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Post occupancy evaluations relating to discomfort glare: A study of green buildings in Brisbane

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ABSTRACT

Glare indices have yet to be extensively tested in daylit open plan offices, as such there is no effective method to predict discomfort glare within these spaces. This study into discomfort glare in open plan green buildings targeted full-time employees, working under their everyday lighting conditions. Three green buildings in Brisbane were used for data collection, two were Green Star accredited and the other contained innovative daylighting strategies. Data were collected on full-time employees, mostly aged between 30 and 50 years, who broadly reflect the demographics of the wider working population in Australia. It was discovered 36 of the 64 respondents experienced discomfort from both electric and daylight sources at their workspace.

The study used a specially tailored post-occupancy evaluation (POE) survey to help assess discomfort glare. Luminance maps extracted from High Dynamic Range (HDR) images were used to capture the luminous environment of the occupants. These were analysed using participant data and the program *Evalglare*.

The physical results indicated no correlation with other developed glare metrics for daylight within these open plan green buildings, including the recently developed Daylight Glare Probability (DGP) Index. The strong influence of vertical illuminance, E_v in the DGP precludes the mostly contrast-based glare from windows observed in this investigation from forming a significant part of this index. Furthermore, critical assessment of the survey techniques used are considered. These will provide insight for further research into discomfort glare in the endeavour to fully develop a suitable glare metric.

1. Introduction

Driven by the desire for sustainable building practices, the Green Building Council of Australia (GBCA) was set up in 2002 as a national, not-for-profit organisation whose goal is to encourage the adoption of green building practices [1]. It developed a voluntary environmental rating system called Green Star that evaluates the environmental design and construction of buildings. As of April 2012 there are 430 projects that are Green Star certified with another 450 awaiting certification. With green building incentives, daylighting is receiving much greater attention in building design than it has previously [2–4]. However, without a sound understanding of the accompanying side-effects of daylighting (such as discomfort glare) there is the risk of achieving poor occupant comfort which may negatively impact on energy savings [5]. At present, this risk appears to be reality, with studies both in Australia and overseas showing no evidence that levels of occupant comfort and satisfaction in lighting are greater in 'green' rather than conventional buildings [6–9].

Despite numerous studies into discomfort glare over the past 60 years there is no universally accepted assessment system that predicts the effects of the luminous environment on building occupants [10–12]. Anecdotal evidence suggests that the perception of glare in contrived laboratory environments may differ from field situations where there are real tasks to perform and windows with interesting visual background stimuli [13]. Thus the need exists for assessment of discomfort glare to take place under real sky conditions in full-scale rooms [14].

This study of discomfort glare in green buildings used three buildings located in Brisbane (Australia). Each of the buildings was specifically designed to include daylight as a significant lighting component as well as provide occupant comfort. Post-occupancy evaluations (POEs) of discomfort glare were conducted and

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luminance maps extracted from High Dynamic Range (HDR) images were used to quantify the luminous environment of occupants. The objective was to explore the suitability of current glare prediction models and use the results to refine the methodology used to investigate discomfort glare.

2. Use of luminance mapping to study visual comfort

A major obstacle in quantifying discomfort glare is the difficulty in analysing complex lighting distributions. Previously, experiments could only be designed to explore the most basic lighting setups. Researchers did not have effective tools to analyse complex variations of luminance within a large field of view. In 1972 Hopkinson developed the Daylight Glare Index (DGI) (Equation (1)) [15] by modification of the British glare index (BGI) [16] to predict glare from a large area source i.e. window. The physical measurements used point luminance readings of fluorescent lamps behind an opal-diffusing screen to validate subjective responses.

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

where $\Omega_s = \omega_s/P$ is the solid angle subtended by the glare source (in (sr)) modified by the position of the source with respect to field of view and Guth's position index, P [17].

The position index expresses the change in discomfort glare experienced relative to the angular displacement (azimuth and elevation) of the source from the observer's line of sight. Iwata and Tokura [18] 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. Attempts have since been made to map the relative sensitivity to glare over the entire visual field [19].

With current digital imaging technology and techniques, such as High Dynamic Range imaging (HDRi) [20], the luminance distributions of spaces are able to be captured and analysed on a pixel-by-pixel basis. This may allow the creation of more effective metrics to predict discomfort glare.

In 2000, Schiler [21] used a conventional digital camera and captured a single exposure image of a real office environment. A light source with known luminance was placed within the space to calibrate the images. A small number of occupants were surveyed on the visual comfort of the room. Histograms of the images were developed and analysed to demonstrate that luminance maps could be used to quantify or predict the presence or absence of glare.

Osterhaus [22] extended the work of Schiler in 2008 by using luminance histograms of HDR images created with the RADIANCE simulation environment [23]. The HDR images replicated the conditions present from a previous study [24] from which subjective responses were collected. Four combinations of two parameters, mean luminance pixel value and median luminance pixel, were used to look for correlations between the subjective data extracted from the previous study. The analysis revealed that images with the highest rating for discomfort glare also produced the largest difference between average (mean) and median pixel luminance. The existing glare assessment methods (Daylight Glare Index [15], CIE Glare Index [25] and Unified Glare Rating [26]) when applied to the same conditions resulted in significantly less predictive correlations.

The most extensive study of glare using luminance mapping technology, published in 2006, was in the development of the Daylight Glare Probability Index (DGP) [27]. Whilst not conducted in a laboratory, the study did use a very controlled 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. These images were analysed using the specially created RADIANCE based program *Evalglare* [28]. The program allowed for a number of strategies to be implemented in assessing glare sources. Existing glare indices were found to have low predictive power, so a new index, the Daylight Glare Probability (DGP) index was created (Equation (2)).

$$\mathrm{DGP} = 0.16 + 5.87\times10^{-5}E_v + 9.18\times10^{-2}\log\left(1+\sum_i\frac{L_{s,i}^2\omega_{s,i}}{E_v^{1.87}P_i^2}\right) \quad (2)$$

where E_v is the vertical eye illuminance (lux); L_s the luminance of source (cd/m^2); ω_s is the solid angle of source; P is the position index [18].

The DGP showed a very strong correlation with users' response regarding glare perception. It should be noted that the DGP (Equation (2)) is only valid for values between 0.2 and 0.8 due to the range of data collected during the experiment.

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) [29,30]. The study used an electronic survey form which was displayed on the participants 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 closely as possible to the occupants seating position at head height and operated automatically [29]. Survey responses and HDR luminance measurements were collected at 30 min intervals during the working day.

The results showed the luminance values experienced at all workstations were relatively low for daylit offices [30]. Even for workstations adjacent to a glazed facade, 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 et al. [31]. 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 2011 Jakubiec and Reinhart conducted RADIANCE simulations of a real and theoretical building in order to compare five discomfort glare indices, DGI, UGR, CGI, VCP and DGP [32]. No survey data was used in the study and *Evalglare* was used to evaluate each metric. The DGP outperformed the other glare metrics, especially when there was direct sunlight within the scene.