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Discomfort glare in open plan green buildings

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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.

Keywords: discomfort glare; luminance mapping; POE; green buildings; office lighting; open plan

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

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Nomenclature

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

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.

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 (Equation 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].

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

$\Omega_s = \frac{\omega_s}{P}\,(sr)$ *is the solid angle subtended by the glare source modified by Guth's position index,* P*;* L_s *= luminance of the glare source; omega*$_s$ *= 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].

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

$E_d\,(lux)$ *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 (Equation 3).

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

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 $0 - 100$, 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 (Equation 4) [28].

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

Developed by Wienold and Christoffersen in 2006, the DGP (*Equation 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 Equation 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 (Equation 6) [30].

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

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.11 in Appendix 8) [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 [32]. The analytical description for a glare source located above the line of sight (and limited to 53° above the horizontal line of sight) is given by Equation 7 [27]:

$$\ln P = \left[35.2 - 0.31889\tau - 1.22e^{-2\tau/9} \right] \times 10^{-3}\sigma \ldots$$
$$+ \left[21 + 0.26667\tau - 0.002963\tau^2 \right] \times 10^{-5}\sigma^2 \tag{7}$$

τ = angle from vertical plane containing source and line of sight; σ = angle between line of sight and line from observer to source.

The analytical equation used for a source located below the line of vision is given by Equation 8 [32].

$$\begin{cases} P = 1 + 0.8 \times \frac{R}{D} & \textit{for} \quad R < 0.6D \\ P = 1 + 1.2 \times \frac{R}{D} & \textit{for} \quad R \geq 0.6D \\ R = \sqrt{H^2 + Y^2} \end{cases} \tag{8}$$

D is the distance eye-to plane of source in view direction; H is the vertical distance between source and view direction; Y is the horizontal distance between source and view direction

The position index has been recently re-evaluated with new subjective data over the entire visual field [33]. It was found there was no significant difference between binocular and monocular vision (i.e. between left or right eye) and that sensitivity to glare was greater if the source was below the line of vision; which is in agreement with Iwata and Tokura's original work [32]. Though there are differences to Guth's original index, the new evaluation method has not yet been widely adopted.

The five indices discussed have many similarities and can all be expressed in the same general form (Equation 9) [34, 35].

$$G = \sum_{i=1}^{n} \left(\frac{L_s^e \omega_s^f}{L_b^g f(\psi)} \right) \tag{9}$$

G = glare index which expresses the subjective sensation; e, f and g = weighting exponents; $f(\psi)$ = function of the displacement angle; L_s = luminance of the glare source; ω_s = solid angle subtended by the glare source; ψ = the angular displacement of the source from the observer's line of sight (vision axis); L_b = background luminance; n is the number of glare sources.

Traditional glare research involves laboratory setups with simple lighting distributions from artificial windows (fluorescent lights behind a diffusing screen). Subjects are asked to rate the level of discomfort glare experienced using subjective scales. This type of discomfort glare research has proven inconsistent in field situations where there are real tasks to perform and interesting visual background stimuli [2, 36–38].

People are more tolerant of discomfort glare from daylight than they are from comparable electric lighting [16, 20, 21]. Windows provide interest, connection to the exterior environment and visual amenity in a workplace. Window views, in particular, influence the subjective impression of glare as daylight glare is mostly derived from windows [18, 39]. Rating a window view as pleasant or of high quality has been shown to increase tolerance to high luminances from windows, which may have otherwise been considered uncomfortable [6, 36, 40]. Location of observers in relation to the window, view type and view quality are also important [41].

Large studies involving discomfort glare are rare. Much of the research into discomfort glare involves very small sample sizes, comprising largely of students from the researching institution or no subjective data at all [42–44]. Presently, most architects and lighting designers prefer not to be guided by glare indices. Instead daylight simulations are commonly used to detect direct sunlight near occupant work spaces or luminance contrast assessments are used to assess potential discomfort [45]. The traditional indices, such as the DGI, persist, despite their inconsistencies, as there is a lack of statistically significant research to enable their replacement. There are many subfactors which potentially complicate the prediction of discomfort glare, however window characteristics have bore much of the focus [20, 23, 46, 47]. However there are many other potential subfactors, such as sex, age or cultural and physical differences which may account for the large variations in individual glare-sensitivity [48]. Studies with a high number of observations involving wide demographics are required to help quantify the diversity in individual preferences.

3. Recent Advances in Discomfort Glare Research

A major obstacle in quantifying discomfort glare has been the difficulty in analysing complex lighting distributions. Previous researchers could only use time-consuming, point-by-point luminance measurements to assess a lighting scene [16]. Accurate assessment of luminance distributions within real environments would have been very difficult due to the dynamic nature of daylight. However, with current digital imaging technology techniques, such as high dynamic range (HDR) imaging, luminance distributions of spaces are able to be captured quickly and analysed on a pixel-by-pixel basis [49]. At present, only a few studies have used captured HDR images with subjective responses to analyse discomfort glare from daylight [29, 50–52]. However, advanced daylighting research increasingly involves the use of simulated HDR images to evaluate spaces for discomfort glare [53–56].

The most extensive study of discomfort glare using luminance mapping was in the development of the Daylight Glare Probability (DGP) (Equation 5)[29]. Unlike previous glare indices, which were conducted under laboratory conditions in artificial lighting, the study used a purpose-built office test room under real sky conditions. The luminance distribution of an occupant's field of view was recorded using relatively expensive but precisely calibrated CCD cameras. The study used two rooms with identical photometric and geometric features, one for subjects and the other for luminance measurements. In total, 76 subjects participated in the experiment, resulting in 349 cases. Subjects were asked via questionnaire to associate the magnitude of glare on a four-point scale with pre-defined glare criteria (imperceptible, noticeable, disturbing and intolerable). Corresponding luminance maps were analysed using the specially-created RADIANCE based program *Evalglare* [57]. Existing glare indices were found to have low predictive power, so a new index, the Daylight Glare Probability (DGP) index was created.

In 2009 Painter, Fan and Mardaljevic conducted real-time discomfort glare monitoring of five workstations in three daylit offices over a one year period at De Montfort University (UK) [50, 58]. The study used an electronic survey form which was displayed on the participantâĂŹs computer screen. Participants were required to mark the level of discomfort glare by moving a slider control along a continuous scale that ranged from 'imperceptible' to 'intolerable'. They also marked the source of the discomfort on a field-of-view image of their workstation. The physical conditions were measured simultaneously using luminance maps derived from high dynamic range (HDR) images. A camera for the luminance measurements was installed as close as possible to the occupant's seating position at head height and operated automatically [50].

The results showed the luminance and illuminance values experienced at all workstations were relatively low for daylit offices [58]. Even for workstations adjacent to a glazed façade, relatively low illuminance values were recorded. However, the survey responses showed glare was regularly experienced by all participants. The study also found similar luminance conditions were rated quite differently by different participants. Values for the most typically used glare metrics were calculated from the luminance maps and compared with the glare ratings recorded during the study. No clear correlation was found for any of the existing glare metrics, including the DGI or DGP.

In 2010, a small study involving real participants in an office test room was conducted by Wymelenberg and Inanici [51]. The experiment used 18 student participants tested in a private university office. Luminance maps were used to investigate luminance metrics (including the DGP and DGI) in relation to visual comfort. Participants were allowed to adjust the daylighting in the office to create 'preferred' and 'just disturbing' lighting. It was found that the simple metric of mean luminance consistently outperformed the more complicated metrics of the DGP and DGI. The authors noted that due to the small sample size and private single office the results could not be expected to directly translate to open plan office types.

In 2012, Hirning et al. conducted 64 discomfort glare surveys of regular full-time office workers in real open plan office buildings [52]. Only the DGI and DGP were investigated. There were large variances in subjective responses to glare for both indices at occupant workspaces. It was found that high vertical illuminances were not prevalent in the workspaces studied compared to those which occurred in the DGP study [29]. Both the DGP and DGI had some correlation to discomfort glare but were inadequate for its prediction. Other investigations have also concluded that due to the strong linear dependence on vertical illuminance (Equation 5), the DGP isn't effective at predicting contrast-based discomfort glare [51, 52, 59, 60].

4. Methodology

This research involved collecting a large number of luminance maps along with questionnaire data to study occupant discomfort in open plan office spaces under daylight conditions. Subjective user assessments were conducted in five green star rated buildings using the building's tenants. In total, 493 complete surveys (questionnaire and associated luminance map) were collected. The majority of surveys correspond to a unique individual. Only 25 occupants completed the survey twice.

4.1. Buildings

Two of the buildings were high rise office buildings located in the Brisbane central business district (CBD), with partially obstructed urban views. The other three were located in isolated industrial areas, providing unobstructed nature views. Only two of the buildings had external shading on the façade and all had internal shading and large floor to ceiling windows.

The building interiors were all open plan office spaces with a few private offices for supervisors. The work tasks of employees in each of the buildings varied greatly, from administration and IT to graphic design and architectural drawing. The surveys were conducted sporadically over 14 days from February to October 2012, covering Autumn, Winter and Spring. The buildings were granted anonymity as a condition of unrestricted access to them.

4.2. HDR Image Calibration

The luminance distribution of an occupant's field of view was derived from HDR images. A calibrated HDR image can be used to represent the luminance distribution of any environment. All that is required is a digital camera fitted with a fisheye lens and the appropriate software [49, 61]. HDR imaging is a useful tool that has the ability to capture luminance values within 10% accuracy across a wide range of luminances and sources [62, 63]. The camera used to acquire all HDR images in this study was the Nikon Coolpix 8400 Digital Camera. In order to capture a subjects field of view the FC-E9 Fisheye lens (focal length = 5.6mm, 190° field of view) with equidistant projection properties was attached to form a camera lens system.

HDR imaging requires multiple exposure images of the same scene. In order to acquire luminance maps suitably accurate for glare analysis, photometric calibration of the camera and lens system is required [64, 65]. Hirning et al provides extended details of the method used to produce the calibrated luminance maps used in this study [66]. Multiple exposure images of the same scene are combined using a self-calibration algorithm to create a single HDR image with relative luminances [67]. Corrections for vignetting and absolute luminance are then applied to HDR images from which an accurate luminance map can be extracted.

Absolute luminance was spot-calibrated in test scenes using a Topcon BM7 Luminance Colour Meter. Further calibrations were applied to correct for vignetting, which is the reduction in brightness registered by pixels far away from the optic axis. An equidistant fisheye causes vignetting because light rays incident at large angles to the optic axis are projected onto a larger area of the imaging plane than those passing through the optical axis. Once acquired, all calibrations remain valid for any subsequent HDR images created by the same camera lens system using the same image settings.

The calibration procedure used the program *pfstools* and its extension *pfscalibration* for HDR image creation and calibration [68]. The system is able to capture a wide range of luminance values to within 8% accuracy in the laboratory. However, in this investigation HDR images were acquired in daylit office buildings, under dynamic lighting conditions. Since no external illuminance or luminance measurements were to be taken during the survey, an assessment of illuminance calculations was undertaken prior to the main investigation. Illuminance was calculated from a weighted average of the luminance pixel values; to assess the potential error in these values, HDR images were captured in conjunction with illuminance measurements for ten test cases (Table 1).

Most of the tests were conducted in interior office scenes with daylight (No.'s 1–7), two were conducted on exterior daylight scenes (No.'s 8–9) and one under dim interior electric light (No. 10). Illuminance measurements were taken with a calibrated Topcon IM5 Illuminance Meter before, during and after HDR image capture. The HDR images had a fisheye diameter of 2080 pixels. These were scaled down to a diameter of 693 pixels for use in *Evalglare* [57]. The table displays the average of the measured illuminance values, illuminance values calculated from the calibrated HDR images, and illuminance values calculated by *Evalglare* from reduced images[1].

Test No.	**Illuminance (lux)**			**Difference**
	M	**C**	**E**	(%)
1	118.5	105.0	103.9	14.1
2	114.8	141.6	141.7	-19.0
3	532.3	576.3	578.3	-8.0
4	515.8	493.6	494.2	4.4
5	519.4	473.6	472.2	10.0
6	672.2	637.6	640.8	4.9
7	154.3	153.7	153.2	0.7
8	1062.4	1306.7	1319.0	-19.5
9	1174.7	1301.3	1311.9	-10.5
10	45.9	43.0	44.6	2.9

Table 1: The table compares measured (M) illuminance, using a Topcon IM5, and calculated (C) illuminance from HDR images against those obtained using *Evalglare* (E). The final column displays the percentage difference between measured (M) and *Evalglare* (E) illuminance.

Table 1 shows that on average, calculated illuminance values were within 7% of the measured values, but could potentially be up to 20% in error (No. 8). The error introduced by reducing image resolution for analysis in *Evalglare* was negligible, as expected.

[1] *Evalglare* used with defaults.

4.3. Questionnaire

Figure 1 is the questionnaire used in each occupant survey, which has been adapted slightly from a questionnaire used in previous investigations [52, 69].

It is a single page, double-sided questionnaire structured as follows:

- Time and location details (assessor completes)
- General lighting questions
- Glare indication diagram, for an occupant to indicate where in their field of view a particular disturbing or distracting light source is
- Personal questions relating to demography and task performance
- Comments on discomfort glare (optional)

The questionnaire is designed to be quick and easy to complete, however it must also capture the important information required. Questions were structured so that a person of a non-technical background could provide a meaningful answer, avoiding answers requiring much interpretation. The questions were all checkbox, making it easy for occupants to fill out quickly. The questionnaire investigates factors which may impact on the occupant's assessment of discomfort, such as lighting quality and view type. It also collects demographic information on factors such as age and the use of any vision correction.

The most significant part of the questionnaire is the glare indication diagram, which assesses whether discomfort glare is being experienced at the time of survey. The occupants only requirement is to indicate where in the field of view, if at all, there is uncomfortable light. Finally, a blank section was left at the end of the questionnaire for occupants to provide any comments if desired.

4.4. Data Collection

The building tenants are aware that the survey will occur but the permission of individual occupants is not granted until the time of survey. The survey was conducted only on fine days with very little or no cloud. No surveys were conducted under overcast or partly cloudy conditions. Clouds moving across the sun create rapidly changing lighting conditions which interfere with HDR image capture. Participation in the survey was completely voluntary. Every effort was made to survey all occupants who were accessible in the open plan areas of the buildings.

The method of collecting data was to ask a single or group of occupants to participate in the survey. A small explanation of the survey and its purpose was given before starting. If the occupants asked any additional questions these were answered for them. The electric lighting was left on during the survey, consistent with the lighting conditions under which the occupant normally worked. Directly after the questionnaire was completed the physical (HDR) data were collected. The fisheye lens was positioned approximately at the same location and view direction as the subject's eye when seated performing the glare assessment.

4.5. Image Post Processing

Before exposure sequences of occupant view points were captured, the time of survey was recorded on the questionnaire. This allowed questionnaires to be matched to the correct exposure sequence via image time stamps. HDR images were created for each survey and corrected for absolute luminance and vignetting. Images were also cropped to a *vision zone*, which is Guths total field of view (Figure 2) [70]. This altered the circular fisheye image to ensure only sources within the field of view as seen by the occupants would be analysed. Luminance maps were then extracted from these HDR images. Image resolution was reduced, from a fisheye diameter of 2080 pixels to 693 for analysis in *Evalglare*.

For each HDR image, two or three image masks were created. The first was for the computer monitor or screen (Figure 2ii). The second for the broader task area which included the monitor, keyboard and some of the surrounding desk space (Figure 2iii). The last mask, if required, was for all glare sources which had been

Queensland University of Technology
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Global Glare Project
Post Occupancy Evaluation

LIGHT NATURALLY
for future generations

The Queensland University of Technology in collaboration with Light Naturally would like to invite you to participate in a global survey on discomfort glare in the workplace. Your participation in this research will help develop our understanding of factors that effect discomfort glare.

REFERENCE: **DATE:**
LOCATION: **TIME:**

LIGHTING QUESTIONS

1. Please tick any number of options that describe the lighting in your workspace?

Gloomy ☐ **Dim** ☐ **Comfortable** ☐ **Bright** ☐ **Glary** ☐

2. How would you describe your exterior window view?

Very Interesting ☐ **Not Interesting** ☐ **Don't know** ☐
Interesting ☐ **No viewing windows** ☐

3. Approximately how long have you worked under these lighting conditions?

< 1 Week ☐ **< 1 Month** ☐ **< 6 Months** ☐ **> 6 Months** ☐

DISCOMFORT GLARE

Images of your workstation will be taken by the surveyor. Please mark the positions on the view diagram which are causing you distracting or uncomfortable glare. Please mark as much of the glare source as is possible. The surveyor can show you an image of your workspace to help locate glare sources.

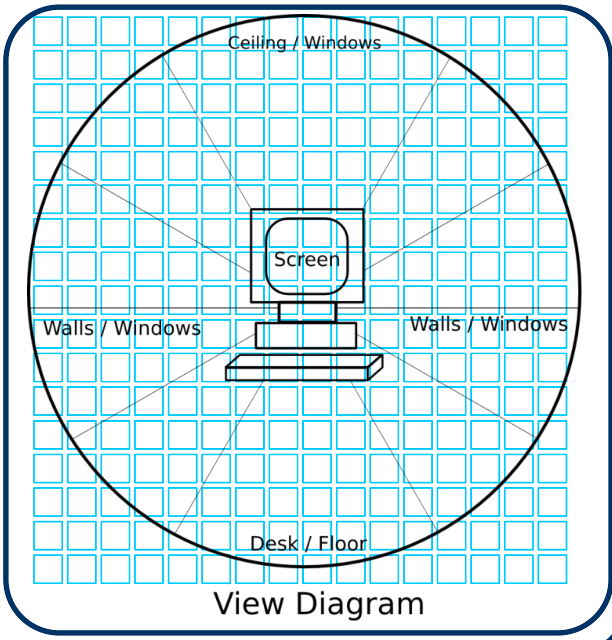

Figure 1: Discomfort glare questionnaire handed out to occupants (p.g. 1).

DEMOGRAPHICS

1. Are you wearing corrective eyewear at the time of this survey?

Glasses ☐ **Contacts** ☐ **No** ☐

2. What is your age?

< 30 ☐ **< 40** ☐ **< 50** ☐ **< 65** ☐ **65 and over** ☐

3. Does your working day consist of predominantly screen based tasks?

All week ☐ **3-4 days week** ☐ **1-2 days week** ☐ **Never** ☐

Thankyou for your participation in this survey. If you have any additional information you would like to contribute please use the space provided.

ADDITIONAL COMMENTS

Please provide any other information you may think could be of value to this research in understanding glare in the workplace.

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Figure 1: Discomfort glare questionnaire handed out to occupants (p.g. 2).

indicated on the view diagram in the questionnaire (Figure 3ii). The location and solid angle subtended by the screen mask was used as input to *Evalglare*. Thus *Evalglare* produced a default circular task zone of equivalent size and location to the screen mask (Figure 2i). This allowed HDR images to be analysed and compared using both customised analysis and *Evalglare*.

4.5.1. Statistical Analysis

Statistical data analysis was used to investigate current glare indices to assess their suitability as glare prediction models in open plan green buildings and to create a new index if required. This was achieved by calculating the linear correlation (through coefficient of determination, r^2) between each index and percentage discomfort.

In this investigation there were only two possible response levels to glare; comfort or discomfort, with a large number of observations. Reporting a correlation that is comparable to other large data sets is necessary when discussing statistical significance of the data. However, coefficient of determination (r^2) is not a good measure to assess categorical response data. To overcome this, responses were grouped together and a percentage (or probability) of people experiencing discomfort calculated for each group. The method converts the two-level categorical data into quantitative data via the creation of ordered "groups".

Initially, all potential glare predictor variables (i.e. glare indices) were calculated for each survey. Surveys were then ordered numerically with respect to the value one selected predictor variable. The ordered surveys were combined into "groups" with numerically adjacent surveys (i.e. those with similar predicted values). The mean value of the predictor variable in each group was calculated, as well as the percentage discomfort (being the ratio of *discomfort* surveys to total surveys for each group). These two values create a data pair for each group. Then coefficient of determination is calculated to assess if there is a significant correlation between the predictor variable and percentage discomfort.

The ideal method of grouping data is to have a system where there are as many response levels as there are observations. Therefore the group size was always chosen as $\sqrt{m}$, where m is the total number of surveys being analysed. Hence the number of surveys in each group is equal to the total number of groups. If there are more observations than possible response levels (i.e. small group size and large number of groups), the system will be underdetermined in terms of correlation (seen in Table 7). Conversely, if there are more response levels than observations (i.e. large group size and small number of groups), the system will be overdetermined and a correlation higher than expected will be reported.

The development of the DGP used a similar grouping procedure [29]. The investigation yielded 345 observations, which were classified into 12 groups with a group size of 29. Therefore, this system is overdetermined and the correlations reported in the analysis, 0.94 for the DGP, and 0.56 for the DGI and CGI, may be unrealistically high. This makes the aforementioned correlations difficult to compare with those found in this investigation.

5. Results

5.1. Survey Response Data

The survey data consisted of 493 complete surveys. Table 2 details the collected frequencies for all response categories gathered from the questionnaire (Figure 1). An occupant response was classified as experiencing *discomfort* if a glare source was indicated on the view diagram in the questionnaire and *comfort* otherwise. In total 242 (49%) surveys were classified as *discomfort* and 251 (51%) as *comfort*. Only in the *Lighting* category could subjects indicate more than one response, hence this column contains 586 responses instead of 493.

In general, responses were very evenly distributed ($\sim$ 50% each) for all response categories that had a large number of observations. There was also an even spread in responses between categories with a few exceptions. Occupants who worked on screen based tasks all week and under their current lighting conditions for longer than six months dominated the survey. The responses

(i) **Evalglare** (ii) **Screen** (iii) **Task**

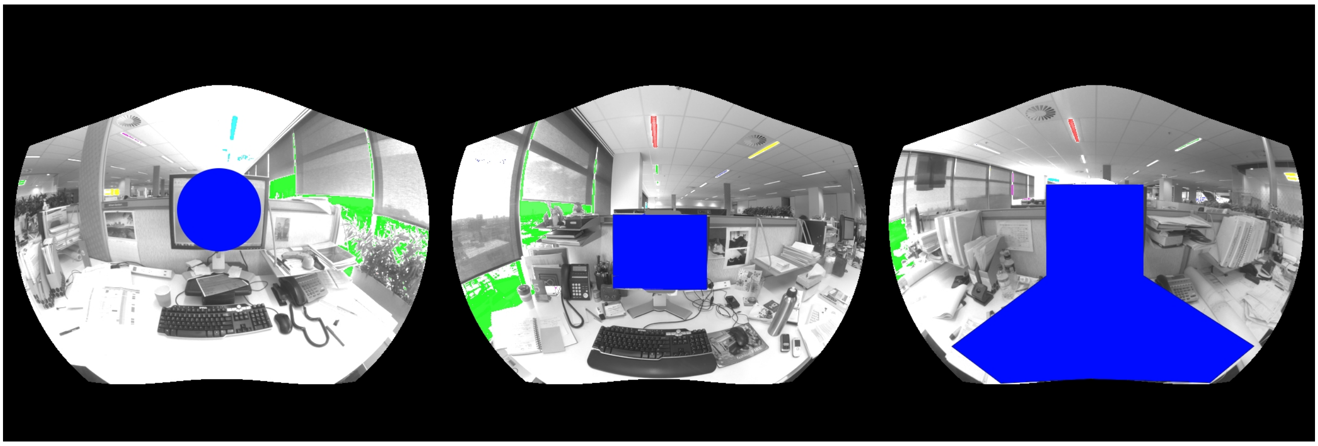

Figure 2: Examples of the three types of task zone investigated (coloured blue). The fisheye image is no longer circular as it has been cropped to Guth's total field of view.

within *Duration*, *Eyesight*, *Age* and *Screen* reflect the wider demographics of the working population in Australia. Many occupants found their window views to be interesting, however there appears to be no obvious relationship between discomfort glare and view interest (*Interest*). General lighting descriptors appear to have a strong correlation to discomfort (*Lighting*).

Tables 3 and 4 present data which was collected indirectly from occupant surveys. The location of a building was used to infer window view type independently of occupants. For buildings located within the CBD, view type was classified as *Urban*. Conversely, buildings that were located in isolated industrial areas, surrounded by mostly grass, trees or water and without the presence of nearby buildings, view type was classified as *Nature*. Responses of *No View* were obtained directly from the *View Interest* responses in the questionnaire (shown in Table 2). The remaining data were inferred from the view diagram (Figure 1i). During data collection, glare sources indicated on the view diagram were recorded as occurring from either daylight or electric source.

During post-processing, using HDR images and the view diagrams, glare from daylight was further subdivided. This included whether glare originated from the *window*, was *reflected* from an internal surface, or was due to *direct* sunlight. In addition, if glare (electric or daylight) impacted the task area (i.e. computer screen or keyboard shown in Figure 2iii), this was categorised as *Task/Screen* glare. Some occupants only allowed imaging of their monitor background, clearing any material on their screen as they conducted sensitive work. These surveys (of which there were 83) were identified during post-processing as they do not display the original task under which the questionnaire was conducted (*Screensaver*).

Table 3 displays similar trends to Table 2 with a very even split between comfort and discomfort for *View Type* and *Screensaver*. Table 4 shows that over ten times more glare occurred from daylight (222) than electric light (21), with the majority of daylight glare originating from the window (167). A significant number of glare sources occurred on the screen/task (63) or were reflected (61). The majority of occupants allowed their current task to be imaged when undertaking the survey (410 out 493).

The final question on the reverse side of the questionnaire (Figure 1ii) asked for any additional comments on discomfort glare. There were 101 comments received from different occupants. All recurring topics or issues within comments were identified. Each comment was classified by the issues raised as well as the tone (*satisfied* or *dissatisfied*) expressed when discussing an issue. Comments were further subdivided into *comfort* or *discomfort* again using the view diagram. Table 5

	Comfort		Discomfort		Total	
Total Comments	49		52		101	
Issue	**Satisfied**	**Dissatisfied**	**Satisfied**	**Dissatisfied**	**Satisfied**	**Dissatisfied**
Excess daylight	12	10	3	25	15	35
Blinds/internal shading	9	9	20	10	29	19
Lighting controls	1	12	4	4	5	16
Monitor/screen glare	-	4	-	13	-	17
Afternoon glare	-	4	-	11	-	15
Internal surfaces	3	3	-	8	3	11
Morning glare	-	6	-	5	-	11
Window view	6	1	4	-	10	1
Electric lighting	4	-	3	3	7	3
External façades/surfaces	-	5	-	3	-	8
Seasonal glare	-	3	-	2	-	5

Table 5: The table shows the most frequently discussed issues in comments including the tone of the comment and whether the occupant indicated discomfort or comfort the view diagram.

displays the overall tallies for each category.

Given the results in Tables 2 and 4 it is not surprising excess daylight (50 comments) was a well-mentioned issue in the questionnaire. Most occupants (35) complained of glare from windows or that their workspace was generally too bright. On the contrary, 15 occupants indicated that even though sometimes they experienced glare, they appreciated that the workplace was well lit by daylight. Occupants who indicated discomfort on the view diagram tended to write mostly dissatisfied comments, whereas occupants who indicated comfort had a more even distribution of positive and negative comments with the exception of lighting controls.

The next most frequently discussed topics were blinds and lighting controls. Most negative comments revolved around blinds not protecting occupants from glare. This was due to daylight coming through the blinds because they were too thin or there were gaps. Daylight penetrating through the gaps in blinds created bands of bright and dark light which many people found to cause glare. Most positive comments came as result of blinds being retrofitted. Three of the buildings had new blinds retrofitted as a result of glare problems. Some occupants stated before installing blinds the buildings were simply too bright.

Most comments on lighting control (21) related to the topic of blinds or internal shading. Occupants who sat deeper in the plan, away from windows, felt they did not have enough control over their own lighting. Negative comments centered around being affected by others' decisions on opening or closing blinds or that they sat near a window but had to compromise on their own preferences to satisfy other occupants. A few mentioned that they were dissatisfied with their lighting situation but felt unable to speak up about the issue.

Almost all comments on window view were positive (10 out of 11 comments). Those occupants who indicated discomfort on the view diagram often mentioned that even though at times they found their workspace too glary, they still enjoyed the window view.

5.2. Physical Data

Table 6 compares occupant indicated glare sources and task zones to *Evalglare's* selection of glare sources. The table consists of two sections; the top section labelled CALCULATED, contains the averaged mean luminance and vertical illuminance. Mean luminance is calculated within the vision zone (Guth's total field of view shown in Figure 2). The table lists averages for the number of glare sources, task luminance (using *Evalglare's* circular task-zone), detected glare source luminance and solid angle of glare sources. *Evalglare* was used with its default settings with glare sources defined as five times the task luminance.

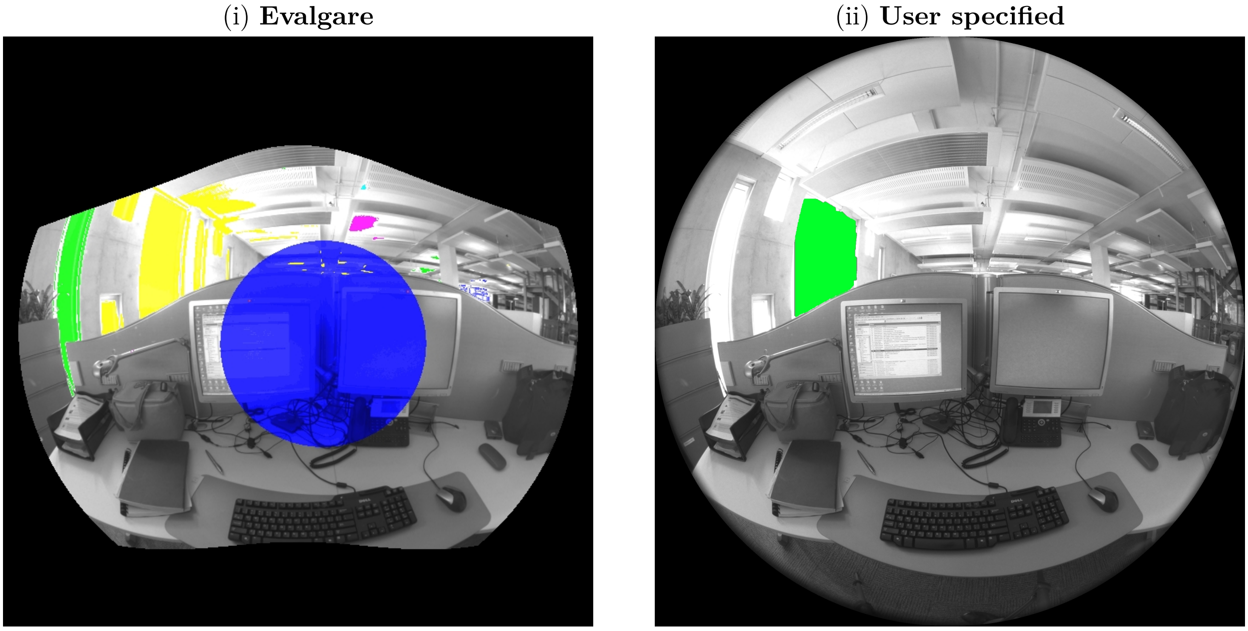

Figure 3: Example images comparing the location and size of *Evalglare* and occupant indicated glare sources. Left: Evalglare task zone (blue) and glare sources (green, yellow, pink). Right: Occupant indicated glare source (green).

The bottom section of the table describes the MEASURED values for user responses to glare. The averaged luminance of the extended task and screen zones (shown in Figure 2) are presented along with the averaged luminance and solid angle of occupant indicated glare sources.

Table 6 shows that all three task zones (screen, broad, *Evalglare*) have similar averaged mean luminances. The averaged FOV luminance (vision zone) was significantly higher for discomfort occupants. Very large standard deviations occurred in all results. The average illuminance was 502 *lux* and 389 *lux* for *discomfort* and *comfort* occupants respectively. The maximum illuminance measured in this investigation was 2354 *lux* (for a *comfort* occupant).

Evalglare over detected glare zones compared to users. The glare source luminances are much lower and solid angle much higher than occupant indicated glare sources. This is partly because *Evalglare* tends to detect the electric lighting as a glare source which most occupants will not have specified as glare (Figure 3). Evalglare detects glare sources based on luminance and is unable to discriminate between regions of equal luminance. Most occupants indicated only one region of uncomfortable luminance, even though the HDR images showed other regions within the FOV to be of equal or higher luminance. In addition, there may be some inaccuracies from occupants incorrectly marking the size and location of glare sources on the view diagram.

5.3. Statistical Analysis of Glare Indices

The major glare indices were investigated for their linear correlation to percentage discomfort under various conditions. Glare indices were calculated with *Evalglare* using the default background multiplier of five. Task luminance was used as the adaptation or background luminance (L_b) in the calculation of glare indices. A region of brightness in the field of view was presumed a glare source if its average luminance was fives times greater than the task luminance. Table 7 investigates the effect of excluding certain types of occupants from data analysis.

Three main exclusions were investigated; *screen glare*, *electric glare* and *screensaver*. A survey was classified as *screen glare* when an occupant indicated glare source overlapped the broader task area; which included the monitor, keyboard and some of the surrounding desk area (Figure 2iii). If any occupant indicated glare source was from the electric lighting, the survey

	Total Counts	Discomfort (%)	Comfort (%)
Lighting			
Glary	92	78	22
Bright	157	69	31
Comfortable	314	36	64
Dim	14	64	36
Gloomy	9	67	33
Interest			
Very Interesting	74	50	50
Interesting	213	51	49
Don't know	77	54	46
Not Interesting	97	46	54
No View	37	35	65
Duration			
>= 6 months	329	50	50
< 6 months	104	48	52
< 1 month	50	44	56
< 1 week	10	40	60
Eyesight			
Glasses	211	49	51
Contacts	17	71	29
Uncorrected	265	48	52
Age			
Over 65	1	-	100
Under 65	54	30	70
Under 50	114	52	48
Under 40	165	55	45
Under 30	159	48	52
Screen			
All week	421	50	50
3-4 days	70	44	56
1-2 days	2	-	100

Table 2: The total number of responses to each individual question on the questionnaire and the percentage of respondents to each question classified as either *discomfort* or *comfort*.

	Total Counts	Discomfort (%)	Comfort (%)
View Type			
Nature	78	46	54
Urban	377	51	49
No View	37	32	68
Screensaver			
No	410	47	53
Yes	83	58	42

Table 3: Total counts and percentages inferred from building location and HDR image.

was classified as *electric glare*, even if daylight glare also occurred in the same survey. Finally, if occupants believed the material on their monitor

Source Type	Total Counts	Daylight Glare	Total Counts
None	250	Window	167
Daylight	222	Reflected	61
Electric	21	Task/Screen	63

Table 4: Total counts for glare source characteristics inferred from HDR images.

was too sensitive to allow viewing of photographing, this was cleared and only the wallpaper background or screensaver was imaged (*screensaver*). Initially all three task zones were investigated (Figure 2). It was discovered that there was no difference in the coefficient of determination (r^2) for all glare indices between *Evalglare's* circular task zone and the screen zone. Correlations for the broader task zone were significantly worse for all glare indices.

This comparison of background task zones has been omitted from Table 7, where only results for *Evalglare's* circular task zone are displayed. This agrees with Table 6 as all three task zone types had very similar average luminances. There was no benefit from using more time consuming calculations involved with extended task zones.

The Fisher-Z transformation was used to compare the Pearson-r correlations for the DGI with no exclusions, to all other DGI Pearson-r correlations. From this, p-values were used to assess if excluding certain occupant types produced significant statistical improvement considering the number of observations (n). Calculating Z and p-values for the other glare indices produced equivalent results and these have been omitted from Table 7.

Excluding *screensaver* had very little effect on correlation. *Electric glare* produced some improvement in correlation, but there were few observations (22) of this occupant type. Removing *screen glare* from the analysis does produce a significant improvement in correlation. Excluding both *screen glare* and *electric glare* produced the lowest p-value, and thus the overall best correlation. Including *screensaver*, which has a large number of observations (83) in the exclusions does not increase correlation enough to compensate for the loss in statistical power. Therefore occupants

CALCULATED		Vision Zone		Evalglare			
		Mean Luminance (cd/m^2)	**Vertical Illuminance (lux)**	**No. of Sources**	**Task Luminance (cd/m^2)**	**Glare Source Luminance (cd/m^2)**	**Solid Angle (rad)**
Discomfort	**Averaged**	180	502	3.7	103	1630	0.272
	St.Dev	120	360	3.2	50	832	0.479
Comfort	**Averaged**	141	389	4.0	89	1470	0.199
	St.Dev	117	337	3.1	47	838	0.411

MEASURED		Broad Task Zone		Screen Zone		Glare Zone	
		Mean Luminance (cd/m^2)	**Solid Angle (rad)**	**Mean Luminance (cd/m^2)**	**Solid Angle (rad)**	**Mean Luminance (cd/m^2)**	**Solid Angle (rad)**
Discomfort	**Averaged**	93	1.760	97	0.484	2800	0.146
	St.Dev	45	0.437	44	0.196	2700	0.188
Comfort	**Averaged**	82	1.790	99	0.499	-	-
	St.Dev	69	0.437	39	0.194	-	-

Table 6: Comparison of averaged luminance data for *Evalglare* and occupant indicated glare sources ($m = 493$).

Exclusions	**n**	**DGI**	**DGP**	**UGR**	**CGI**	**VCP**	**Z**	**p**
none	493	0.059	0.062	0.058	0.060	0.039	-	-
electric glare	471	0.087	0.098	0.085	0.088	0.053	-0.87	0.38
screen glare	430	0.124	0.098	0.126	0.128	0.081	-1.8	0.070
screensaver	410	0.066	0.072	0.066	0.066	0.053	-0.22	0.83
screen & electric glare	419	0.158	0.134	0.159	0.163	0.096	-2.6	0.0096
screensaver, electric glare	393	0.096	0.118	0.095	0.095	0.070	-1.1	0.28
screensaver, screen glare	361	0.131	0.102	0.132	0.132	0.101	-1.89	0.059

Table 7: The effect of excluding certain types of occupants on coefficient of determination (r^2). Fisher-Z transformation (Z) was calculated for the DGI in each category including the significance (p-values) of the exclusions.

with *screen glare* and *electric glare* were excluded from further analysis.

In addition to the major glare indices, many parameters and combinations of parameters were investigated for their correlation to discomfort. However, the established glare indices performed significantly better than all other tested predictor variables. Table 8 shows the coefficient of determination for selected glare predictor variables. A fixed sample size of 419 was now used to establish 21 groups with a group size of 20 (see Section 4.5.1). Glare indices were determined using *Evalgare* using the task luminance multiplier of five.

Index	$\mathbf{r^2}$	**Z**	**p**
DGI	0.738	-	-
DGP	0.683	0.33	0.74
UGR	0.739	-0.01	0.99
CGI	0.771	-0.23	0.82
VCP	0.502	1.18	0.24
$\mathbf{E_v}$	0.387	1.61	0.11
$\mathbf{L_{av}}$	0.420	1.50	0.13
$\mathbf{L_{screen}}$	0.0007	2.84	0.0045
$\log(\mathbf{E_v})$	0.657	0.48	0.63
$\log(\mathbf{L_{av}})$	0.685	0.32	0.75

Table 8: Coefficient of determination for the major glare indices, including vertical illuminance (E_v), average FOV luminance (L_{av}) and screen luminance (L_{screen}). Correlations for each metric is compared to the DGI using Fisher-Z transformation to assess statistical significance ($m = 21$).

No glare index was statistically more significant than another. Again the Fisher-Z transformation was used to compare the Pearson-r correlations. The p-values for comparing the DGI to the other glare indices is displayed in the final column of Table 8.

Figure 4 shows data plots of the five glare indices with error bars representing the standard deviation of the group mean. The plots of glare indices indicate that linear transformations are appropriate for the DGP, DGI, UGR and CGI. The plot for the VCP indicates that a linear relationship and thus the r^2 obtained is not an appropriate reflection of the data. All glare indices significantly underestimated discomfort compared to occupants (based on Table A.11 in Appendix A).

The logarithm of both average luminance and vertical illuminance display appropriate linear relationships and high correlations (0.685 and 0.657) respectively. It is not surprising then that all glare indices have similar correlations as they in general produce a metric based on the logarithm of luminance. The DGP, which has a very strong linear dependence on vertical illuminance, obtained a lower correlation than most of the other indices due to the low correlation of vertical illuminance (0.387). It was again found that the logarithm of vertical illuminance provided a much higher correlation to discomfort (0.657).

Screen luminance appears to be completely uncorrelated to discomfort (Table 8 and Figure 4viii). It was expected that screen luminance would provide an adaptation luminance, which in turn would produce some effect on discomfort. However, large variations in screen luminance between occupants did not occur, especially compared to other parameters such the average field of view or glare luminance (Table 6). Almost all occupants in a building have the same monitors, which are all about the same brightness level. Thus there was not enough variation in screen or task luminance to be able to observe an effect on discomfort. However this may provide an important simplification for predicting glare in office-type buildings.

Table 9 investigates the effect of changing the background multiplier in *Evalglare* on coefficient of determination for the UGR, CGI and DGI. A large range of multipliers were investigated but only multipliers from 1–12 are shown in Table 9. Values of r^2 dropped sharply for higher multipliers. Two types of glare source definitions were explored using *Evalglare*, the (previously used) circular task-zone and no task-zone. In the latter case the background is calculated based on the average luminance of the entire field of view.

Using a task-zone gave consistently good correlations for all background multipliers. However not using a task-zone produced the highest correlations for each index and was consistently better performing for background multipliers three to seven. This agrees with the results in Table 8, as average field of view luminance had a high correla-

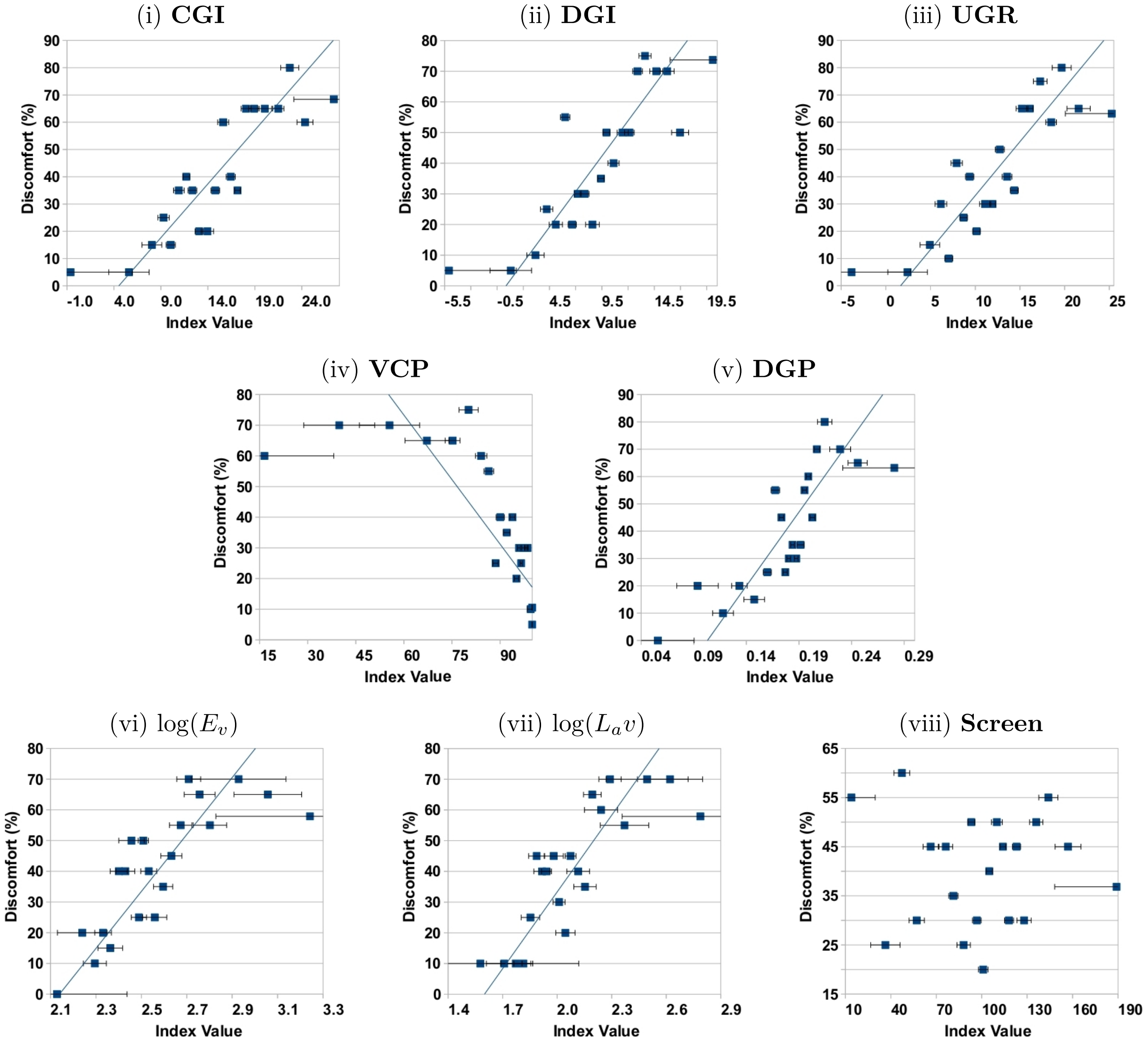

Figure 4: Percentage discomfort plotted against glare indices with standard error and best fit line.

	With Task-Zone			Without Task-Zone		
g-m	**UGR**	**CGI**	**DGI**	**UGR**	**CGI**	**DGI**
1	0.69	0.72	0.65	0.45	0.74	0.28
2	0.78	0.79	0.73	0.74	0.71	0.58
3	0.70	0.74	0.70	0.79	0.74	0.82
4	0.75	0.80	0.77	0.85	0.85	0.74
5	0.74	0.77	0.74	0.87	0.81	0.81
6	0.84	0.82	0.70	0.83	0.80	0.89
7	0.85	0.83	0.77	0.79	0.83	0.87
8	0.78	0.81	0.81	0.72	0.78	0.79
9	0.78	0.82	0.80	0.72	0.72	0.83
10	0.78	0.82	0.78	0.74	0.72	0.74
11	0.77	0.72	0.79	0.72	0.75	0.74
12	0.77	0.75	0.76	0.71	0.73	0.70

Table 9: The table shows the coefficient of determination of the major glare indices for a range of glare multipliers (g-m) with $m = 21$.

tion to discomfort, and screen luminance is known to be similar across all surveys. All three glare indices produced their highest correlations with background multipliers between five and seven with correlations almost identical ($r^2 = 0.89$ for the CGI and $r^2 = 0.87$ for the DGI and UGR).

Figure 5 shows the results produced using no-task zone for the UGR with a background multiplier of five. The outliers from Figure 4iii have been retracted towards the line of best fit producing a better correlation. Other forms of glare equations were tested by modifying the coefficients and exponents of the glare indices. However this did not produce any higher correlations than those already achieved.

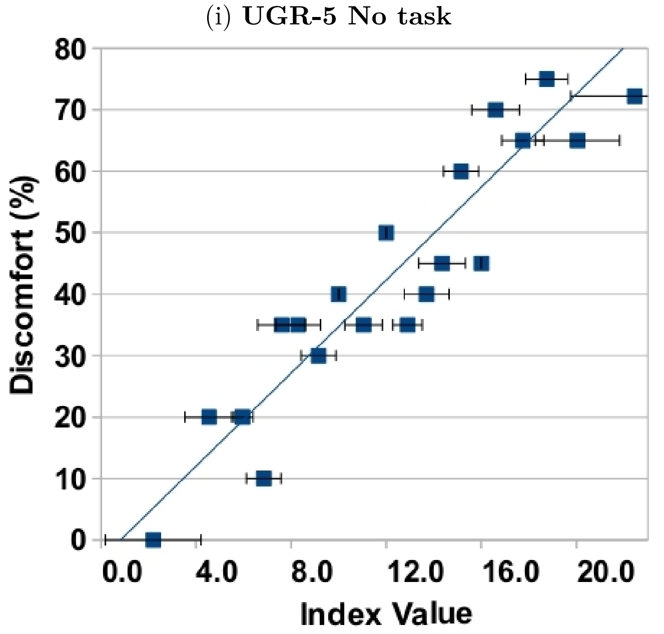

Figure 5: UGR with no task zone and background multiplier of five.

6. Other Factors

Data collected from the questionnaire were also used to investigate other factors that may possibly impact discomfort glare. Table 2 was used as a guide to select the following variables;

- Age
- (View) Interest
- Eye (Correction)

The UGR (without a task zone and background multiplier five) was used to help investigate these other categorical factors. The UGR was chosen because it is the least complicated index to calculate and does not require illuminance measurements. It also has the nice property of additivity of glare source area's i.e. solid angle has a exponent of one (ω^1) [71]. The DGI and CGI do however produce statistically identical results. Multiple linear regression was used to analyse the effect of these various factors on discomfort glare. The results are displayed in Table 10.

Table 10 shows that the glare index was the only statistically significant predictor of discomfort. View Interest showed weak significance (p-value = 0.07) in the model. However, the factor

Model Summary

R	R^2	Adjusted R^2	SE
0.41	0.17	0.16	0.45

ANOVA

	SS	df	MS	F	p
Regression	16.99	4	4.25	20.97	0.00
Residual	83.67	414	0.20		
Total	100.67	418			

Coefficients

	B	SE	β	t	p
(Const)	-0.0389	0.077	0.00	-0.50	0.61
UGR	0.0320	0.0036	0.40	8.85	0.00*
Age	-0.0059	0.023	-0.01	-0.26	0.80
Eye	-0.0083	0.024	-0.02	-0.35	0.73
Interest	0.0367	0.020	0.08	1.81	0.07**

Table 10: The top section of the table displays R, R^2, adjusted R^2 and the standard error (SE) of the model with $m = 419$. The middle section displays the total sum of squares (SS), degrees of freedom (df), mean square error (MS), F-statistic (F) and p-value (p) for the model. The bottom section of the table displays the coefficient summary which includes the unstandardised regression coefficients (B) and their standard error (SE), the standardised regression coefficients (β), t-score (t) and p-value (p).
* Indicates significant p-values < 0.05
** Indicates weakly significant p-values < 0.10

has a very large standard error (0.020) which is 54% of the regression coefficient (0.0367). There is too much error in the coefficient to warrant including this factor in the final model (Equation 10).

In light of these results the most effective method for predicting discomfort in open plan office buildings are the current glare indices, UGR, CGI and DGI. Equation 10 presents the UGR transformed to a probability prediction scale from its categorical ratings. A regression coefficient of 3.2×10^{-2} has been applied to the original UGR equation (Equation 3) and renamed the Unified Glare Probability (UGP).

$$UGP = 0.26 \log_{10} \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_s^2 \omega_s}{P^2} \qquad (10)$$

7. Discussion

The questionnaire showed that glare was a significant issue within green buildings with 49% surveys classified as uncomfortable (Table 2). Three of the five buildings already had new blinds or shading controls retrofitted to reduce the impact of glare in these buildings. Two had disabled their automated blind systems which is a common occurrence within green buildings [12].

The comments obtained from occupants who participated in the survey revealed lighting control within open plan buildings to be a significant issue in causing and controlling glare. The decisions of occupants near windows to open or close blinds not only impacted occupants in the immediate vicinity of the window, but also those further away. Viewing angles and seating positions played a significant role in the open plan arrangements. Many occupants felt they were compromising their own lighting preferences for the sake of the comfort of others within the workspace.

Low vertical illuminance readings were recorded at occupants workspaces. The average illuminance was $445\,lux$, with the maximum illuminance recorded being $2354\,lux$. This is in contrast to the DGP investigation, which recorded very high illuminances, up to $10000\,lux$. The difference is possibly due to the difference in setup between the DGP experiment and real office buildings. In the former, occupants faced the nearest window. The amount of daylight passing through the window was the primary cause of glare which caused the strong linear dependence of the DGP on vertical illuminance. In open plan green buildings, occupants seated next to windows are usually not facing them directly, but sit adjacent to them. Glare comes not necessarily from the adjacent window, though this is common, but from windows which are further away that are directly in the field of view. The glare experienced in this situation is often a luminance contrast glare which distracts from the task. In this investigation vertical illuminance was calculated from the average fisheye luminance. Therefore the average field of view luminance and vertical illuminance are similar measures, which correlated strongly to the log of their values (Table 8). This non-linear dependence supports the assertion that glare experienced in open plan green buildings is from high luminance contrast.

All five major glare indices (DGI, DGP, CGI, UGR and VCP) were tested for their correlation to discomfort. It was found that the DGI, UGR and CGI all performed very similarly, however all five indices tested take the same general form (Equation 9). The VCP had significantly less correlation to discomfort and was not sensitive enough in scale to capture appropriate discomfort measures in this context. As previously discussed, vertical illuminance correlated poorly to discomfort ($r^2 = 0.34$) affecting the DGP, which also did not perform as well as the other three indices.

Similar to many other investigations into discomfort glare, there were large variations in individual perception of discomfort. This variation in survey responses was large enough that the exponents and coefficients of the glare indices were somewhat invariant to discomfort correlation. The UGR was thus chosen to represent the general form of the equation due to its simplicity and additivity of glare source areas [71]. The categorical scale of the UGR was modified to a probability and termed the UGP (Unified Glare Probability). The probability represents the percentage of disturbed persons under a particular light scene.

The probability scaling is more applicable than the previous categorical scalings of the index, which have proven unreliable in real environments. Though occupants were not required to estimate a magnitude of discomfort during this investigation, anecdotal evidence from the survey suggests that occupants who indicated discomfort are equivalently rating “just uncomfortable” to “uncomfortable”. No occupant is experiencing intolerable glare. Employees in these buildings had flexible working hours and majority of the occupants had worked under their lighting conditions for over six months. Occupants have an acute awareness of the time of day when glare becomes intolerable. At these times occupants simply make sure they are not required at their desk.

Furthermore, there are occupants with a high tolerance to large luminance contrasts. This is evident in the extreme range of the data. In all glare indices, the correlation to discomfort was stronger for lower index values. At higher index values, once percentage discomfort reached over 50%, the data becomes less correlated. The UGP produced an experimental maximum of 0.75. This is due to the individual tolerance of discomfort. For many occupants, higher index values would correspond to intolerable glare. These more glare sensitive occupants would not undertake the survey in these conditions because they had already left their workspace. This was observed anecdotally while undertaking the survey. Occupants would indicate verbally or via comments that particular times they experienced high levels of discomfort glare, i.e. late in the afternoon, when low angle sun would penetrate through blinds. However, at these times there would be a sharp decrease in the occupancy rate of the buildings and fewer occupants would be available for survey. Thus the higher index values are unduly influenced by occupants with a high tolerance to large luminance contrasts.

Three factors were tested alongside the UGR relating to age, eye correction and view interest. It was discovered that none of these factors were statistically significant. This suggests that only physical luminance and solid angle parameters influence discomfort glare. However, Table 10 showed view interest to have a statistically weak influence within the model. Other research has shown that view type and view interest do influence the subjective appraisal of discomfort glare [41, 47]. The results of this investigation do not conclusively disagree with those results. The DGP also showed a weak improvement in correlation when age was applied to the equation [72]. There may have been other factors, not accounted for in this study which have a significant influence on discomfort, however measuring and accounting for more of these types of factors could be problematic. It remains to be seen if there are geographical or cultural influences on discomfort glare. This would have ramifications for the applicability of any glare index.

In this investigation the variation in the individual perception of discomfort glare was large enough to mask any factors which were not very strongly statistically significant. As such it may be that using only the physical luminance and solid angle parameters is the only practical solution to adequately predict or assess potential discomfort glare. Taking into account both occupant comments and the statistical results, it is possible that view type and view interest are important factors overall in occupant satisfaction. However they do not mitigate the sensation of discomfort. Instead, in a real environment, the evidence suggests occupants are willing to compromise personal comfort for short periods, in order to experience daylight and interesting views most of the time.

8. Conclusion

This study presents the largest known general investigation on discomfort glare with 493 surveys collected from five green buildings located in Brisbane, Australia, under clear skies. The study was conducted at the occupants own workplaces, all of whom had no affiliation with the research institution. The data thus reflects the screen-based work tasks, lighting variations and occupant demographics present in these environments. Discomfort glare was highly prevalent within the green buildings investigated, 49% of occupants surveyed reported some discomfort at the time of survey.

The investigation revealed occupants were more sensitive to glare than any of the current indices could account 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 (or percentage) of disturbed persons. The index uses the average field of view luminance for the background (L_b) and a background multiplier of five to determine glare sources ($L_s \geq 5L_b$). The final result produced an r^2 value of 0.87. However, all glare indices had some correlation to discomfort. Statistically, there was no significant difference in correlation between the DGI, UGR and CGI.

$$UGP = 0.26 \log_{10} \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_s^2 \omega_s}{P^2} \qquad (11)$$

Very large vertical illuminances ($> 2500\,lux$) were not observed in the open plan workplaces surveyed. Instead large luminance contrasts were the main cause of occupants discomfort. The logarithm of the average field of view luminance correlated strongly to discomfort ($r^2 = 0.685$). This factor was the most useful measure of background (or adaptation) luminance for glare indices.

The factors of age, eye correction, and view interest were investigated and found to not play a statistically significant role in predicting discomfort. Window views were also found not to significantly mitigate discomfort, even so, the questionnaire revealed they are important in user acceptance of the lighting.

Many studies have produced conflicting results with respect to magnitude assessments of discomfort glare. All glare indices tested in this investigation severely underestimated discomfort. The experimental circumstances under which the UGP and all other glare indices were developed is an important consideration in their application. The UGP is the only large study conducted in green open plan office buildings using non-affiliated office workers. Therefore, it is the appropriate index to assess discomfort glare for screen-based tasks in open plan office buildings, under clear sky conditions in sub-tropical climates.

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Appendix A. Criteria Comparison Between Glare Indices

	DGP	DGI	UGR	VCP	CGI
Imperceptible	< 0.35	< 18	< 13	$80 - 100$	< 13
Perceptible	$0.35 - 0.40$	$18 - 24$	$13 - 22$	$60 - 80$	$13 - 22$
Disturbing	$0.40 - 0.45$	$24 - 31$	$22 - 28$	$40 - 60$	$22 - 28$
Intolerable	> 0.45	> 31	> 28	< 40	> 28

Table A.11: The table relates index values (for CGI, DGI and UGR) to discomfort probability (for DGP) and comfort probability (for VCP) to Hopkinson's 1950 categorical rating scheme for discomfort glare [31, 60, 73].