The impact of interior design on visual discomfort reduction: a field study integrating lighting environments with POE survey

Zhe Kong[a*], D. Michael Utzinger[a], Kara Freihoefer[b], Troy Steege[b]

[a]School of Architecture and Urban Planning, the University of Wisconsin Milwaukee, WI 53201, USA

[b]HGA Architects and Engineers, 333 East Erie Street, Milwaukee, WI, 53202

Abstract

This paper presents a POE study integrated with physical lighting quantities in an open-plan office. The southwest-facing office has external overhangs and internal mechoshades as the solar controls. However, 65.9% of the participants in the office still complain about daylighting glare at their workstations. Aiming to improve indoor environmental quality, a renovated layout is constructed in a section of the office. The office results in two types of layouts, the original and renovated ones, in addition to three window heights. The research uses mixed methods to explore the environmental variations that influenced occupants' lighting experience and investigate the effectiveness of the renovated layout in terms of glare reduction. HDR image techniques are utilized for field measurements and calibration of a simulation model. The questionnaire generated based on the interviews with occupants is distributed to the office. The calibrated simulation model presents annual daylighting performance outside of data collection periods. The results show that taller windows, seating orientations towards windows, and adjacent to windows lead to more glare for

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occupants. Although replacing the original cubicle workstations with more open workstations allows more daylighting penetration and prolongs the annual glare duration in the renovated layout, more accessible outside views and flexible furniture designs increase occupants' tolerance of glare and satisfaction with daylighting environments. This research demonstrates the effectiveness of utilizing multiple methods to comprehensively assess daylighting qualities in open-plan offices. It also demonstrates the important role interior designs play in creating comfortable daylighting environments.

Key words: Visual discomfort, Daylighting simulation, High Dynamic Range photography, Interior design and layout, Post Occupancy Evaluation

1. Introduction

1.1. Background

Taking good advantage of daylight in building designs can fulfil people's well-being needs and conserve building energy consumption. Substantial studies demonstrated the positive influence of daylight on people's task performance, comfort, and well-being [1]. Daylight satisfies people's biological needs and enhances their circadian rhythms [2]. Daylight also plays a key role in conserving building energy consumption. Artificial lights contribute to significant amount of carbon emissions, adding to global warming. Previous studies showed that the integration of artificial lighting controls with daylighting designs can potentially save energy between 7% and 60% [3-4]. Therefore, harvesting sufficient daylight in buildings can provide occupants with healthy environments and reduce energy consumption.

Designing a comfortable daylighting environment is a challenging task. To take advantage of daylight in buildings, architects need to comprehensively understand the dynamic characteristics of daylight. Daylighting design merges with building designs in varying scales, from site plan to building form and orientation, from window configuration to furniture arrangement. Although a substantial number of studies investigated building parameters and their impact on daylighting performance, limited research explores daylighting performance from the perspective of interior design and layout. Concerning daylighting design strategies, architects tend to focus on the influence of various building parameters but interior design and layout. For example, Littlefair published a book of design guide of site layout to achieve good sunlight and daylight [5]. Bakers and Steemers introduced daylighting designs from site and building form to room design and advanced daylighting elements. However, the daylighting design strategies related to interior designs concentrated on reflectance of interior surfaces and glazing transmission [6]. Researchers are interested in daylighting performance affected by façade designs and shading devices [7]. The International Energy Agency Solar Heating and Cooling program, for example, comprehensively documented the lighting performance and energy savings of twelve daylighting systems [8]. Given that the effects of interior design and layout on daylighting performance are seldom studied, this paper takes an open-plan office as an example to fill this gap.

1.2. Research methods

An open-plan office is the most commonly designed office prototype that over 70% of office workers occupy [9]. Many previous studies correlated physical environmental measurements with occupant satisfaction. One important consensus derived from these studies is that lighting environments play an important role in occupant satisfaction and overall indoor environmental quality [10-13]. Many researchers combined physical measurements and POE survey as the dominant method. Moreover, illuminance values on horizontal or vertical working planes were recorded to represent indoor lighting quality [10-13]. With the development and availability of High Dynamic Range (HDR) image techniques [14], however, researchers have a more effective tool to capture large quantities of luminance values.

The combination of HDR image techniques and POE survey has been widely utilized in evaluating indoor lighting qualities. Combining HDR image techniques and POE survey, Konis comprehensively assessed the outcomes of the retrofitted elevation of an open-plan office building in terms of daylighting quality [15]. Hirning et al. carried out a series of studies that correlated the results of POE studies with luminance maps in open-plan offices to generate a new glare index, Unified Glare Probability (UPG) [16-17]. Jin et al. utilized both HDR image techniques and POE survey to explore occupants' comfortable lighting levels in shopping malls [18]. Although these studies proved the effectiveness of this combined method of assessing indoor daylighting quality, they all limited the lighting data within the periods of data collection. To explore the lighting performance out of data collection periods, this study encompasses simulations in addition to the combination of HDR image techniques and POE study.

Unlike HDR image techniques that record luminance distributions within existing building spaces, simulations are an effective tool to predict lighting performance at design stage. Moreover, compared with field measurements, simulations can accurately replicate a real-world context and generate large quantities of data at low cost. With the aim of integrating field measurement and simulations, this research extends the replicable method of predicting visual discomfort [19].

This field study investigates the daylighting quality based on physical measurements and simulations, along with subjective interviews and questionnaires. The objectives of the paper include: 1) explore the interior environmental factors that affect occupants' visual comfort and lighting satisfaction; 2) comprehensively assess the effectiveness of the renovated layout in terms of visual discomfort reduction; 3) correlate simulated luminance maps with field measurements in terms of visual discomfort prediction; 4) confirm visual discomfort analysis of physical lighting data with subjective assessments; 5) propose effective strategies of visual discomfort reduction from the interior design perspective.

2. Methods

2.1. Office characteristics

2.1.1. Office overview

This research was conducted in Hammel Green & Abrahamson (HGA) Inc. (43.0 N, 87.9 W), which is in downtown Milwaukee, Wisconsin (Fig. 1 & Fig. 2). The building is a five-floor mixed-function building with the HGA Milwaukee office on the first floor and residential space on the remaining four floors. The office measures 95.5m along the southwest axis by 32.2m along the northeast axis. The entire office has the same ceiling height. Following the site slope, the office was designed in four tiers, with a 0.76m height differential between each tier. Fig. 3 shows the layout of the office and the four tiers. As the building's southwest elevation faces the Milwaukee River, the architects designed large windows to provide outside views and daylight for occupants. There are three window heights in the office. Tier One had the greatest window height (3.6m), Tiers Two and Three had a lower window height (3.2m), and Tier Four had the lowest window height (2.8m).

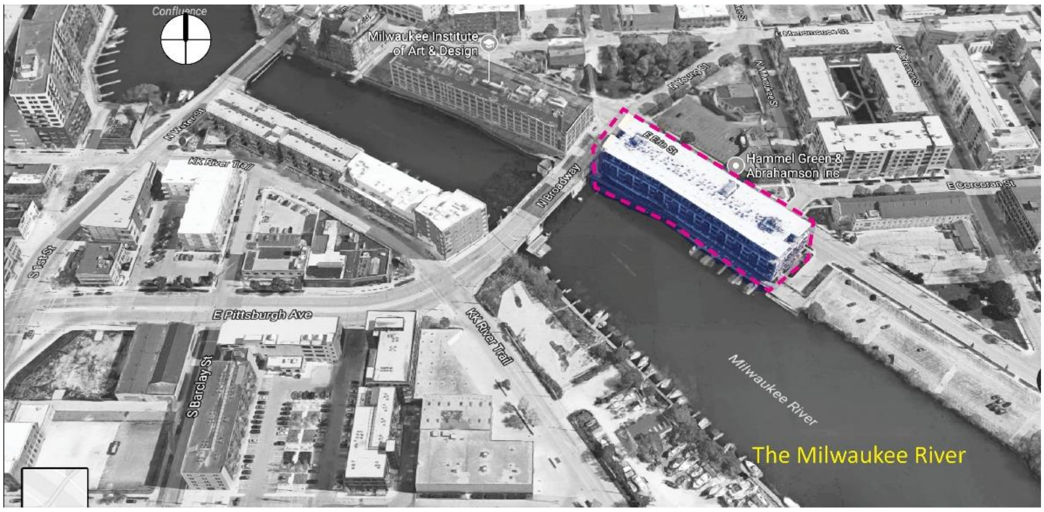

Fig. 1. Bird view of HGA.

Fig. 2. Exterior view of HGA.

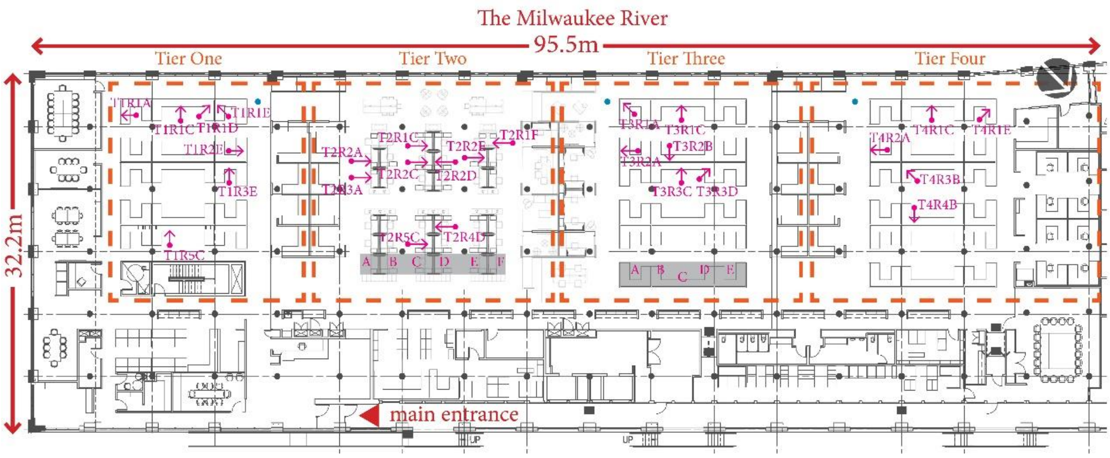

Fig.3. HGA's layout.

The office has both external and internal solar controls. The balconies on the second floor and the overhangs between the balconies block the sunlight at high angles (Fig. 4). The interior mechoshade systems are automatically controlled by both the outdoor solar radiometers on the roof and the indoor photometric sensors on the floor. Even though the office has both static external and movable internal shading systems, the occupants reported their visual discomfort experience. Staff members' way of occupying the office indicated their dissatisfaction with daylighting environments. The occupants sitting adjacent to the southwest windows put up foam core boards along the cubicles to protect them and their monitors from direct sunlight (Fig. 5). Some staff members complaint that they sometimes had to wear sunglasses on sunny days while working.

Fig. 4. External overhangs.

2.1.2. Office renovation

Aiming to improve staff members' satisfaction with their working environments and solve visual discomfort, HGA started an office renovation project in 2016. When the study was carried out, the office had two layout designs, the original layout in Tier One, Tier Three, and Tier Four, along with the renovated layout in Tier Two. The original layout was comprised of 2.1 x 2.8m cubicles. Each cubicle had one or two sides enclosed by 1.3m opaque partitions and another side enclosed by a 1.7m opaque partition. All the cubicles were arranged along the southwest façade, which led to eight seating orientations. On the other hand, the renovated layout in Tier Two consisted of 1.5 x 1.8m new workstations. Each workstation had one opaque partition reaching 1.3m to block the opposite staff member's sight. All the workstations were perpendicular to the southwest windows, which led all seating orientations parallel to the windows. The workstations in Tier Two were set 2.3m further from the windows.

2.2. Data acquisition

This study employed multiple methods to comprehensively evaluate the office environmental variations' impact on occupants' daylighting experience. Interviews and questionnaires were used to collect occupants' assessments of daylighting environments. HDR image techniques were used to record daylighting distributions in the office and calibrate a simulation model. Simulations were utilized to provide annual daylighting performance and extend the data outside data collection periods.

2.2.1. Questionnaire survey

First, 23 employees were interviewed to discover the main daylighting issues in the office. The responses were analysed to summarize the common issues regarding daylighting quality and shading systems. The categorized themes were designed into each question with detailed information as the options. Second, a pilot study was conducted by distributing the questionnaire to 30 participants. Based on these 30 participants' responses and comments, the questionnaire was modified to effectively reveal the issues relative to interior daylighting quality.

This paper selected seven questions from the questionnaire. These questions included seven-point Likert scale questions concerning occupant satisfaction levels with lighting environments, along with degrees of visual discomfort based on occurring periods and causes. The degrees of visual discomfort followed Osterhaus and Bailey's system of rating discomfort glare on the bright aspect [20]. This study also included the multiple-choice questions that asked seasons and sky conditions when visual discomfort frequently occurred. All the select questions are listed in the Appendix.

2.2.2. Field measurement of lighting distributions

This research recorded interior daylighting distributions via HDR image techniques. HDR image technique combine multiple Low Dynamic Range (LDR) images into one HDR image that presents accurate luminance distributions of a scene with an average error of 5.8% for outdoor environments and 10.1% for daylit interior scenes [14]. In this study, the LDR images were taken by a Canon EOS 6D with a SIGMA EXDG f/3.5 fisheye lens. The camera's settings followed Mehlika's study [21]. While LDR images were taken, the luminance values on a grey card that was placed at the centre of each scene were recorded by a Gossen Starlite 2 for image calibration. Interior HDR images were taken in four sunny afternoons: March 20th, May 7th, May 27th, and July 29th, 2017. Fig. 3 illustrates the workstations where the HDR images were taken from occupants' perspectives. Each workstation was numbered by a combination of its tier number, row number, and alphabetical seating number. The grey bars in Fig.3 show the alphabetical seating numbers. For instance, T1R3A represents the first workstation from the left in Tier One and Row Three. LDR images were assembled in hdrgen, and then proceeded the vignetting correction and luminance calibration to guarantee the luminance accuracy [14].

2.2.3. Simulation

The office model was built in Rhino [22] based on the blueprints and onsite measurements. Then the model was exported to DIVA-for-Rhino for lighting simulations. The material properties of the office were measured onsite (Fig. 5). When the interior HDR images were taken, a weather station was placed on the roof of the office to record solar irradiance. For calibrating the simulation model, the Perez all-weather sky model was generated by entering the measured solar irradiance into gendaylit. The annual DGP was calculated in DIVA with Milwaukee Typical Meteorological Year (TMY3) file [23] to reflect visual discomfort from a long-term perspective. In annual DGP simulations, when sunlight penetration was perceived by the indoor sensors on the floor (the blue dots near the windows in Fig. 3, the mechoshade was dropped to the pre-set positions. According to the settings in the reality, the percent of windows covered by the mechoshade in Tier One, Tiers Two and Three, and Tier Four were 80%, 87.5%, and 77.5%, respectively.

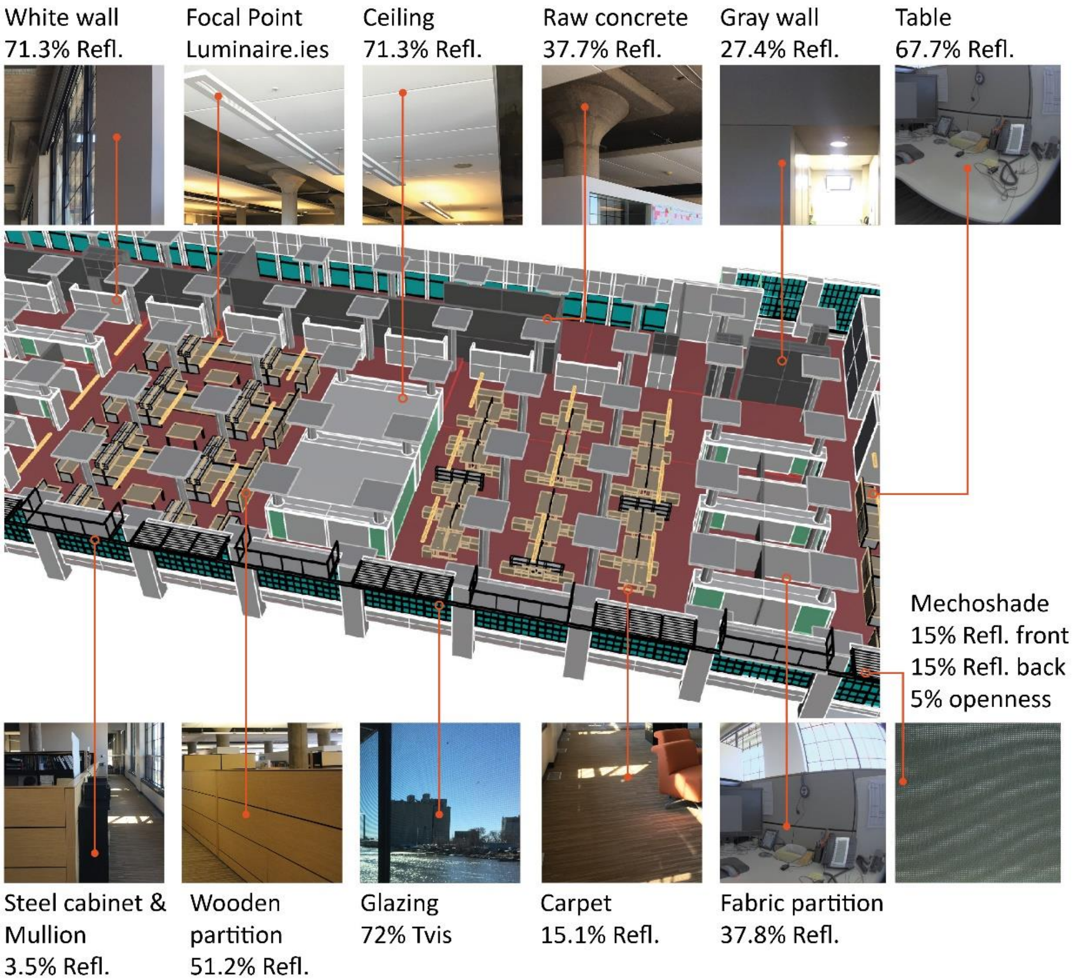

Fig. 5. Material properties at HGA.

2.3. Data analysis

2.3.1. Analysis of questionnaire responses

All valid responses were coded and exported to SPSS 23 for data analysis. The satisfaction items were rated on a seven-point Likert-type scale (1=very satisfied to 7=very dissatisfied). The degrees of visual discomfort were also rated on a seven-point Likert-type scale of the bright aspect [20] (4=comfortable, 5=perceptible, 6=disturbing, and 7=intolerable). The environmental variations that were expected to have impacts on occupants' lighting experience were defined as tier (Fig. 3), zone (As shown in Fig.7, the workstations were grouped based on the distance between workstations and the façade), and seating orientation (Fig. 8). Table 1 lists the number of participants grouped by each environmental variation. The Kruskal-Wallis Test [18] was used to reveal participants' different attitudes toward lighting quality among two or more groups. Based on the Kruskal-Wallis Test results, the Dunn-Bonferroni post hoc was utilized to identify statistically significant differences between a pair of groups.

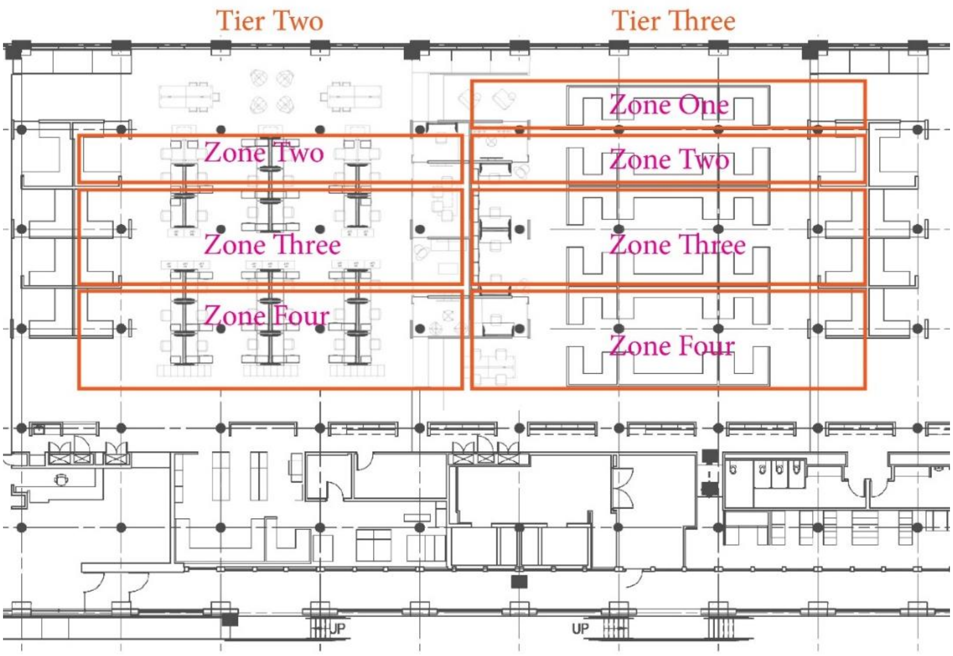

Fig. 7. Environmental variation of zone.

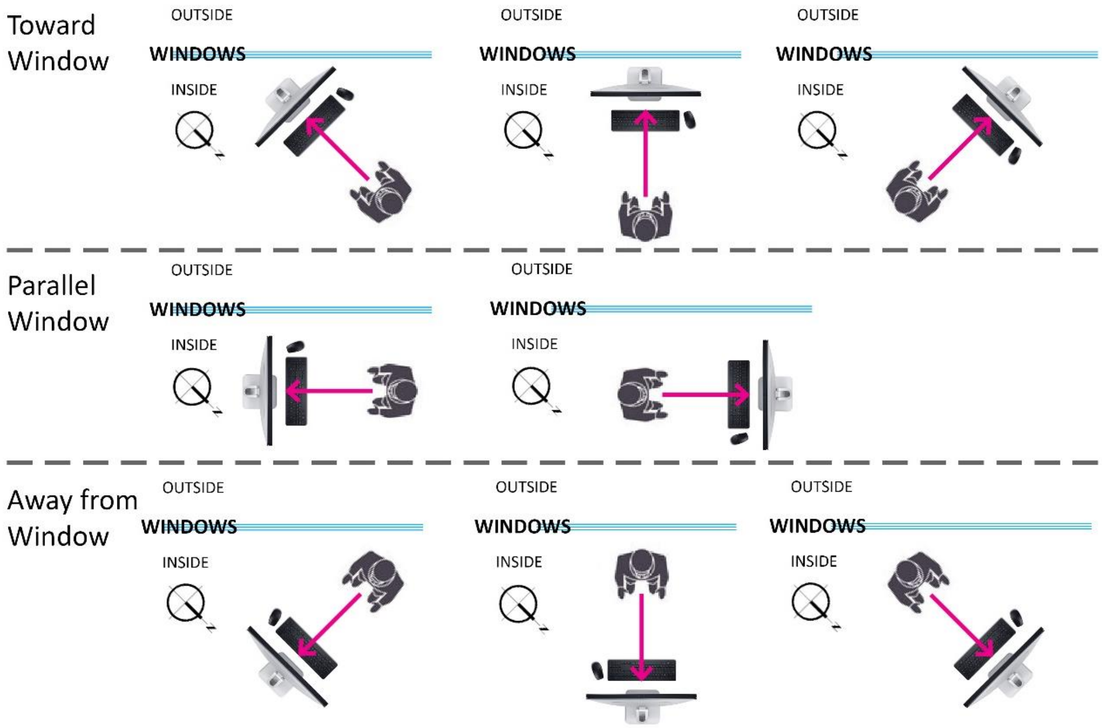

Fig. 8. Environmental variation of seating orientations.

Table 1

Participants count grouped by the environmental variations.

Environmental variation		Frequency of occupants	Environmental variation		Frequency of occupants	Environmental variation Environmental variation		Frequency of occupants
Tier	Tier One	24	Zone	Zone One	12	Seating orientation	Toward windows	28
	Tier Two	23		Zone Two	12		Parallel windows	34
	Tier Three	17		Zone Three	33		Away from windows	26
	Tier Four	24		Zone Four	31			

2.3.2. Analysis of lighting data

First, the vertical eye illuminance (E_v) of all the HDR images taken onsite was calculated to check the occurrence of luminous overflow as illuminance values at the lens opening were not taken before and after taking the HDR images [24]. Ten out of 88 HDR images with E_v over 5,000 lux were excluded from the data analysis due to luminous overflow [24]. Seven of these excluded HDR images presented intolerable glare. Second, Daylight Glare Probability (DGP) [25] of all the HDR images and simulated luminance maps was calculated in evalglare [26]. This study employed DGP as the glare index since it outperformances other glare indices with its robust and consistent results under daylighting conditions when large regions of lighting source exist [27]. A DGP result includes two parts: a number and an image. The number reflects the percentage of people who are disturbed by glare in a given scene, while the image uses randomly chosen colours to highlight the regions of glare. A DGP result smaller than 0.35 indicates imperceptible glare; the results between 0.35 and 0.4 indicate perceptible glare; the results between 0.4 and 0.45 indicate disturbing glare; and the results greater than 0.45 indicate intolerable glare [26]. To identify glare sources, both predetermined absolute luminance threshold and scene-based mean luminance threshold were used. In this research, 2000 cd/m^2 was considered as the absolute luminance threshold [28], and five times of the mean luminance of a scene was regarded as the scene-based luminance threshold [29].

3. Results

3.1. Subjective assessments

3.1.1. Participants

The questionnaire was distributed to all 145 employees through the internal HGA email system. From the 106 responses, 88 were valid, which resulted in a 60.7% response rate. The characteristics of the 88 participants are in Table 2. Of the 88 participants, 57 were males (64.8%) and 31 were females (35.2%). Over 80% of the participants were between 20 and 49 years old. Seventy-seven participants (87.5%) had been working in the office more than one year, and 67 participants (76.1%) spent more than 30 hours in the office per week. The high percent of the participants who had stayed in the office over one year and their long weekly working duration indicate their comprehensive understandings of the lighting environments. Seventy-four participants (84.1%) spent 61% or more of their time working on computers per week, which demonstrates the important role that computer-based work plays in the office.

Table 2

Participants' general information.

	Measure	Frequency of occupants	Percent of total		Measure	Frequency of occupants	Percent of total
Gender	Male	57	64.8	Age	20-29	25	28.4
	Female	31	35.2		30-39	28	31.8
Weekly working hours at your workstation	Less than 20 hours	5	5.7		40-49	18	20.5
	20-30 hours	16	18.2		50-59	13	14.8
	30-40 hours	50	56.8		60-69	4	4.5
	Over 40 hours	17	19.3				
	Measure	Frequency of occupants	Per cent of total		Measure	Frequency of occupants	Per cent of total
Years of working in the office	Less than 1 year	11	12.5	Percent of using computer weekly	Less than 20%	2	2.3
	1-2 years	16	18.2		21-40%	1	1.1
	2-5 years	28	31.8		41-60%	11	12.5
	5-10 years	10	11.4		61-80%	20	22.7
	Over 10 years	23	26.1		Over 81%	54	61.4

3.1.2. Descriptive data

Table 3 shows the participants' rating of visual discomfort based on daily occurrence. Most participants (83.9%) indicated that they were comfortable with the lighting environment between 8 a.m. and 2 p.m. However, 34.4% of the participants experienced disturbing or greater visual discomfort between 2 p.m. and 4 p.m., and 33.3% of the participants experienced disturbing or greater visual discomfort between 4 p.m. and 6 p.m. After excluding the participants who reported no visual discomfort, the mean degree of visual discomfort between 2 p.m. and 4 p.m. was 5.17, and the mean between 4 p.m. and 6 p.m. was 5.01. Values greater than 5 demonstrate the occurrence of perceptible or greater visual discomfort. The larger the value, the more severe the degree of visual discomfort. The results indicated that visual discomfort often occurred in the afternoon.

Table 4 demonstrates the participants' ratings of visual discomfort based on three causes: direct sunlight on faces and/or eyes, sunlight on monitors, and high contrasts between monitors and backgrounds. Over forty percent of the participants experienced direct sunlight on their faces and/or eyes and ranked this experience disturbing or greater. Nineteen-point-five percent of the participants considered direct sunlight on their monitors as disturbing or greater. Only 13.8% of the participants suffered from disturbing or intolerable degrees of high contrasts between their monitors and backgrounds. After excluding the participants who reported no visual discomfort, the mean degrees of direct sunlight on people's face and/or eyes, direct sunlight on monitors, and high contrasts were 5.45, 5.12, and 4.87, respectively. The results indicated that direct sunlight on people's faces and/or eyes was the most severe cause of visual discomfort in the office.

Table 3

Participants ratings of daily visual discomfort.

	Comfortable (+4)	Perceptible (+5)	Disturbing (+6)	Intolerable (+7)	NA (0)	Mean (exclude NA)	SD (exclude NA)

8 a.m. - 10 a.m.	83.9%	3.4%	0.0%	1.1%	11.5%	4.08	0.39
10 a.m. - 12 p.m.	77.0%	11.5%	0.0%	0.0%	11.5%	4.13	0.34
12 p.m. - 2 p.m.	64.4%	19.5%	4.6%	0.0%	11.5%	4.32	0.57
2 p.m. - 4 p.m.	27.6%	27.6%	26.4%	8.0%	10.3%	5.17	0.97
4 p.m. - 6 p.m.	39.1%	18.4%	26.4%	6.9%	9.2%	5.01	1.02
After 6 p.m.	57.1%	10.7%	3.6%	2.4%	26.2%	4.34	0.72

Table 4

Participants ratings of three causes of visual discomfort.

	Comfortable (+4)	Perceptible (+5)	Disturbing (+6)	Intolerable (+7)	NA (0)	Mean (exclude NA)	SD (exclude NA)
Direct sunlight on faces and/or eyes	19.3%	10.2%	30.7%	10.2%	29.5%	5.45	1.05
Direct sunlight on monitor	17.2%	20.7%	14.9%	4.6%	42.5%	5.12	0.94
High contrast	29.9%	25.3%	6.9%	6.9%	31.0%	4.87	0.96

Furthermore, 78% of the participants selected clear/sunny skies as the sky condition when visual discomfort occurred most frequently. Sixty-one percent of the participants selected winter as the season when visual discomfort occurred most frequently.

3.1.3. Environmental variations

This section reports the results of Kruskal-Wallis Test that revealed different attitudes towards lighting environments with respect to the three environmental variations, tiers, zones, and seating orientations.

Tier variance

As shown in Table 5, three subjective attributes had statistically significant differences among the four tiers: participant satisfaction levels with natural light (H(3)=12.17, p=0.007), degrees of direct sunlight on people's faces and/or eyes (H(3)=9.48, p=0.024), and degrees of visual discomfort between 2 p.m. and 4 p.m. (H(3)=11.50, p=0.009). Fig. 9 shows the results of the pairwise tests. There was a statistically significant difference between Tier One and Tier Four (Test Statistic=-21.81, Adj. Sig.=.012), along with a statistically significant difference between Tier Two and Tier Four (Test Statistic=-19.31, Adj. Sig.=.041). Tier One and Tier Four had statistically significant difference (Test Statistic=21.51, Adj. Sig.=.012) in terms of degrees of visual discomfort between 2 p.m. and 4 p.m. Additionally, the results of the pairwise test displayed the greater degree of direct sunlight in Tier One than in Tier Four (Test Statistic=20.02, Adj. Sig.=.027). Compared with the participants in Tier Four, the participants in Tier One with the tallest windows were more satisfied with their natural lighting environments. However, the participants in Tier One also suffered greater degrees of direct sunlight on them, especially between 2 p.m. and 4 p.m.

Table 5

Kruskal-Wallis results among four tier groups.

Tier	Satisfaction with natural light			Direct sunlight on people's faces/eyes			Degree of visual discomfort between 2 p.m. and 4 p.m.		
	Mean rank	Chi-square	Sig.	Mean rank	Chi-square	Sig.	Mean rank	Chi-square	Sig.
One	36.1	12.17	.007*	52.0	9.48	.024*	54.1	11.50	.009*
Two	33.6			47.9			46.6		
Three	47.5			40.1			35.8		
Four	53.4			32.0			32.6		

Note: *p<0.05; **p<0.01; ***p<0.001.

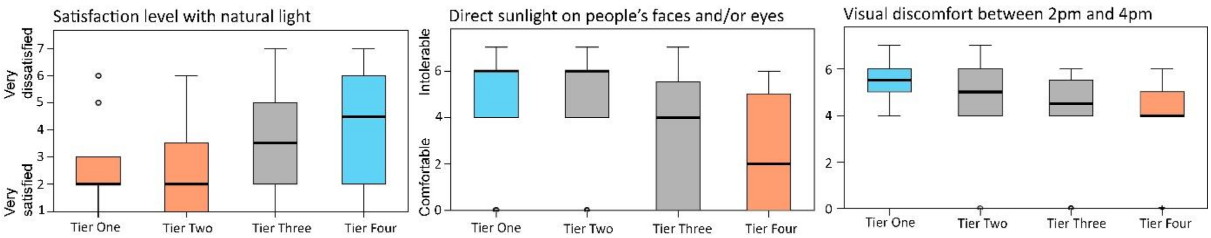

Fig.9. Pairwise tests of satisfaction levels with natural light (left), degree of direct sunlight on people's face and/or eyes (middle), and visual discomfort between 2 p.m. and 4 p.m. (right) among four tiers.

Zone variance

Table 6 illustrates that all three causes of visual discomfort, direct sunlight on people's faces and/or eyes (H(3)=9.30, *p*=0.026), sunlight on monitors (H(3)=14.93, *p*=0.002), and high contrasts (H(3)=8.30, *p*=0.04), had statistically significant differences among the four zones. Fig. 10 presents the results of the pairwise test of the three causes. Compared with Zone Three (Test Statistic=24.33, *p*=.019) and Zone Four (Test Statistic=21.86, *p*=.044), the participants in Zone One experienced more severe direct sunlight on their faces and/or eyes. Likewise, Zone One presented higher contrasts than Zone Three (Test Statistic=22.32, *p*=.032). The participants in Zone Two experienced more direct sunlight on their monitors than the participants in Zone Four (Test Statistic=27.92, *p*=.003).

Table 6

Kruskal-Wallis results among four zone groups.

Zone	Direct sunlight on people's faces/eyes			Sunlight on monitors			High contrast		
	Mean rank	Chi-square	Sig.	Mean rank	Chi-square	Sig.	Mean rank	Chi-square	Sig.
One	61.4	9.30	.026*	52.0	14.93	.002*	59.6	8.30	.040*
Two	43.0			58.8			37.8		
Three	39.5			41.3			37.3		
Four	37.0			30.9			40.6		

Note: *p<0.05; **p<0.01; ***p<0.001.

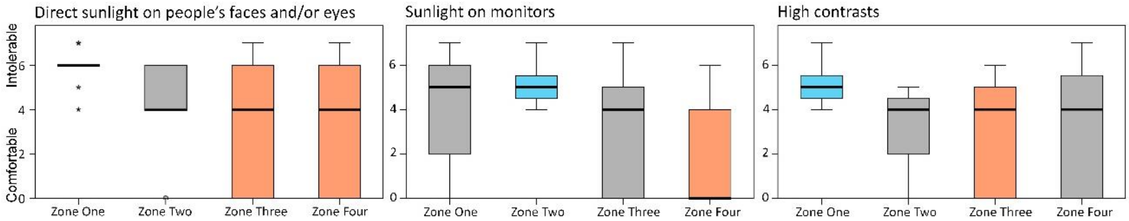

Fig.10. Pairwise tests of direct sunlight on people's face and/or eyes (left), high contrast (middle), and direct sunlight on monitors (right) among four zones.

Seating orientation variance

The results of the Kruskal-Wallis test demonstrated that the degrees of visual discomfort between 2 p.m. and 4 p.m. (H(2)=10.33, *p*=0.006) and direct sunlight on people's faces and/or eyes (H(2)=11.10, *p*=0.004) had statistically significant differences among three seating orientation groups (Table 7). As presented in Fig. 11, compared with the participants facing away from the windows, the participants facing towards the windows suffered from greater visual discomfort between 2 p.m. and 4 p.m. (Test Statistic=20.74, *p*=.005) and direct sunlight on their faces and/or eyes (Test Statistic=22.01, *p*=.003).

Table 7

Kruskal-Wallis results among three groups of seating orientation.

Seating orientation	Degree of visual discomfort between 2 p.m. and 4 p.m.			Direct sunlight on people's faces/eyes		
	Mean rank	Chi-square	Sig.	Mean rank	Chi-square	Sig.
One	51.7	10.33	.006*	51.3	11.10	.004*
Two	38.7			40.0		
Three	30.9			29.3		

Note: *p<0.05; **p<0.01; ***p<0.001.

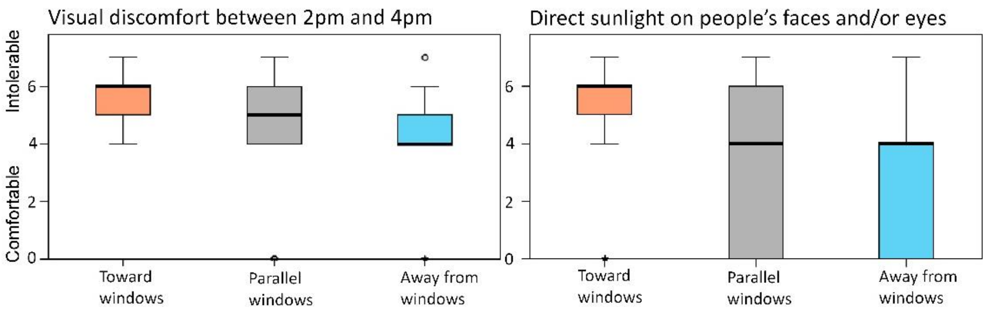

Fig.11. Pairwise tests of degrees of visual discomfort between 2 p.m. and 4 p.m. (left) and direct sunlight on peoples' faces and/or eyes (right) among three seating orientation groups.

3.2. Objective lighting environments

3.2.1. HDR image analysis

Fig. 12 shows the HDR images, falsecolor images, and DGP results of twelve scenes, three scenes from each tier. The left column contains the LDR images of the twelve scenes converted from the HDR images. The second from left column lists the falsecolor images that demonstrate luminance variance according to the legends. The third and fourth columns display the results of the DGP analysis. The falsecolor images showed that the great luminance values of each scene concentrated on the window areas. Even though the windows in Tier Three were 0.4m taller than the ones in Tier Four, it is difficult to visually discern different luminance values by comparing T3RIC with T4R1C, both of which were in Zone One. However, the zone and seating orientation variations had greater impact on the luminance variations. For instance, compared with T1R3E, T1R5B presented much lower luminance distributions since it was two-cubicle further away from the façade. All the scenes facing the windows, like T3R1C and T4R1C, presented greater luminance distributions. As all the workstations in Tier Two were perpendicular to the windows, all the HDR images taken in Tier Two presented lower luminance distributions. Based on the DGP results listed in Table 3, the scenes directly facing the windows all had disturbing or intolerable glare. The only exception was T1R5B, which was located at the rear of the office with a small portion of accessible glazing. All the scenes in Tier Two had DGP values lower than 0.35, meaning no glare was detected in Tier Two.

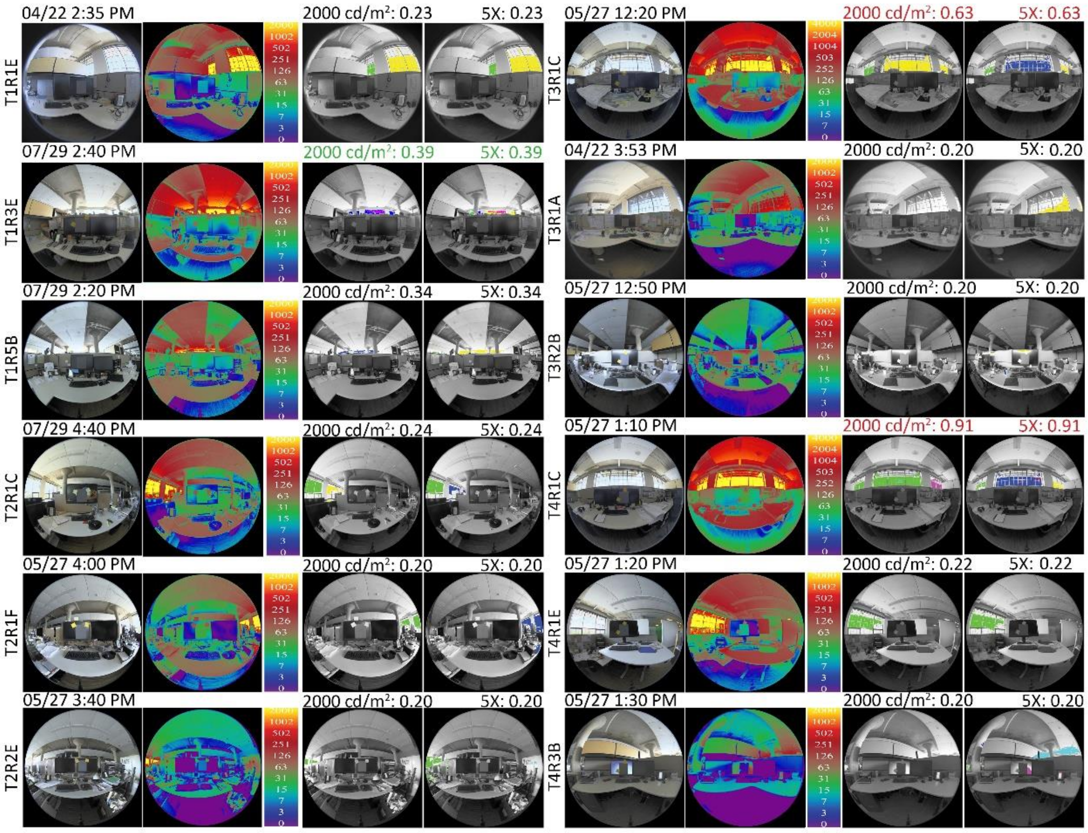

Fig. 12. The HDR images, falsecolor images, and the DGP analysis of twelve scenes (Please refer to the web version of this article for the colorful figure).

Table 8

The DGP results for all the scenes.

Scene No.	DGP_{2000}	DGP_{5X}	Scene No.	DGP_{2000}	DGP_{5X}	Scene No.	DGP_{2000}	DGP_{5X}
T1R1E	0.23	0.23	T2R2E	0.20	0.20	T3R1A	0.19	0.19
T1R1C	1.00	1.00	T2R4D	0.22	0.22	T3R2B	0.21	0.20
T1R1D	0.24	0.24	T2R5C	0.18	0.18	T3R3C	0.63	0.63
T1R1A	0.20	0.19	T2R2D	0.19	0.19	T3R3D	0.22	0.22
T1R2E	0.18	0.18	T2R1F	0.28	0.28	T4R1E	0.91	0.91
T1R3E	0.39	0.39	T2R2A	0.21	0.21	T4R2A	0.20	0.20
T1R5B	0.34	0.34	T2R3A	0.20	0.20	T4R1E	0.22	0.22
T2R1C	0.24	0.24	T3R1C	0.63	0.63	T4R3B	0.18	0.19
T2R2C	0.21	0.21	T3R2A	0.24	0.23	T4R4B	0.20	0.21

3.2.2. Model calibration

Fig. 13 shows the falsecolor images of the HDR images and simulations at eight workstations, two from each tier. The falsecolor images in all four tiers demonstrate comparable luminance distributions between the HDR images and simulated luminance maps. Comparing with the 78 valid HDR images taken on site, the simulated luminance maps presented 92% of accurate glare prediction. This result also agrees with Jones and Reinhart's conclusion [30]. The results indicate that the model can accurately represent the real lighting environments in terms of visual discomfort prediction. Hence, representative workstations were selected to present their annual visual discomfort profiles.

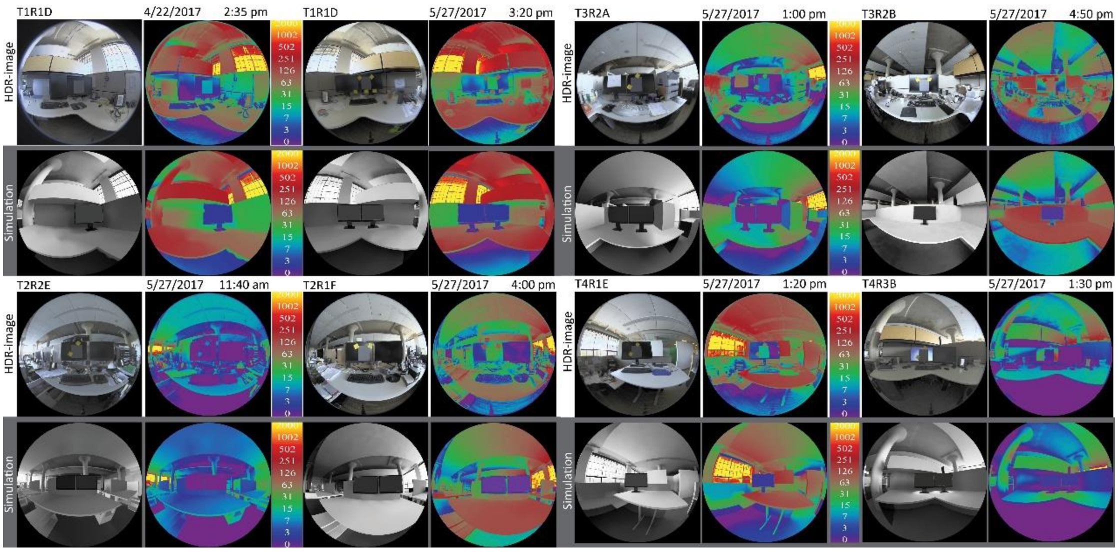

Fig. 13. Luminance comparison between HDR images and the simulated luminance maps (Please refer to the web version of this article for the colorful figure).

3.2.3. Annul DGP simulations

Fourteen workstations were selected to present long-term visual discomfort. Fig. 14 shows the annual DGP profiles at three of the select workstations. The horizontal axis represents 365 days per year, while the vertical axis represents daytime from 8 a.m. to 6 p.m. The red, orange, and yellow represent intolerable, disturbing, and perceptible glare, respectively. The green indicates imperceptible glare. The three workstations, T1R1C, T3R1C, and T4R1C, all faced towards the southwest façade with the same distance away from the façade. The DGP profiles demonstrated that visual discomfort occurred more frequently during the winter, especially in the afternoon after 2 p.m., which confirmed the conclusion of the questionnaire. Due to the tallest windows in Tier One, T1R1C had the longest duration of annual glare. As shown in Table 9, the annual disturbing and intolerable glare at T1R1C, T3R1C, and T4R1C lasted 315 hours, 246 hours, and 221 hours, respectively. The comparison of the annual DGP profiles at the three workstations demonstrated that the tallest windows in Tier One resulted in the longest annual glare duration.

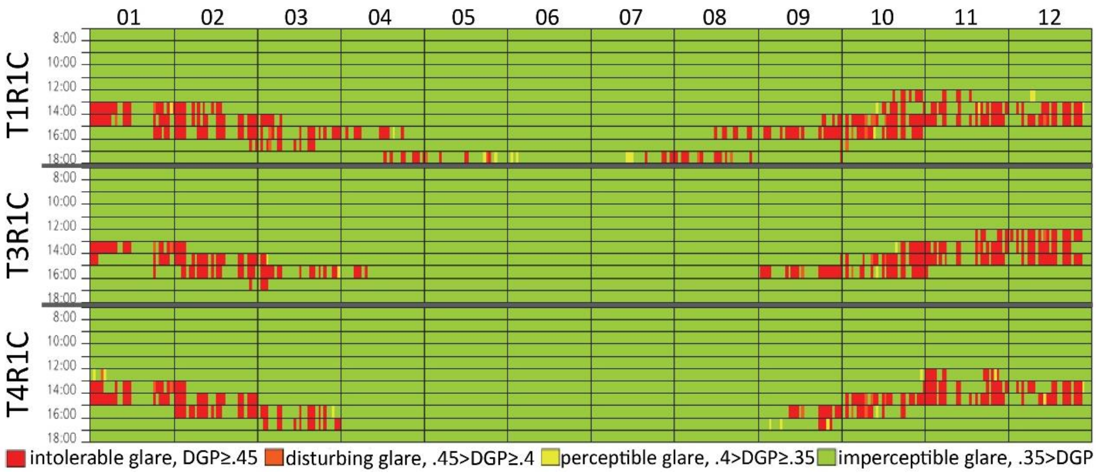

Fig. 14. The variation in window heights with respect to annual DGP profiles (Please refer to the web version of this article for the colorful figure).

Fig. 15 displays the annual DGP profiles at T3R2A, T2R1A, and T2R1F. All three workstations were the same distance from the façade, with the seating orientation parallel the windows, and in the Tiers with the same window height. However, the original cubicle workstations (T3R2A) had no glare, while the more open workstations (T2R1A and T2R1F) had 30 hours of glare per year. The results showed the increase of annual glare duration caused by the more open workstations in the renovated layout.

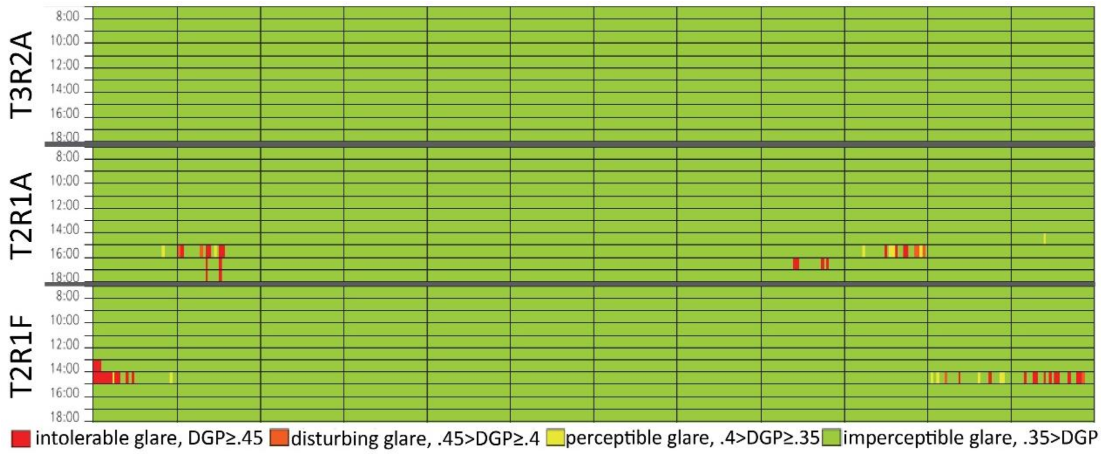

Fig. 15. The variation in workstation enclosure with respect to annual DGP profiles (Please refer to the web version of this article for the colorful figure).

Fig. 16 presents the annual DGP profiles at T1R1C, T1R3E, and T1R5C. All three workstations were in Tier One and directly faced the windows with varying distances away from the southwest windows. Compared with the 315 hours of disturbing and intolerable glare at T1R1C, T1R3E presented 84 hours of disturbing and intolerable glare, while T1R5C had no glare. The DGP results indicated that the more distant a workstation from the windows, the shorter annual glare duration at that workstation, which confirmed the conclusion of the zone variation from the questionnaire analysis.

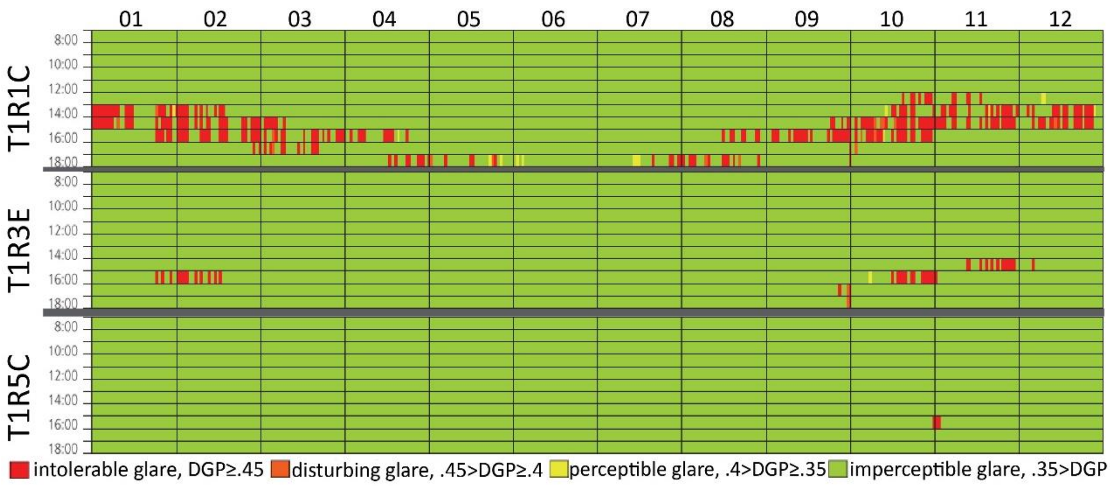

Fig. 16. The variation in distance between workstation and the windows with respect to annual DGP profiles (Please refer to the web version of this article for the colorful figure).

Fig. 17 demonstrates the annual DGP profiles at four workstations. Compared with T1R1C, T1R1E presented shorter annual glare duration due to the seating orientation. As shown in Table 9, T1R1E had 182 hours shorter annual glare duration. The same conclusion can be drawn from the comparison between T4R1C and T4R1E, one directly faced the windows while the other was at an oblique angle. The latter possessed 143 hours shorter annual glare than the former.

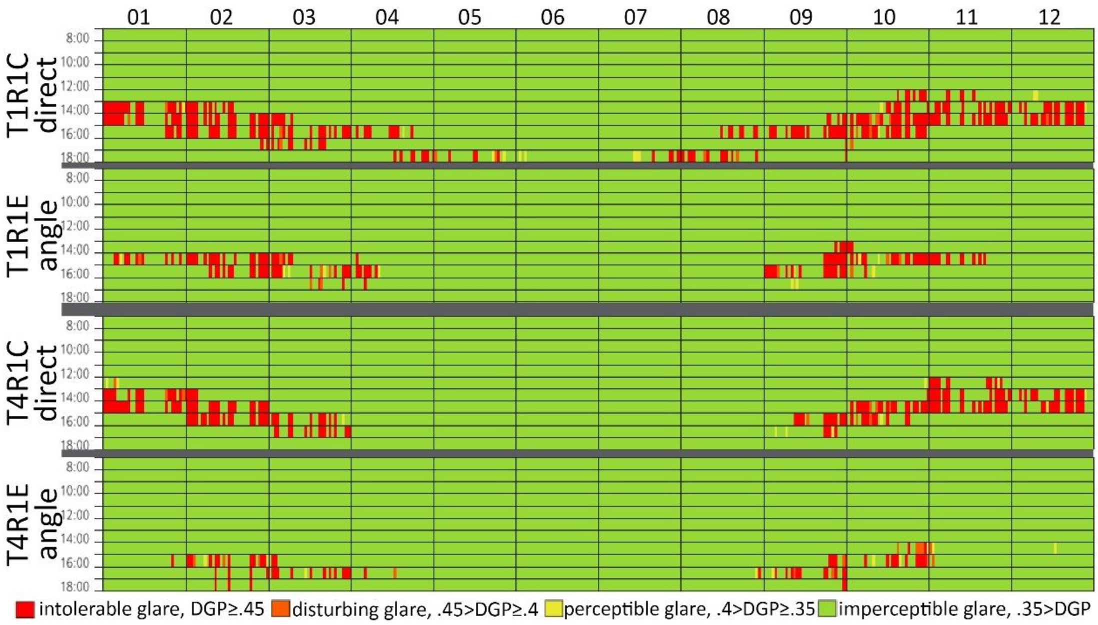

Fig. 17. Effect of seating orientation on the annual DGP profiles at four workstations (Please refer to the web version of this article for the colorful figure).

Table 9

Annual glare duration based on three degrees at 14 workstations.

Workstation	T1R1C	T1R1E	T1R3E	T1R5C	T2R1A	T2R1F	T2R4C
Intolerable	299	123	42	0	17	29	0
Disturbing	16	10	42	0	5	2	0
Perceptible	15	11	42	0	0	7	0
Workstation	T2R4D	T3R1C	T3R2A	T3R4E	T4R1C	T4R1E	T4R3E
Intolerable	0	238	0	0	212	61	0
Disturbing	0	8	0	0	9	17	0
Perceptible	0	4	0	0	12	10	0

4. Discussion

4.1. Daylighting quality in original layout

According to the analysis from both subjective and objective perspectives, the external and internal solar controls failed to provide comfortable lighting environments for most of the occupants in the office. Thirty-two-point nine percent of the participants were dissatisfied with daylighting environments. Sixty-five-point nine percent of the participants reported that they experienced visual discomfort caused by daylight. The descriptive responses to the questionnaire revealed that the main cause of visual discomfort was direct sunlight on people’s faces and/or eyes, which usually occurred on sunny days. Visual discomfort happened more frequently between 2 p.m. and 6 p.m., which can be explained by the office’s southwest orientation. Additionally, neither exterior overhangs or interior mechoshade systems successfully blocked direct sunlight during winter when the sun was low in the sky. “See the sun through the mechoshade fabric” was selected by 36.3% of the participants, which was the second most frequently voted problem of the mechoshade systems.

The results of the Kruskal-Wallis Test showed that Tier One, Zone One, and seating orientations toward the windows all presented high risk of visual discomfort. As shown in Fig.14, Tier One with the tallest windows (3.6m) led the occupants to longer periods of solar exposure. The tallest windows in Tier One resulted with the most severe visual discomfort between 2 p.m. and 4 p.m., as well as direct sunlight on people’s faces and/or eyes. Although tall windows are encouraged in design strategies for deeper sunlight penetration [6], architects need to provide controls for occupants to strike a balance between the amount of accessible daylight and visual discomfort.

Obviously, occupants who sat adjacent to windows or faced towards windows had a higher risk of experiencing visual discomfort. Although the original layout had a walkway functioning as a buffer zone between the southwest windows and the workstation areas, the spacing was insufficient for occupants to completely avoid direct sunlight. Another interesting finding revealed by the Zone variation was the high frequency of sunlight on the monitors in Zone Two. Given the fact that all occupants in Zone Two were either parallel or facing away from the windows, direct sunlight easily fell on the monitors rather than the occupants. Facing toward the windows also caused high contrasts between the bright windows and relatively dark monitors on cloudy days when the mechoshade systems were completely retracted.

4.2. Daylighting quality in renovated layout

The examination of objective lighting environments and occupant assessments between Tier Two and the remaining three tiers demonstrated that the renovation to Tier Two successfully improved its occupant satisfaction with their daylighting environments. The renovated design strategies were divided into two categories based on their influences on the interior daylighting environments, to reduce visual discomfort and to introduce positive impacts.

The design decisions that reduced occupants' visual discomfort included unifying workstations' seating orientations and enlarging the space between the windows and the working area. Compared with the original layout in the three tiers, all the workstations in Tier Two were arranged parallel to the windows. Therefore, all the monitors were perpendicular to the windows and the visual discomfort caused by facing towards the windows was solved. In other words, the solid angles between the glare source, the windows, and occupants' task views were effectively reduced. In addition to seating orientations, the whole working area was set half a bay, 2.3m further from the windows, which protected the occupants from most direct sunlight falling on them. Enlarging the spacing between the workstations and the windows resulted in an effective daylighting buffer zone in Tier Two. These two renovated design strategies reduced occupants' chances of experiencing visual discomfort and laid a foundation for the renovated layout.

Furthermore, the design decisions with positive impacts on lighting environments included the more open workstations and the flexible furniture. As shown in Fig. 15 in Section 3.2.3, T2R1A and T2R1F had 30 hours of glare in a year, while T3R2A had no glare. Considering that Tier Two replaced the original enclosed workstations with the more open workstations, it was reasonable to expect more daylight penetration and longer visual discomfort. However, the renovated layout also provided more easily accessible outside views for the occupants, which had greater impact on occupants' satisfaction. As shown in Fig. 18, the occupants in Tier Two were more satisfied with their natural lighting environments (mean satisfaction level = 2.61) than the occupants in Tier Three (mean satisfaction level = 3.56). As previous studies found that outside views containing interesting information, like the Milwaukee River and passing boats mentioned by the interviewees in Tier Two, can increase occupants' tolerance for visual discomfort [31, 32], this field study confirmed their conclusion.

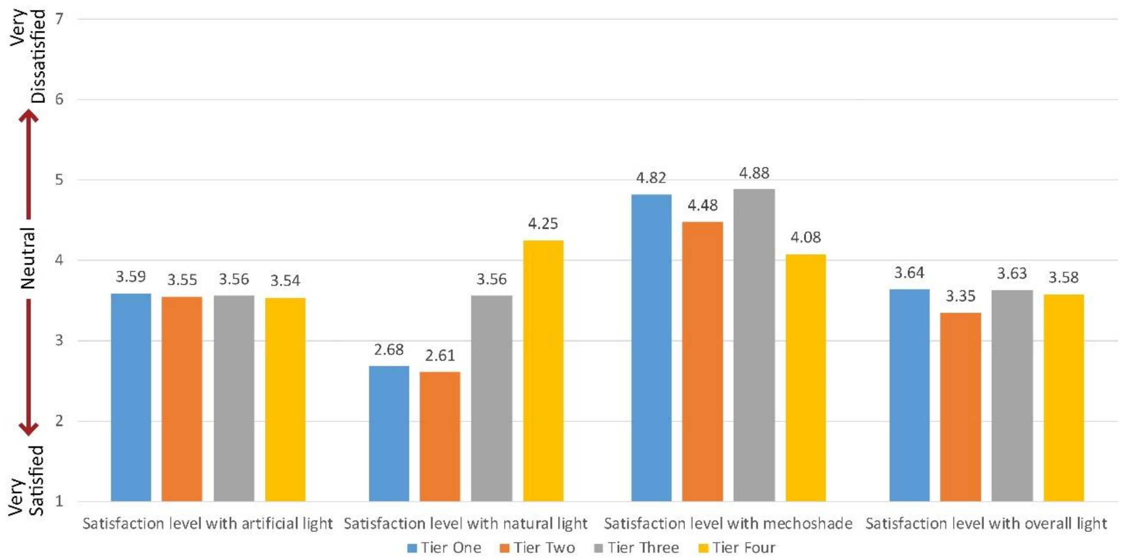

Fig. 18. Mean satisfaction levels of the four tiers.

Finally, the flexible furniture designs compensated for occupants' lack of control over their lighting environments. Although both the original and renovated workstations were adjustable in height, more occupants in Tier Two adjusted their desk heights than the occupants in the three original tiers. The responses to the questionnaire also showed that occupants in Tier Two adjusted themselves and/or their workstations more frequently to resume visual comfort. The flexible furniture encouraged occupants' coping behaviours [33] and increased their adaptation under the changing daylighting environments. This agrees with previous studies that easily reconfigurable office furniture has positive influence on occupant satisfaction with environments [34, 35].

5. Conclusions

This paper investigated the environmental variations in window heights and design layouts with regards to office's daylighting quality and occupant satisfaction. The study revealed that the environmental variations, including window heights, distances between workstations and windows, and seating orientations, had significant impacts on occupant satisfaction with daylighting environments. By introducing positive environmental factors, like interesting outside views and flexible furniture, occupants' intolerance for visual discomfort was increased. The success of renovated Tier Two in terms of visual discomfort reduction demonstrated the importance of integrating interior layout and furniture designs with building designs to achieve comfortable daylighting environments. This paper also showed the effectiveness of utilizing HDR image techniques as a tool to collect lighting data and calibrate simulation models. The calibrated models that can accurately predict visual discomfort provide future planning and design teams with more confidence to employ lighting simulations during the design stage.

Finally, this field study introduces two possible directions for future research. One is to simulate the overall lighting environments that involves mechoshades and artificial light from a long-term perspective. Relationships between occupants' assessments and lighting quantities can be explored. Another direction is to investigate occupants' coping behaviours and their impact on mitigating occupants' visual discomfort.

6. Recommendations

Based on the comprehensive evaluations of the daylighting qualities at HGA's open-plan office, the following recommendations are proposed. These recommendations stem from a public open-plan office where neither the controls of artificial light nor shading devices are available to most occupants.

- Avoid the cubicle designs that have two or more sides of opaque partitions. Consider lowering partition heights and incorporating translucent materials to allow more daylight penetration and more outdoor views for the majority of the occupants.
- Provide flexible furniture design like tables and chairs that are adjustable in height, and monitors that are easily to rotate.
- Avoid orienting occupants towards the glazing in high transmittance. Seating orientations parallel windows can strike a balance between visual discomfort and outdoor connection.
- Predict sunlight penetration during the design stage. Simulations of sunlight penetration with shading devices need to be conducted during the design stage to guarantee that occupants are protected from direct sunlight throughout the day.

- Consider the effectiveness of mechoshades in terms of blocking the solar disc within occupants' task views. Mechoshade systems in 5% openness factors cannot completely block the solar disc. Mechoshades in 2% and 3% openness factors are recommended.
- Consider placing buffer zones between windows and working areas. Ensure sufficient depth of a buffer zone that can avoid direct sunlight on occupants during the majority of their occupied hours. Buffer zones can be designed as circulations or public meeting spaces to increase occupants' connections with the outside.

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