DISCOMFORT GLARE IN ENERGY EFFICIENT BUILDINGS: A CASE STUDY IN THE MALAYSIAN CONTEXT

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This paper was presented at the CIE 2016 "Lighting Quality and Energy Efficiency", 3 – 5 March 2016, Melbourne, Australia

***To cite this article**:* Hirning, M.B., Lim, G.H., Reimann, G.P. (2016) Discomfort Glare in Energy Efficient Buildings: A Case Study in the Malaysian Context. *In Proceedings of CIE 2016 Lighting Quality and Energy Efficiency*, Melbourne, Australia, 3 – 5th March, 2016, pp 212 – 223. ISBN 978-3-902842-65-7. Article No 27

Abstract

Discomfort glare is a well known problem within the built environment. However very little research has been conducted on discomfort glare in purely tropical environments. This preliminary investigation focussed on the ST Diamond Building located in Putrajaya, Malaysia. In total, 68 surveys were collected during the investigation. The surveys consisted of a questionnaire as well as luminance mapping of the occupant's visual environment.

Luminance maps were analysed via Evalglare to calculate the Daylight Glare Probability (DGP) and Unified Glare Probability (UGP). It was discovered that occupants were more tolerant to potential glare than expected, most likely due to the high luminance uniformity from innovative daylighting strategies employed in the building. Occupant position in relation to the window had a significant effect on both glare indices tested. The UGP was much better at predicting glare for occupants further away from the façade.

Type 2 (or false-negative) analysis was conducted on both glare indices. A false-negative result occurs when the survey response was "uncomfortable" but the index being tested predicted "comfortable". The method showed promising results for UGP in the case of the ST Diamond Building, with an index threshold of 0.35 required to achieve 95% accuracy in predicted comfort. The DGP required an index threshold of 0.07, which may be impractical to implement in lighting design.

Keywords: Discomfort Glare, Luminance Mapping, Daylighting

1 Introduction

The tropics is a well suited environment for daylight harvesting in buildings. The sun path remains relatively stable throughout the entire year compared to more temperate climates, which have extreme differences in sun position and number of daylight hours between summer and winter solstices (Figure 1). This allows passive design strategies for daylight harvesting to be used to maximum effect. Incorporating daylight into buildings has many potential benefits, not only for saving energy, but also for the health and well-being of occupants (BOYCE, 2003; ONAYGIL, 2003; VAN DEN BERG, A.E, 2005).

However, even if daylight harvesting is done well, it only takes a small percentage of dissatisfied occupants to sabotage a daylighting strategy (HMG, 2005; GENTILE, 2015). The usual result is that the blinds remain drawn most of the entire year, cutting off window views and increasing electric lighting consumption (EMBRECHTS, 1997). Therefore discomfort glare is counterproductive to the energy efficiency requirements of building owners and tenants, as well as the comfort and well-being requirements of occupants. This leaves building designers with the task of harvesting daylight to maximise both building performance and occupant comfort. To achieve this balance building designers require reliable metrics to predict potential discomfort glare.

In the tropics, thermal comfort is usually the primary concern in façade design (PIECHOWSKI, 2007). Traditionally this kept window-to-wall ratios very low, with windows provided for a view out rather than for daylighting (HOFFMANN, 2012). However, recent advances in spectrally selective glass, air-tight glazing and double skin facades allow for thermal comfort in buildings using much larger window-to-wall ratios (LEE, 2006). Thus many modern office buildings have very high window-to-wall ratios, allowing much more daylight into the interior; which if doesn't cause glare, is useful as a supplementary source of light (Figure 2).

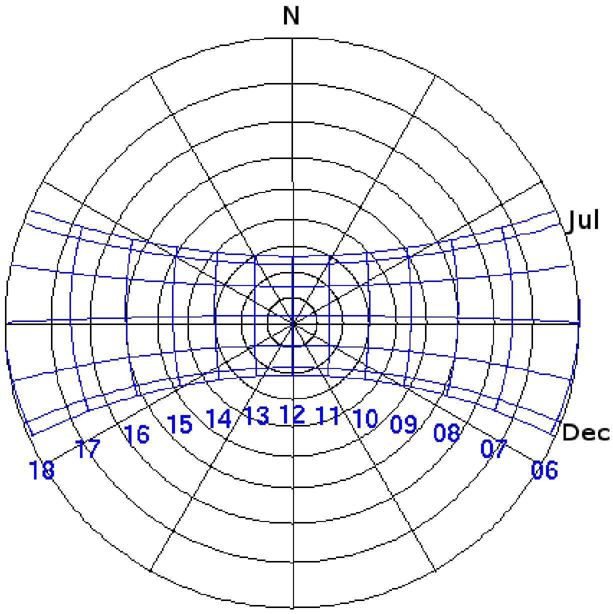


Figure 1 – Sunpath diagram for Putrajaya, Malaysia (JACOBS, 2011)

2 Methodology

This investigation into discomfort glare in Malaysian buildings takes as a case study the Suruhanjaya Tenaga Diamond Building (ST Diamond), located in Putrajaya, Malaysia (Figure 3). The building, completed in 2010, has a fully gazed self-shading façade, daylight redirecting louvers above the viewing window and an internal daylit atrium. It was the first building in Malaysia to be awarded LEED Platinum and won most energy-efficient building at the Asean Energy Awards (AEA) 2012. The building has an averaged building energy index (BEI) of 65 kW/m^2/year compared to a BEI of 210 kW/m2/year for a typical office building in Malaysia (ST, 2013). The layout of the building is open plan with low semi-transparent partitions, and accommodates office workers who perform mostly screen-based tasks all week. The crown of the atrium has spectrally selective glazing to block excessive infrared and UV radiation. The ST Diamond also features an integrated cooling system (cooling coils embedded in the concrete floor slabs), air-tightness, building integrated PV (roof) and energy efficient plug loads (IEN CONSULTANTS, 2015).

Discomfort glare in the building was surveyed through the use of luminance mapping of the occupant's visual environment in conjunction with a questionnaire (Figure 4). Luminance maps of occupant's viewpoints were obtained using an LMK (Mobile Luminance Camera) from TechnoTeam GmBH (POSCHMANN, 2014). The LMK is fitted with a Sigma 4.5mm circular fisheye lens which has a 180º field of view and allows luminance maps to be obtained quickly and accurately. The questionnaire assessed potential factors relating to discomfort glare. Included in the questionnaire was a view diagram for occupants to mark the location and size of any perceived glare sources. This methodology was adapted from a previous study investigating discomfort in green buildings in a sub-tropical climate (HIRNING, 2014). The survey was conducted over two days under clear sky conditions during August 2015. A total of 68 surveys (questionnaire and corresponding luminance map) were obtained, 19 occupants were surveyed twice. If an occupant was situated close to the facade, at the time of survey, and was working with their blinds drawn down; they were asked to perform the survey again with their blinds drawn up. However, if people were already working with their blinds drawn up, they only performed the survey once. This allowed comparative insights into occupant blind usage.

Figure 2a – Older towers in Kuala Lumpur: Low window-to-wall ratio.

Figure 2b – Medium window-to-wall ratio (Petronas Towers, Kuala Lumpur)

Figure 2c – Modern commercial buildings (Putrajaya): High window-to-wall ratio (note most blinds are drawn down)

Figure 2d – Modern commercial office tower (Kuala Lumpur): High window-to-wall ratio.

Figure 2 – Window-to-wall ratios for various buildings throughout Malaysia

Figure 3 – ST Diamond Building, Putrajaya, Malaysia (IEN CONSULTANTS, 2015).

The method of collecting data was to ask a participant to fill in the survey, and then immediately afterwards the physical data (images for the luminance map) were captured. The occupant under survey is required to temporarily vacate their seat while the LMK is adjusted to the approximate seated eye position of the occupant via a tripod. Nine Canon RAW images

(***.cr2***) of the scene were captured using the burst function of the camera. The images acquired range in exposure time from 1/4000s to 2.5s.

Glare Study for Buildings in Malaysia for Building Sector Energy Efficiency Project

BSEEP in conjunction with UNDP would like to invite you to participate in a survey on discomfort glare in a Malaysian workplace. Your participation in this research will help develop our understanding of discomfort glare in Malaysia.

Reference: Date:
Level: Time:

GENERAL LIGHTING

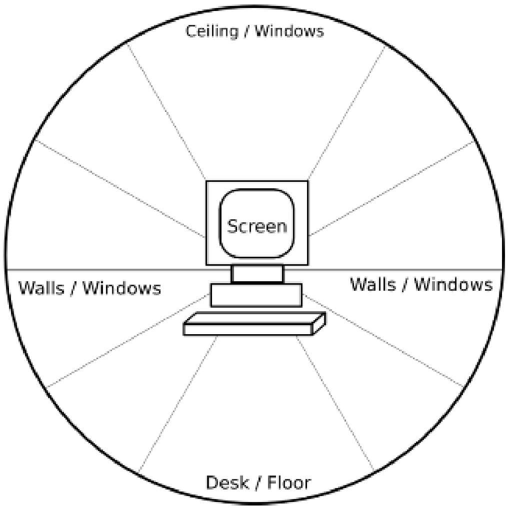
1. Please tick the option that best describes the general lighting in your workspace?
Gloomy ☐ Dim ☐ Comfortable ☐ Bright ☐ Glary ☐

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 at your current workspace?
< 1 Month ☐ < 6 Months ☐ < 12 Months ☐ > 12 Months ☐

DISCOMFORT GLARE

Images of your workstation will be taken by the consultant. Please mark the positions on the View Diagram light sources which are distracting or uncomfortable at this current time. Please mark as much of the glare source as is possible. The consultant can show you an image of your workspace to help locate glare sources.



View Diagram

GLARE SOURCES

1. Please indicate the type of glare you find most uncomfortable at this time?
Direct sun around work area ☐ Electric Lighting ☐ Other Reflections ☐
View of Sky ☐ Daylight on computer screen ☐ None ☐

Please turn over

Figure 4 – Survey handed out to occupants (page 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** ☐ **< 60** ☐ **< 70** ☐

3. Under what light source do you prefer to work?

Daylight ☐ **Electric Light** ☐

4. What is your gender?

Male ☐ **Female** ☐

Thank you 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 may be of value to this research in understanding glare in the workplace.

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Figure 4 – Survey handed out to occupants (page 2)

The aperture of the lens was kept constant at F11 and ISO (sensitivity) was set to 100. Once the survey was completed, timestamps were used to match collected questionnaires and images. Luminance maps were generated using the LMK LabSoft program by TechnoTeam (POSCHMANN, 2014). The program contains calibration files for each available camera setting and can create highly accurate luminance maps, which are stored in the special ***.pf*** (picture float) format. All ***.pf*** files generated were converted to ***.hdr*** (High Dynamic Range) files so that they could be used with other software programs, such as *Evalglare,* which was used to cut the luminance map to the spatial field of view of human eyes (vision zone) (Figure 5) (WIENOLD, 2012; WIENOLD, 2013). Image masks were applied to the luminance maps to obtain luminances from particular areas of the image if they existed i.e. sky, blinds, window, screen and glare (as marked by occupants) (Figure 5d) (results are shown in Table 7).

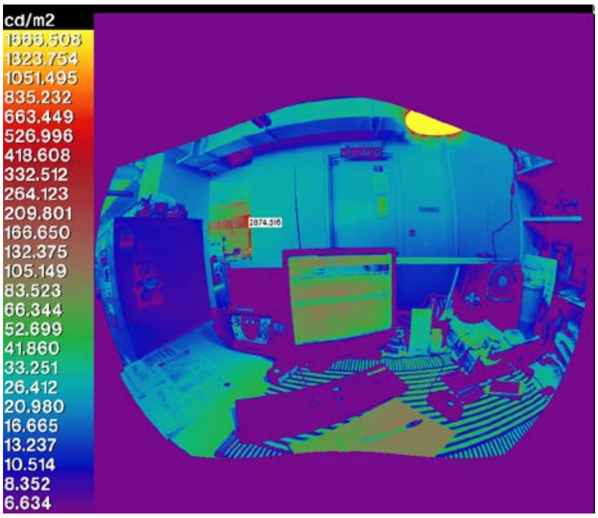

Figure 5a – Luminance Map: Deep plan occupant

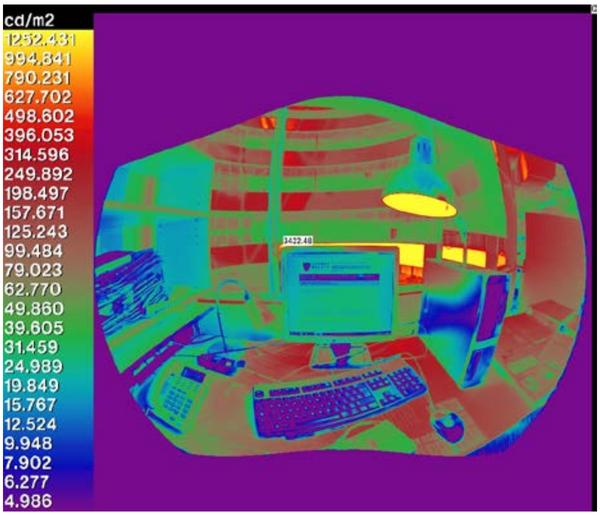

Figure 5b – Luminance Map: Interior atrium facade

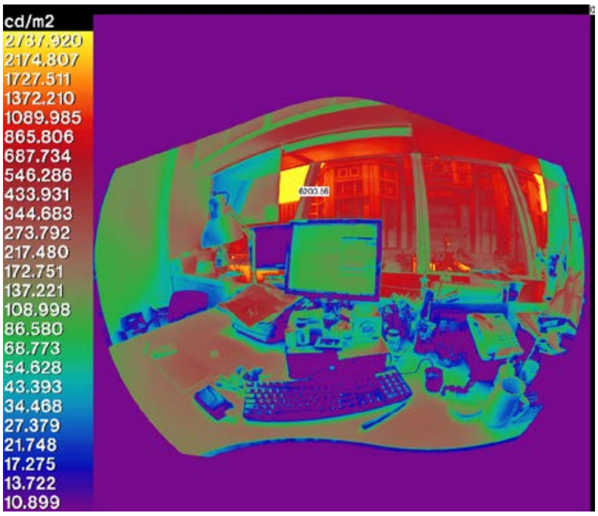

Figure 5c – Luminance Map: Exterior window facade occupant

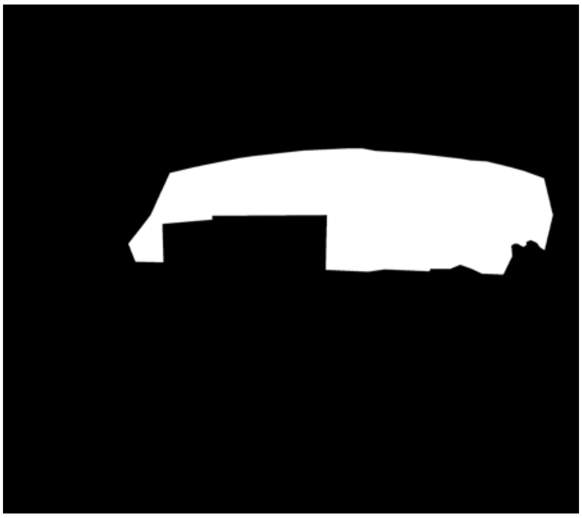

Figure 5d – Example of window mask applied to luminance map (shown in Figure 5c)

Figure 5 – Example luminance maps and image mask

In addition to the survey, several other variables were recorded from the images themselves. These variables were whether a task light was used, if the electric lighting was on, if the blinds were up or down and where the occupant was located in relation to the facade (either deep plan (Figure 5a), next to the interior atrium facade (Figure 5b), or next to the exterior window facade (Figure 5c)).

Luminance analysis was conducted using the program *Evalglare* to calculate two daylight glare indices, the Unified Glare Probability (UGP) and Daylight Glare Probability (DGP) (Equation 1; 2). Both indices estimate the likelihood of discomfort, a value of 0.5 would indicate that 50% occupants would find the luminous environment uncomfortable. Developed by Wienold and Christofferson, the DGP surveyed volunteers in a single occupant office (WIENOLD, 2006). The index relies heavily on vertical illuminance, which was found in the development of the UGP to inadequately predict contrast glare in normal to low lighting levels (HIRNING, 2013; HIRNING, 2014).

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

In contrast, the UGP surveyed real workers at five green buildings in Brisbane, Australia (HIRNING, 2014). The index is a modified version of the Unified Glare Rating (UGR) commonly used to assess discomfort glare from electric lighting. The study found most occupants in open plan buildings experienced glare as a result of contrast glare from windows.

$$UGP = 0.26 \log_{10} \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{P_i^2} \quad (2)$$

In Equations 1 and 2: L_s is the luminance of the glare source; ω_s is the solid angle of the glare source; E_v is the vertical illuminance; n is the number of glare sources; P is the position index related to the position of the glare source and observers line of sight; L_b is the background luminance;

3 Results

The tables below highlight selected results obtained from the questionnaires and analysis of luminance maps from the ST Diamond. The results showed that 39% of occupants were experiencing glare at the time of survey under their normal working conditions (Table 1).

Table 1 – Overall Discomfort

	Occupants %
Discomfort	39
Comfort	61

Of those occupants who indicated discomfort glare, 33% primarily experienced glare from reflected light in the atrium, 61% from sky light and 6% from other sources (such as direct sunlight or electric light). Possible sources of glare sources are dependent on the occupants' location. Due to its interior layout and atrium, the ST Diamond has the majority of occupants situated close to the exterior window (50%), some in deep plan (30%) and the remaining seated next to the atrium (20%). Adjusting for this difference in occupancy between areas, the number of occupants that experience glare in each location is similar (Table 2).

Table 2 – Discomfort in Location

	Occupants %
Atrium	42
Window	39
Deep	40

As expected, most occupants preferred to work under daylight rather than electric light (Table 3). The majority of occupants were working purely under daylight (86%), with some using supplementary task lighting (6%) and only a few (8%) using top lighting (Table 4). The gender split within the ST Diamond was almost even, 47% male and 53% female.

Table 3 – Light Source Preference

	Occupants %
Daylight	76
Electric	24

Table 4 – Electric Lighting

	Occupants %
Task Lights	6
Top Lighting	8
Both Task and Top Lighting	0

Table 5 shows that many occupants (71% overall) were working with blinds down, even though only 39% of occupants were uncomfortable when surveyed. This is representative of a perceived glare problem within the building. At some previous period of time throughout the day or year these occupants experience glare and draw down their blinds. The blinds then remain drawn down permanently even though the uncomfortable light source may no longer be present.

Table 5 – Blinds

	Occupants %	Subtotal	Window %	Atrium %	Deep %
Down	71		31	14	26
Up	29		16	0	13

Table 6A shows the mean luminance values obtained from the image masks applied to occupant workspaces in the ST Diamond. Some of these values can be compared directly to Table 6B which lists the results obtained in the development of the UGP (HIRNING, 2014).

Table 6A – Luminance Statistics for ST

	Mean Comfort (cd/m^2)	Mean Discomfort (cd/m^2)
Average	162	347
Sky	*3948*	*5268*
Windows	*987*	*1640*
Blinds	*132*	*181*
Screen	69	72
Glare Source	-	4180

Table 6B – Luminance Statistics for UGP

	Mean Comfort (cd/m^2)	Mean Discomfort (cd/m^2)
Average	140	180
Screen	99	97
Glare Source	-	2800

Window luminance produced the most notable difference between comfortable and uncomfortable occupants, though this table doesn't take into account the size (solid angle) of the variables, which is important. However, comparing Table 6A and 6B does show that occupants were able to tolerate higher than expected luminances. The average sky luminance was just under 4000 cd/m^2 for comfortable lighting conditions, much higher than the average glare source (2800 cd/m^2) in the UGP findings.

4 Analysis

Evalglare was used to assist in calculating four parameters (UGP, DGP, vertical illuminance and average luminance) for each luminance map (Table 7) (WIENOLD, 2013). All parameters show significant differences between occupant responses for comfort and discomfort respectively. However, of the two glare indices, only the UGP predicts discomfort in the correct range. It's not surprising that the UGP predicts glare reasonably well overall in this building. The average luminance of a scene in the development of the UGP was 140 and 180 cd/m^2 for comfort and discomfort respectively, compared to 142 and 357 cd/m^2 as shown in Tables 6A and 6B.

Table 7 – Luminance Statistics

	Mean Comfort	Mean Discomfort
UGP	0.402	0.576
DGP	0.162	0.223
Vertical Illuminance (lux)	571	1276
Average Luminance (cd/m^2)	142	357

Table 7 highlights that both illuminance and average luminance of a scene show potential as a predictor of glare for this building. Since 50% of occupants surveyed sit close to a window (a large area light source) the occupants have a much higher adaptation luminance than those who sit in the deep plan areas. The cause of glare is then usually veiling luminance or too much light in the eye, rather than contrast glare; as would be the case from a small area glare source, experienced by those who sit further away from the window. If the same statistics are analysed, but only for those who sit in the deep plan areas, a different trend is seen (Table 8).

Table 8 – Glare In Deep Plan

	Mean Comfort	Mean Discomfort
UGP	0.165	0.439
DGP	0.0639	0.0829
Vertical Illuminance (lux)	126	165
Average Luminance (cd/m^2)	37	49

Table 9 – Glare Near Windows

	Mean Comfort	Mean Discomfort
UGP	0.540	0.640
DGP	0.229	0.262
Vertical Illuminance (lux)	826	1453
Average Luminance (cd/m^2)	226	386

Previously in Table 7 it appeared that vertical illuminance and the DGP were indicative of glare; however in Table 8, where only deep plan occupants are considered, these parameters no longer show a strong contrast between comfort and discomfort. The UGP, which can take into account strong contrast glare from smaller glare sources, is effective at differentiating between comfortable and uncomfortable occupants. Table 8 also shows that the UGP index is slightly under predicting discomfort glare for deep plan occupants.

If occupants who sit next to the exterior window are separated out of the results of Table 7 then the opposite trend is seen (Table 9). The UGP is not predicting glare as well for people near the façade (atrium occupants not included). In this case it is slightly over predicting discomfort. Vertical illuminance also shows a much bigger difference between average values for comfort and discomfort. The discrepancies between results of the UGP in Tables 7, 8 and 9 highlight the influence of location in the space. The original open plan buildings in the in the development of the UGP had proportionally many more occupants in deep plan locations than the ST Diamond. Thus the UGP, for now, is weighted more to occupants in mid-plan to deep plan locations within buildings.

The small number of surveys collected from this single building don't warrant more in-depth analysis of other test statistics for discomfort glare. The usual practice with thermal comfort is to design for a 90 or 95% comfort threshold, where 95% of the buildings occupants should be thermally comfortable. In post occupancy evaluation, if 80% of occupants are thermally comfortable, then the thermal comfort of the building is considered acceptable. Applying a similar principal to a glare metric is yet to be done. As a test case for predicting glare in Malaysian buildings this investigation has performed type 2 error analysis (Table 10). A type 2 or a false-negative result occurs when the survey response was "uncomfortable" but the index being tested predicted "comfortable". The objective in terms of glare prediction is that the occurrence of a false-negative carries more consequence than a false-positive result. If a glare index predicted uncomfortable lighting but the occupant response was comfortable, this result is not detrimental to building design, unlike a false-negative.

It was found for the DGP that using the accepted discomfort categories for the index (DGP > 0.35 corresponds to "perceptible glare") that the rate of false-negatives was 45% i.e. the DGP predicted an uncomfortable survey as comfortable for 45% of surveys. In order to reduce the rate of false-negatives to less than 5% the DGP would have to use a categorical scale of DGP>0.065 corresponding to perceptible glare. In contrast, the UGP, gave a false-negative rate of 4.6% for UGP>0.35 (Table 10).

Table 10 – Type 2 Errors

	Index Threshold for Discomfort	Mean Discomfort
DGP	0.35	46
DGP	0.07	5.00
UGP	0.50	15
UGP	0.35	4.60

If the results in Table 10 are applied to lighting design, the UGP metric does not appear to be impractical or prohibitive to innovative lighting (Table 11). Comfortable building occupants with a measured UGP of around 0.35 have very achievable lighting metrics, the same is not true for the DGP. A DGP value of 0.07 would restrict the vertical illuminance of the occupant to approximately 140 lux, which is impractical to implement for occupants in real buildings.

Table 11 highlights the need for a complex method for discomfort glare prediction. The selected occupants (1-4) have vastly different lighting at their workspace, yet experience similar discomfort based on the UGP index. The human eye can adapt and function well over a large range of lighting environments. It is not advantageous to apply a blanket strategy to all lighting design in the hope of avoiding glare. There needs to be some flexibility. In the case of the ST Diamond, occupants show a much higher tolerance to luminance than in similar surveyed buildings (HIRNING, 2014). The Malaysian BSEEP Passive Design Guidelines currently suggests not exceeding viewing luminances of 2000 cd/m^2 to avoid glare (TANG, 2013). However, the ST Diamond has large area windows, translucent low internal partitions, and light redirecting louvers above the windows. These elements help make the lighting in the office spaces much more uniform in brightness than with just windows alone; therefore people are able to tolerate higher luminances than what is usually expected in a typical office building.

Table 11 – Example Occupants

	UGP	Average Luminance (cd/m^2)	Vertical Illuminance (lux)
Occupant 1	0.31	58	159
Occupant 2	0.29	338	1165
Occupant 3	0.39	9	35
Occupant 4	0.39	269	994

5 Conclusion

This investigation attempts to highlight some of the current issues and the potential next steps way forward in determining appropriate glare prediction for sub-tropical and tropical office buildings. The results from the ST Diamond demonstrate the need for complex glare metrics, which may require more variables than those currently used, particularly with respect to view direction and occupant position within a space.

The method of type 2 error analysis as applied to the UGP showed positive results in the case of the ST Diamond. People in similar lighting situations can naturally experience very different levels of comfort or discomfort. Type 2 analysis would help weight a glare metric for low-tolerance individuals who are likely to sabotage a daylighting design; though caution is required to ensure that using low metric thresholds doesn't restrict innovation in lighting design. The results suggest a probability scale of 0.35 or less if the UGP is to be used to minimise discomfort glare to very low levels, though this is only an exploratory analysis. More importantly, it was uncovered that an occupants' position within a building (close to or far from the façade) has a significant effect how discomfort glare is likely to be perceived.

Based on these findings future work will continue to assess what method of prediction is most appropriate, particularly with respect to occupant position in relation to the nearest façade. Currently, all assessments of the UGP have been conducted under clear skies. The UGP predicted discomfort glare quite well overall in the ST Diamond, though it remains to be seen how well the metric will perform under other sky conditions.

Acknowledgments

This research was supported by the Building Sector Energy Efficiency Project (BSEEP), Malaysia. The authors would also like to thank Hamidah Abdul Rashid and Norakmal Amat Nor along with all the other staff at the Suruhanjaya Tenaga Diamond Building for their assistance.

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