Building and Environment xxx (2016) 1–14

Contents lists available at ScienceDirect

Building and Environment

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

Prediction of discomfort glare from windows under tropical skies

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ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form
5 August 2016
Accepted 5 August 2016
Available online xxx

Keywords:
Discomfort glare
Luminance mapping
Green buildings
POE
Tropics
Overcast sky
Intermediate sky
Daylighting

ABSTRACT

Discomfort glare is common problem in modern buildings that employ highly-glazed façades. Glare not only has negative impacts on occupant comfort but can also increase energy use in buildings. Yet a robust discomfort glare metric, particularly with regards to daylight, has proven elusive. The Unified Glare Probability (UGP), developed using 493 surveys under clear skies in Brisbane, Australia, shows promise as useful tool for estimating glare from windows. This investigation attempts to validate the UGP using a similarly large number of surveys under different sky conditions, different building types and demographics in the tropical climate of Kuala Lumpur, Malaysia.

The study uses a similar methodology to the initial investigation of the UGP, using a combination of luminance mapping with a post-occupancy evaluation (POE) questionnaire on discomfort glare. A total of 341 surveys were collected from six buildings; three green-rated and three regular office buildings. Hypothesis testing of the luminance data collected in these buildings indicate that the ratio of window to background luminances are a more sensitive measure of occupant discomfort than ratios of window to task luminances.

The results for the UGP show agreement in predicting discomfort from windows between both data sets using regression analysis. A simple hypothesis test showed discomfort was accurately predicted by the old UGP model for 69% of new surveys. The agreement between the two data sets for window glare enabled them to be combined into one massive data set of 813 surveys to update the UGP. The updated metric uses a logistic curve in place of the original linear transformation of the Unified Glare Rating (UGR) to prevent illogical values of probability being obtained from the metric.

1. Introduction

Visual discomfort from glare is a significant problem in office buildings, especially in green-rated or sustainable building designs with high proportions of glazing on exterior walls. For example, in an international survey of lighting conditions, 2540 people in 36 sustainable (green) buildings across 10 countries found glare to be an issue [1]. Using a 7 point scale, (1 − no glare to 7 − too much) median values for glare were as high as 4.37, far from the ideal of 1 (no glare). It is well established that building occupants usually close blinds due to glare [2] and open plan office spaces in particular are more likely to have their daylight design sabotaged as a result of occupant complaints than other space types [3]. Glare from windows is produced by the non-uniform luminance distribution within the visual field, or by high luminance contrast between a window and it surroundings. Visual discomfort can act as both a cognitive stressor and a distraction that affects workers' performance [4] as well as significantly impact occupant-rated satisfaction of lighting in buildings [5], and it has been identified as a potentially doubling energy consumption in green buildings when occupants devise ad hoc interventions to improve their comfort [6].

Some more specific post occupancy evaluation studies on visual discomfort in open plan office spaces demonstrate the magnitude of the problem by reporting proportions of building occupants who reported glare conditions:

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http://dx.doi.org/10.1016/j.buildenv.2016.08.005
0360-1323/

Nomenclature

β	simple linear regression coefficient
μ	mean of sample
ω_s	solid angle of a glare source (sr)
C	residual of the regression
E_v	vertical illuminance at the eye (lux)
L_b	background luminance (cd/m^2)
L_s	glare source luminance (cd/m^2)
M	sample size or number of observations
m	group size or number of groups
n	number of glare sources
P	Guth's Position Index
p	probability of two sample *t*-test
r^2	coefficient of determination in simple linear regression
S.D.	standard deviation of sample
t	test statistic following a t-distribution
BCD	Borderline Comfort Discomfort
CGI	CIE Glare Index
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
FOV	field of view
GSV	Glare Sensation Vote
POE	Post-Occupancy Evaluation
PPD	Percentage Persons Dissatisfied
UGP	Unified Glare Probability
UGR	Unified Glare Rating
VCP	Visual Comfort Probability
vlt	visible light transmittance
wwr	window-to-wall ratio

- Hirning et al. (2013) – study of 64 people found 56% of workers in open plan office buildings in Brisbane reported discomfort from daylight and electric light sources [7].
- Konis (2013) – study of 44 people found that 60–70% of workers in an open plan building in San Francisco reported visual discomfort from windows, with almost 20% reporting glare as very uncomfortable [8].
- Hirning et al. (2014) – study of 493 people found that 49% of occupants of green buildings in Brisbane reported some visual discomfort [9].

The magnitude of the problem highlights the need for reliable tools to predict potentially uncomfortable visual conditions in buildings. However a robust measure to predict discomfort due to daylight has proven elusive. The idea of a single, robust metric is complicated by several factors:

- The general physiological mechanisms for visual discomfort are ill-defined, so attempts to quantify it require empirical study; early studies defining glare indices were conducted under laboratory conditions [10] or in mock office setups [11,12] and have not been easily replicated in field studies [8,9,13,14];
- Daylight is a dynamic source that fluctuates in colour, intensity, direction and availability, making field studies difficult to conduct and potentially difficult to translate between different climates;
- Field studies frequently show occupants can have different visual responses to similar lighting conditions [15,16]; often using different subjective criterion for assessing discomfort (Hopkinson multiple criterion [17], Glare Sensation Vote (GSV), Percentage Persons Dissatisfied (PPD), Borderline Comfort Discomfort (BCD) etc) and too few subjects to effectively compare research outcomes between studies.
- Visual discomfort can be experienced in more than one way (e.g. direct view of the sun or veiling contrast on a monitor can both cause glare but each condition provides very different visual stimulus);
- Environmental factors such as qualitative aspects of window view [18–20], window access [21], interactions of daylight with interior architecture and electric lighting design, seasonal [22] and location specific factors impact on visual comfort perception [23];
- Occupant-based factors, such as: age [24], vision diagnosis, awareness/knowledge of lighting, the time of day [25], view direction [26], long term exposure [27], task difficulty [4] and blind use [23,28] can also influence individuals' perception of visual comfort.

Given this complexity, it is likely that one single metric for all these factors for all situations is not achievable, and that different metrics that best reflect the conditions of different situations may be more appropriate. The development of a metric suitable for glare evaluation specifically for open-plan office buildings was described by Hirning et al., in 2014, where luminance maps of occupants' field of view (FOV) were matched to a POE questionnaire for 493 occupants in five Green Star buildings in Brisbane, Australia [9]. The study found occupants to be more sensitive to glare than any previous metric could account for. A modified glare index called the Unified Glare Probability (UGP) was developed to take into account the scope of the results. The index used a linear transformation of the UGR to calculate the probability of an occupant reporting visual discomfort. Based on the range of collected data used in its development, the caveat of the UGP was that it applied only to glare from windows, and that it was optimal for screen-based tasks in open plan green buildings, under clear sky conditions in subtropical climates.

Highlighted in the investigation were some unresolved issues from the large collected data set. The study attempted to take into account known parameters which were expected to affect occupants' discomfort such as age, eye correction and view properties etc, however only parameters relating to luminance and solid angle showed significant influence. It was suggested that apparent large individual differences in glare sensitivity might have masked other influencing factors. Consideration was also given to the possibility that parameters not recorded during data collection had influenced occupants' perception of discomfort, and that geographical or cultural influences might also exist. Therefore, in order to further validate this metric a new POE study of six buildings in a tropical climate has been performed in a new location (Kuala Lumpur) and is presented here.

Consequently, this paper examines the accuracy and applicability of the UGP to assess window glare in open-plan offices for different location, sky conditions and building types from those used in its development.

2. Methodology

The methodology and analysis used in this research was