Energy & Buildings 166 (2018) 145–153

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

A global evaluation of discomfort glare metrics in real office spaces with presence of direct sunlight

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ARTICLE INFO

Article history:
Received 22 June 2017
Revised 22 November 2017
Accepted 22 January 2018
Available online 2 February 2018

Keywords:
Visual comfort
Discomfort glare
Glare model
Daylight
Human subject study

ABSTRACT

Existing glare metrics are usually tested in controlled studies and have certain limitations when predicting extremely bright scenes typical of clear sky with great daylight availability. A field-based research was carried out, where 26 real offices with direct sunlight were evaluated. Different daylight glare metrics were selected (luminance and illuminance levels, luminance ratios, luminance distribution). These were divided into two categories: "absolute glare values" and “relative glare values” following a study made by Suk et al. [22]. The contributions of these metrics about glare sensation (GSV scale) were statistically analyzed. In addition, the DGP model and uniformity values were calculated to complement this analysis. This paper demonstrates that Suk’s proposal is a viable alternative; however, the “percentage of central and near FOV with luminance greater than 2000 cd/m^2” metric showed a better correlation with the subjective response. Finally, a glare equation based on an absolute and a relative glare factor was proposed. This model is recommended to be used specifically when direct sunlight is present in the work area.

1. Introduction

The building sector consumes approximately 40% of the world’s energy [1,2]. Artificial lighting represents an important part of the total energy consumption in non-residential buildings (between 20% and 30%) [3]. Lighting is an important issue in reducing overall energy consumption [4], particularly through the use of daylight. Daylight has great potential for energy conservation in buildings, especially in sunny sky condition. In addition, this light source has important benefits on visual comfort and health. However, when daylight is not properly controlled glare problems occur, and their consequences on visual comfort.

The International Commission on Illumination (CIE) holds that visual comfort is associated with the control of the luminance distribution, illuminance, glare, the direction of the light, color temperature of light, shading, among other factors [5]. Carlucci et al. [6] affirm that visual comfort indices study the relationship between human needs and the light environment, and they proposed a more recent classification, which evaluates a lit environment in order to achieve visual comfort: a) Glare, b) Quantity of light, c) Uniformity of light, and d) Quality of light [6]. In addition, visual comfort is characterized largely by individual differences and context [7,8]. Both definitions of visual comfort are compatible, and both consider glare as one of the most important features of an environment with clear sky and great daylight availability. For this reason, glare is one of the factors that require appropriate control during daylight hours [9], especially in offices.

Over the years, many methods have been developed to assess glare. However, the existing methods are not able to consistently predict glare problems in extremely bright scenes [10]. The most common methods found in the literature are: 1) Glare predictive models, 2) Absolute glare values such as luminance and illuminance values, 3) Relative or contrast values usually expressed as luminance ratios, and 4) Relation between absolute and contrast values.

The most validated model for daylight are the DGP index (Daylight glare probability) [11]. The basis of the DGP model is to compare areas of high luminance with respect to vertical eye illuminance. This last factor is the principal component of the equation. The DGP index performs better than the existing metrics in the presence of daylight [12,13]. However, DGP showed limitations for glare prediction in extreme sun situations, which are frequently found in sunny climates [13].

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https://doi.org/10.1016/j.enbuild.2018.01.024
0378-7788/

Regarding absolutes glare values, on the one hand, vertical eye illuminance is a reasonable and simple indicator for discomfort glare [11]. Many studies have been carried out to find the best way of avoiding glare by analyzing proper eye illuminance values. Different situations have shown different illuminance values, for example, reasonable threshold values for avoiding glare are accept at: between 1000 and 1500 lx [14], or values up to 2551 [15]. On the other hand, the maximum luminance value of a scene is also recommended. Some authors advise levels of up to 2500 cd/m^2 [16,17], while other values go up to 6000 cd/m^2 for avoiding uncomfortable glare and 8000 cd/m^2 for avoiding intolerable glare [18]. Another way to address the glare problem is to calculate the glare area. One study suggests that "preferred" scenes never exceed 10% of the field of view with 2000 cd/m^2 [19].

Regarding relative and contrast ratios, typical recommendations assume a 1:3 ratio between the visual task and its immediate surroundings, a 1:10 ratio between the visual task and other closer surfaces in the visual field and a ratio of 1:20 for the more distant surfaces in the visual field [20,21]. There is a lack of specification as to how to calculate this data [12]. However, a recent study made under daylight conditions showed that the ratio between the mean luminance of the task and the average luminance of the glare source showed the best correlation with subjective response. This study recommends a ratio from 0 to 22.0 for achieving an imperceptible glare zone [22].

Suk et al. argue that existing glare methods do not specify the cause of a glare issue; these methods only specify the levels of visual discomfort [23]. In order to solve this problem, they propose addressing the glare problem from the relation between absolute and relative glare values. Understanding the dominant glare factor (absolute or relative factor) could help in finding a more suitable solution for resolving glare problems.

Besides glare, uniformity also plays an important role in visual comfort. The tolerated degrees of uniformity also vary greatly, especially in climates with clear skies. Many authors recommend high levels of uniformity by avoiding sun filtration over work stations or above the visual field of the office workers, in order to achieve visual comfort [24]. However, numerous studies also support the presence of uncontrolled direct sunlight in offices. The presence of direct sunlight is related to the pleasurable effect that the entry of daylight produces [19,25].

This study was focused on discomfort glare in real working spaces with the presence of direct sunlight in sunny climates. There is a lack of consensus within the scientific community about which metric to employ and with what criteria to apply it with, especially, in spaces with direct sunlight. This lack of consensus is due to inconsistencies in visual comfort studies that support contradictory recommendations [12,26]. This analysis aims to evaluate different daylight glare metrics from the subjective point of view of the office workers, and, in this way, understand which metric best evaluates glare sensation. The selected metrics were: luminance and illuminance levels, luminance ratios, luminance distribution, which are divided into two categories: "absolute glare values" and "relative glare values" following the study by Suk et al. [22].

2. Methodology

A field-based research was carried out, where a total of 26 participants were evaluated in two lighting conditions, obtaining a total of 52 tests. This sample size is recommended by IEA [27], in order to obtain any significant conclusion from post-occupational studies. Participants were all postgraduate students, 7 male and 19 female, the mean age was 27.00 (SD = 3.01) and only 8 subjects wore glasses.

The offices were located in the scientific and technological center, CCT-Mendoza, Argentina, on the ground and first floor oriented towards the east (Fig. 1). The total area of each office is 4.62 × 2.32 m, with a window bay of 1.56 × 1.8 m, composed of three panels of glass (Fig. 2). The solar shading devices in all of the offices were horizontal movable exterior sun shades (Louver 12 cm, white color, reflectance r = 0.85) (Figs. 3 and 4), and the shading device element that varies in each office were the curtains which cover the first pane of glass. Curtains were fully open in all offices during the experiment period.

The investigation was done between 8:30 and 11.00 in the morning during the month of September and October 2017. In this period of time the highest income of sunspot was registered. Each participant was asked to perform the experimental task at the VDT (Visual Display Terminal), and afterward to answer a brief survey. In the meantime, photometric measurements were taken by the researchers (Table 1).

These offices were evaluated under clear sky conditions, which were characterized by the presence of direct sunlight in the working environment and the only light source was the window. Participants had to evaluate two lighting conditions under different shading setting: 1) Preferred lighting condition (PLC), where blinds were adjusted to the subject's own preferences and 2) Unfavorable lighting condition (ULC), where the blind were adjusted to achieve the highest glare level. The highest glare level reported was in a short period of time due to the dynamism of the daylight sources. The order of exposure to the two lighting conditions was switched in order to avoid order effect.

2.1. Experimental procedure

Table 1 described the sequence of activities developed during the experiment, as well as the approximate time each stage required.

After the participants complete their personal data, they performed a reading task, the text was typed in 12pt, Arial, double-spaced and color black; and the background was white.

2.2. Subjective assessments

The assessment methods selected for visual comfort were semantic differentials and multiple choice questions. Some questions of the survey were based on the procedure described by Christoffersen and Wienold [28]. Four relevant questions focused on glare and uniformity was asked for this study:

Q1 seeks to measure the level of perceived glare. It was measured with GSV (Glare sensation vote) scale [29]. This method originates from the work of Hopkinson [30]. GSV scale is an ordinal scale of four points: 1-imperceptible, 2- noticeable, 3- disturbing and 4-intolerable. The participants must associate the degree of perceived glare with this four points scale. Participants should evaluate the total level of perceived glare, including glare from windows, from direct sunlight as well as reflections from the screen. The survey included a definition for each point on the scale, where the four glare categories were linked to an approximate period of time that a given source of glare would be tolerated. Q2 asks participants the level of comfort associated with the magnitude of perceived glare. Q3 asks participants to be aware of the presence of the sunspots at their work space and the lack of uniformity and Q4 to the association of this lack of uniformity.

Q1: What is the degree of glare experienced while reading the screen?

Imperceptible/noticeable/disturbing/intolerable

Q2: How do you assess the perceived glare?

Very uncomfortable/very comfortable (Five point scale)