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Discomfort glare in open plan green buildings

M.B. Hirning*, G.L. Isoardi, I. Cowling

Queensland University of Technology, Brisbane, Australia

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ABSTRACT

This study presents the largest-known, investigation on discomfort glare with 493 surveys collected from five green buildings in Brisbane, Australia. The study was conducted on full-time employees, working under their everyday lighting conditions, all of whom had no affiliation with the research institution.

The survey consisted of a specially tailored questionnaire to assess potential factors relating to discomfort glare. Luminance maps extracted from high dynamic range (HDR) images were used to capture the luminous environment of the occupants. Occupants who experienced glare on their monitor and/or electric glare were excluded from analysis leaving 419 available surveys. Occupants were more sensitive to glare than any of the tested indices accounted for.

A new index, the UGP was developed to take into account the scope of results in the investigation. The index is based on a linear transformation of the UGR to calculate a probability of disturbed persons. However all glare indices had some correlation to discomfort, and statistically there was no difference between the DGI, UGR and CGI. The UGP broadly reflects the demographics of the working population in Australia and the new index is applicable to open plan green buildings.

1. Introduction

Controlled use of daylight has the potential to provide both health and energy benefits in commercial buildings. Used as a supplementary light source, daylight can provide energy savings through increased thermal and lighting efficiency [1,2]. Positive non-visual health benefits of natural light include increased well-being, alertness and sleep quality [3,4]. Daylight from windows allow occupants a connection to the outside and can enhance work performance and visual comfort [5,6].

In Australia, building designers are encouraged, through the sustainability rating system, Green Star [7], to design spaces which deliver these benefits to occupants. Built on existing international systems, BREEAM (UK) and LEED (US), a six-star rated building indicates world leadership in environmental design. It has been demonstrated that if occupant comfort is rated highly, green buildings can achieve significant energy savings and increased perception of productivity [8]. However, studies both in Australia and overseas show little evidence that overall levels of occupant comfort and satisfaction in lighting or thermal comfort are greater in ‘green’ rather than conventional buildings or that they achieve the energy consumption predicted in the design stage [9–11]. It is a common occurrence in these buildings for blinds to be retrofitted post occupancy due to intolerable glare from the sun and sky [12]. Thus the consequences of poor daylighting can negate or completely override any desired benefits. Discomfort glare is a phenomenon arising from high luminance contrasts or unsuitable luminance distributions in the visual field causing discomfort. Many researchers agree there is a lack of adequate knowledge to effectively predict discomfort glare in practical situations [2,13,14]. The ability to predict discomfort glare in complex lighting environments, if possible, would be invaluable for daylighting design in green buildings.

This study presents the largest known investigation of discomfort glare in green buildings. Data were collected from five buildings located in Brisbane, Australia and its immediate surrounds. Two of the buildings were five-star rated green buildings, the other three buildings were six-star rated. Each of the buildings was specifically designed to include daylight as a significant lighting component as well as provide occupant comfort. A total of 493 surveys on discomfort glare were conducted. Each survey involved a questionnaire on discomfort glare and an accompanying luminance map extracted from high dynamic range (HDR) images. This allowed a thorough comparison of major glare indices through the analysis of luminance maps and subjective responses. Anecdotal responses and demographic information collected during the survey provided a basis to evaluate potential subfactors believed to influence discomfort glare i.e. window view. This demonstrates a practical method of evaluating discomfort glare in real buildings. The benefits and limitations of the results may help guide future investigations on discomfort glare.

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* Corresponding author. Tel.: +61 731385362.
E-mail address: m.hirning@qut.edu.au (M.B. Hirning).

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ω_b	solid angle of a background source (sr)
Ω_s	solid angle of a glare source modified by Guth's position index
ω_s	solid angle of a glare source (sr)
ψ	angular displacement between glare source and line of sight (rad)
D	distance eye-to plane of source in view direction
E_d	direct vertical illuminance at the eye from glare sources (lux)
E_i	indirect illuminance at the eye (lux)
E_v	vertical illuminance at the eye (lux)
H	vertical distance between source and view direction
L_b	background luminance (cd/m^2)
L_s	glare source luminance (cd/m^2)
L_{av}	average FOV luminance (cd/m^2)
L_{screen}	screen luminance (cd/m^2)
L_{task}	task luminance (cd/m^2)
m	sample size or number of observations
n	number of glare sources
P	Guth's position index
R^2	coefficient of determination in multiple linear regression
r^2	coefficient of determination in simple linear regression
Y	horizontal distance between source and view direction
CGI	CIE Glare Index
CIE	Commission Internatiónale de l'Éclairage
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
DGPs	Simplified Discomfort Glare Probability
FOV	field of view
HDR	high dynamic range
IESNA	Illuminating Engineering Society of North America
UGP	Unified Glare Probability
UGR	Unified Glare Rating
VCP	Visual Comfort Probability

2. Discomfort glare indices

The phenomenon of discomfort glare is a sensation of annoyance or pain caused by unsuitable distributions of brightness in the field of view, significantly higher than the luminance to which the visual system is adapted. Discomfort glare may be accompanied by disability glare, the reduction of visual performance, but it is a distinctly different phenomenon [15]. The most cited model or index for the prediction of discomfort glare is the Daylight Glare Index (DGI) [16]. The DGI is a function of source size and location, source and background luminance, and direction of view (Eq. (1)). The DGI is a modification of earlier work by Petherbridge and Hopkinson to predict glare from a large area source, such as a window [17].

$$\mathrm{DGI} = 10\log_{10}0.48\sum_{i=1}^{n}\frac{L_s^{1.6}\Omega_s^{0.8}}{L_b + 0.07\omega_s^{0.5}L_s} \tag{1}$$

$\Omega_s = \omega_s/P$ (sr) is the solid angle subtended by the glare source modified by Guth's position index, P; L_s = luminance of the glare source; ω_s = solid angle subtended by the glare source; L_b = background luminance; n is the number of glare sources.

The DGI uses categorical ratings to explain quantitative values, operating between 16 (just noticeable) to 28 (intolerable glare). Validation studies of this equation show that the correlation between glare from windows (daylight) and predicted glare is not as strong as it is for the case of artificial lighting [18,19]. The DGI has been shown to overestimate discomfort under daylight conditions [20,21]. Despite its inconsistencies the index is still widely used in discomfort glare research, with several attempts made to extend the basic formula [22,23].

Since the DGI, several other indices of note have been developed. In 1979 the CIE Glare Index (CGI), developed by Einhorn, built upon Hopkinson's earlier work to become the preferred method by the CIE [24,25].

$$\mathrm{CGI} = 8\log_{10}\frac{2[1 + E_d 500]}{E_d + E_i}\sum_{i=1}^{n}\frac{L_s^2\omega_s}{P^2} \tag{2}$$

E_d (lux) is the direct vertical illuminance at the eye due to all sources; E_i (lux) is the indirect illuminance at the eye ($E_i = \pi L_b$).

Later, in 1995, the CIE adopted the Unified Glare Rating (UGR), which combined aspects of both the CGI and DGI [26]. In recent years, the UGR as recommended by the CIE, has become the most widely used general formula for assessing glare from indoor electric luminaires (Eq. (3)).

$$\mathrm{UGR} = 8\log_{10}\frac{0.25}{L_b}\sum_{i=1}^{n}\frac{L_s^2\omega_s}{P^2} \tag{3}$$

While the DGI, CGI and UGR relate index values to a degree of sensation, the Visual Comfort Probability (VCP) is a rating on a scale from 0 to 100, given to indoor fixtures to indicate how well accepted they are likely to be [27]. For example a VCP rating of 70 indicates that 70% of the occupants in a given viewing location would not be bothered by direct glare. Calculating the VCP involves a rather complicated procedure and though the IESNA adopted standard conditions for the calculation of VCP, the approach never gained a wide following (Eq. (4)) [28].

$$\mathrm{VCP} = 279 - 110\left[\log_{10}\sum_{i=1}^{n}\ \ldots\left(\frac{0.5L_s\left(20.4\omega_s + 1.52\omega_s^{0.2} - 0.075\right)}{P \times E_{av}^{0}.44}\right)^{n^{-0.0914}}\right] \tag{4}$$

Developed by Wienold and Christoffersen in 2006, the DGP (Eq. (5)) is a modification of the DGI [29]. The index is similar to the VCP but uses its scale in the reverse direction. For example, a calculated DGP value of 0.70 indicates 70% of occupants would be disturbed by discomfort glare for a given scene.

$$DGP = 5.87 \times 10^{-5}E_v + \quad \ldots 9.8 \times 10^{-2}\log\left(1 + \sum_{i}\frac{L_{s,i}^2\omega_{s,i}}{E_v^{1.87}P_i^2}\right) + 0.16 \tag{5}$$

E_v is vertical illuminance at the eye.

The DGP is only valid for values between 0.2 and 0.8. In development of Eq. (5), it was found that the vertical illuminance (E_v) at eye level showed good correlation to glare perception ($r^2 = 0.77$). From this, a simplified version of the equation (called the DGPs), was derived (Eq. (6)) [30].

$$\mathrm{DGPs} = 6.22 \times 10^{-5}E_v + 0.184 \tag{6}$$

Weinold also related the index values of the DGP to the categorical ratings of the other major glare indices (DGI, UGR, CGI, and VCP) (Table A.1 in Appendix A) [31].

The DGI, UGR and DGP all require use of Guth's position index (P), which expresses the change in discomfort glare relative to the angular displacement (azimuth and elevation) of a glare source from the observer's line of sight for any interior luminaire [27]. Iwata and Tokura showed that sensitivity to glare caused by a source located below the line of vision was found to be greater than the sensitivity to glare caused by a source above the line of vision