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Light level, visual comfort and lighting energy savings potential in a green-certified high-rise building

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ABSTRACT

Over-illumination and poor distribution of light are among the factors that lead to visual comfort problems. This paper reports on the outcomes of a post-occupancy survey that evaluated visual performances in a highly glazed green building and the perceptions of the tenants towards their visual environment. Measurements of light source luminances and work area illuminances were carried out using calibrated equipment and survey forms were distributed to the tenants. The degree of perceived discomfort glare at the studied areas was calculated using the field data collected. The results show that although the indoor spaces were generally well lit from 10am to 3.30pm using natural daylight, discomfort glare was predicted at workstations near to the window area. However, most of the tenants were satisfied with the perceived lighting levels during the survey, possibly owing to the use of internal curtain blinds when they experienced discomfort glare. The high illuminance in the open-plan office compartments was a major concern which necessitated the use of shading devices to prevent visual discomfort. While improved lighting energy management can be achieved via reducing the dependency on artificial light fittings, more studies on the costs incurred to further enhance lighting energy efficiency and the interior visual environment using newer glazing materials, lighting technologies and control strategies are required.

1. Introduction

Occupant visual discomfort, which is often caused by glare or insufficient lighting, has been found as one of the major indoor environmental quality (IEQ) issues in modern high-rise commercial buildings [1-2]. Many previous works have reported that inappropriate lighting conditions could bring glare problems, visual discomfort, negative impacts on the workers' productivity and may lead to other health and behavioural issues [3–5]. In order to reduce the unfavourable impacts of visual discomfort on the tenants, building operators around the globe have been entrusted with the obligation of ensuring the building interiors receive adequate lighting to improve work and living quality.

Natural lighting has been used as the main source for illumination since the earliest of human civilisation, but its application has largely been outlined by the use of artificial lighting since the industrial revolution due to safety, reliability and other applicable purposes. The artificial lighting system in Malaysian offices accounts for almost 20% of commercial electricity use [6], which is the largest energy consumer in buildings after air-conditioning. As the lighting fixtures have been found as one of the highest energy users in high-rise buildings, studies related to ways of reducing the amount of energy used in providing illuminations to people have been carried out worldwide, which include better lighting technologies [7–8], arrangement of lighting fixtures and shading [9], enhanced control strategies [10–12], improved glazing and windows [13-14] and others.

Even so, the usefulness of natural lighting in providing a comfortable and healthy environment for the tenants and reducing artificial lighting consumption has been acknowledged in many sources [15–17]. In Malaysia, the provision of natural lighting in Malaysian buildings is prescribed under sub-section 39 (1) of the Uniform Building By-Laws 1984 [18]:

> "*Every room designed, adapted or used for residential, business or other purposes except hospitals and schools shall be provided with natural lighting and natural ventilation by means of one or more windows having a total area of not less than 10% of the clear floor area of such room and shall have openings capable of allowing a free uninterrupted passage of air of not less than 5% of such floor area*".

Until recently, the introduction of the green building concept has

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partially reversed the lighting use and design concept of the building professionals, especially for buildings in the equatorial regions where abundance of sunlight is available. Among the green building tools, the green building index (GBI) was introduced back in 2008 and this tool was specially designed based on the current social, economic, infrastructure and the tropical climatic conditions of Malaysia. Many local building designers and engineers have since undertaken the responsibility of developing both energy- and resource-efficient buildings by adhering to the requirements stipulated in the GBI assessment tools for both eco-conscious and financial purposes. Under the IEQ section of the GBI assessment criteria for non-residential existing building (NREB) [19], 7 out of 21 points are allocated for criteria related to the enhancement of the tenants' visual satisfaction. Due to that reason, natural lighting is now a more preferred source for illumination during daytime and many new commercial buildings intended to go for green certifications are designed to have enhanced daylighting features, such as providing larger window areas to optimise daylight use to meet the desirable indoor illuminances to reduce the dependency on lighting fixtures. However, the available information about the effect of higher glazing to floor area ratios towards indoor lighting environment is limited at the moment, which suggested the necessity of analysing the light provision level in buildings to ensure that the visual comfort of occupants is not compromised by the savings in energy cost. The work of Vanhoutteghem et al. [20] which studied the effect of window façade designs towards daylighting potentials had proposed that more similar works to be carried out in the warmer regions of the world. Besides, solar heat emission into buildings via fenestrations is normally encountered in tropical countries and this contributes significantly to the increase in energy costs for cooling and other purposes [21].

Since natural daylight is a lot more difficult to be controlled as compared to its artificial counterpart because of its dynamic and variable in nature features [17], there are several concerns over its application in buildings going green: what is the range of lighting levels in the open-plan office area during working hours if only natural sunlight is used as the main source of light? How much lighting is needed to create a visually comfortable environment? How do the local tenants perceive their visual environment due to the high variability of daylight in their buildings?

In order to address the questions raised, there is a need for a field study targeting the lighting levels and visual comfort receptions of the tenants in such office buildings that usually utilised large glazed window areas to maximize the use of daylighting. Some earlier works had applied the post-occupancy comfort survey (PCS) method in assessing the indoor environment of selected buildings and the effectiveness of this method have been highlighted [22–25]. The issues of daylight discomfort glare - the unpredictability of the glare source luminance and occupant perceived evaluation of discomfort glare have also been the research interests of many studies where the concept of Daylight Glare Index (DGI) and other glare indices were commonly applied for sources with non-uniform luminance levels [26-27]. This paper seeks to discover the potential of applying natural daylight as the main source of illumination during normal working hours in a green certified high-rise building and the effect of this setting towards the perception of luminous comfort among its tenants, following the assessment criteria of a green building tool. The degree of perceived discomfort glare in the office was evaluated by determining the luminous levels of the main light sources and surroundings. The data collected throughout a PCS were analysed and compared to the latest building standards' specifications by focusing on the daylight provision to the building occupants. Analysis was made on the data collected on site only as this study was part of an indoor climate condition enhancement effort, which covered both physical and questionnaire measurements. The possibility in reducing energy use and potential cost savings in the studied building that comes together with the application of daylight are also presented.

2. Methodology

A government-owned green commercial building which fulfilled the "platinum" rating criteria of the GBI tool was selected for lighting ergonomics analysis. This building was designed to serve as a landmark building in the country and to achieve an energy use index of 85 kWh/m^2/year, which is only half of the energy typically required by other comparable conventionally designed buildings. Some of the important green features it possesses include the large façade design to allow more daylight into the building, the use of double glazed low-emissivity glasses to prevent visual discomfort, solar photovoltaic (PV) electricity generation, floor-slab cooling technology with a separate air-side ventilation system to enhance occupant comfort, rain water harvesting and dual-flush toilets to conserve water use. The field survey undertaken encompassed two separate strategies that were carried out concurrently – physical measurement of two visual comfort parameters and questionnaire survey. Since Malaysia is a tropical country, daylight is abundant and there is barely any seasonal variation in its availability. The outdoor illuminance and irradiance levels are quite constant throughout the year. The sky clearness index of several major cities was found to vary between 0.47 and 0.57, with a mean value of 0.52 [26-27]. The hourly illuminance during working hours ranged from 44018 to 82105 lux [28]. Permission was granted by the management to the research team that measurements were allowed to be conducted at the open-plan office area of the 2nd to 6th floor, which was the location where more than 80% of the office staff were seated. No measurement was taken at the highest floor (7th floor) of the building because it was usually used for staff meetings and social gatherings. Private rooms, which were occupied by senior management staff, were not considered in this work due to security and privacy reasons.

Table 1 shows the building design information of the green building. The ratio of window to floor area was within 19.5–29.1% (with the first floor excluded) and this is presumably higher than the 10–20% ratio for most high-rise conventional buildings. The architectural floor plan that indicates the locations of both windows and atrium is illustrated in Fig. 1. The office building was designed in such a way that 50% of its illuminance source were from natural lighting. It was measured during the initial green building assessment process that the daylight factor at more than 30% of the building's net lettable area (NLA) was within 1.0–3.5%. The atrium was designed to optimise the utilization of daylight and automated blind curtains with six different arrangements were installed to keep the indoor illuminance at a suitable level. Besides, these blinds with 30% light transmittance were useful to prevent potential glare problem, especially at the higher floors. To enhance the use of daylight at all working floors, a band of reflector panels were installed at the 4th and 5th floors with an inclination of 10° to deflect excessive daylight in a semi-diffuse manner to the lower floors [29], as shown in Fig. 2. The solar heat transmission and ultra-violet (UV) that may cause skin damage and fading of in-house furniture were strategically minimized with the use of double glazed low-emissivity glasses and other

Table 1
Design information of the green building.

Floor	Total Floor Area (m^2)	Estimated Glass Area (m^2)	Ratio of Glass/ Floor Area	Estimated Floor Height (m)
Basement 1	3534	–	–	3.4
Basement 2	2208	–	–	3.4
First Floor (Sports Club, Prayer Room)	1216	110.0	9.0%	3.4
Second Floor	1229	357.6	29.1%	3.4
Third Floor	1449	387.8	26.8%	3.4
Fourth Floor	1697	420.7	24.8%	3.4
Fifth Floor	1965	453.6	23.1%	3.4
Sixth Floor	2242	486.2	21.7%	3.4
Seventh Floor	2574	520.8	20.0%	3.4

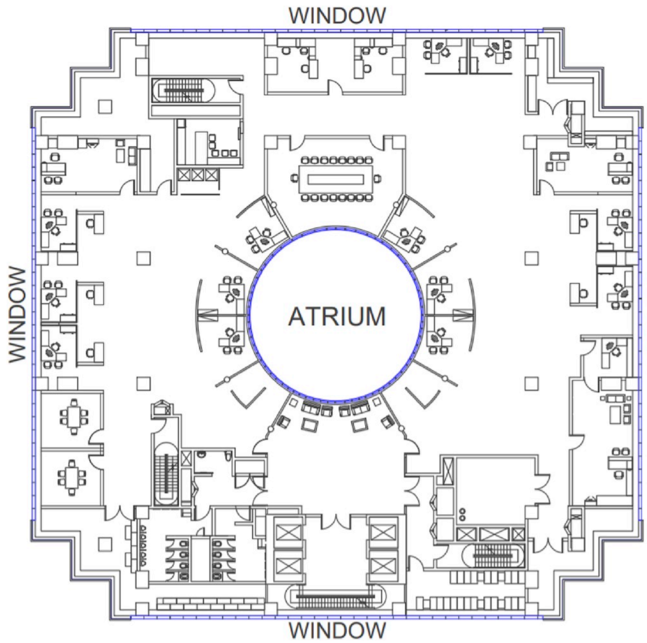

Fig. 1. Floor plan of the building.

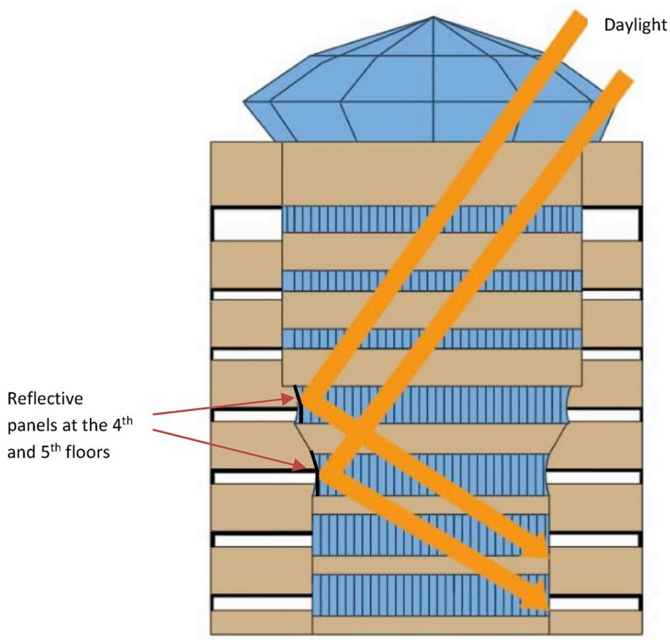

Fig. 2. Cross-sectional view of the atrium and the locations of reflector panels.

shading devices such as curtains and extruded external louvers installed at several areas of the building. As for artificial lights, the ceiling suspended T5 light fixtures with electronic ballasts and with a luminous efficacy of 104 lumen/W were available in the general office area while compact fluorescent lamps (CFLs) were used in the transitional spaces. These light fittings are daylight responsive with light sensors installed on each floor's façade and in the atrium of the building and controlled by the building automation system to maximize daylighting.

Throughout this survey, the measured indoor spaces were illuminated entirely by natural lighting. This was to reduce the energy consumption of the lighting system, to determine the luminance values of light sources and to investigate the sufficiency of daylight in providing a visually comfortable environment.

2.1. Physical measurements

An illuminance and ultra-violet (UV) recorder with a measuring range of 0–130,000 lux (lumen/m^2), an accuracy rate of ±3% at maximum value and a resolution of up to 3.0 lux was used to measure the horizontal work-plane illuminance at selected locations within the office complex. On the other hand, the measurement of computer and window's luminances were carried out using a data logging luminance meter with measuring levels ranging from 0.001 to 1999k cd/m^2, ±3% of accuracy. The data were transferred to a portable computer using compatible software. To compare the brightness at selected locations within the building with the recommended average value stipulated in CIBSE [30] and MS 1525 [31], the illuminance meter was positioned at the working plane level of the visual task area, which was about 0.75 m above the floor level (office table height) following the recommended height of measuring level for workplaces [32]. The photosensor of the luminance meter was fixed on a tabletop tripod and adjusted to be at the viewing angle of the computer users, as presented in Fig. 3. In order to determine whether there are any significant differences between the illuminances measured at different floors in thebuilding, the SPSS one-way analysis of variance (ANOVA) test was used.

2.2. Questionnaire survey

A PCS form that covered thermal, visual, acoustical comfort and indoor air quality enquiries was used. This survey form was developed based on the sample questionnaire given in DOSH ICOP [32] which was developed for Malaysian buildings and other related works and it was modified accordingly to suit the office buildings conditions. The questions on visual acuity are shown in Fig. 4. All the tenants who had remained seated at their respective work stations for at least 30 min and near to the atrium/windows of the building at which the measuring device was positioned were invited to take part in the survey as they were assumed to be "adapted" to the visual environment. This is to ensure that a statistical accuracy of at least ±5% could be obtained. In this work, only the visual comfort results are presented.

2.3. Glare index calculation

As daylit office spaces were selected for visual comfort analysis, the Daylight Glare Index (DGI) concept developed by Hopkinson [33] to predict glare from windows and other large openings was applied to analyse the potential glare source. This concept has been widely applied in interior lighting design analysis which involve large glare sources, such as windows [34]. The DGI was determined using the following equation:

$$DGI = 10\,log_{10} 0.478 \sum_{i=1}^{n} \left(\frac{L_s^{1.6} \Omega^{0.8}}{L_b + 0.07 \omega^{0.5} L_s} \right) \tag{1}$$

where L_s = light source luminance in cd/m^2, L_b = mean background luminance in cd/m^2, Ω = solid angular subtense of the source modified for the effect of the observer's position in steradian, and ω = angular size of the luminance source as seen by the eye. The glare regions and degree of perceived glare had also been introduced, as shown in Table 2.

3. Results and discussion

It was assumed that the peak working time in the office building were from 10.00 am to 3.30 pm as most of the administrative staff were available in the building. This was particularly important for the field measurements because both physical and questionnaire measurements were to be conducted at the same time. During the field survey, internal raise/lower blinds at the windows and atrium were lifted to allow the electronic sensors to capture the task area illuminance, window and computer luminances and the research team to evaluate actual occupant

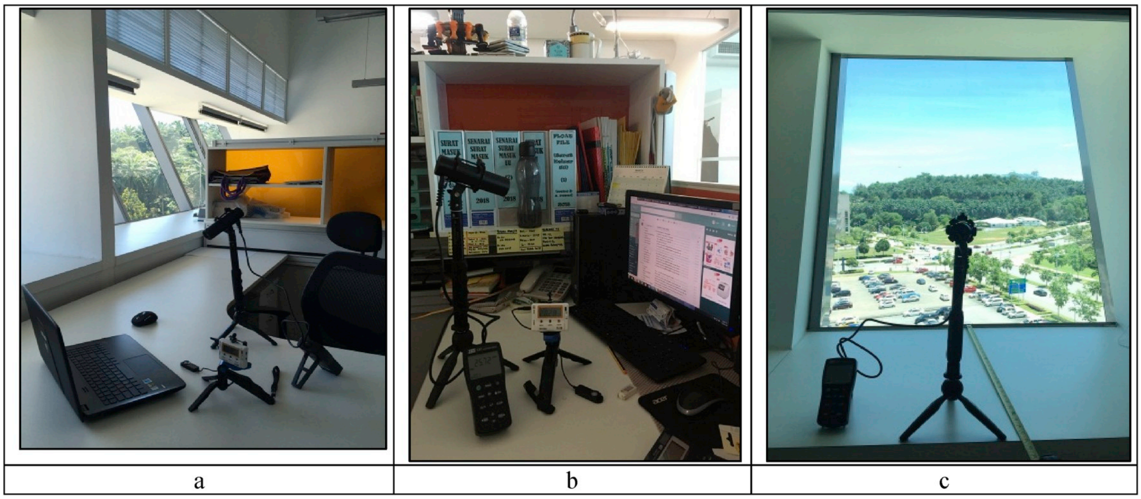

Fig. 3. Measuring equipment and locations (a) luminance and illuminance measurements at work plane level of an executive's workstation, (b) luminance and illuminance measurements at a workstation using desktop computer, and (c) Measurement of window luminance.

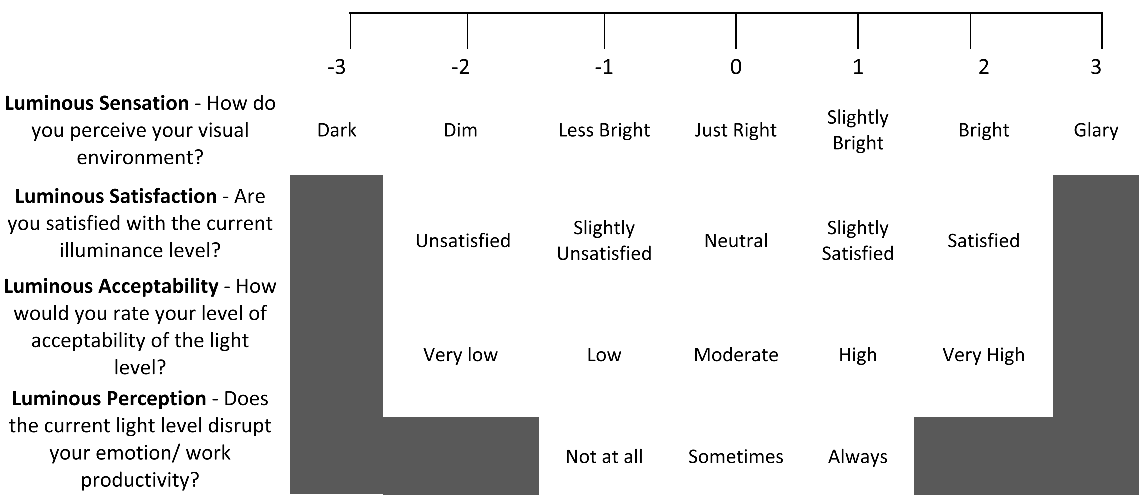

Fig. 4. Questionnaire contents on visual comfort and rating scale.

Table 2
Relationship between DGI, perceived glare degree and comfort zone [35-36].

Zone	Perceived glare degree	DGI
Comfort	Just perceptible	16
	Noticeable	18
	Just acceptable	20
Borderline	Acceptable/Just uncomfortable	22–24
Discomfort	Uncomfortable	26
	Just intolerable	28
	Intolerable	>28

Table 3
Mean luminances of light sources and DGI.

Location	Sources (cd/m^2)					Mean DGI
	Window	Atrium	Ceiling	Screen	Background[a]	
Second Floor	–	269.88	62.84	95.27	46.61	25.25
Third Floor	1093.71	155.52	76.68	111.12	39.22	32.35/ 20.71
Fourth Floor	1238.40	259.60	59.55	105.12	24.43	32.41/ 24.83
Fifth Floor	2079.09	–	47.85	112.59	32.05	35.41
Sixth Floor	3620.11	–	99.86	78.92	56.62	36.75

[a] Floor and cubicle partition or wall, depending on locations.

visual acuity, which are the main focuses of this work. Using the results obtained, a simple energy cost savings analysis was also carried out to demonstrate the energy efficiency potential of the lighting system.

3.1. Objective measurement and calculation

The illuminance was measured concurrently with the brightness of light sources during the field survey. All the desktop computers that were used by the office staff were of the same model, except for departmental leaders who were seen using portable computers. The data for light source luminances for each measured floor are tabulated in Table 3. From the indoor luminance tests, it was found that the average computer luminances varied from 78.92 to 112.59 cd/m^2, while the luminances of the surrounding windows/atrium were generally above 200 cd/m^2, and the peak value was measured as 4,388 cd/m^2. It should be noted that only the luminance values of the nearest windows/atrium to the respective workstations were obtained. The mean luminance on the ceiling area ranged from 47.85 to 99.86 cd/m^2, while from other background lightings (walls, partitions etc) was within 24.43 and 56.62 cd/m^2. Based on the results obtained, the mean DGI at the different floors of the building ranged between 20.71 (just acceptable) to 36.75 (intolerable level). Excessive luminance from the windows was the main reason for which the automatic roller blinds and manually controlled curtains were used, as complaints of discomfort glare were made by the workers to the management prior to this survey. The research team tested the effect of the curtain blinds on the window luminance at the 3rd floor of the building, and found that the use of blinds could effectively reduce up to 90% (from 2328 to 216 cd/m^2) of the luminance value. It was identified that the background luminance was slightly affected by the use of artificial lighting at the corridor and entrance door, and the luminance readings of adjacent walls of the workstations not directly located beside the window or atrium showed only slight variations with one another.

The horizontal workspace illuminance at nearest windows to the measuring points was identified as within 1441–4179 lux. The measured mean horizontal workspace illuminance at 20 measuring points during working hours ranged from 372 to 575 lux with an overall mean value of 446 lux, as shown in Fig. 5. The highest mean illuminance value of 576 lux was measured at around 1 pm, and gradually reduced to below 500 lux after that. This finding shows that the illumination provided by sunlight was within the maintained illuminance range specified in the CIBSE lighting guideline [30] and higher than the recommended illuminance of 300 lux for office spaces stipulated in the Malaysian Standard (MS) 1525 [31]. Besides, although GBI NREB [19] specifies that the light level at horizontal workplace should be controlled below 2000 to prevent glare issues, the calculations of DGI showed that discomfort glare could have potentially occurred at all floors of the building, mostly due to the notable difference between main source (window) luminance and the background ones [37]. It should be noted that the measuring equipment used might have added to this discrepancy, as only one point of measurement was taken for each room surface of the workstations. The results also indicate that higher lighting levels were recorded at the 6th floor of the building, which was built with an estimated glass area of 486.2 m^2. For other floors with smaller glass areas, the lighting levels were found to be lower and ranged between 181 lux and 549 lux. Based on the field survey outcomes, it can be safely assumed the use of lighting fixtures was not required at the open plan office area for about six hours a day, except for the spaces where natural daylight was not available, such as the pantries, washrooms and some of the interior ancillary spaces where artificial lightings are required under the building safety requirement [18].

As for the statistical analysis using one-way analysis of variance (ANOVA) test, a null hypothesis was made where the difference of lighting levels at each floor and within the same floor of the building were not statistically significant. However, as summarised in Table 4, it was identified that the difference between illuminance conditions at each floor of the office building was statistically significant since the p-value is less than 0.05 in this test. This outcome was expected because of the notable difference in measured illuminance levels between the top floor (6th floor), mid-level floors (4th – 5th floor) and the lower ones (2nd – 3rd floor). Owing to the interior architectural design of the building, the distribution of workstations at each floor was different, and the workstations at the higher floors were arranged to be more confined to areas near to the windows to maximise the use of natural daylight (as depicted in Fig. 6). The locations selected for data collection were therefore not entirely the same at each floor. The types of partition used, placement of large office equipment and arrangement of the workstations had somewhat restricted the locations available for measurement. This has contributed to the difference in the level of lighting recorded at different floor to a certain extent.

Table 4
Statistical analysis of illuminance levels using ANOVA.

Illuminance level	Sum of Squares	Degrees of Freedom	Mean Square	F	*P
Between Groups	511120.406	4	127780.102	15.307	**.000**
Within Groups	125219.719	15	8347.981		
Total	636340.125	19			

Significant when *P < 0.05, N = 20.

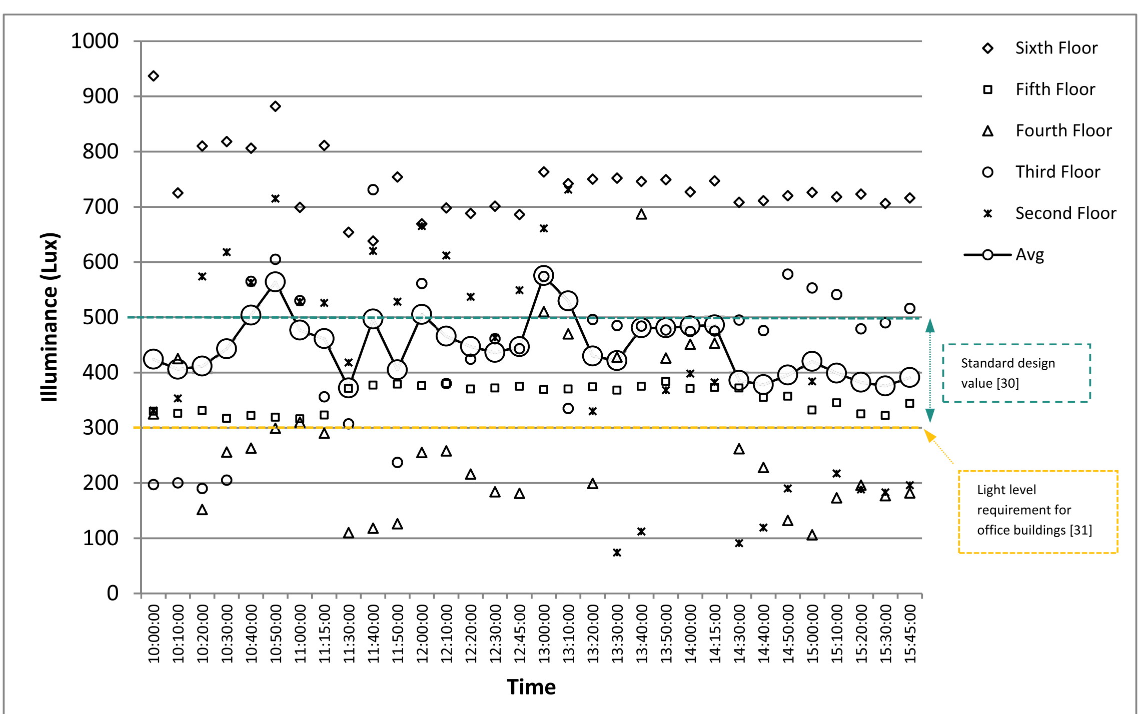

Fig. 5. Measured illuminance profile at working plane level of task area.

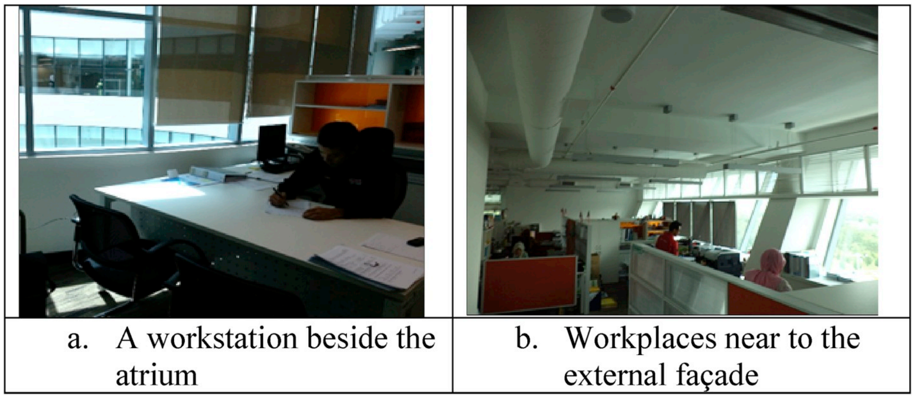

Fig. 6. Indoor environment and workstation distribution in the green office building. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

An interesting finding was that the mean illuminances at the atrium of the lower floors were higher, albeit slightly, than that of the middle floors. It was found that the difference in illuminances was more than 10% between the 2nd and 4th floor. This is largely owing to the higher glass to floor area ratios where the glass size is larger as it is deeper into the atrium and the use of a band of reflector panels (as presented in Fig. 2) to deflect the natural daylight across the atrium to the lower floors [29], which were alleged to have lower illuminances during the design stage of this green building. This has caused the measured illuminances at the lower floors to exceed the Malaysian standard's illumination requirement, but somehow fulfilled the objective of the atrium design. Hence, some adjustments on the reflector panels were required so as to make sure that sunlight via the atrium was distributed more evenly. While this study did not consider the effects of façade design and building orientation on luminous intensity, the results obtained have shown fair agreement with some previous works, which indicated that effective use of sunlight could largely contribute to energy efficiency improvement by making artificial lighting only complementary [11,20]. In general, it was safe to conclude that natural daylight alone was sufficient to provide illumination in this office building, according to the range of acceptable lighting requirements for offices stated in the relevant building guidelines.

3.2. Subjective assessment

The actual visual comfort perception of the tenants residing green buildings that admit daylight via fenestrations and other openings is an interesting subject that requires detailed analysis. In order to understand the occupant perception of visual comfort, a subjective rating survey was carried out concurrently with the field data measurement. Almost all of the employees approached agreed to participate in this survey. Of the 42 respondents who completed the survey, 28 (66.6%) of them responded that they found daylighting alone was sufficient in providing the required illumination for their daily work since they voted within the three central categories (−1, 0, +1) of the scale, as shown in Fig. 7. With regard to the issue of possible over-illumination based on the measured light levels, a significant percentage of the votes (30.9%) were placed on the brighter side of the scale (+2, +3), which pointed out that the open-plan office areas received more than sufficient lighting during office hours. Based on the survey results, 60% of the respondents seated near to the windows claimed that the surrounding was too bright for them. Only 1 respondent opined that the surrounding was dim and none

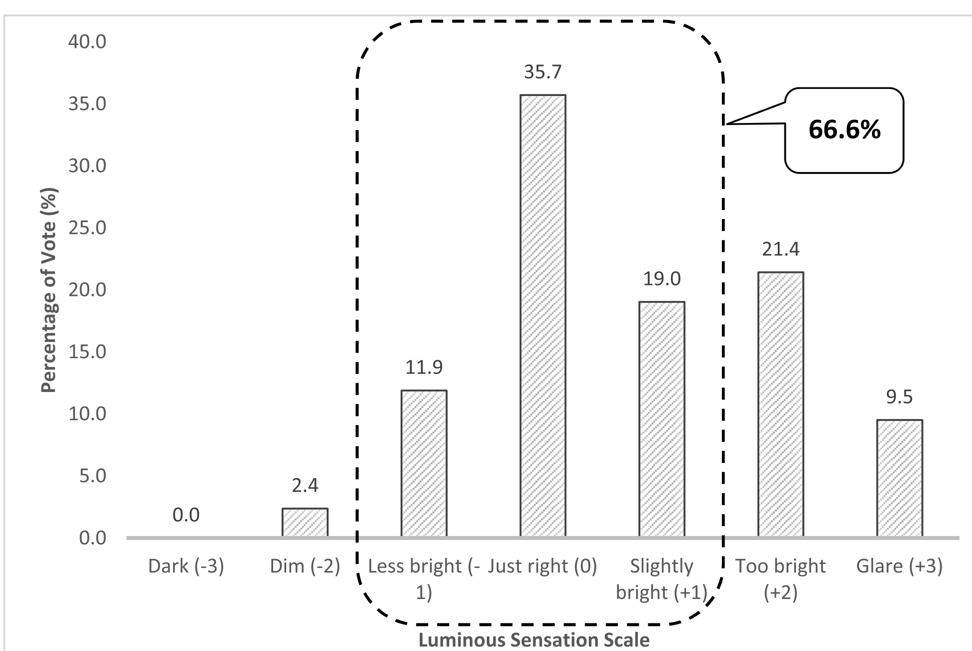

Fig. 7. Distribution of subjective luminous sensation vote.

of the votes were placed in the dark (−3) category of the visual sensation scale. It was further observed that the use of roller blind curtains, which were only set up several months before the field survey at locations where complaints of glare were received, did significantly change the tenants' luminous sensation in which some of them opined that the office area was "slightly bright" or "bright" instead of the extreme "glary".

The result for light level acceptability is shown in Fig. 8 and it presents that 73.8% of the respondents were visually comfortable, since their votes were placed on the "very high" and "high" categories of the acceptability scale. This also demonstrates that they generally had a higher acceptance of their visual surroundings than their Australian counterparts, where the results reported in a visual comfort survey conducted in Australian green buildings found that less than half of the respondents experienced acceptable visual comfort at their workplace [25]. A possible explanation for this discrepancy was that thelights were not switched on during this field survey, as the use of lamps was identified in several case studies as the main cause for over-illumination of indoor space besides window glare. Other factors, such as difference in light level tolerance may be the reason for some respondents to claim that the visual environment was acceptable, although it was actually glary. It was found that most of the votes that were placed on the "poor" and "unacceptable" categories were collected from those who voted other than the "Just right" category of the luminous sensation vote, which shows that those occupants either found the lighting conditions too bright or less luminous for them. This indicates that the open-plan office area was successfully designed to provide sufficient lighting even without the use of electric luminaires during peak working hours, partly attributed to the higher glazing to floor area ratios. Some tenants had nevertheless reported in the survey form that they had experienced discomfort glare and it was difficult for them to read from the PC monitor screen and printed documents due to excessive reflections, or contrast-glare. This is in line with the very high luminous levels at the window areas that was observed during the field survey. Besides, this finding is consistent with the work of Yun et al. [24], which highlighted that luminous comfort and lighting intensity are closely related in an office environment. From the luminous sensation vote, about 81% of the respondents opined that the light level would "sometimes" affect their emotion or productivity, while 12% of them claimed that the indoor lighting conditions had very little influence on them and the remaining 7% viewed the daylighting effect on their feelings as "always".

In order to avert the uncomfortable sun glare, it was suggested that the automatic sunlight monitoring system of the building could be extended to the control of blind curtains at the façade windows that have high sunlight reflective rates, and the workers seated nearby are allowed to access to an incorporated manual override function which enables them to adjust the blind curtains during office hours. Better visual acuity could possibly be obtained by installing additional shading materials, such as outdoor blinds and external louvers to the fenestrations at locations where over-illumination was reported or a complete refurbishment of the glazing system of the building to eliminate potential glare problems. In furtherance, the control of illuminances and solar heat gain at high illuminance building areas using solar film coatings coupled with daylight-linked lighting control yields favourable results [38]. It was also found in a simulation work using Radiance software that well-designed light shelf, which is positioned at the suitable position, angle and height could optimise daylighting performance and reduce energy cost in office buildings [39]. A more recent work [14] proposed the use of a newer glazing system which was found to be capable of enhancing both thermal and visual environments by reducing space cooling load and glare. This has suggested the need to consider the influence of solar heat gain via the fenestration towards comfort perception of the tenants. Although these findings sound promising, the implication on maintenance and replacement costs should be taken into consideration prior to any new installations or modifications to the existing glazing system are made.

The findings from this part of study pointed out the need for further work to identify the cost-effectiveness to appraise the desirability, effects on users, aesthetic value of the building and implications on the overall building operation if such thoughts are to be put into practice. Besides visual comfort, the influence of heat gain due to the solar influx towards the overall comfort perception of occupants should be studied in details, at which the application of a pyranometer and software simulations may be required to identify the intensity of heat gain from glazing throughout working hours.

3.3. Energy savings potential

Artificial light fittings are installed in commercial buildings to comply with the requirements of building standards as well as to sustain visual comfort. Although utilising natural sunlight has long been recognized as a useful strategy for energy conservation and visual comfort in buildings, building services designers in the tropics generally

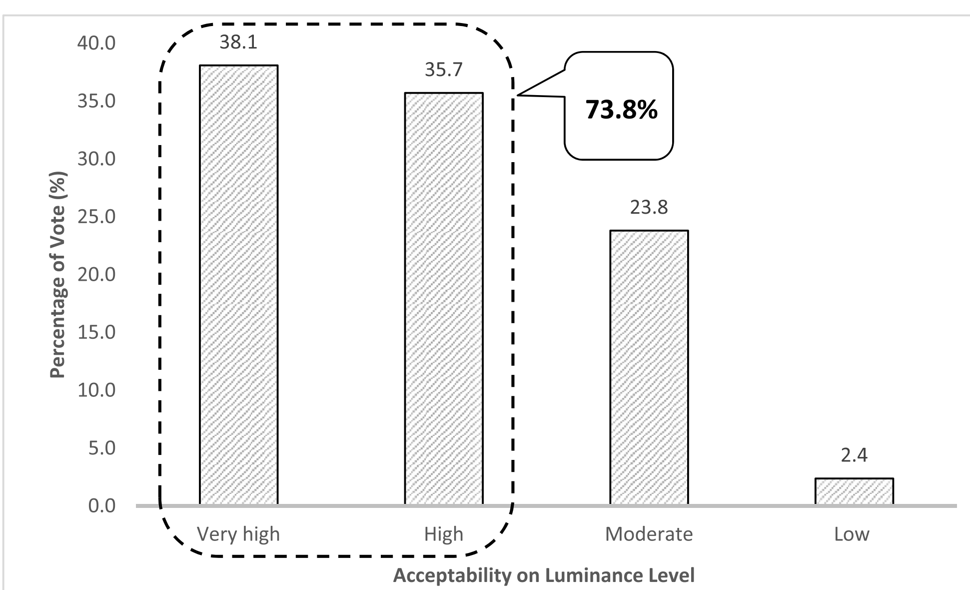

Fig. 8. Light level acceptability of occupants.

paid less attention to the possibility of applying natural daylight as the illumination sourceduring daytime, and some even claimed that natural daylight was inconsistent and unreliable. This is among the factors where natural illumination by penetration of direct solar and diffuse sky visible radiation are restricted to the work of the architects in passive architecture. From the questionnaire votes, a substantial majority of the respondents stated that their immediate surrounding was bright enough during office hours. The objective measurement in the office building also presented that dthe illuminance was higher than the acceptable range specified in the MS 1525 [31] from 10 a.m. to 3.30 p.m., and some locations were found to be glary. The energy-saving opportunity by taking the glare problem from windows into consideration had also been discussed in an earlier study [40].

For artificial lighting, the planned maintenance schedule includes regular cleaning of light fittings to ensure the most efficient use of energy [41]. Since the lamps in the office are not used during office hours and were kept at a lower temperature due to the chilled slab, the lifespan is prolonged and light output are maximized. The operating cost of the lighting system was estimated based on the number of installed T5 compact fluorescent lamps with electronic ballasts. The total installed office lighting was 8.4 W/m^2, but a recent study showed that unit lighting power was only about 4 W/m^2 [29]. Therefore, the total used capacity of the lighting system was approximately 51,762 W. Since the nominal wattage of the light tubes was 14 W and the number of tubes per fixture was 4 pieces with a magnetic ballast, a total number of 925 light fixtures were required.

Assuming that all the lights within the office building (except washrooms, corridors and other protected areas) have been turned off during the peak office hours, a monthly energy savings of about 1,787.10 kWh will be obtained, which is about 1.92 kWh/m^2/year if the concept of BEI is used. The cost calculation is shown below:

Total energy saving per day = N x P x H

= 925 lamps x 14 W × 6 h

= 77.70 kWh

where N = Number of electric fixture, P = Present input watts/electric fixture, and H = daily operating hours.

Total energy saving per month (Assuming 23 working days per month) = 77.70 kWh x 23

= 1,787.10 kWh

The electricity cost of office buildings in Malaysia falls under the commercial category of Tariff C1 – Medium voltage general commercial tariff. For this category, the cost for each kWh is 36.5 cents, according to the electricity/power producer [42]. An estimated annual energy-cost savings amounting to RM 7,827.50 (about USD 2,236.43) can be obtained by utilising daylight during office hours, which is roughly 50% savings from the electricity used to provide lighting in the building surveyed according to the energy consumption data. This result shows similarity with a previous study conducted in a tropical climate using software simulations [16], which suggested a possible reduction of 50–80% of the artificial lighting energy consumption with daylighting. It should be noted that the effect on maximum demand was not considered in this simple cost saving analysis.

Since natural daylight was sufficient in providing the occupants with visually comfortable surroundings during working hours and there is no need to achieve the recommended illuminance level of 300 lux after work, a lighting control scheme can be developed based on the results obtained from this study. Focuses should be placed on reducing glare at locations where high illuminances were recorded and achieving overall lighting energy efficiency, which is a priority in green buildings. Some specific energy saving measures include the use of occupancy and light sensors [12] which can be integrated to the building energy management system (BEMS), delamping and relamping at over-illuminated areas and replacing general lighting with the more specific task lightings. Changing the CFLs with the newer ones with smaller input power or replacing them with high quality light-emitting diode (LED) lamps can be considered at locations where sunlight is limited. The prospect of savings at the common areas, especially the guest waiting areas at each floor can be analysed in future studies as it was not within the scope of this work. For a better description of the overall cost saving opportunities of the lighting systems, a detailed economic payback analysis that considers the capital and maintenance of the luminaires, glazing and other daylighting features are therefore required, and the findings will be epoch-making for development of more cost-effective green buildings with guaranteed visual comfort in the future.

4. Conclusion

The applicability of natural daylight as the main source for illumination during office hours was evaluated, as this was essential for energy savings and comfort improvement purposes. To achieve the objectives of this study, the luminance and illuminance values were systematically measured together with the subjective assessment of occupant visual comfort in a Malaysian green building. The key conclusions that are drawn from the findings are as follows:

(i) Excessive daylight that led to over-illumination was found at several locations within the studied office area, which showed that natural sunlight alone was sufficient to provide the required brightness level for most of the occupants with good control strategies. From the calculated DGI values, it was predicted that the window luminances were high enough to cause daylight discomfort glare if curtain blinds were not used during working hours, as most workers at four out of five floors of the building were predicted to have “intolerable” perceived glare degree.

(ii) In most cases, the measured work surface light level was higher than the recommended visual comfort range stipulated in the local building guideline, which was rather consistent with the luminous intensity. The mean illuminances measured at the office tables were generally within 300–500 lux, which suggested an opportunity for lighting energy savings. As this study only concentrated on the workstations, the light level at the common areas and senior management offices was not measured.

(iii) A significant variation of illuminances between different floors of the building diagnosed was identified in the statistical analysis, mainly due to the different window to floor area ratios, availability of interior shading and the locations selected for measurements. The light level at the atrium area of the lower floors was found to be slightly higher than the middle ones because of the daylight deflection by the reflector panels, which proposed the need for a more evenly distributed daylight at this part of building.

(iv) Although it was predicted that the occupants might find their workstations extremely bright, a discrepancy of survey outcomes was found, as about 73% of the participants opined that the office’s brightness was acceptable. A possible explanation for this was that some of the occupants were able to modify the brightness level at their workstations by adjusting the height of the nearest curtain. Hence the relatively short exposure to high luminance when this study was conducted was deemed to be bearable. A comparison of the luminous acceptability and sensation scales showed that almost all respondents who voted within the three central categories of the sensation scale found that the illuminance levels in the office sufficient to provide visual comfort. In spite of this, a certain extent of “light pollution” was reported by 9.5% of the occupants who experienced discomfort glare, possibly owing to their adaptation level and personal preferences.

(v) Using the field survey data, the energy cost analysis showed that about 50% of the lighting energy can be reduced if artificial lighting was not used during peak working hours. An estimated annual savings of USD 2,236.43 could be obtained if only daylight was applied. Other savings prospects included delamping/relamping especially at the over-illuminated areas and use of more energy-efficient light fittings at locations where sunlight is limited. The findings also underscore the need for further investigations into complete cost-savings analysis of the application of newer and more efficient lighting technologies and glazing materials, which considers the overall maintenance and replacement costs for the purpose of developing green buildings that are more energy efficient, comfortable and better-performing in the future.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Qi Jie Kwong: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Validation, Project administration, Funding acquisition.

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