental procedure*

Figure 3 describes the sequence of activities developed during the experiment. The upper part of the flowchart shows the researchers' activities, while its lower part shows the tasks of the volunteers. After signing the informed consent, the participants entered the laboratory, sat down and the experimental proceeding was then explained to him/her. The participants then had to fill in a form with their personal information and basic demographic data. Each volunteer then performed the Stroop test. Once the task was completed, the volunteer answered a survey in relation to the task and the indoor environmental conditions. The researcher registered the physical conditions and the photometric data at the end of the experiment.

## Photometric and thermal study: glare indices and subjective indicators

### *Illuminance*

Illuminance was obtained with an LMT light meter (range = 0.1–120 000 lx) with cosine correction and v lambda filter. The indicators selected to evaluate daylight quality were horizontal illuminance in the work space ($E_h$), vertical VDT illuminance ($E_{VDT}$) and vertical illuminance at the eye ($E_y$).

### *Uniformity and mean illuminance*

The horizontal illuminance on the workstation was measured from three reference points, allowing the mean illuminance on the desk and its illuminance uniformity to be calculated (Slater & Boyce, 1990). Importantly, many authors argue that this uniformity criterion is not suitable for daylit environments where tolerance to non-uniform illuminance may be greater than environments lit with artificial light.

$$\frac{Eh_{\min}}{Eh_{\max}} > 0.5 < 0.7 \tag{3}$$

where $E_{h\ min}$ is minimum desk illuminance; and $E_{h\ max}$ is maximum desk illuminance.

### *Luminance ratio*

In order to calculate the luminance ratio, the open source software HDRscope (version 1.0) was used (Kumaragurubaran & Inanici, 2013). This program allows the reading of luminances through HDR images, isolating the portion of pixels from the rest of the image. The advantage of this software is a feature that allows the user to select regions of interest using different selection tools (*i.e.* rectangle, circle, polygon). In particular, the polygon tool allows an accurate selection of complex surfaces. The task and source areas were determined by two masks located within the field of view (Figure 4). The first mask includes the VDT and the second includes the window and the desktop region with sunspots. These masks involve the same region for all three scenarios evaluated.

### *Air temperature and humidity*

Air temperature and humidity were monitored during the whole experiment at the beginning and the end of each trial by means of a 'Lutron' LM 8000 instrument of environmental measurements.

### *Subjective glare indicator*

The level of glare perceived from the screen was measured with a glare sensation vote (GSV) ordinal scale (Iwata & Tokura, 1998). In a survey the participants were asked to associate the magnitude of the glare on a four-point scale with predefined glare criteria: 1 = imperceptible, 2 = noticeable, 3 = disturbing and 4 = intolerable. A definition for each point of the scale was presented to the participants. The glare categories were connected to an approximate period of time that a given degree of glare would be tolerated (Osterhaus, 1996).

### *Thermal comfort*

Brager and de Dear (1998) describe three broad classes of thermal comfort research that can be discerned in the literature. Following their classification, the method used in this work is within class III: field studies based on simple measurements of indoor temperature, humidity and subjective assessments. Also, a

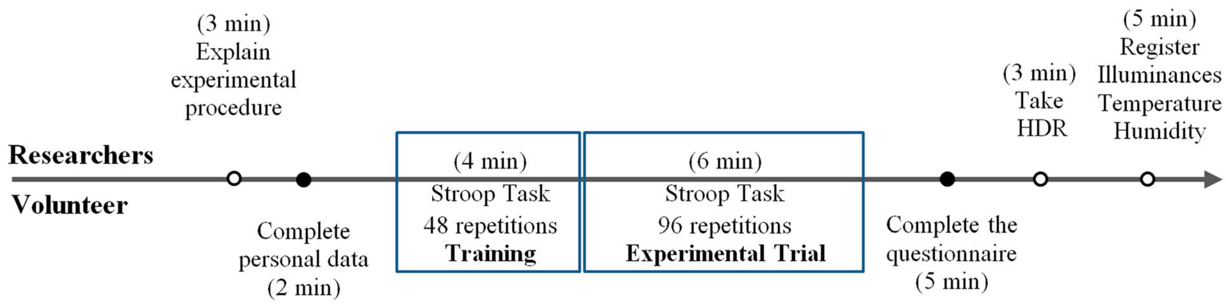


**Figure 3** Experimental flux

questionnaire provided the participant's actual thermal sensation vote (TSV), values upon which subsequent statistical analysis was carried out. ASHRAE's seven-point scale (+3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, −1 = slightly cool, −2 = cool, −3 = cold) (ASHRAE, 2003) used in this experiment will be referred as TSV within this paper.

#### *Glare index*

The DGP index was used because it is the only glare prediction model designed from scratch including natural light. It was calculated from luminance mappings obtained by means of high dynamic range images (HDRI). A series of low dynamic range images (LDRI) were obtained with a Nikon Coolpix 5400 camera with a Nikon FC-E9 fisheye lens. Each image was taken at eye level, pointing to the centre of the screen. The HDRI were built using a Photosphere v. 1.8 program for Macintosh. The resulting HDRI were calibrated with actual control luminances obtained with a Minolta LS100 luminancemeter. Finally, the HDR were post-processed with a Evalglare v. 1.11 program developed by Wienold. In order to obtain the glare indexes (DGP); Evalglare calculates the scene's mean luminance, the solid angle subtended by the source, the background and source luminances, and the position of each glare source within the HDR scene. The task luminance criterion was selected as a threshold for glare source detection. It calculates the average luminance of a given zone (task area) and counts every section as a glare source that is $x$ times higher than the average luminance of this zone. Finally, the *-i* option was included in Evalglare's command line in order manually to introduce $E_y$ values into the DGP calculation (Table 1).

## Results

DGP, GSV and TSV were evaluated on their ability to assess the three scenarios. A comparison (Wilcoxon and $t$-test) and correlation (Pearson, success rate) between scenarios was then made. In the next step, a selection of photometric and thermal variables not currently included in glare models were correlated with the actual perception of glare (GSV). Finally, in order to know how much the explanatory variable (perceived temperature) contributes to the model, an ordinal regression was performed.

### Photometric and thermal results

Table 2 shows mean values and standard deviation (SD) of temperature, humidity, $E_h$, $E_{VDT}$, $E_y$ and uniformity values. The normality of those variables was evaluated by the Kolmogorov–Smirnov test. The results of these tests showed that the variables used in the statistical analyses were reasonably normally distributed ($p > 0.05$).

**Table 1** Interpretation of glare indices

| Discomfort glare criteria | Glare range values | |
|---|---|---|
| | GSV | DGP |
| Imperceptible | 1 | < 0.30 |
| Noticeable | 2 | 0.30–0.35 |
| Disturbing | 3 | 0.35–0.45 |
| Intolerable | 4 | > 0.45 |

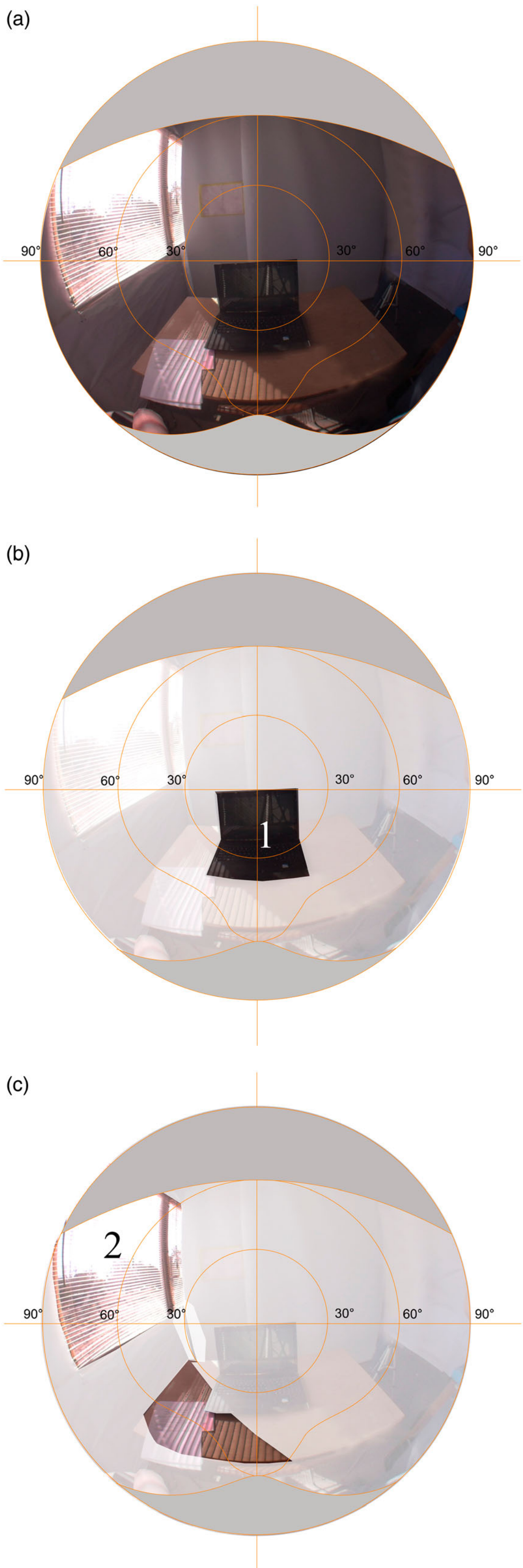


**Figure 4** (a) Entire 180° scene; (b) 180° scene including a de luminance task mask (VDT); and (c) 180° scene including a de luminance source mask (window and sun spots over the desk surface)

Photometric and thermal data of the three scenarios were compared using paired *t*-tests for related samples. Regarding illuminance values, no significant difference was found in $E_y$ ($p > 0.05$) among the three scenarios. Temperature, humidity, $E_h$ and $E_{VDT}$ were statistically different in the three situations ($p = 0.001$).

Table 3 shows the luminance ratios of the three scenarios, which were obtained from the mean luminance of the source in relation to the mean luminance of the task. According to IESNA recommendations (DiLaura et al., 2010), the appropriate luminance ratio between the task and the light source is 1:20. This approach was taken despite these recommendations not indicating how luminance ratios with daylight were computed; importantly, this lack of methodological specification could impact the obtained results (Van den Wymelenberg & Inanici, 2014).

The luminance ratios show that in the SUMMER-28, WINTER-20 and WINTER-13 scenarios, the source luminance was between 20 and 25 times higher than the task luminance (Figure 5). These results are slightly above the current IESNA *Lighting Handbook* recommendations (DiLaura et al., 2010).

Table 4 shows mean DGP, GSV (visual comfort) and TSV (thermal comfort) values for the three situations. On the one hand, the DGP defined the glare environment of the three scenarios as ‘noticeable’; this is because the basic equation for the DGP includes vertical illuminance at the eye ($E_y$) as a primary input, while for the source luminance the solid angle and position index were secondary inputs. DGP predicted the same value because the primary input was kept constant and all the other parameters had relatively low SDs. On the other hand, the GSV scale considered the SUMMER-28 scenario as ‘disturbing’, while the WINTER-20 scenario was rated as ‘noticeable’ and the WINTER-13 scenario as ‘imperceptible’. It can be noticed that in situations where the subjects were outside the area of thermal comfort, the actual perception of glare (GSV) did not match with the DGP prediction (Figure 6). It is important to note that the GSV and DGP models showed the same value in the WINTER-20 scenario. This result suggests that DGP is reliable only when the person is in thermal comfort. Finally, the TSV scale indicated that the SUMMER-28 scenario was mostly rated as warm, the WINTER-20 scenario was evaluated as thermally neutral and the WINTER-13 was evaluated as slightly cool and cool. As predicted by TSV, the only condition in which participants were in thermal comfort was WINTER-20.

The DGP values of the three scenarios were compared using a paired *t*-test (parametric analysis) showing that the DGP index predicts the same value of glare in the

**Table 2** Descriptive statistics of physical and photometric variables

| | SUMMER-28 | | WINTER-20 | | WINTER-13 | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Indoor air temperature (°C) | 28.58 | 1.61 | 19.19 | 1.75 | 13.65 | 1.31 |
| Humidity (%) | 30.94 | 3.59 | 40.96 | 9.90 | 44.66 | 6.47 |
| $E_y$ (lx) | 2361.05 | 370.30 | 2638.30 | 345.24 | 2453.40 | 386.02 |
| $E_{VDT}$ (lx) | 7687.77 | 2186.46 | 5375.75 | 3652.74 | 7212.50 | 1425.58 |
| $E_h$ (lx) | 8667.12 | 2726.50 | 6624.11 | 2964.99 | 9062.25 | 2879.97 |
| Illuminance uniformity $E_{h\,min}/E_{h\,max} > 0.5 < 0.7$ | 0.43 Non-uniform | | 0.38 Non-uniform | | 0.43 Non-uniform | |

*Note*: $E_y$ = vertical illuminance at the eye, $E_{VDT}$ = vertical visual displays terminal (VDT) illuminance, $E_h$ = horizontal illuminance in work space, $E_{h\,min}$ = minimum illuminance, $E_{h\,max}$ = maximum illuminance

three situations ($p > 0.05$). The GSV and TSV values of the three scenarios were compared using a Wilcoxon test (non-parametric analysis), which showed a statistically significant difference of both GSV and TSV values among scenarios ($p < 0.05$).

The correlation between GSV and TSV was moderate and significant ($r = 0.67$, $p = 0.001$) (Figure 7). This is in accord with the statistical criterion that considers correlation coefficients above 0.7 as high and coefficients higher than 0.4 as moderate (Walpole, Myers, Myers, & Ye, 1993). These results show a significant relationship between the subjective perception of glare and thermal sensation, suggesting the need to include it in glare prediction models.

In order to know if other variables besides the perceived temperature affect glare sensation, $E_{VDT}$ and $E_h$ were correlated with GSV. Both variables are not included in the DGP calculation and they were statistically different among the experimental situations. The results showed that $E_h$ had no correlation with GSV, while $E_{VDT}$ had a low correlation with GSV ($r < 0.4$). Because this correlation is low, the influence of $E_{VDT}$ in the perception of glare was not considered in the subsequent regression analysis. Finally, the perceived temperature was the variable (not included in DGP) that had the highest correlation with the sensation of glare ($r > 0.6$), raising as a promising proper variable to be incorporated in the glare prediction model (Table 5).

Finally, in order to know how the perceived temperature contributes to the glare model, a logistic regression was made. The independent explanatory variable was perceived temperature (TSV) and the dependent variable was glare sensation (GSV). The results show that the model that includes the perceived temperature improved the ability of the model to predict the outcome, in relation to a baseline model without any explanatory variables (chi-squared = 37.618; d.f. = 1; $p \leq 0.001$). The goodness of fit of the model showed that the observed data were consistent with the fitted model (chi-squared = 0.539; d.f. = 4; $p = 0.970$). A large $p$-value means that the model predictions are similar, hence the model is good. The results also show a Nagelkerke pseudo-$R^2 = 0.528$ with $p = 0.001$, indicating that the perceived temperature effectively contributed to the prediction of glare.

The parameters estimate (Table 6) shows the relationship between the explanatory variables and the outcome. The category 'ES-ranges' is the reference category. The coefficients for the other scenarios were

**Table 3** Luminance ratios

| | SUMMER-28 | | WINTER-20 | | WINTER-13 | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Mean luminance task (mask 1) | 90.82 | 15.65 | 58.23 | 28.38 | 106.25 | 22.28 |
| Mean luminance window (mask 2) | 3401.75 | 529.23 | 2015.50 | 390.54 | 3244.36 | 621.12 |
| Luminance ratio: mean luminance window/mean luminance task | 19.70 | 7.75 | 25.82 | 13.34 | 20.37 | 6.23 |

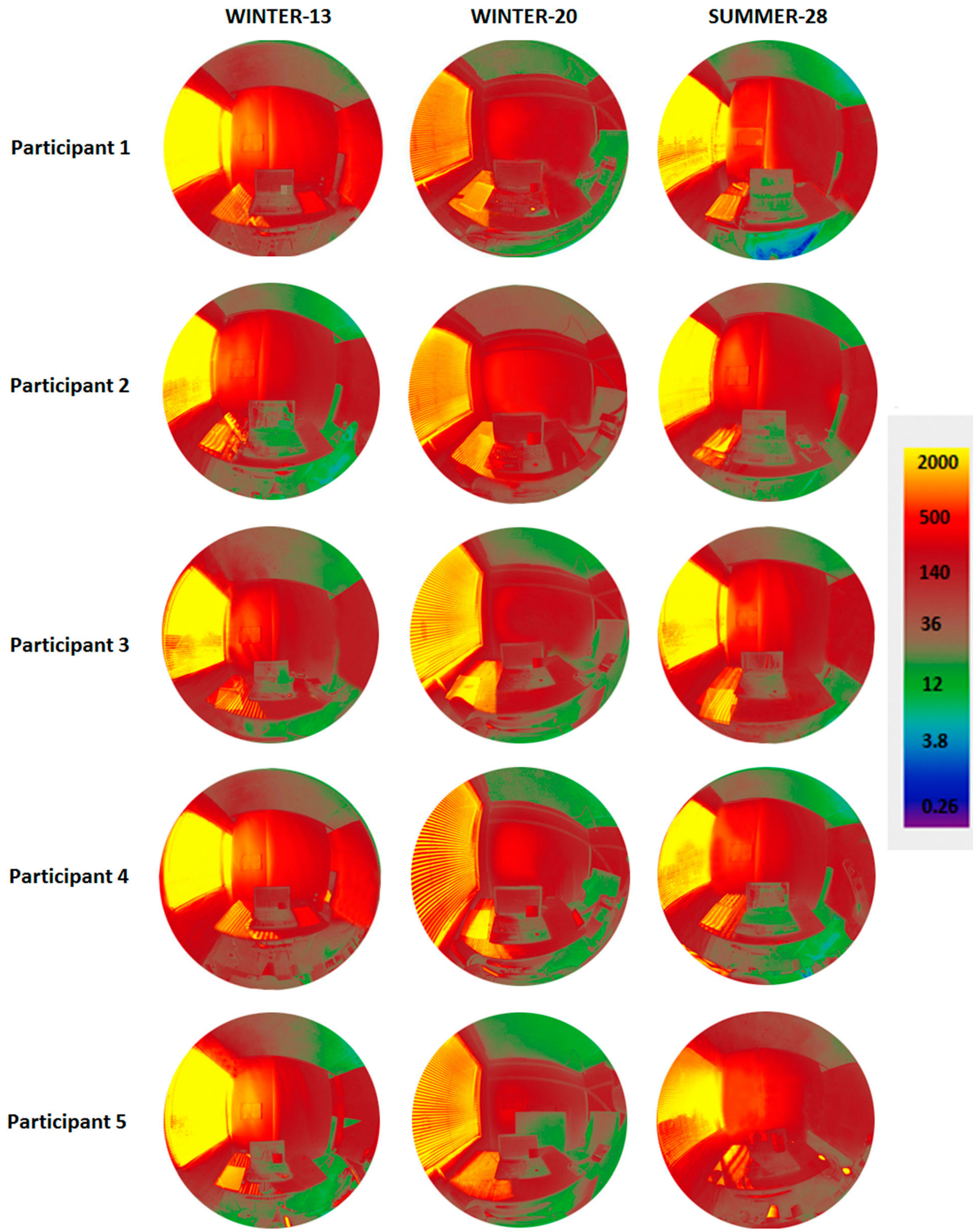


**Figure 5** High dynamic range (HDR) of five participants in the three situations

**Table 4** Descriptive statistics of the discomfort glare and thermal comfort

| | SUMMER-28 | | | WINTER-20 | | | WINTER-13 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Mode/median | SD | Mean | Mode/median | SD | Mean | Mode/median | SD |
| GSV | 2.28 | 3 | – | 2.11 | 2 | – | 0.30 | 1 | – |
| DGP | 0.31 | – | 0.02 | 0.31 | – | 0.12 | 0.31 | – | 0.02 |
| TSV | 1.70 | +2 | – | 0.11 | 0 | – | −1.23 | −1 | – |

negative (−5.218 for the cold setup and −1.912 for the neutral one). This means that lower temperatures are associated with poorer GSVs. Based on the small observed significance levels, it can be concluded that there is a statistically significant relationship between temperature and glare sensation.

Table 7 allowed a calculation to be made of the relative risk (RR) of being disturbed by the glare source in the experiment. RR is the ratio of the probability of an event occurring (in this case, discomfort glare) in an exposed group (to thermal discomfort) against the probability of the event occurring in a comparison, non-exposed group:

$$\mathrm{RR} = \frac{p \text{ event when exposed}}{p \text{ event when non} - \text{esposed}} \tag{4}$$

RR includes two important features: (1) a comparison of risk between two 'exposures' puts risks in context; and (2) 'exposure' is ensured by having proper denominators for each group representing the exposure. RR was chosen instead of the odds ratio because the former is simpler and more direct to interpret than the latter. GSV was converted into a dichotomous variable in order to calculate the RR of being disturbed by the glare source in the presence of thermal discomfort. The first three steps of GSV as 'no sensation of discomfort glare' and the final two steps as the 'presence of sensation of discomfort glare' were recoded.

Pair comparisons were made by considering the neutral environment as the non-exposed one. Because no one was disturbed by the glare source in the cold scenario, it was not possible to calculate its RR. Comparing the hot scenario with the neutral scenario, an RR = 2.6 was calculated. When the risk is equal to 1, the probability of being disturbed is the same for both situations. The result indicates that when participants were exposed to a hot environment, the probability of occurrence of discomfort glare was more than 2.5 times higher in relation to a thermally comfortable environment.

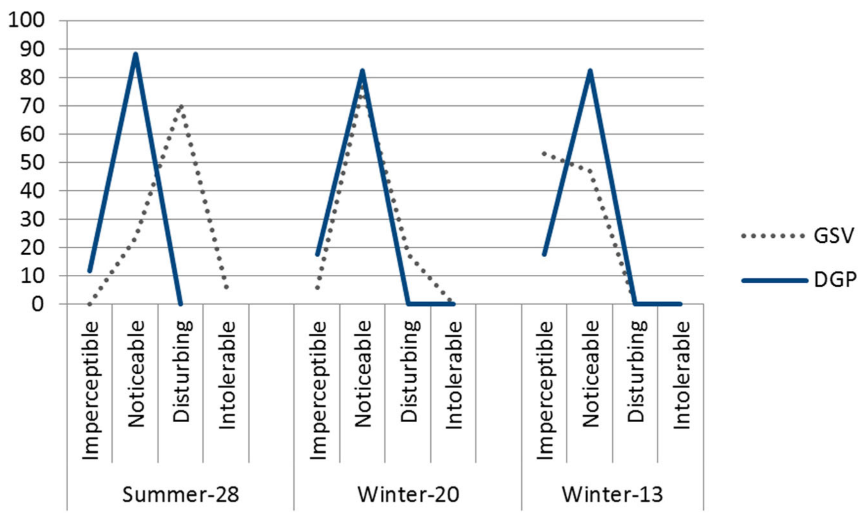


**Figure 6** Glare sensation vote (GSV) and daylight glare probability (DGP) performance
*Note*: The *x*-axis indicates the perception of glare: imperceptible, noticeable, disturbing and intolerable; the *y*-axis indicates the percentage of people

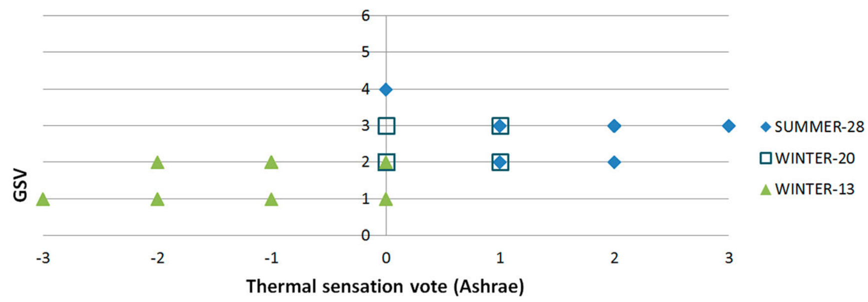


**Figure 7** Relationship between glare sensation vote (GSV) and thermal sensation vote (TSV) in the three situations

**Table 5** Correlations between measured environmental factors and subjective assessments of comfort

| | GSV | | TSV | |
|---|---|---|---|---|
| | r | *p* | r | *p* |
| $E_{VDT}$ | 0.251 | 0.051 | 0.372 | 0.003 |
| $E_h$ | 0.042 | 0.755 | −0.65 | 0.623 |

It is important to point out that the discrepancy between the GSV and DGP results cannot be attributed only to thermal comfort. In the experiment a large number of variables were kept constant; however, some comments are warranted. There are photometric parameters, such as the scene luminance distribution analysis, that require further study. Specifically, the effect of non-uniform luminance sources in glare sensation (Eble-Hankins & Waters, 2009), or the inconsistencies in the application of the recommended luminance ratios (Van den Wymelenberg, Inanici, & Johnson, 2010). In addition, there are parameters related to the psychological and physiological states of the observer. For example, the importance of a view outside (Tuaycharoen & Tregenza, 2007) or individual differences (Rodriguez & Pattini, 2012), among others. Therefore, a comprehensive analysis is necessary where the relative weight of each factor is evaluated holistically.

## Conclusions

The desire for sustainable building practices lead to building codes, standards and voluntary rating systems that promote the use of glazing and windows. This in turn might increase the risk of poor occupant visual and thermal comfort. A reliable daylight prediction method does not yet exist. Current metrics had many limitations: for simplicity, one limitation is that they consider only the visual parameters involved in discomfort glare. Other factors include, but are not limited to, individual differences in glare

**Table 6** Ordinal regression to test the statistical significance of the observed effects

| | Estimation | SD | Wald | d.f. | Significance | 95% Confidence interval | |
|---|---|---|---|---|---|---|---|
| | | | | | | Lower limit | Upper limit |
| *GSV* | | | | | | | |
| [ES-GSV = Imperceptible] | −5.194 | 1142 | 20.693 | 1 | 0.000 | −7.432 | −2.956 |
| [ES-GSV = Noticeable | −0.805 | 0.493 | 2.671 | 1 | 0.102 | −1.771 | 0.160 |
| [ES-GSV = Disturbing] | 3.040 | 1.028 | 8.741 | 1 | 0.003 | 1.025 | 5.055 |
| *T°* | | | | | | | |
| [ES-ranges = Cold] | −5.218 | 1.214 | 18.464 | 1 | 0.000 | −7.598 | −2.838 |
| [ES-ranges = Neutral] | −1.912 | 0.714 | 7.165 | 1 | 0.007 | −3.312 | −.512 |
| [ES-ranges = Hot] | 0 | . | . | 0 | . | . | . |

**Table 7** Relative risk (RR) calculation

| ES-TSV-R | ES-GSV-R | | Total |
|---|---|---|---|
| | No | Yes | |
| 1 (Cold) | 19 | 0 | 19 |
| 2 (Neutral) | 14 | 5 | 19 |
| 3 (Hot) | 6 | 13 | 19 |
| Total | 35 | 18 | 57 |

tolerance, view content, time of day, etc. This experiment tested the effects of thermal comfort on glare sensation and showed different glare responses in similar lighting scenarios with different perceived temperatures.

The results showed that when participants were out of their thermal comfort zones, their actual glare sensation (GSV) did not match that of the predictive glare model (DGP). While the DGP index considered the glare environment of the three scenarios as 'noticeable', the GSV scale considered the SUMMER-28 scenario as 'disturbing', the WINTER-20 scenario was rated as 'noticeable' and the WINTER-13 scenario as 'imperceptible'. This discrepancy between the DGP index and GSV scale may be caused by the fact that DGP bases its glare prediction on luminance ratios and vertical illuminance at the eye. Since those variables were statistically similar in all three scenarios, the prediction of glare was the same.

The perceived temperature was the variable that had the highest statistically significant correlation with the sensation of glare ($r > 0.68$; $p = 0.001$). For this reason it was considered appropriate to incorporate the perceived temperature to the ordinal regression analysis. The ordinal regression results showed that the amount of variance explained by temperature was ($r^2 = 0.52$; $p = 0.001$), indicating that the temperature effectively contributes to the prediction of glare.

In conclusion, the data obtained suggest that if a person is outside their thermal comfort zone, his/her perception of discomfort glare will be affected. The predictive glare model (DGP) currently used does not predict this phenomenon. On the one hand, the evidence obtained shows that the accuracy of the DGP depends on the thermal environment, hence it should be used only while the participant is within their thermal comfort zone. On the other hand, the data show that while current glare prediction methods needs to be improved, the inclusion of the perceived temperature is one of the variables not yet considered that at least requires further research and validation.

Any improvement in the understanding of daylight glare phenomena allows researchers to develop and improve glare prediction methods. An enhanced glare model could be applied to dynamic simulations of natural lighting, allowing the development of daylight metrics in specific thermal contexts (*e.g.* useful daylit hours while in visual comfort specifically for winter and summer), resulting in positive impacts in terms of energy savings and an occupant's well-being.

Eventually technical committees and international regulation organizations may promote standards, recommendations and good practices concerning the matter. Practitioners then will have the proper tools to make informed decisions about sustainable design considering occupants' comfort.

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