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Lighting energy efficiency in offices under different control strategies

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ABSTRACT

Lighting represents a major part of building energy use. Therefore, energy savings in a lighting system can be very important for reducing building energy consumption. This article presents a study of the energy performance of various lighting systems and control strategies applied in open-plan offices. All of the experiments were carried out on a test bed. The energy saving potential of various lighting control strategies is simulated and analyzed, and a combined lighting control strategy of background dimming lighting plus task lighting is studied on the test bed. Moreover, visual comfort is investigated to determine the optimal background dimming lighting illumination and energy performance of the combined lighting system. Savings from general lighting control can reach 50% or higher. With task lighting control combined with dimmable general lighting, the energy savings rate can be increased to 59%.

1. Introduction

Lighting represents a major part of building energy use. It makes up about one-third [1] of commercial building electricity consumption in the US and consumes approximately 20–40% [2] of total electricity in large office buildings in China. Lighting control systems aim to both reduce the energy consumption and guarantee the visual comfort of occupants. Thus, a number of studies exist in the field of lighting energy efficiency using different control strategies.

Literature reviews of lighting control technologies and analyses of their performance in different types of buildings have been performed [3,4]. Roisin et al. tried to determine the energy saving potential of different lighting control systems in offices [5]. They concluded that dimming electric lights based on the outside lighting conditions could lead to savings of 45–61%, while an occupancy sensor can further increase savings. L.L. Fernandes et al. [6] monitored the actual performance of lighting systems in The New York Times Headquarters Building. They found that the savings from dimming control reached 20% relative to the prescriptive code. It is suggested that the monthly lighting energy savings in atrium corridors using dimming controls range from 14 to 65% [7].

Visual comfort plays a significant role in the quality of life of occupants in buildings. Lisa Heschong et al. [8] found that the presence of daylight promotes human performance and visual comfort. It has been proven that the productivity of office workers is directly influenced by the comfortable conditions indoors [9]. Thus, when applying a particular lighting control system, the visual comfort of occupants should be carefully considered.

This article is a study on the energy performance of various lighting systems and control strategies applied to open-plan offices. All of the experiments were carried out on a test bed located at Tongji University Main Campus, Shanghai, China. The test bed can realize various control strategies, including daylighting dimming control and on/off control by occupancy detection. The illuminance data and power were monitored, displayed and recorded automatically by an online data acquisition system. Online tests were conducted on various lighting control strategies for a period of time, and the energy usage was compared to that of a lighting system in a baseline office. The energy saving potential of various lighting control strategies was simulated and analyzed. Moreover, a combined lighting control strategy of background dimming lighting with task lighting was studied on the test bed. Occupant behavior and visual comfort were investigated to determine the optimal background dimming lighting illumination and energy performance of the combined lighting system.

The main research objectives are as follows:

Abbreviations: PLC, programmable logic controller; DF, daylight factor; DA, daylight autonomy; DA_{con}, continuous daylight autonomy; DA_{max}, maximum daylight autonomy; UDI, useful daylight illuminance; PLR, part load ratio; AHP, analytic hierarchy process; RI, random consistency index; CR, consistency ratio; MLE, maximum-likelihood estimation.

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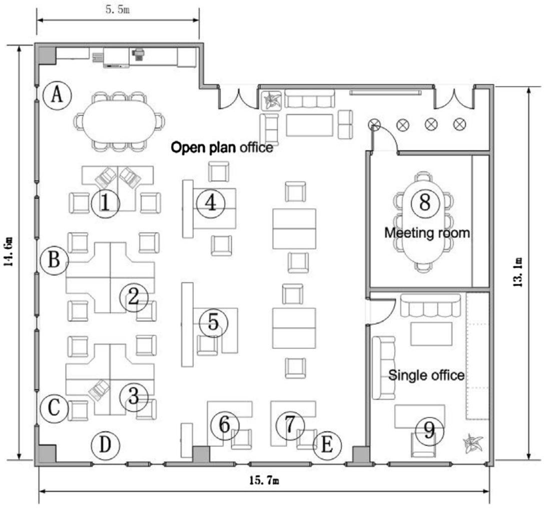

Fig. 1. Office plan and testing points (A–E; 1–9).

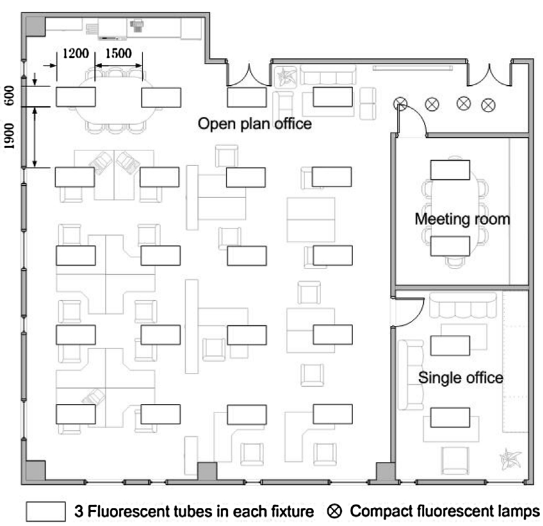

Fig. 2. Locations of lamps.

1. To determine the daylight utilization potential
2. To compare the energy efficiencies of different general lighting control strategies
3. To analyze the energy savings potential of task lighting combined with dimmable general lighting while guaranteeing the visual comfort of occupants

2. Test bed

The 15m × 15 m office where the test bed was installed is located on the west corner of the 8th floor (Room 801) of an office building at Tongji University, with both the southwest and northwest facade sunlit through windows. The office has 3 spaces: an open-plan office, a meeting room and a personal office. Its plan is shown in Fig. 1. In the open-plan office, lamps are suspended from the ceiling, while in the other two spaces, lamps are recessed. The location of each lamp is shown in Fig. 2. All of the lamps in the office can be switched on/off manually in groups. In order to realize a long-term, more than one year, monitoring and compare the energy savings of different strategies, we chose Room701 at the 7th floor which has the same layout, size and orientation as the test bed as the reference baseline office for comparison. Both Room701 and Room801 locate in the same place of a standard floor with an identical story height of 4 m which ensures their outdoor environment is identical. And the lighting system of Room701 is the same as that of Room801 before the test bed was built. Fig. 3 shows the exterior facade of the building where the test bed is located and Room 701 and Room 801 are plotted in the red circles.

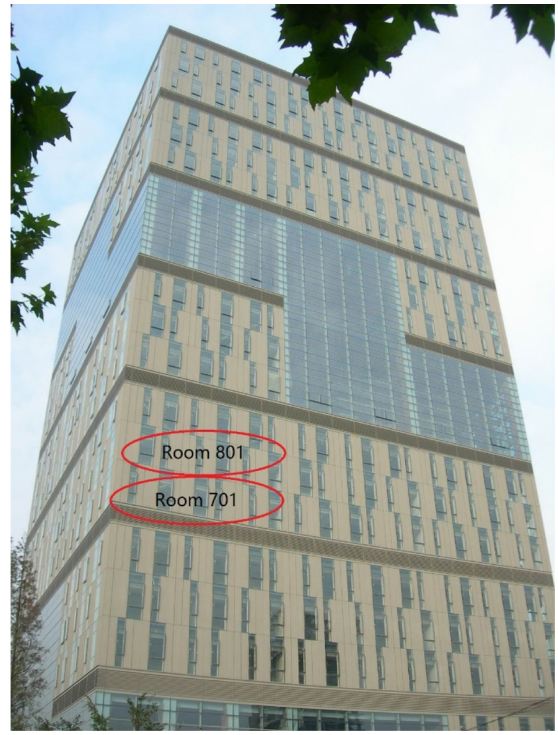

Fig. 3. building's exterior facade (Room 801 and Room 701 in the red circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We installed six OSRAM LS/PD MULTI 3 sensors in the office. According to the technical specification of the sensor, the detection angle is approximately 100°. If installed at a height of 3 m, the sensor can monitor an area with a maximum diameter of 7 m [10]. Thus, with appropriate installation, no blind areas exist. Fig. 3 illustrates the grouping of lamps, controllers and sensors. Zone 1 and zone 3 have two sensors each, while the other two zones have one sensor each.

The monitored data include the illuminance and power. Only the illuminance in Room 801 (test bed) is measured and recorded by illuminance sensors with standard 4–20 mA output signals. These sensors are installed next to the OSRAM sensors. Two more sensors are attached on the inside surfaces of the northwest and southwest windows to measure the illuminance caused by window-transmitted sunlight, which is regarded as the effective outdoor illuminance. Later in this report, we use LUX_7 for the NW sensor and LUX_8 for the SW sensor. The lighting power and energy use in both offices are monitored by power meters.

The data gathering core is a PLC (programmable logic controller) that collects all of the input signals and then sends the measured data immediately to a PC. PC Worx and Visu+ from the PLC manufacturer are used for programming, allowing database storage of the monitored data and visualization on the PC screen (Fig. 4).

The lamps in the open-plan office are controlled in 4 groups with one DALI MULTI 3 controller for each group with 1 or 2 combined sensors (see Fig. 3), which can measure both the occupant signal and illuminance. The individual office has the same system. In the meeting room, a rotary knob is used for dimming and as the on/off switch.

Fig. 4. Control zone and responsible sensors.

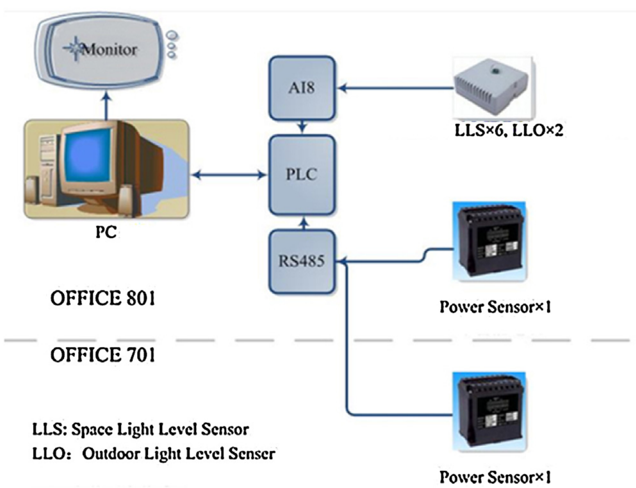

Fig. 5. Schematic of the monitoring system.

For task-lighting investigation, a desk lamp is installed on each desk for occupant use, as shown in Fig. 5.

3. Daylight utilization potential analysis of the test bed

To evaluate the daylight utilization potential, site measurements were taken in the office space under daylighting only with the artificial lighting switched off. Fig. 1 shows the locations of all of the testing points.

We used specialized lighting simulation software Ecotect and Daysim [11] to evaluate the daylight utilization potential of the office. A geometric model is developed in Ecotect; the model is exported, and a Daysim input file is produced. Daysim runs the model with Shanghai TMY weather data. Lighting control is set to manual control.

The illuminance of each testing point was measured every minute from 8:00 to 16:59 during the period of Sep. 24 to Oct. 30, 2011. The cumulative frequency of illuminance during working hours is shown in Fig. 6. The testing points SW and NW are near windows, and points 1–6 are in the open-plan office area (for locations of testing points see Fig. 1). According to Fig. 7, testing points 1, 2, 3, and 6 have illuminance levels meeting the standard requirement (300lx) in nearly 80% of the working hours. However, testing points 4 and 5 cannot meet the lighting standard under daylighting only and need to be illuminated by artificial lighting because they are far from windows.

The simulation results are presented in Table 1.

Fig. 6. Task-Lighting and General Lighting in the Test Bed.

The simulation results show that daylight factor (DF) is more than 2% in only 39% office area which cannot meet the requirement of LEED-NC2.1 [12], Item 8.1 (DF > 2% in at least 75% of the area). However, according to its definition, DF can't represent the influence of building location, orientation and the locality of openings. It's usually used as an auxiliary index and other indices listed above were also used to comprehensively evaluate the daylight utilization potential. DA is higher than 90% in 45% of the area, DA_{con} is higher than 80% in 85% of the area and Useful Daylight Illuminance (UDI100-2000) is higher than 90% in 47% of the area, which shows a significant daylight utilization potential in most of the office area. DA_{max} exceeds 5% in approximately 30% of the area, mainly along the perimeter, which might cause glare and visual discomfort.

In all, most area of the office shows good daylight utilization potential but glare might occur in perimeter. According to the simulation and measured results of DA, in the optimal condition, artificial lighting in perimeter is needed in only 20% working hour.

4. Energy efficiency of general lighting control strategies

In this section, we tried to find out energy efficiency of 8 different general lighting control strategies. Results of Section 3 show that the office where test bed was built has high daylight utilization potential. And the office is not always occupied, occupant detection can be applied. Thus, the test bed lighting system can be controlled by both occupant and daylight detection.

In

Table 2 we list all of the preset control modes for the general lighting system. Occupant detection is controlled by motion sensors with three control modes: (1) enabled; (2) enabled, not automatically switched on if detecting occupant motion; and (3) disabled. The difference between (1) and (2) is that the luminaires are turned on automatically when occupant motion is detected in (1), but not in (2). In (2), occupants need to switch the lights on manually. Daylight-linked control is controlled by illuminance sensors with five control modes: disabled, enabled and three limited enabled modes. Luminaires are controlled independently in each group, and no signal is shared among the different control groups.

The lighting system operated for one week under each strategy. The testing period lasted from Aug. 22, 2011 to Oct. 30, 2011. P801 and P701 represented the lighting power in Room 801 and Room 701, respectively.

Fig. 7 illustrates the cumulative occurrence frequency of power as a percentage under all 8 control strategies. The horizontal axis represents the percentage of the actual power at one moment in the installed power. This percentage could also be considered to be a part load ratio (PLR). The vertical axis represents the proportion of

Table 1
Utilization potential of daylight in the office.

No.	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	UDI < 100 [%]	UDI100-2000 [%]	UDI > 2000 [%]	Annual daylight exposure [lux·h]
1	1.3	82	93	1	3	95	3	2,239,592
2	2.3	94	97	2	1	95	4	3,636,473
3	4.5	98	99	17	1	58	42	8,605,041
4	0.4	13	64	0	15	85	0	746,283
5	0.8	63	86	1	5	93	2	1,580,455
6	2.7	95	98	6	1	85	13	5,108,322

DF: Daylight factor.
DA: Daylight Autonomy. The percentage of occupied hours per year when the minimum illuminance level can be maintained by daylight alone.
DA_{con}: Continuous Daylight Autonomy. In contrast to conventional daylight autonomy, partial credit is attributed to time steps when the daylight illuminance is below the minimum illuminance level.
DA_{max}: Maximum Daylight Autonomy. The percentage of occupied hours per year when the illuminance level is over 10 times the designed value.
UDI: Useful Daylight Illuminance. This term aims to determine when the daylight levels are 'useful' for the occupant, i.e., neither too dark (<100lx) or too bright (>2000lx).

Table 2
Preset control strategies in controller DALI MULTI3 [13].

Test No.	Occupant detect	Daylight linked control
1	Enabled	Disabled
2	Enabled, not automatically switched on if detecting occupant motion	Disabled
3	Disabled	Enabled, not automatically switched on with insufficient daylight
4	Disabled	Enabled, not automatically switched off with sufficient daylight
5	Enabled	Enabled
6	Enabled	Enabled, daylight-linked control according to last manually selected dimming level
7	Enabled, not automatically switched on if detecting occupant motion	Enabled
8	Enabled, not automatically switched on if detecting occupant motion	Enabled, not automatically switched off with sufficient daylight

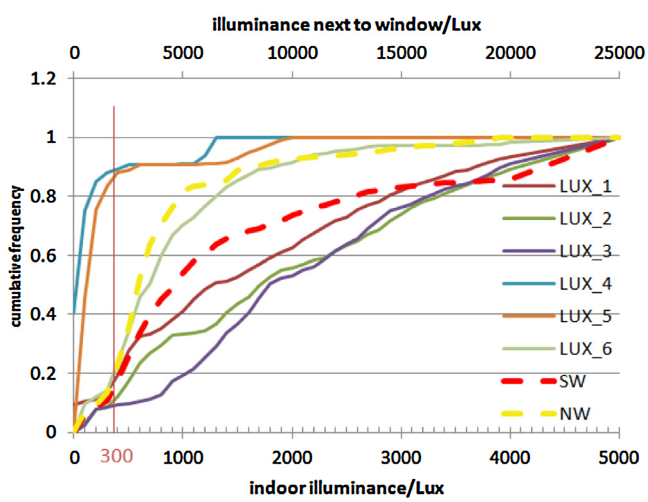

Fig. 7. Cumulative frequency of illuminance occurrence without artificial lighting.

the period when the actual power is below a certain value relative to the entire working period.

As seen from Fig. 7, the closer the curve is to the left, the greater the power and energy use required by the control strategy. Concerning the baseline office curve, when the lighting power is 80% of the installed power, only 80% of the needs are met. In contrast, the power and energy use are lower when the curve is closer to the right, which means that the lighting power is lower for a longer period of working time. Therefore, strategies 3 and 7 should be the lowest energy consumption strategies.

The curve shape of TEST 1 is different from that of the others. With a dramatic turning point at 67% of the PLR, it is indicated that the lighting system operates at a PLR of 67% during most of the working period.

The relative energy saving ratio for each strategy is calculated based on the following equation:

$$\text{Relative energy saving ratio} = 1 - \frac{\text{Full load equivalent hours}}{\text{Full load equivalent hours for baseline}} \quad (1)$$

$$= 1 - \frac{\dfrac{\text{Lighting energy use in testbed}}{\text{Installed lighting power in test bed}}}{\dfrac{\text{Lighting energyuse inbaseline office}}{\text{Installed lighting power in baseline office}}}$$

According to Table 3 among the 8 control strategies tested, control modes 3 and 7 show the best energy savings performance. Considering the uncertainties brought by human behavior, an electricity saving rate could be conservatively estimated to be 50% or higher. Contrasting mode 3 to mode 7, mode 7 includes occupant detection, whereas mode 3 does not and runs the risk of having lamps left on all night. Thus, mode 7 is recommended.

Lighting is only on when manually switched on in mode 2, which can avoid unnecessary lamp use and tap into the energy conservation potential of the intelligent control system, differentiating it from mode 1. Thus, this function can save approximately 30% of energy. Dimming control can help even the illuminance at the desktop while ensuring the visual comfort of users. Therefore, the space could be more efficiently illuminated by daylight. Comparing modes 2 and 7, daylight-linked dimmable fluorescent lamps use 23% less electricity. In mode 8, the luminaires are switched on or off less frequently, which can extend their service life. Thus, the performance of mode 8 is also acceptable.

5. Task lighting combined with dimmable general lighting

5.1. Test plan

In this stage, we aim to determine the most energy efficient combination of task lighting and general lighting while guaranteeing the visual comfort of the occupants. Fig. 8 shows the schematic of the test plan.

Visual comfort related factors including objective parameters, subjective perception indicators and other environmental parameters were first determined according to corresponding standards

Table 3
Energy saving ratio and relative energy saving ratio of various control strategies.

Test No.		1	2	3	4	5	6	7	8
Lighting Energy use in the test bed	kWh	61	33	23	39	42	38	24	28
Lighting energy use in the baseline office	kWh	39	54	65	45	51	67	59	47
Relative energy saving ratio	%	−63.7	34.3	63.2	8.3	11.5	39.1	57.4	35.8

*When performing TEST 5, the defect lamps in the baseline office were repaired, so the installed power changed to 2.92 kW.

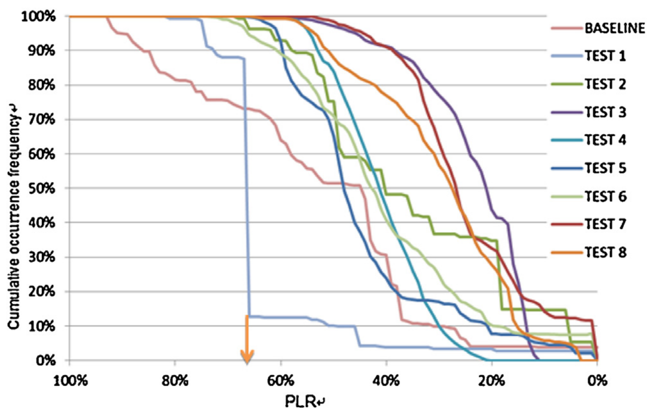

Fig. 8. A cumulative occurrence of PLR under different control strategies.

and studies. Then survey and measurements were conducted under the four different test scenarios to find out the optimal combined lighting system. This test will be described in detail in the following sections.

5.2. Test scenarios

According to the *Standards for Lighting Design of Buildings* [14], the illuminance on a work plane should not fall below 300lx and the luminous contrast should be greater than 1/3. Test Scenarios will be designed to adhere to these two basic standards to avoid uncomfortable perception.

Four scenarios will be investigated. In each scenario, general lighting illuminance will be preset and fixed at 75lx/100lx/150lx/200lx. Before the survey was conducted, the illuminance on work plane was adjusted as close to 300lx as possible by turning the desk lamp to different positions (0%, 25%, 50%,100%). Then, occupants will be asked to adjust their desk lamp luminance to the most comfortable level and finish the survey. The target work plane illuminance is specified as 300lx,[1] and the actual illuminance is measured after the occupants finish their lighting adjustment.

5.3. Visual comfort indicators

To develop a more efficient lighting strategy for task lighting and avoid the risk of sacrificing visual comfort, an evaluation of visual comfort was conducted to ensure that the energy savings from each control strategy was calculated using the same baseline. The evaluation consists of subjective and objective indicators and other comfort related environmental indicators.

5.3.1. Objective visual comfort parameters

Illuminance, uniformity of illuminance, luminance and so on are generally the objective indicators to evaluate lighting environment. In this test, illuminance and corresponding uniformity, and luminance are measured.

[1] 300lx is defined as the standard value in *Standards for Lighting Design of Buildings*.

A. Illuminance and Uniformity of Illuminance Measurement

According to the China standard for an interior lighting measurement [15], the location of the testing points are set as shown in Fig. 9.

Before the test, the test bed is adjusted to maximize CRF (Contrast Rendering Factor) and avoid the obstruction effect of furniture, as instructed by the research in [16]. The illuminance level requirement for a common office work plane is 300lx in the Chinese standard [14]. The illuminance of a test point and its distance to the luminaire satisfy the following equation:

$$E_1 \cdot d_1^2 = kE_2 \cdot d_2^2 \qquad (2)$$

where, E_1 – Illuminance on floor plane, lx;
E_2 – Illuminance on work plane (0.8 m high), lx;
d_1 – Distance between luminaire and floor plane, m;
d_2 – Distance between luminaire and work plane, m.

To obtain k, a set of measurements was taken in the test bed room from a floor point and the point 0.8 m above it where the obstruction effect was not present. With coefficient k and floor plane illuminance, theoretical illuminance at 0.8 m height can be calculated. With this information, the desk test point was relocated to the point where the illuminance was closest to the theoretical value. Then the illuminance was measured under the four scenarios.

The ratio of the minimal illuminance to the average illuminance on work plane is the uniformity of illuminance. According to Chinese standard [14], the uniformity is advised to be no less than 1/3.The more uniform the illuminance is, the more comfortable the lighting environment is. Otherwise, visual fatigue can be caused.

B. Luminance Measurement

Luminance was measured through an indirect method. For a diffuse reflective surface, luminance is determined by:

$$L = E \cdot \rho / \pi \qquad (3)$$

where,
L—— surface luminance , cd/m^2;
E —— surface illuminance, 1x;
ρ —— reflect factor of surface, ‰
ρ can be determined by:

$$\rho = E_f / E_R\,(\%) \qquad (4)$$

where,
E_f — reflect illuminance, 1x;
E_R —incident illuminance, 1x.

Illuminance, reflect illuminance and incident illuminance of 3–5 test points located on each surface were measured. The measured surfaces were the work plane, the floor and the walls. Arithmetic mean values of illuminance and reflect factor were used.

5.3.2. Subjective visual comfort indicators

The scope of subjective indicators varies across the literature. In [17], 9 indicators influencing visual comfort in the office were investigated based on a previous study: flexibility and convenience of the lighting control, pleasure, width of space, clarity, conformity, proper luminance contrast, color rendering, glare and visual contact to the outside. Clarity, order, spaciousness, pleasure, privacy and relaxation are regarded as subjective indicators of visual impression [18–21]. Successors of Flynn also carry out similar

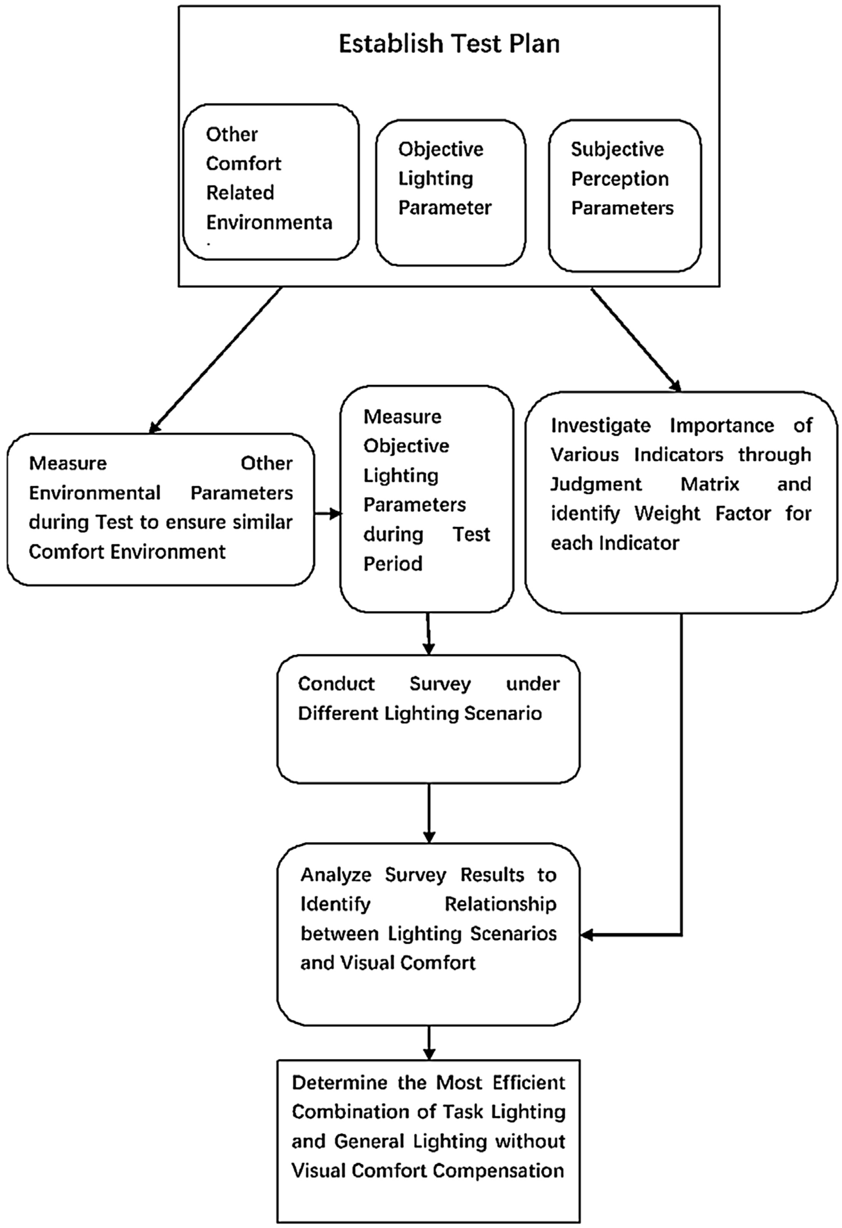

Fig. 9. Schematic of test plan.

researches [22–26]. Wen [27] proposes several factors to evaluate lighting environment: first impression, surface ornament and color, indoor structure and layout, lighting distribution, glare, color rendering and so on. Zhan ([28] generalizes requirements for lighting environment into three levels: bright (proper illuminance and uniformity on the work plane, proper environment luminance), comfort (no glare and stroboflash, proper luminance contrast, flexibility and convenience of the lighting control, pleasure) and artistic expression (attractive environmental luminance, beautiful space and decoration).

After fully considering visual comfort subjective indicators, basic functions and characteristics of office and relevant studies on subjective impression of lighting environment, from the survey conducted in the test, the 5 most relevant indicators were selected for a subjective evaluation of visual comfort, as listed in Table 4.

The results of the survey were processed using the following methods to establish an expert group synthetic judgment matrix and determine the weight factor of each indicator:

A. Analytic Hierarchy Process (AHP)

Because an occupant's perception of comfort consists of more than one indicator, the Analytic Hierarchy Process (AHP) is used to identify a weight factor for each indicator. The decision goal of the process is the general satisfaction level.

Against the goal, we established the judgment matrixA = $\left(a_{ij}\right)_{5\times5}$. Element a_{ij} represents the importance based on pairwise comparisons of the criteria. Based on the theory from Saaty [29], numbers 1–9 and their reciprocals are used for calibration. The specific definitions of the numbers are listed in Table 5.

Table 4
Subjective Evaluation Survey.

Indicator	Very unsatisfied 1	Unsatisfied 2	Satisfied 3	Very satisfied 4
A, Pleasure				
B, Clarity				
C, Proper luminance contrast				
D, Color rendering				
E, Glare				
F, General Satisfaction Level				

Table 5
Definition of the numbers in the evaluating matrix.

Calibrator	Definition
1	importance of the two compared elements are the same
3	the former is relatively more important than the latter
5	the former is apparently more important than the latter
7	the former is strongly more important than the latter
9	the former is extremely more important than the latter
2,4,6,8	calibration in between the adjacent values above
reciprocal	calibrator of importance for the latter against the former

The weight factor of the evaluating matrix can be derived with the following formula:

$$W_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \quad (i = 1, 2, \cdots, 5) \tag{5}$$

The largest characteristic root of the matrix:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n} a_{ij}W_j}{W_i} \tag{6}$$

To evaluate if the matrix is consistent, the following formula is used to calculate the consistency ratio CR:

$$\mu = \frac{\lambda_{max} - n}{n-1} \tag{7}$$

$$CR = \frac{\mu}{RI} \tag{8}$$

For 5 elements, the mean random consistency index is RI = 1.12. If CR < 0.1, the matrix is considered consistent.

B. Establish an Expert Group Synthetic Judgment Matrix

When building the judgment matrix, the preference of individual expert may lead to decision-making error. To avoid this problem and optimize the matrix, both Delphi Method and Maximum-Likelihood Estimation (MLE) were applied and the precision was checked.

Based on the analytic hierarchy, we build the group synthetic judgment matrix$\hat{A} = \left(\hat{a}^*_{ij}\right)_{n\times n}$. First, we invite m (m > 1) experts to give a judgment matrix for the same element and name each matrix $A_k = \left(a^{(k)}_{ij}\right)_{n\times n}$, k = 1,2,⋯,m. Assuming $A^* = \left(a^*_{ij}\right)_{n\times n}$, the ideal matrix complies with the consistency requirement. To minimize the deviation between A_k andA^*, the synthetic matrix$\hat{A} = \left(\hat{a}^*_{ij}\right)$ is established to reflect group will as it consists with reality. Deviation between $a^{(k)}_{ij}$ and a^*_{ij} is named as ξ_k with $\xi_k \sim N(0, \alpha^2_k)$and $E\left({\xi_{ij}}^{(k)}\right) = a^*_{ij}$. The smaller the value of σ_k, the higher judgment capability the expert obtains. This capability can be evaluated with p_k:

$$p_k = \frac{e^{-10(m-1)\mu_k}}{\sum_{i=1}^{m} e^{-10(m-1)\mu_k}}, k = 1, 2\cdots, m \tag{9}$$

Where $\mu_k = \frac{\lambda^{(k)}_{max} - n}{n-1}$, $\lambda^{(k)}_{max}$ is the largest eigenvalue of A_k.

To obtain the optimal synthetic matrix, the likelihood function is used:

$$L\left(a^{(k)}_{ij}, \cdots, a^{(m)}_{ij}; \sigma^2_1, \cdots, \sigma^2_m, a^*_{ij}\right) = \prod_{k=1}^{m} f\left(a^{(k)}_{ij}, \sigma^2_k, a^*_{ij}\right) \tag{10}$$

The known density function for ${\xi_{ij}}^{(k)}$ is:

$$f\left(a^{(k)}_{ij}, \sigma^2_k, a^*_{ij}\right) = \frac{1}{\sigma_k\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2_k}\left(a^{(k)}_{ij} - a^*_{ij}\right)^2\right] \tag{11}$$

Therefore:

$$L\left(a^{(k)}_{ij}, \cdots, a^{(m)}_{ij}; \sigma^2_1, \cdots, \sigma^2_m, a^*_{ij}\right) = (2\pi)^{-\frac{m}{2}}\left(\prod\nolimits_{k=1}^{m}\sigma_k\right)^{-1} \exp \left[-\sum_{k=1}^{m}\frac{1}{2\sigma^2_k}\left(a^{(k)}_{ij} - a^*_{ij}\right)^2\right] \tag{12}$$

The unique solution for $\frac{d(\ln L)}{da^*_{ij}} = 0$ is:

$$\hat{a}^*_{ij} = \frac{\sum_{k=1}^{m} P_k a^{(k)}_{ij}}{\sum_{k=1}^{m} P_k} \tag{13}$$

Therefore, $\hat{a}^*_{ij}$ is the MLE of a^*_{ij} and $\hat{a}^*_{ij} = \frac{\sum_{k=1}^{m} P_k a^{(k)}_{ij}}{\sum_{k=1}^{m} P_k}$ is the optimal synthetic matrix. $\hat{a}^*_{ij}$ represents the weighted average of the element. The mean square error is:

$$\sigma_{\hat{a}^*_{ij}} = \sqrt{\frac{1}{m-1}\sum_{k=1}^{m} P_k\left(a^{(k)}_{ij} - a^*_{ij}\right)^2} \tag{14}$$

The error upper-limit is ε which pertains to the number of experts and is generally selected as 0.5. If$\sigma_{\hat{a}^*_{ij}} \leq \varepsilon$, $\hat{a}^*_{ij}$ is considered to comply with the convergence requirement. If not, $\hat{a}^*_{ij}$ needs to be reevaluated.

Table 6
Measured Floor Plane and 0.8 m High Illuminance.

No.	Illuminance on floor plane(lx)	Illuminance on 0.8-m height(lx)
1.	50	63
2.	70	86
3.	91	112
4.	104	131
5.	121	146
6.	143	176
7.	165	208
8.	185	229
9.	206	253
10.	219	268
11.	232	282
12.	245	309
13.	264	327
14.	280	345
15.	300	369

5.3.3. Other comfort-Related environmental parameters

The comfort of an office occupant is influenced by various parameters. Therefore, the influence of other comfort-related environmental parameters should be excluded.

Based on research from the HOPE project in Europe [30], air temperature, air humidity, air velocity, noise and air quality were selected for testing. Only when all four parameters were within the comfort range was a test conducted. The thermal environment was regarded as comfortable when the indoor condition was within the comfort zone stipulated in *ASHRAE 55* [31]. Noise was under the annoyance threshold. Air quality was considered to be acceptable if PM2.5 was lower than 75 $\mu g/m^3$, which is defined as level 2 in *Ambient air quality standards* [32].

5.4. Results

5.4.1. Results of objective parameters

A. Results of illuminance and uniformity of illuminance

To obtain the value of k in Formula (2), a set of measurements was taken in the test bed room from a floor point and the point 0.8 m above it where the obstruction effect was not present at all. The measured results are listed in Table 6

Then, when we substitute the values of d_1 and d_2 ($d_1 = 2.67m, d_2 = 1.87m$) into the formula, we can derive

$$E_1 = 0.809E_2 \text{and} k = 1.565$$

Test points on work plane were then relocated to those whose illuminance was closest to the theoretical value. The measured illuminance under 4 scenarios and calculated uniformity are listed in Table 7:

B. Results of the Luminance

The reflect illuminance and incident illuminance of each surface were measured and the reflect factor calculated. The results from different surfaces are listed below (Tables 8–10):

The measured results of the floor and work plane luminance under the fourth scenario are shown in Figs. 10 and 11:

Requirements of reflect factor in a long-time working room are stated in Table 11:

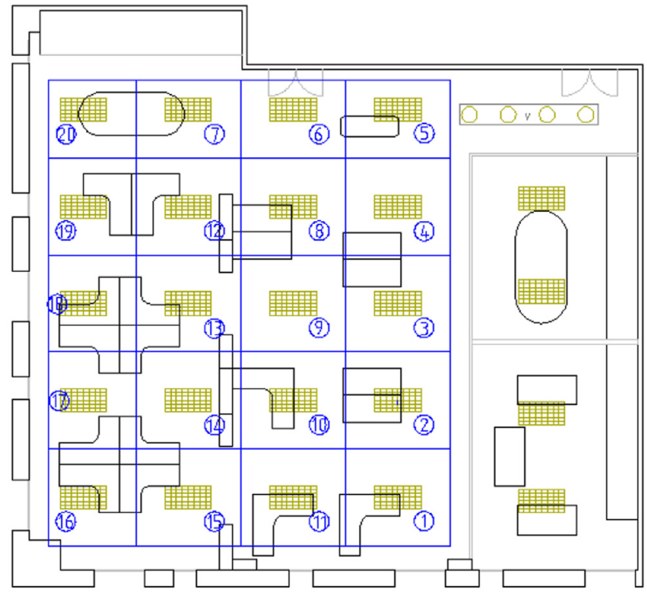

Fig. 10. Layout of the Measurement Points.

As the results above shows, all of the objective visual comfort indicators meet the requirements of Chinese standard. The required illuminance which is 300lx on work plane can be satisfied with the help of task lighting. And the uniformities under different scenarios are more than 1/3 except that of 75lx general lighting which is slightly lower than the prescribed value. As for luminance, reflect factors of each room surface lie in the recommended range meaning that glare won't happen (Figs. 12–15).

5.4.2. Weight factors of the visual comfort indicators

In the test, 6 experts from the lighting environment field were invited to make a pairwise comparison of the selected 5 indicators. Some of the experts are doing lighting related research, others are professional lighting technicians. Thus, we regard their evaluation results as credible. Based on each expert's judgment matrix, a synthetic matrix was established, and then, calculation of the weight factors was solved for using Matlab. The first round of results are as follows:

The mean square error shows that the synthetic judgment matrix meets the convergence requirement. However, with Eq. (5)–(8), the calculated CR is 0.1125, which is larger than 0.1 and does not meet the consistency requirement. Concerning the results, the experts disagree on the weight factor for B (clarity) and C (contrast). The treated matrix with its average and mean square error were given back to these experts to allow them to revise their initial judgments. These steps were repeated until the convergence and consistency requirements were both met. The final matrix has a CR of 0.06. The judgment matrix, mean square error and weight factor of each indicator in the final round are listed below (Tables 12 and 13).

Table 7
Work plane illuminance and minimal uniformity under different scenarios.

Test Scenario	Background illuminance (lx)	Illuminance at 0.8 m height (lx)	Minimal compensation illuminance of task lighting (lx)	Minimal uniformity
1	75	95	205	0.32
2	100	124	176	0.41
3	150	184	116	0.61
4	200	243	56	0.81

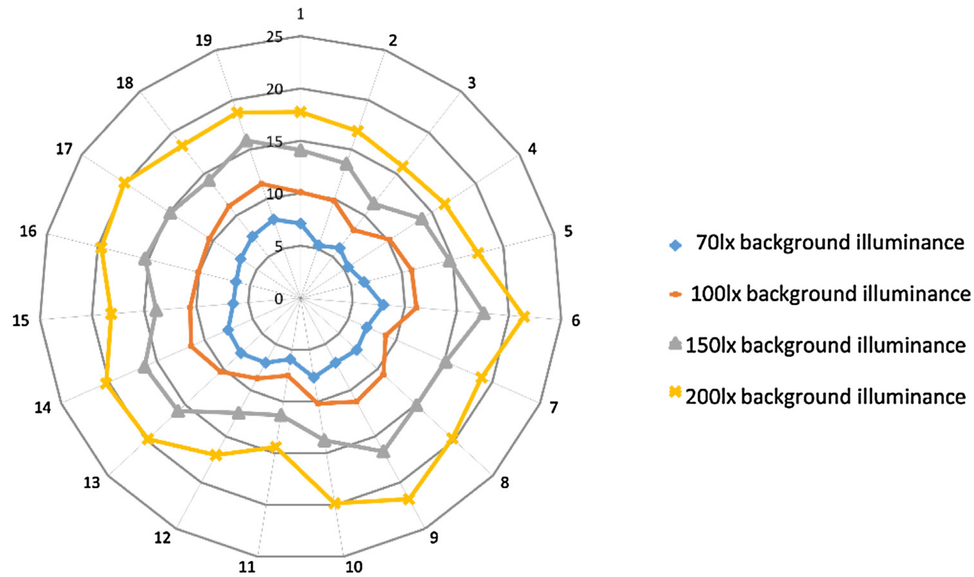

Fig. 11. Floor luminance distribution (1–19 are the numbers of the measured points on the floor).

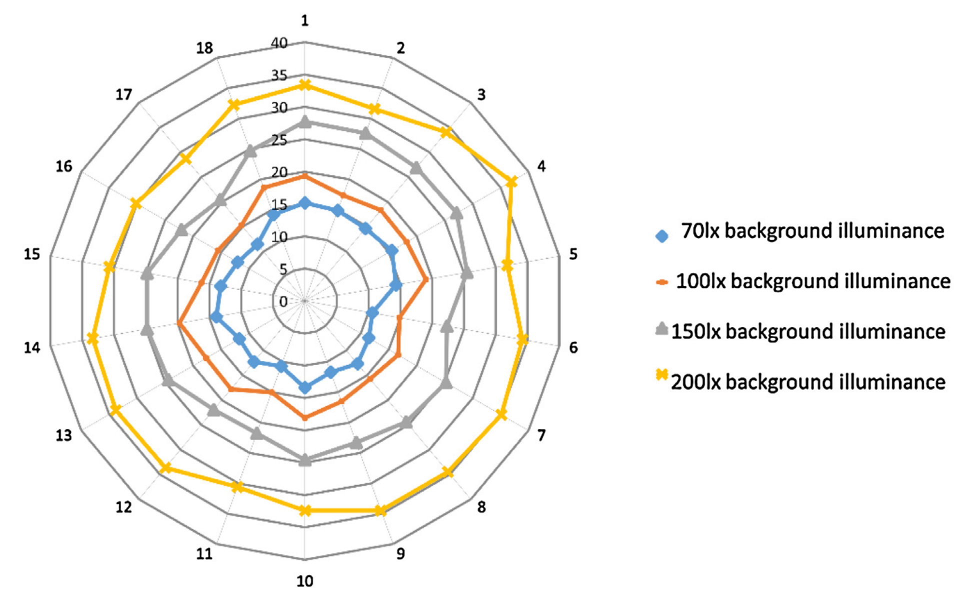

Fig. 12. Work plane luminance distribution (1–18 are the numbers of measured points on the desks).

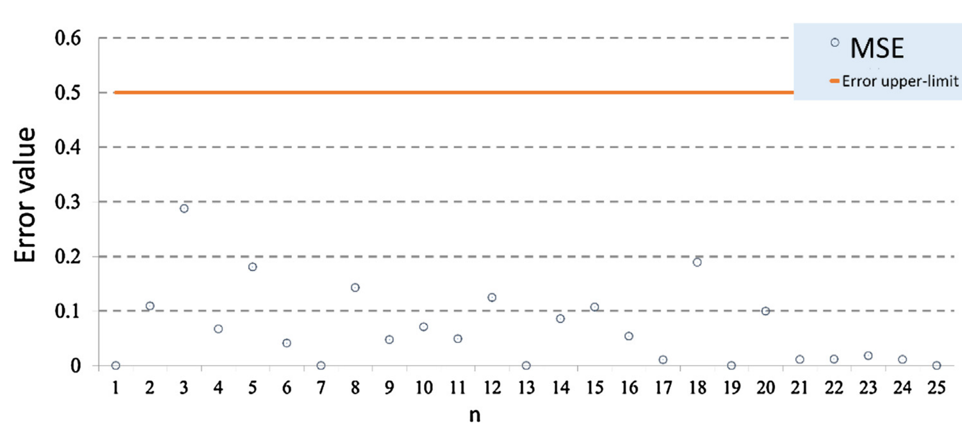

Fig. 13. Mean Square Error of the Synthetic Matrix, 1st Round.

Table 8
Reflect factor of work plane.

Work plane	Reflect illuminance(lx)	Incident illuminance(lx)	Reflect factor
Point 1	82	185	0.44
Point 2	86	200	0.43
Point 3	83	192	0.43
Point 4	76	178	0.43
Reflect factor of desktop			0.43

Table 9
Reflect factor of floor.

Work plane	Reflect illuminance(lx)	Incident illuminance(lx)	Reflect factor
Point 1	47	158	0.30
Point 2	43	148	0.29
Point 3	71	236	0.30
Point 4	80	279	0.29
Reflect factor of floor			0.29

Table 10
Reflect factor of wall.

Work plane	Reflect illuminance (lx)	Incident illuminance (lx)	Reflect factor
Point 1	53	99	0.54
Point 2	66	124	0.53
Point 3	76	139	0.55
Point 4	90	168	0.55
Reflect factor of wall			0.54

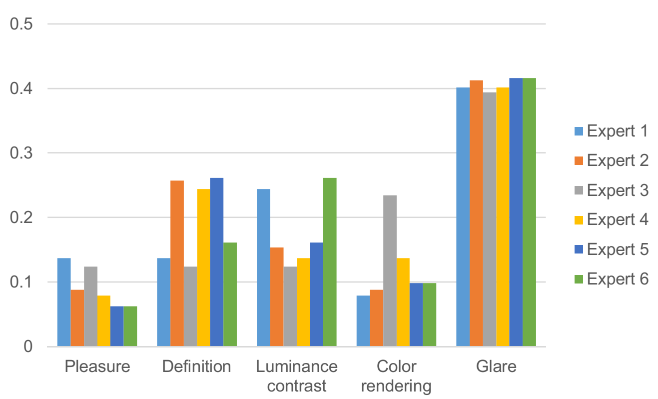

Fig. 14. Weight Factors of Each Visual Comfort Indicator, 1st Round.

Thus, the comprehensive subjective evaluation function for satisfaction of the visual environment can be deduced as:

$$F = 0.3703 \times Y_{glare} + 0.2156 \times Y_{clarity} + 0.1688 \times Y_{luminance\,contrast} + 0.1488 \times Y_{colorrendering} + 0.0961 \times Y_{pleasure} \quad (16)$$

With this equation, we can calculate the satisfaction level under different control scenarios and help to evaluate visual comfort. It also helps to validate the response of each response. When the difference between general satisfaction level of the response and the calculated satisfaction level is more than 1, we regard the response as invalid.

Since there's no standard or regulation about satisfaction percentage of visual comfort, relevant indices are taken into consideration when determining the acceptable satisfaction percentage. Acceptable thermal environment prescribed in ASHRAE 55–2013 [31] means that a substantial majority (more than 80%) of the occupants find it thermally acceptable. Visual Comfort Probability (VCP) whose value scale runs from 0 to 100 means the percentage of occupants that finds the lighting arrangement comfortable and usually a value of 70 is regarded as acceptable [33]. Thus, satisfaction percentage of 85% is decided to make sure that the majority of the occupants' visual comfort is achieved. Only when over 85% of

Table 11
Requirements of reflect factor(14).

Surface	Reflect factor
Work plane	0.2–0.6
Wall	0.3–0.8
Floor	0.1–0.5
ceiling	0.6–0.9

Table 12
Synthetic Judgment Matrix, 1 st Round.

Indicator	A	B	C	D	E
A	1	0.60	0.57	0.85	0.27
B	2.28	1	1.32	1.93	0.41
C	2.11	1.06	1	1.76	0.38
D	1.56	0.81	0.90	1	0.32
E	3.81	2.53	2.71	3.34	1

Table 13
Synthetic Judgment Matrix, Final Round.

Indicator	A	B	C	D	E
A	1	0.43	0.55	0.77	0.30
B	2.45	1	1.45	1.74	0.5
C	2	0.78	1	1.37	0.43
D	1.78	0.73	0.93	1	0.40
E	3.45	2	2.45	2.74	1

With the final round matrix, the weight factor can be calculated:

Table 14
Weight factor of visual comfort indicators.

Prioritized in Importance	Indicator	Weight Factor
1	glare	0.3707
2	clarity	0.2156
3	Proper luminance contrast	0.1688
4	color rendering	0.1488
5	Pleasure	0.0961

occupants whose response is valid find the lighting environment as satisfactory, the corresponding lighting scenario qualifies as an optimal option. As can be seen from the equation, the weight factor of glare is 0.3707 which means glare is the most influential subjective indicator on visual comfort. Thus, glare should be avoided when designing a lighting environment. Besides, clarity, luminance contrast and color rendering also have significant influence on visual comfort. Pleasure should be taken into account too. For instance, to increase work plane luminance to some degree or to utilize daylight are both measures to improve occupants' pleasure.

5.4.3. Satisfaction degree under different scenarios

We surveyed 226 subjects under the 4 test scenarios described above, including the 6 experts mentioned above. Within the 220 ordinary subjects, 144 were male and 76 were female, aged from 16 to 27 years old. The test was conducted from 19:00 to 22:10 each evening with 18 subjects normally participating.

When the subject finished adjusting the lighting, the survey was conducted. And the response of each questionnaire was validated using the evaluation function [16]. The test results are shown in Table 14. F of 3 is defined as "Satisfied". Fig. 16 shows the occupants' satisfied ratio and maximum and minimal illuminance on work plane under each scenario (Fig. 17).

Fig. 16 shows the results based on all of the validated samples. When the general lighting illuminance is 75lx, only 37.86% occupants find the lighting environment satisfactory. Though under this scenario lighting energy consumption may be the lowest, this strategy won't be adopted due to the terrible visual comfort.

Table 15
Statistics for the Task Lighting Status in 4 scenarios.

Scenario	General lighting level	Usage Ratio of Task Lighting (%)			
	Lx	100% On	Dim To 50%	Dim To 20%	Off
N1	75	7.35	80.03	12.62	0.00
N2	100	6.37	42.66	50.97	0.00
N3	150	2.91	24.76	72.33	0.00
N4	200	2.91	17.47	79.12	0.49

Under scenario N2, the overall satisfaction rate is lower than 85% (Table 15).

When narrowing the sample range to illuminance between 355lx and 380lx on work plane, the ratio of satisfied occupants reaches 88.37%. Satisfaction rates in scenario3 and scenario4 are both more than 85%. On the other hand, lighting energy consumption increases in sequence of these four scenarios. Thus, regarding to visual comfort and energy efficiency, N2 (100lx illuminance) is a proper strategy. Since students aged from 16 to 27 make up a major part of the participants, N3 (150lx illuminance) is the optimal strategy under most cases.

5.4.4. Energy savings of task lighting combined with dimmable general lighting

Energy consumption of the optimal combination of task lighting and dimmable general lighting is simulated to find out the energy efficiency of this strategy.

The percentage of additional artificial lighting power needed to achieve the prescribed illuminance of 300lx can be determined from an annual dynamic daylight simulation using Daysim. Thus, the energy consumption of general lighting can be computed, while the energy consumption of task lighting needs to be calculated separately. To estimate the savings of this strategy conservatively, the power from each task lighting lamp is regarded to be 5 W, which is the power when the lamp is fully switched on. The operating procedure specifies the task lighting be switched on when there is an occupant at the desk and the illuminance is below the required value. Otherwise, the task lighting is off. The results are exported to EnergyPlus to calculate the integrated artificial lighting energy consumption. The simulation results are listed below in Table 16. As can be seen, energy saving of task lighting combined with general lighting can reach nearly 59%. Noted that task lighting is assumed to be fully switched on which means that energy saving of this strategy can be higher.

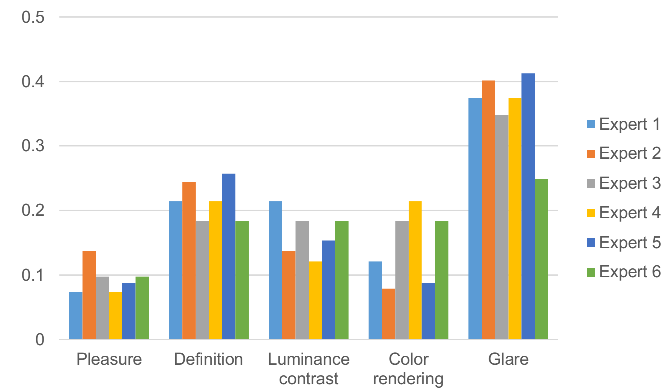

Fig. 16. Weight Factor of Each Visual Comfort Indicator, Final Round.

6. Discussion

This paper presents lighting energy efficiency under different control strategies including general lighting control and task lighting combined with general lighting control. Particularly, visual comfort is studied considering objective and subjective perception indicators under four scenarios. The contributions of this paper are elaborated as follows:

(1) Energy efficiency of different control strategies is analyzed using measured or simulated results. Regarding to general lighting control, occupant detection and daylight dimming are implemented on the test bed. Energy consumption is metered and processed to analyze energy savings. Energy saving of task lighting combined with general lighting is simulated using results from daylights utilization potential in Section 1 and optimal combination determined in Section 5.
(2) Optimal combination of task lighting and general lighting is decided. Visual comfort related parameters are studied to ensure that they are within the comfort or the required range. Surveys on subjective perception are carried out to find out satisfaction degree of each scenario. The one which has a satisfaction rate over 85% and better energy performance is determined as the optimal combination.
(3) Weight factors of each subjective indicator are determined. In this paper, we establish an Expert Group Synthetic Judgment Matrix using Delphi Method and Maximum-Likelihood Estimation (MLE) based on the responses of the experts. When the matrix is verified to be consistent, weight factors are calculated using Analytic Hierarchy Process (AHP) method. Function that

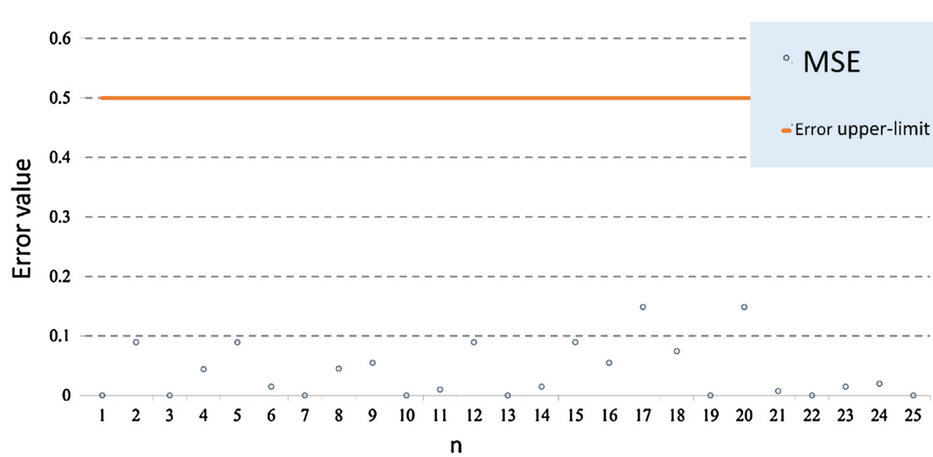

Fig. 15. Mean Square Error of the Synthetic Matrix, Final Round.

Table 16
Estimated Annual Energy Saving Rate of Various Lighting Control Strategies.

	General Lighting A(KWh)	General Lighting Dimming B(KWh)	General Lighting Dimming + Task Lighting C(KWh)	Reduction Ratio of General Lighting Dimming (A-B)/A	Reduction Ratio of General Lighting Dimming + Task Lighting (A-C)/A
Annual Value	3470	1886	1432	45.65%	58.73%

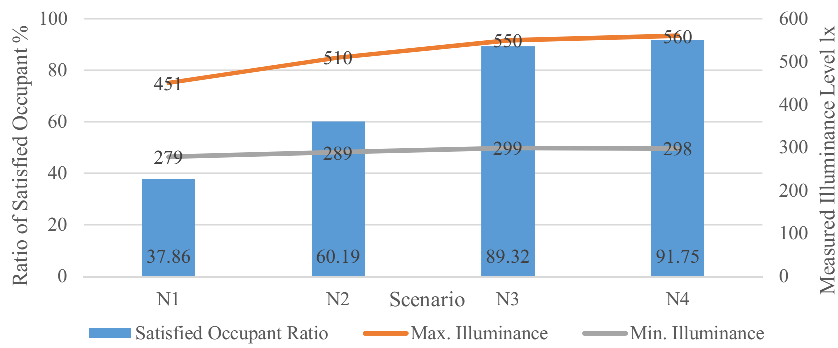

Fig. 17. Resulting Statistics from the Subjective Evaluation Survey of Visual Comfort.

relates satisfaction level with subjective indicators is proposed and used to evaluate satisfaction level under different scenarios.

7. Conclusions and future work

By analyzing the test data from the test bed, the following conclusions can be drawn:

(1) Manually switched-on and automatically switched-off lighting control strategy is the most energy efficient one. Energy saving of using proper occupant detection can reach to more than 30%. And using daylight linked control alone, lighting energy can be reduced by 23% or more.
(2) Occupant detection is highly recommended. During our experiment, when people were not familiar with how to switch off the lights or forgot to turn them off, lights might be left on all night. Occupant detection can prevent this from happening. However, the accuracy of motion sensors still needs improvement and long-time sedentary status may be mistakenly determined as not occupied.
(3) Mode 7 is the recommended way to control general lighting: occupant detection is enabled, but lights are not automatically switched on if occupant motion is detected, and daylight-linked dimming is enabled. Considering the uncertainties brought by human behavior, an electricity saving rate could be conservatively estimated to be 50% or higher.
(4) Weight factors of subjective perception indicators are calculated with the responses of experts. The satisfaction level can be obtained with function:

$$F = 0.3703 \times Y_{glare} + 0.2156 \times Y_{clarity} + 0.1688 \times Y_{luminancecontrast} + 0.1488 \times Y_{colorrendering} + 0.0961 \times Y_{pleasure}$$

(5) The optimal lighting scenario is the one that combines 150lx general lighting with task lighting under which the lighting environment is considered as comfortable.
(6) When the illuminance is lower than the required 300lx, human behavior in implementing task lighting can help achieve the desired visual comfort level.
(7) Dimmable general lighting has an energy savings rate of approximately 50%. Task lighting can increase energy savings to approximately 60% without compromising visual comfort.

Daylight-linked dimming and occupant-detecting on/off control both have a high impact on lighting energy savings. These combined with individual adjustable task lighting can reach an energy savings rate of 60%. However, energy efficiency optimization should not be performed at the expense of visual comfort. Therefore, though lower general lighting intensity decreases the energy consumption of the lighting system, the amount of reduction in general lighting should be limited. Otherwise, uncomfortable glare, high luminance contrast and other predictable comfort issues will arise due to an ultra-low general lighting level.

The test results also show that human behavior can help compensate for visual comfort through active adjustment of the task lighting. However, visual comfort is a complex result of various factors, and the effects of activating task lighting to achieve a satisfying lighting environment are limited.

Despite the merits of this study, problems still exist to be further tackled. Firstly, if the test bed can be built in larger scale like a floor or a whole building, results of the experiment will be more universal and representative. In processing experiment results, how to select proper baseline is worth considering. The optimal condition cannot be met in reality and that's why results of many studies are based on simulation. In our study, Room 701 and Room 801 are basically identical but the uncertainties of human behavior may still have some influence on the results. Moreover, the surveyed participants are mainly students who are relatively young. Visual comfort of those who are 27–60 years old are not considered. Future research needs to be done to include all possible age groups.

Acknowledgments

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