

# Visual Comfort and Energy Savings in Classrooms using Surveillance Camera derived HDR Images for Lighting and Daylighting Control System

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## Visual Comfort and Energy Savings in Classrooms using Surveillance Camera derived HDR Images for Lighting and Daylighting Control System

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### Abstract:

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Classroom lighting significantly influences students' performance and productivity, as well as building energy consumption. Numerous studies highlight prevalent suboptimal lighting in education, with almost half of students expressing discomfort, emphasizing the need to enhance lighting environments. To address the issues mentioned and accommodate diverse learning activities with varying lighting needs and equipment, this paper introduces an innovative HDRi Surveillance Lighting Control System (HSLDCS). An experimental study investigates the implementation of the HSLDCS in ten classrooms with various learning activities. High Dynamic Range image (HDRi) photography is employed to assess lighting quality using the HDRi spatial luminance distribution, DGP and UGR, while a questionnaire survey is conducted to evaluate student well-being. Despite limitations regarding the adjustment time for window blinds and lamps, the results demonstrate that the adoption of appropriate HSLDCS can yield energy savings ranging from approximately 43% to 63%, while still ensuring visual comfort for the majority of students. Over 70% of the students expressed satisfaction, even when classroom brightness was reduced by 30%. Considering the widespread use of laptops or tablets by students during class, reducing brightness levels is as a viable strategy for conserving energy and preventing visual fatigue. The implementation of the HSLDCS is a promising solution for alleviating suboptimal lighting conditions, enhancing energy efficiency, and promoting user well-being. This study also creates new opportunities for further exploration in the field of lighting technology and emphasizes the importance of prioritizing perceived brightness over illuminance.

**Keywords:** classroom lighting; energy saving; HDRi surveillance lighting and daylighting control system; HDR vision sensor; visual comfort.

*Declaration of Interest: None*

## **Nomenclature**

BL	Brightness level of lamp (%)
DGP	Daylight glare probability
DMX	Digital Multiplex DMX-512 protocol
HDRi	High dynamic range image
IP	Internet protocol
L	Luminance ( $\text{cd}/\text{m}^2$ )
LCS	Lighting control system
HSLDCS	HDRi surveillance lighting and daylighting control system
UGR	Unified glare rating
$\theta_B$	Angle of bottom window blinds ( $^\circ$ )
$\theta_T$	Angle of top window blinds ( $^\circ$ )

## **1 Introduction**

Classroom lighting is crucial for learning as it directly impacts student performance, productivity, mood, and visual health [1,2]. In addition, some classrooms feature excessive artificial lighting and daylight, leading to inefficient energy consumption, headaches, and impaired visual performance [3]. Other classrooms do not harness natural light; instead, they obstruct it with curtains [4]. Excessive brightness is a challenge in modern classrooms with whiteboards and projection screens, as increased

brightness levels cause whiteboards to produce glare and can reduce the clarity of the projection screen [4].

A study conducted in a university in Taiwan revealed that close to 50% of participants indicated that the lighting conditions were suboptimal for task performance [4]. In another study conducted in architecture studios that are also used for lectures in Cairo, 49% of participants reported experiencing visual discomfort issues [5]. Research done in Singapore involving the use of on lecture halls revealed that 26.6% of individuals perceived the lighting environment as excessively bright, 24% found it uncomfortable, and 55.7% expressed a wish to reduce the lighting level [6]. At a university in Nanjing, in a survey done with participants occupying three classrooms and two offices, only 52% of the respondents expressed that the lighting conditions at their workstations satisfactory [7]. These findings from diverse studies conducted in various educational settings underscore the prevalence of suboptimal lighting conditions, with almost half of participants expressing discomfort and dissatisfaction, emphasizing the need for comprehensive strategies to address and improve lighting environments in educational spaces worldwide.

Classrooms require adaptive and dynamic lighting conditions to accommodate different learning activities [8]. The Chartered Institution of Building Services Engineers recommends an illuminance range of 250-500 lux in working environments for general classroom tasks. For more demanding activities such as drawing or drafting, the recommended illuminance range is 500-1000 lux, as illuminance levels exceeding 1000 lux may cause discomfort. In a study by Sun et al. [9], various lighting modes were proposed based on different learning contexts, such as science, the arts, self-studying, slideshows, exams, and group teaching, as various tasks have specific illumination requirements. For instance, the recommended minimum illuminance level



for a standard classroom is 350 lux. In contrast, the recommended minimum illuminance levels for classes using slideshow presentations are 100 lux, 200 lux, and 300 lux for seats near the front, middle, and back of the classroom, respectively. In comparison, discussion room and self-study areas, should have uniform illuminance levels of 500 lux.

Although the recommended minimum illuminance level for a standard classroom is 350 lux [9], Kong and Jakubiec [6] reported that lecture halls with an average horizontal illuminance level of approximately 370 lux were deemed too bright, with more than 50% of the students requesting a decrease in lighting. This seemingly contradictory result can be attributed to the diverse tasks conducted in modern classrooms nowadays, such as paperwork and computer work using laptops, mobile phones, and tablets. Therefore, classroom illuminance levels need to consider the types of activities and tasks done. Illuminance levels exceeding 500 lux are suitable for paperwork but excessively bright for computer work. Conversely, illuminance levels of approximately 300 lux are sufficient for computer work but too low for paperwork [10]. Inadequate lighting design when performing various tasks in a classroom setting results in visual discomfort [5].

Various sensing-based Lighting Control Systems (LCSs), mostly employ light and/or motion sensors, have been proposed to control window blinds and dim lamps for visual comfort and energy savings [11]. Shi et al. [12] developed intelligent LCSs with light and infrared sensors featuring three control modes (automatic, timing, and manual) to regulate classroom light intensity within the range of 100 to 300 lux. Luansheng et al. [13] introduced a smart LCS incorporating illuminance sensors placed in various areas within a classroom. The system automatically switches lamps on or off in specific areas to maintain an illumination level between 200 and 500 lux. De Rubeis et al. [14]

proposed a smart LCS that utilizes multiple light and motion sensors strategically placed in classrooms, resulting in a savings of up to 69.6% in energy consumption. Martirano [15] developed integrated LCSs with daylight and motion sensors for light dimming, resulting in an approximately 50% reduction in energy consumption. Suresh et al. [16] introduced LCSs in the classroom, employing grid divisions with motion sensors for automatic appliance control and dynamic light dimming based on student presence, leading to a potential energy consumption reduction of up to 36%. Lee et al. [17] suggested a context-aware LED lighting control system that adjusts lighting based on the current class activity, utilizing occupancy sensors to recognize teacher and student locations and behaviors. A recent iteration of the said systems was introduced by Budhiyanto and Chiou [18], wherein the LCS could adapt to diverse activities and lighting requirements. The said prototype LCS demonstrated an effective energy consumption reduction of 20-80%, depending on the room layout and implementation. However, these studies face several challenges. First, using of multiple light and/or motion sensors in classrooms may result in high costs for sensing devices [19–21]. Second, light levels are controlled based on universal set points and do not align with evolving trends in education, which emphasize interactive and student-centered teaching methods, necessitating flexible lighting controls [22,23]. Finally, despite the provision of context-aware LCSs, these systems have not been implemented in real classrooms and have not been proven to enhance students' visual comfort and satisfaction.

To address the cost concerns of required sensors, recent LCSs have utilized digital cameras as vision sensors to measure luminance levels and illuminance distributions using <sup>8</sup> high dynamic range (HDR) photography since digital cameras are inexpensive and commercially available [24,25]. It offers a measurement capability, allowing for

the rapid and efficient collection of <sup>16</sup> high-resolution luminance data across a wide field of view, a feat unattainable with a luminance meter. Nevertheless, to ensure absolute validity, <sup>8</sup> calibration against a point or area of a dependable standard target using a reliable luminance meter is necessary [26]. Although this approach is not as accurate as using luminance/illuminance meters, this method has acceptable accuracy [27]. Another limitation of the HDRi technique is its requirement for stable conditions during the capturing process. Dynamic lighting <sup>8</sup> changes between differently exposed photographs can compromise the accuracy of the final result [26]. Nevertheless, conventional HDR imaging techniques have been widely accepted and employed as assessment tools in lighting design to measure objective visual comfort [24,28–30]. Objective assessments using HDR images demonstrate a more robust <sup>12</sup> correlation with subjective glare assessments than do current glare prediction models, such as the daylight glare index, daylight glare probability or unified glare rating [4,29]. A shading control strategy using a low-cost camera was explored by Goovaerts et al. [31] to optimize the use of daylight while reducing visual discomfort. In a study by Motamed et al. [28], an LCS employing a digital camera as an HDR vision sensor was developed <sup>17</sup> to reduce energy costs while maintaining visual and thermal comfort. During a long-term experiment conducted in an office building, the LCS was able to successfully reduced energy costs by approximately 48% while maintaining visual comfort for approximately 88% of working hours [32]. Although LCSs effectively reduce energy consumption while maintaining indoor illuminance levels, occupants have expressed a desire to control and override such systems, as multiple instances of occupants overriding the control system were observed [31,33].

This study aims to propose the practical implementation of an LCS with a <sup>6</sup> commercial surveillance camera serving as an HDR vision sensor in classrooms,

accommodating different activities and learning contexts. The goal is to develop an HDRi Surveillance Lighting and Daylighting Control System (HSLDCS) <sup>17</sup> to achieve energy savings while maintaining high visual comfort and satisfaction among students.

Table 1 demonstrates how the proposed system addresses the limitations identified in the previously developed systems.

Table 1. The proposed system is designed to address the limitations of previous systems.

Limitation	Previous system	Proposed system
Utilization of sensors	Multiple light sensors and motion sensors in a classroom [13,15,16].	A surveillance camera is utilized to measure several spots in a classroom.
Brightness setting	Employs or adopts a universal set point, uniform brightness around 300 or 500 lux [12,13].	Several control rules with different brightness ranges based on the learning context.
Application	Simulation or prototype scale [13,17,18].	Real classrooms.

## 2 Method

This study adopted an experimental design in a classroom setting with students as participants, driven by the utilization of the HSLDCS to control window blinds and lamps for optimal environmental illumination. The inclusion of students' feedback was essential for evaluating the HSLDCS performance, ensuring a comprehensive understanding of its effectiveness in real-world classroom scenarios. Several control rules tailored to various learning activities were implemented to regulate <sup>1</sup> the brightness level of the lamps and the angle of the window blinds. Field measurements employing HDR technology were conducted to monitor the performance of the SLSC and environmental illumination. A questionnaire study was carried out to evaluate students' performance and perception.

### 2.1 Experiment setting

The experiment was performed <sup>1</sup> in the RB Building at the National Taiwan University of Science and Technology, Taiwan (25.0133° N, 121.5406° E). A southeast-facing classroom on the 7<sup>th</sup> floor was designated for the field experiment. The classroom had a floor area of 7 m (depth) × 6.5 m (width) and a height of 3 m, resulting in a room depth that was 2.33 times the height. White fabrics were installed to cover the classroom walls, as some of the walls had glass material applied. The classroom had two windows, each measuring 1.7 m (width) × 2 m (height), positioned <sup>1</sup> at a height of 1 m above the floor. The window-to-wall ratio was 32% (Fig. 1).

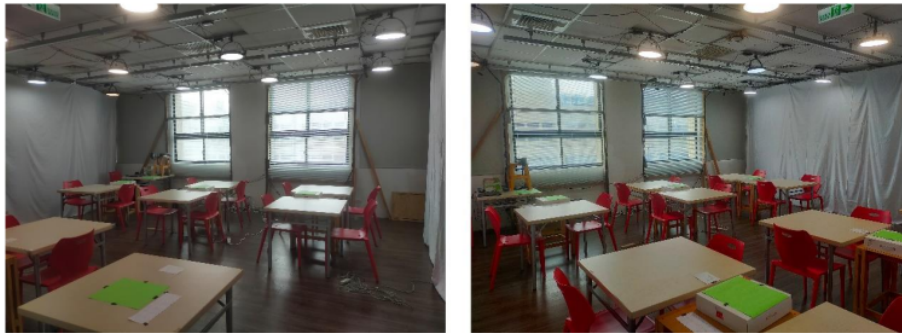


Fig. 1. The classroom setting on the 7<sup>th</sup> floor of RB Building, National Taiwan University of Science and Technology.

The split-blind system consisted of two parts installed on both windows. The upper part measures 0.7 m in height and redirects daylight deeper into the room, while the lower part (1.3 m in height) blocks or allows direct daylight and sunlight near the windows [34,35]. These blinds were operated automatically using an Arduino Uno and continuous MG 996R motor servos.

A total of 16 R-S60B LED soft light dimmable lamps capable of dimming from 10% to 100% were installed in the room. These lamps were equipped with a dimmable DMX driver, which was automatically controlled using an Arduino Uno functioning as the DMX controller. The lamps were arranged in four rows (I-IV) and four columns

(A-D) on the ceiling, as depicted in Fig. 2a. An energy meter was installed in the room to monitor energy consumption.

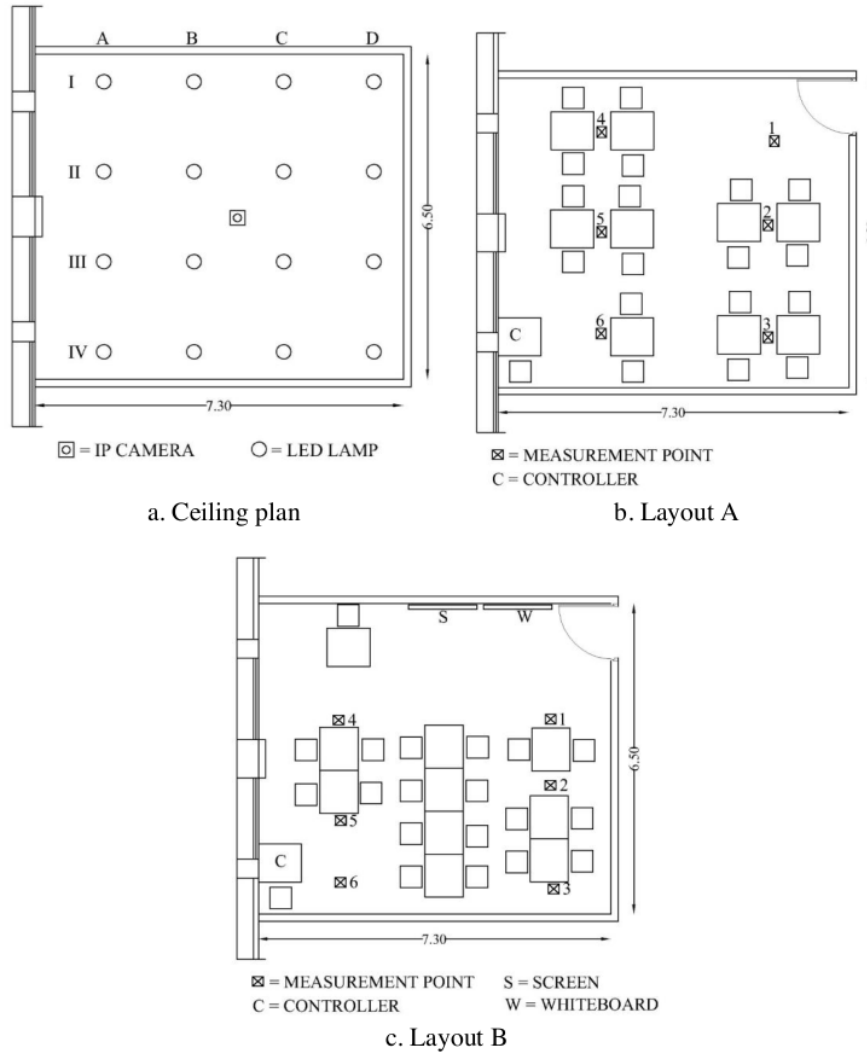


Fig. 2. The ceiling plan (a) and classroom seating layout for group discussion and/or self-study (b) and for slideshow (c).

Two seating layouts (Fig. 2b and c) were adopted to accommodate classroom learning activities, such as slideshow presentations, group discussions, and self-study

sessions. These activities have different lighting needs. For slideshow sessions, minimum illuminance levels of 100 lux, 200 lux, and 300 lux are recommended for the front, middle, and rear seats, respectively. For group discussions and/or self-study sessions, a uniform illuminance level of 500 lux is suggested for the entire area [9].

This study centers on two common learning types in the classroom: discussion and/or self-study activities, and slideshow learning. These learning activities exhibit variations in seating positions, lighting requirements, and learning equipment. Ten classrooms were selected for this study. Classrooms A1 to A5 were designated for discussion and/or self-study activities, following Layout A. Classrooms B1 to B5 were used for slideshow learning, following Layout B. However, Classroom B1 also adopted Layout A as per student preference.

Although the standard illuminance level primarily focuses on paperwork activities [9], it is important to note that both paperwork and computer work have distinct lighting requirements. The illumination for computer work is typically 30-40% less than that for paperwork [6,10]. Due to these differences, corresponding classrooms were configured with different brightness settings despite having the same set of students. These classroom pairs include A1 and A2, A4 and A5, B2 and B3, and B4 and B5. Classrooms A1, A4, B1, B2, and B4 followed the standard illuminance level proposed by Sun et al. [9], while in classrooms A2, A3, A5, B3, and B5, the illuminance level was reduced by 30%. In addition to considering diverse tasks, reducing illuminance levels can potentially enhance energy savings. Table 2 and Fig. A1 (under Appendix A) show the details and conditions used in each classroom.

Table 2. The condition of each classroom.

Classroom	Date, time	Number of students	Age of students	Sky condition
A1	24 April, 13.00-14.30	14; M=9, F=5*	20-35	Overcast
A2	30 April, 13.00-14.30	14; M=9, F=5	20-35	Overcast
A3	10 May, 13.00-14.30	11; M=4, F=7	23-36	Overcast turning clear
A4	11 May, 9.00-10.30	11; M=6, F=5	19-32	Clear
A5	11 May, 10.45-12.15	11; M=6, F=5	19-32	Clear
B1	24 April, 14.45-15.45	14; M=9, F=5	20-35	Overcast
B2	3 May, 9.30-12.00	13; M=4, F=19	23-30	Overcast
B3	10 May, 9.30-12.00	13; M=4, F=19	23-30	Clear
B4	10 May, 13.00-14.30	11; M=6, F=5	19-32	Clear
B5	10 May, 14.45-16.15	11; M=6, F=5	19-32	Clear

Note: \* M = male, F = female

## 2.2 HDR vision sensor

A Vivotek FE8174/74V IP camera, equipped with a 360-degree fish-eye lens, served as the HDR vision sensor. Ten low dynamic range images with different exposures were captured within one minute. These images were combined using the Davebec algorithm [36,37] to create HDRis. To address the limitation associated with the calibration point, real-time calibration based on the HDRi luminance value was performed using a Konica Minolta CS-150 chroma meter (Eq. (1)).

$$L = (0.265 \times R + 0.670 \times G + 0.065 \times B) \times c \quad (1)$$

where  $L$  represents the pixel luminance value ( $\text{cd}/\text{m}^2$ );  $R$ ,  $G$ , and  $B$  represent the spectrally weighted radiance values of the pixel ( $\text{W}/\text{m}^2\text{sr}$ ); the coefficients 0.265, 0.67, and 0.065 were derived from the CIE chromaticity used by Radiance [38]; and the calibration factor ( $c$ ) was determined by dividing the luminance value of the chroma meter by the luminance value at the calibration point.



To correct for the vignetting effect, the correction factor described in Eq. (2) (with  $R^2=0.98$ ) was applied. <sup>25</sup> A Konica Minolta Luminance meter LS-110 luminance meter was used to validate the luminance values obtained from the created HDRis. The HDR measurements collected under various lighting conditions, including more than 160 samples, validated that this technique yields an accuracy <sup>1</sup> range of 5-23% [51], which was deemed acceptable for measurements using commercial products [27,37].

$$y = -5E-12x^4 + 7E-09x^3 - 3E-06x^2 + 0.0005x + 0.9895 \quad (2)$$

Since the IP camera takes one minute to capture the LDRis and generate an HDRi, it is crucial to avoid changes in lighting conditions during this period, such as movement of window blinds and/or dimming of lamps. Consequently, in this system, a 2.5-minute interval is implemented to produce an HDRi, ensuring another one-minute HDRi is generated after any window blinds or lamp dimming changes.

Although Inanici [26] and Pierson et al. [38] recommended midrange gray targets for obtaining luminance values, Kruisselbrink et al. [27] stated that gray targets have a greater error than colored targets for indoor condition measurements. In the initial measurements, the average errors for the gray color compared to the green color were 13.2% and 11.6%, respectively, when the luminance value was less than 25 cd/m<sup>2</sup>. Additionally, the average errors for the gray color compared to the green color were 10.5% and 10.7%, respectively, when the luminance value ranged from 25 to 500 cd/m<sup>2</sup>. Green papers were utilized to measure luminance to accommodate the need for a low-brightness environment in classrooms for slide show presentations.

Six green papers were positioned on the desks to represent the students' working spaces. Additionally, paper was placed on the whiteboard for classrooms that utilized whiteboards (Fig. 2). Papers 1 to 3 were positioned in the area far from the window, while papers 4 to 6 were placed on desks near the window. Papers 1 and 4 were

positioned in the front area, papers 2 and 5 were in the middle area, and papers 3 and 6 were positioned in the back area. The IP camera captured the luminance values of these green papers, and a Konica Minolta Chroma meter CS-150, placed on the controller desk, was used for real-time calibration.

### 2.3 Control system and control rule

The control system framework (Fig. 3) uses an IP camera to capture classroom images to generate HDRis. A chroma <sup>6</sup>meter was used to calibrate the luminance values of each paper extracted from the HDRis. LabVIEW software was used as the control platform to read the calibrated luminance values and determine the window blind angles and LED lamp brightness levels. The Arduino Uno executes these outputs by directly controlling the servo motors to adjust the window blinds and LED lamps, ensuring the desired lighting conditions in the classroom.

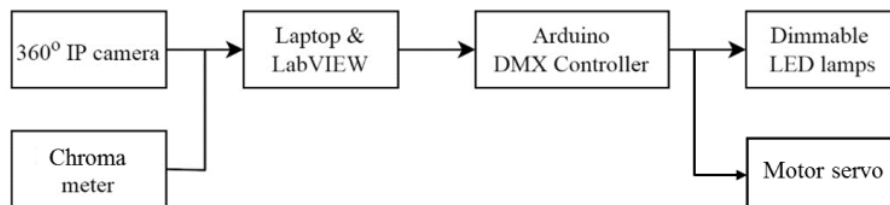


Fig. 3. Control system framework.

Four control rules were established based on selected learning activities (slideshow, group discussion and/or self-study) and the corresponding required brightness levels. Since the reference of the brightness level is mostly based on illuminance values [9], these values should be converted to luminance values. To convert the illuminance values to luminance values, measurements were conducted in

advance<sup>1</sup> using an illuminance meter, a luminance meter, and green paper. Each control rule consists of three parts, except for control rule 4. The first part involves<sup>1</sup> controlling the angle of the window blinds. The default angle of the window blinds is 0° (open). The window blinds can rotate counterclockwise by 45° (half-closed) to block daylight, and when fully closed, the window blinds reach a 90° angle. When low daylight levels are detected, the window blinds rotate by 45° to allow daylight to enter the room (-45° angle). The second part equalizes the brightness level of the area far from the windows with the brightness level of the daylight area by increasing the brightness level of the lamps in the area far from the windows. The final part involves adjusting<sup>1</sup> the brightness levels of the lamps to meet the required luminance level. The first and second parts are not included in control rule 4 because the windows need to be completely blocked to achieve the desired luminance value in the front row.

### 2.3.1 Control rule 1

Control rule 1 was implemented in Classrooms A1 and A4 for discussion and/or self-study activities. The set threshold for closing blinds is 1000 lux (approximately 200 cd/m<sup>2</sup>) [39], and when the illuminance falls below 500 lux (approximately 200 cd/m<sup>2</sup>), the blinds open and/or the lamp brightness increases [9]. The luminance levels for these classrooms ranged between 100 and 200 cd/m<sup>2</sup>. Control rule 1 is defined as follows:

Part 1

$$X = \begin{cases} \theta_B + 45^\circ, & \text{if } L_4 \vee L_5 \vee L_6 > 200 \text{ cd/m}^2 \wedge \theta_B < 90^\circ \\ \theta_B - 45^\circ, & \text{if } L_4 \vee L_5 \vee L_6 < 100 \text{ cd/m}^2 \wedge \theta_B < -45^\circ \\ \theta_T + 45^\circ, & \text{if } L_1 \vee L_2 \vee L_3 > 200 \text{ cd/m}^2 \wedge \theta_T < 90^\circ \\ \theta_T - 45^\circ, & \text{if } L_1 \vee L_2 \vee L_3 < 100 \text{ cd/m}^2 \wedge \theta_T < -45^\circ \end{cases} \quad (3)$$

Part 2

$$X = \begin{cases} BL_D + 10\%, & \text{if } (L_1 + L_2 + L_3)/3 \times 0.8 < (L_4 + L_5 + L_6)/3 \\ BL_C + 10\%, & \text{if } (L_1 + L_2 + L_3)/3 \times 0.8 < (L_4 + L_5 + L_6)/3 \wedge BL_C < BL_D \end{cases} \quad (4)$$

Part 3

$$X = \begin{cases} BL_A \wedge BL_D + 10\%, & \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_6 < 100 \text{ cd/m}^2 \\ BL_B \wedge BL_C + 10\%, & \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_6 < 100 \text{ cd/m}^2 \wedge BL_C < BL_D \wedge BL_B < BL_A \end{cases} \quad (5)$$

where  $\theta_B$  denotes the bottom blind angle,  $\theta_T$  denotes the top blind angle,  $BL_A$ ,  $BL_B$ ,  $BL_C$ , and  $BL_D$  denote the brightness level of the lamps in columns A, B, C, and D, respectively, and  $L_n$  denotes the luminance value of point n. Points 1 to 3 are the papers placed far from the windows, while points 4 to 6 are the papers placed near the windows. Eq. (3) defines a function in which the angles of the bottom and top window blinds are determined based on different conditions, including luminance measurements ( $L_n$ ) and angles ( $\theta_B$  and  $\theta_T$ ). If any value of  $L_4$  to  $L_6$  is greater than 200  $\text{cd/m}^2$  and  $\theta_B$  is less than  $90^\circ$ ,  $\theta_B$  is increased by  $45^\circ$ . However, if any value of  $L_4$  to  $L_6$  is less than 100  $\text{cd/m}^2$  and  $\theta_B$  is less than  $-45^\circ$ ,  $\theta_B$  is decreased by  $45^\circ$ . If any value of  $L_1$  to  $L_3$  is greater than 200  $\text{cd/m}^2$  and  $\theta_T$  is less than  $90^\circ$ ,  $\theta_T$  is increased by  $45^\circ$ . However, if any value of  $L_1$  to  $L_3$  is less than 100  $\text{cd/m}^2$  and  $\theta_T$  is less than  $-45^\circ$ ,  $\theta_T$  is decreased by  $45^\circ$ .

Each iteration or loop takes 2.5 minutes because the IP camera needs 1 minute to produce HDRi. Whenever the window blind angle or the lamp brightness level changes, another HDRi needs to be produced.

When the luminance at all points is between 100 and 200  $\text{cd/m}^2$ , the movement of the window blinds stops, and the second part of the control rule is executed according to Eq. (4). If the average of  $L_1$  to  $L_3$  multiplied by 0.8 is less than the average of  $L_4$  to  $L_6$ ,  $BL_D$  is increased by 10%. In the next iteration, if the condition still holds,  $BL_C$  increases by 10%. This process continues until the average of  $L_1$  to  $L_3$  is approximately equal to the average of  $L_4$  to  $L_6$ .

Once the control rule determines that any value of  $L_1$  to  $L_3$  is less than  $100 \text{ cd/m}^2$ , the last part of the rule, defined in Eq. (5), is executed. In this case,  $BL_A$  and  $BL_D$  are increased by 10%. In the next iteration, if the same condition still applies, the  $BL_B$  and  $L_C$  increase by 10%.

### 2.3.2 Control rule 2

Control rule 2 was applied in Classrooms A2, A3 and A5. As the brightness level in the room decreased by approximately 30%, the luminance values for these classrooms ranged between  $60$  and  $150 \text{ cd/m}^2$ , or approximately  $300$  and  $750 \text{ lux}$ . Control rule 2 consists of three parts. Part 2 is identical to part 2 of control rule 1, which is described in Eq. (4). However, parts 1 and 3 have slight differences in terms of the luminance values and are defined in Eq. (6) and Eq. (7), respectively:

Part 1

$$X = \begin{cases} \theta_B + 45^\circ, & \text{if } L_4 \vee L_5 \vee L_6 > 150 \text{ cd/m}^2 \wedge \theta_B < 90^\circ \\ \theta_B - 45^\circ, & \text{if } L_4 \vee L_5 \vee L_6 < 60 \text{ cd/m}^2 \wedge \theta_B < -45^\circ \\ \theta_T + 45^\circ, & \text{if } L_1 \vee L_2 \vee L_3 > 150 \text{ cd/m}^2 \wedge \theta_T < 90^\circ \\ \theta_T - 45^\circ, & \text{if } L_1 \vee L_2 \vee L_3 < 60 \text{ cd/m}^2 \wedge \theta_T < -45^\circ \end{cases} \quad (6)$$

Part 3

$$X = \begin{cases} BL_A \wedge BL_D + 10\%, & \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_6 < 60 \text{ cd/m}^2 \\ BL_B \wedge BL_C + 10\%, & \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_6 < 60 \text{ cd/m}^2 \wedge BL_C < BL_D \wedge BL_B < BL_A \end{cases} \quad (7)$$

The first part of this control rule is defined in Eq. (6). If any value of  $L_4$  to  $L_6$  is greater than  $150 \text{ cd/m}^2$  and  $\theta_B$  is less than  $90^\circ$ ,  $\theta_B$  is increased by  $45^\circ$ . On the other hand, if any value of  $L_4$  to  $L_6$  is less than  $60 \text{ cd/m}^2$  and  $\theta_B$  is less than  $-45^\circ$ ,  $\theta_B$  is decreased by  $45^\circ$ . The same conditions are applied to  $\theta_T$  based on the values of  $L_1$  to  $L_3$ .

If the average of  $L_1$  to  $L_3$  are approximately equal to the average of  $L_4$  to  $L_6$  in the second part of the control rule, as shown in Eq. (4), the control rule proceeds to the last part, as described by Eq. (7). In this part, if any value of  $L_1$  to  $L_3$  is less than  $60 \text{ cd/m}^2$ ,

$BL_A$  and  $BL_D$  increase by 10%. In the next iteration, if the same conditions still hold,  $BL_B$  and  $BL_C$  increase by 10%.

### 2.3.3 Control rule 3

Control rule 3 was applied in Classrooms B1, B2, and B4 for slide-show learning. The minimum luminance values for these classrooms are set at 100 lux (approximately 20  $\text{cd/m}^2$ ) for the first seats, 200 lux (approximately 40  $\text{cd/m}^2$ ) for the middle seats, and 300 lux (approximately 60  $\text{cd/m}^2$ ) for the rear seats, maintaining a contrast ratio of approximately 1:2:3. Consequently, the brightness level of the lamps above those seats increases when the luminance on the corresponding seat falls below the specified threshold. As the maximum threshold allowed in the class is 200  $\text{cd/m}^2$ , to ensure that the contrast ratio does not exceed 1:2:3, the maximum luminance values for the first seat, middle seat and back seat are set at 50  $\text{cd/m}^2$ , 100  $\text{cd/m}^2$ , and 200  $\text{cd/m}^2$ , respectively. The blinds were controlled based on the luminance values of the first seat, requiring it to be darker than the other seats. The blinds open if the luminance value is less than 20  $\text{cd/m}^2$  and close if the luminance value exceeds 50  $\text{cd/m}^2$ . Control rule 3 is defined as follows:

Part 1

$$X = \begin{cases} \theta_B + 45^\circ, & \text{if } L_4 > 50 \text{ cd/m}^2 \wedge \theta_B < 90^\circ \\ \theta_B - 45^\circ, & \text{if } L_4 < 20 \text{ cd/m}^2 \wedge \theta_B < -45^\circ \\ \theta_T + 45^\circ, & \text{if } L_1 > 50 \text{ cd/m}^2 \wedge \theta_T < 90^\circ \\ \theta_T - 45^\circ, & \text{if } L_1 < 20 \text{ cd/m}^2 \wedge \theta_T < -45^\circ \end{cases} \quad (8)$$

Part 2

$$X = \begin{cases} BL_D + 10\%, & \text{if } (L_1 + L_2 + L_3)/3 \times 0.8 < (L_4 + L_5 + L_6)/3 \wedge L_w \neq 0 \\ BL_C + 10\%, & \text{if } (L_1 + L_2 + L_3)/3 \times 0.8 < (L_4 + L_5 + L_6)/3 \wedge BL_C < BL_D \wedge L_w \neq 0 \\ BL_{DII} \wedge BL_{DIII} \wedge BL_{DIV} + 7\%, & \text{if } (L_1 + L_2 + L_3)/3 \times 0.8 < (L_4 + L_5 + L_6)/3 \\ BL_{CII} \wedge BL_{CIII} \wedge BL_{CIV} + 10\%, & \text{if } (L_1 + L_2 + L_3)/3 \times 0.8 < (L_4 + L_5 + L_6)/3 \wedge BL_{CII} < BL_{DII} \end{cases} \quad (9)$$

Part 3

$$X = \begin{cases} BL_{IV} + 10\%, & \text{if } L_3 \vee L_6 < 60 \text{ cd/m}^2 \\ BL_{III} + 10\%, & \text{if } L_2 \vee L_5 < 40 \text{ cd/m}^2 \\ BL_{II} + 10\%, & \text{if } L_1 \vee L_4 < 20 \text{ cd/m}^2 \\ BL_{CI} \wedge BL_{DI} + 10\%, & \text{if } L_w \neq 0 \wedge L_w < 30 \text{ cd/m}^2 \end{cases} \quad (10)$$

In control rule 3, the movement of the window blinds is based on  $L_1$  or  $L_4$ , both of which are placed in the front row since they represent the darkest area.  $\theta_B$  is increased by  $45^\circ$  if  $L_4$  is greater than  $50 \text{ cd/m}^2$  and  $\theta_B$  is less than  $90^\circ$ . Conversely, if  $L_4$  is less than  $20 \text{ cd/m}^2$  and  $\theta_B$  is less than  $-45^\circ$ ,  $\theta_B$  is decreased by  $45^\circ$ . Similarly,  $\theta_T$  is changed based on  $L_1$ , as shown in Eq. (8).

The second part of this control rule, shown in Eq. (9), is similar to the second parts of control rules 1 and 2 if a whiteboard is used in the classroom ( $L_w \neq 0$ ). However, if a whiteboard is not used, only  $BL_{DII}$ ,  $BL_{DIII}$ , and  $BL_{DIV}$  increase by 10%. Then,  $BL_{CII}$ ,  $BL_{CIII}$ , and  $BL_{CIV}$  are increased by 10% in the next iteration. This process is repeated until the average of  $L_1$  to  $L_3$  are approximately equal to the average of  $L_4$  to  $L_6$ . In this case,  $BL_{DI}$  and  $BL_{CI}$ , which are placed in the first row, remain turned off.

The last part of the control rule, represented by Eq. (10), determines the lamp brightness levels based on the locations of the seats. In the back row, if  $L_3$  and/or  $L_6$  is less than  $60 \text{ cd/m}^2$ , the brightness levels of the lamps in row IV ( $BL_{IV}$ ) increase by 10%. Then, the luminance value of the middle row is examined, and if  $L_2$  and/or  $L_5$  is less than  $40 \text{ cd/m}^2$ , the brightness levels of the lamps in row III ( $BL_{III}$ ) increase by 10%. Finally, in the front row, if  $L_1$  and/or  $L_4$  is less than  $20 \text{ cd/m}^2$ , the brightness levels of the lamps in row II ( $BL_{II}$ ) increase by 10%.

When a whiteboard is utilized in the classroom,  $BL_{CI}$  and  $BL_{DI}$  increase by 10% if  $L_w$  on the whiteboard is less than  $30 \text{ cd/m}^2$ . Considering that the measured luminance value of the projector screen or TV used in the classrooms is approximately  $90\text{-}120 \text{ cd/m}^2$ , the luminance ratio between the projection screen and the whiteboard is set to 3 to 1 [4].

#### 2.3.4 Control rule 4

In classroom control rule 3, even when Venetian window blinds are closed and the blind angle is  $90^\circ$ , the blinds cannot completely block daylight, resulting in a higher luminance in the front area. To address this issue and reduce the overall brightness level in the room by approximately 30% of the brightness level in Classrooms B1, B2, and B4 (ranging from 15 to 30  $\text{cd/m}^2$  for the front seats, 25 to 60  $\text{cd/m}^2$  for the middle seats, and 40 to 150  $\text{cd/m}^2$  for the rear seats), the existing thick roller blind shading devices are used to block the windows in the classrooms implementing control rule 4. As a result, control rule 4 is simplified and includes only one part, as shown in Eq. (11):

$$X = \begin{cases} BL_{IV} + 10\%, \text{ if } L_3 \vee L_6 < 30 \text{ cd/m}^2 \\ BL_{III} + 10\%, \text{ if } L_2 \vee L_5 < 25 \text{ cd/m}^2 \\ BL_{II} + 10\%, \text{ if } L_1 \vee L_4 < 15 \text{ cd/m}^2 \\ BL_{CI} \wedge BL_{DI} + 10\%, \text{ if } L_w \neq 0 \wedge L_w < 30 \text{ cd/m}^2 \end{cases} \quad (11)$$

In control rule 4,  $L_3$  and  $L_6$  are examined first. When either  $L_3$  or  $L_6$  is less than 30  $\text{cd/m}^2$ , the brightness levels of the lamps in row IV ( $BL_{IV}$ ) increase by 10%. Subsequently, if  $L_2$  and/or  $L_5$ , located in the middle of the room, are less than 25  $\text{cd/m}^2$ , the brightness levels of the lamps in row III ( $BL_{III}$ ) increase by 10%. Finally, if  $L_1$  and/or  $L_4$ , located in the front row, are less than 15  $\text{cd/m}^2$ , the brightness levels of the lamps in row II ( $BL_{II}$ ) increase by 10%. Additionally, if the classroom utilizes a whiteboard ( $L_w \neq 0$ ), the  $BL_{CI}$  and  $BL_{DI}$  increase by 10% only if  $L_w$  at the whiteboard is less than 30  $\text{cd/m}^2$ .

The maximum brightness level of the lamps is set to 50%. This limitation is imposed to ensure that the area under the lamps does not exceed a luminance value of 200  $\text{cd/m}^2$  (illuminance= 1000 lux), as recommended by IESNA [40], to prevent visual discomfort.



## 2.4 Field measurements

Field measurements were conducted using a Konica Minolta LS-110 luminance meter and HDRi photography. The HDR images were used to analyze the lighting conditions in the classrooms. An Olympus OM-D-E-M5II DSLR camera with a Laowa MFT 4 mm F2.8 210° circular fisheye lens captured ten low-dynamic range images with various exposures. A tripod was used to ensure image stability. The camera was positioned at a height of approximately 1.2 meters, matching the perspective of a seated student. A luminance meter was used to measure the luminance levels at the designated locations to calibrate the HDRis. Fig. 4 shows the camera positions for capturing different scenes. The images and measurements were collected during class breaks to minimize lecture disruptions. In addition to the lighting condition measurements, an energy meter was used to measure and monitor the energy consumption during the experiments.

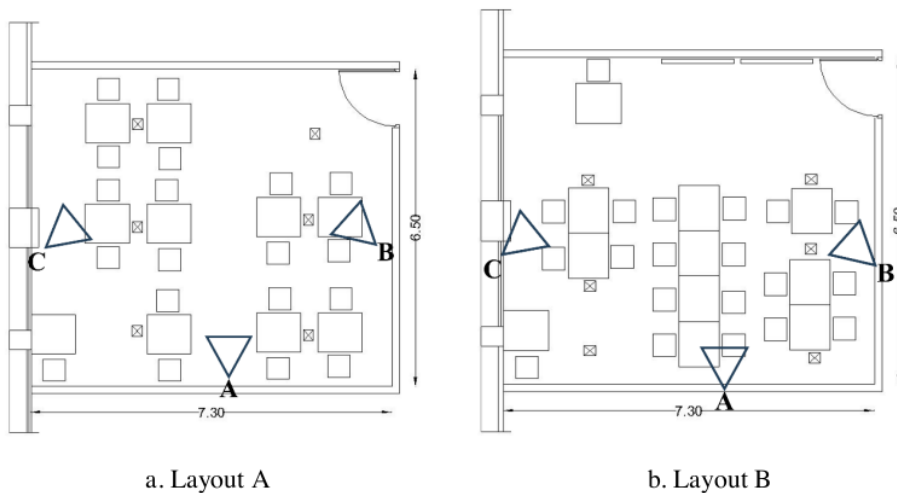


Fig. 4. The positions of capturing HDRi photographs.

## 2.5 Questionnaire survey

Considering the limitation of the IP camera as HDR vision sensor, a four-part questionnaire survey was conducted to assess the students' learning performance and visual comfort in the classrooms [4]. To ensure inclusivity for respondents who primarily use <sup>1</sup> Mandarin Chinese as their language, Chinese translations were provided alongside each question. The questionnaire was created using Google Forms and administered online. Before the class started, the students were given instructions on how to complete the questionnaire. The participants were then provided with an opportunity to fill out the online questionnaires during the class break or before the class ended. The full questionnaire is presented in Appendix B.

### 2.5.1 Part A. Physiological symptoms

Part A of the survey was used to collect information about the physiological symptoms that participants may have experienced. It consisted of six "yes or no" questions. Each question addressed a specific symptom, including <sup>1</sup> dry eyes, heavy eyes, strained and sore eyes, slight headache, continuous blinking, and a dazzled feeling. While physical symptoms do not always indicate discomfort [4,41], this section aimed to assess the number of individuals who experienced physical symptoms and examine any associations between symptom occurrence and varying lighting conditions.

### 2.5.2 Part B. <sup>1</sup> Visual annoyance and task performance

Part B of the survey focused on users' performance and the disturbances they may have experienced during the lecture sessions. The questions were divided into several categories: <sup>1</sup> receiving information through the projector/TV, receiving information through the whiteboard, reading, writing at the desk, using laptops/mobile

phones/tablets, and task switching based on the understanding that classroom users must consistently concentrate on multiple working surfaces. For each question, respondents were required to provide a numerical response on a scale ranging from -2 (lowest satisfaction) to 2 (highest satisfaction).

#### 2.5.3 Part C. Student perception

Part C of the survey was used to examine the respondents' perceptions and preferences regarding the lighting conditions in the classroom. This part consisted of five questions that addressed various aspects of the classroom environment, including room brightness, projector brightness, window blinds, and lamp settings. The objective of this section was to collect feedback based on the participant's satisfaction with the existing classroom environment, particularly the implemented HSLDCS.

#### 2.5.4 Part D. Overall student experience

Part D of the survey was used to evaluate the respondents' overall visual comfort and satisfaction in the classroom. The questions aimed to assess the participants' comfort level while utilizing the space and determine the primary factors contributing to discomfort and dissatisfaction.

### 2.6 Data analysis process

#### 2.6.1 Lighting conditions in the classrooms

Throughout the experiments, the luminance values were documented by the IP camera and subsequently utilized to analyze the lighting conditions in the classrooms. A box plot was generated to represent those values. Given that the luminance values

fluctuate due to the influence of daylight and because the HSLDCS require time to adjust the blinds and lamps—typically requiring approximately twenty minutes depending on daylight conditions—the mode values of the recorded data were used. As the mode <sup>15</sup> represents the most frequently occurring value in the dataset, it provides a measure of central tendency for the data [42]. This approach aimed to reduce data bias during the adjustment period.

The adjustment time for each classroom was documented as the HSLDCS needed time to adjust the window blind angles and lamp brightness levels. Following the adjustments, the angles of the top and bottom window blinds, along with <sup>1</sup> the brightness levels of the lamps in each classroom, were represented to illustrate how the HSLDCS adapted to various sky conditions and learning contexts.

#### 2.6.2 HDR images and glare analysis

The HDRis captured during the field measurements were subsequently processed using HDRshop software and calibrated using HDRscope software, which was developed to analyze HDR images <sup>19</sup> [43]. The false color false images were used to provide visual representations of the luminance distribution in the classrooms, and a <sup>1</sup> glare analysis was performed using the Evalglare program integrated into HDRscope. Glare analysis was employed to evaluate the sensation of glare in the classrooms utilizing <sup>5</sup> the daylight glare probability (DGP) and unified glare rating (UGR) metrics. The DGP was chosen for its accuracy in predicting the subjective perception of daylighting glare [5,7], whereas the <sup>1</sup> UGR is the CIE glare index specifically designed for indoor lighting, making it more suitable for such environments [4,44]. Table 3 presents the degrees of DGP and UGR [45].

Table 3. Degree of glare in DGP and UGR.

Degree of perceived glare	Imperceptible	Perceptible	Disturbing	Intolerable
DGP	< 0.35	0.35–0.40	0.40–0.45	> 0.45
UGR	< 13	13–22	22–28	> 28

### 2.6.3 Energy saving analysis

The energy consumption was subsequently measured during the experiments compared to the baseline conditions. In the baseline conditions for Classrooms A1 to A5, all 16 lamps were used at 40% brightness, matching the illuminance levels of the classrooms at approximately 500 lux [39]. For Classrooms B1 to B5, the baseline condition involved turning off the lamps in the first row and using the remaining 12 lamps at 40% brightness, reflecting the typical classroom usage pattern for slide show presentation [4]. As the lesson times varied for each class, the energy consumption was measured to correspond to the duration of each class (Table 4).

Table 4. The baseline energy consumption of each classroom.

Classroom	Duration (hour)	Baseline (kWh)
A1 – A5	1.5	580
B1	1	290
B2 , B3	2.5	720
B4, B5	1.5	435

### 2.6.4 Questionnaire analysis

Percentage analysis was employed to analyze the questionnaire, except for Part B. For Part B of the survey, mean value analysis was conducted to assess students' comfort levels while performing various tasks in a classroom setting.

## 3 Results

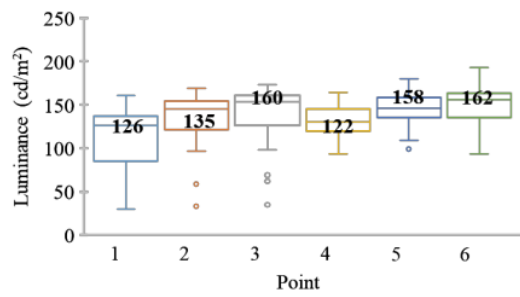
### 3.1 Lighting environment in the classrooms

The HSLDCS performance was analyzed by recording the luminance values in each classroom. Fig. 5 presents the recorded luminance values and the measures of central tendency for each measurement point. The recorded luminance values indicate that the system is generally effective at maintaining the desired lighting conditions in classrooms. For Classrooms A1 and A5, which implemented control rule 1, the mode values suggest that the HSLDCS successfully maintain luminance values between 100 and 200  $\text{cd/m}^2$ , as intended. Similarly, for Classrooms A2, A3, and A4, which implemented control rule 2, the mode values indicate that the HSLDCS effectively maintain the luminance values within the range of 60 to 150  $\text{cd/m}^2$ , except for  $L_5$ , which exceed 150  $\text{cd/m}^2$ . Additionally,  $L_5$  in Classrooms A3, A4, and A5 are greater than those at the other points.

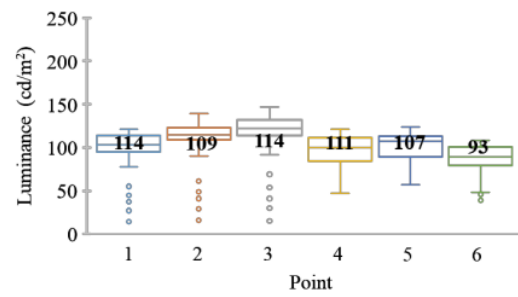
In the classrooms implementing control rule 3, <sup>13</sup>the luminance values of the front, middle, and rear areas were mainly observed to be within the ranges of 20 to 40  $\text{cd/m}^2$ , 40 to 70  $\text{cd/m}^2$ , and 60 to 100  $\text{cd/m}^2$ , respectively. For classrooms implementing control rule 4, <sup>13</sup>the luminance values of the front, middle, and rear areas were primarily within the ranges of 15 to 25  $\text{cd/m}^2$ , 25 to 60  $\text{cd/m}^2$ , and 50 to 70  $\text{cd/m}^2$ , respectively. Despite the brightness contrast for the first, middle, and rear seats, the brightness contrast in all the classrooms exceeded a ratio of 1:2:3. The relatively small size of the classrooms and the close proximity of the seats contributed to the excessive contrast in brightness, as the lamps not only illuminate the seats directly below them but also affect the surrounding seats. Moreover, in classrooms utilizing a whiteboard,  $L_1$  (which is associated with the whiteboard area) tends to be higher than the required value because lamps CI and DI are used to illuminate the whiteboard and maintain <sup>1</sup>a luminance value of approximately 30  $\text{cd/m}^2$ .

The observed differences in luminance between points near the windows and points far from the windows in certain classrooms indicate potential weaknesses in the HSLDCS control rules. In Classrooms A3, A4, and A5, L<sub>4</sub>, L<sub>5</sub>, and L<sub>6</sub> (near the windows) were noticeably greater than L<sub>1</sub>, L<sub>2</sub>, and L<sub>3</sub> (far from the windows), particularly the luminance value of point 5. This can be attributed to the sudden change in sky conditions from overcast to clear at approximately 13:40 after parts 1 and 2 of the control rules were executed. This indicates that the existing control rules may not effectively address the variability in daylight conditions. In contrast, in Classroom A2, L<sub>1</sub>, L<sub>2</sub>, and L<sub>3</sub> were slightly greater than L<sub>4</sub>, L<sub>5</sub>, and L<sub>6</sub>. This finding suggested that the control rules implemented in this classroom may not adequately adjust the lighting levels in areas near the windows to match those in areas far from the windows. Similarly, in Classrooms B1, B2, and B4, L<sub>3</sub> was higher than L<sub>6</sub>. This discrepancy indicates a weakness in the control rules, as they may not effectively account for the variations in daylight conditions and thus fail to maintain equal lighting levels between areas near and far from windows.

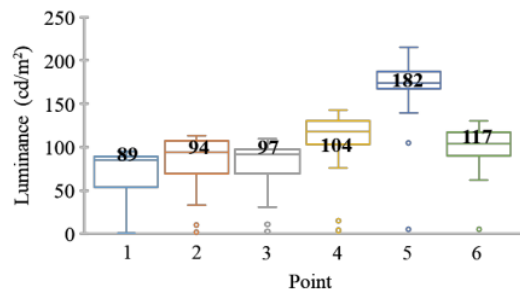
The calibrated HDRis and false color images visually representation the classroom luminance distribution. A 500 cd/m<sup>2</sup> scale is employed to render false color images (Fig. 6). The images show that Classrooms A1 to A5 generally have higher luminance values than Classrooms B1 to B5. For classrooms with whiteboards and projection screens, the projection screen can be clearly observed in Classroom B1, which did not have a whiteboard. In classrooms with whiteboards or TV screens, false color images show distinguishable colors for the whiteboard and TV screen, although the clarity varies. Compared to classrooms B2 and B4, the whiteboards in classrooms B3 and B5 are more clearly visible.



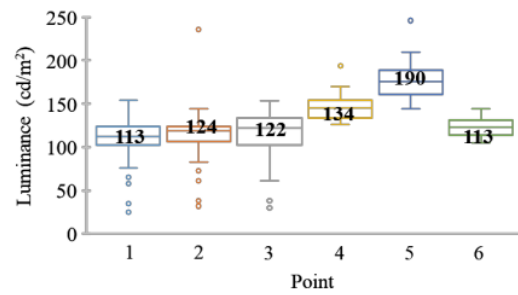
a. Classroom A1



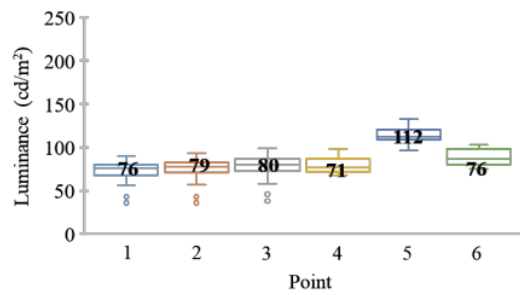
b. Classroom A2



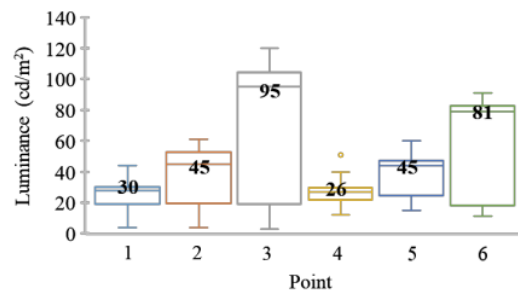
c. Classroom A3



d. Classroom A4



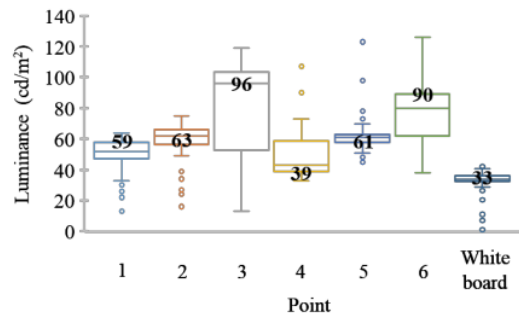
e. Classroom A5



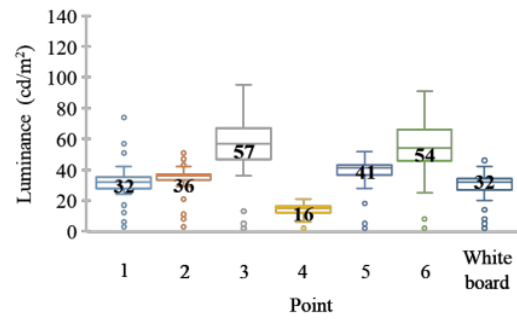
f. Classroom B1

Fig. 5. The luminance and mode value of measurement points of each classroom

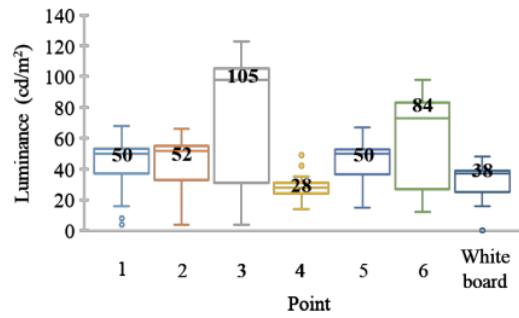




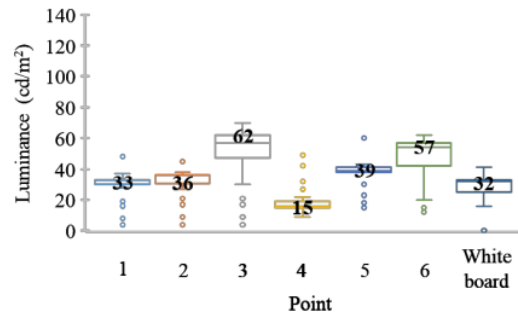
g. Classroom B2



h. Classroom B3



i. Classroom B4



j. Classroom B5

Fig. 5. The luminance and mode value of measurement points of each classroom (continued).

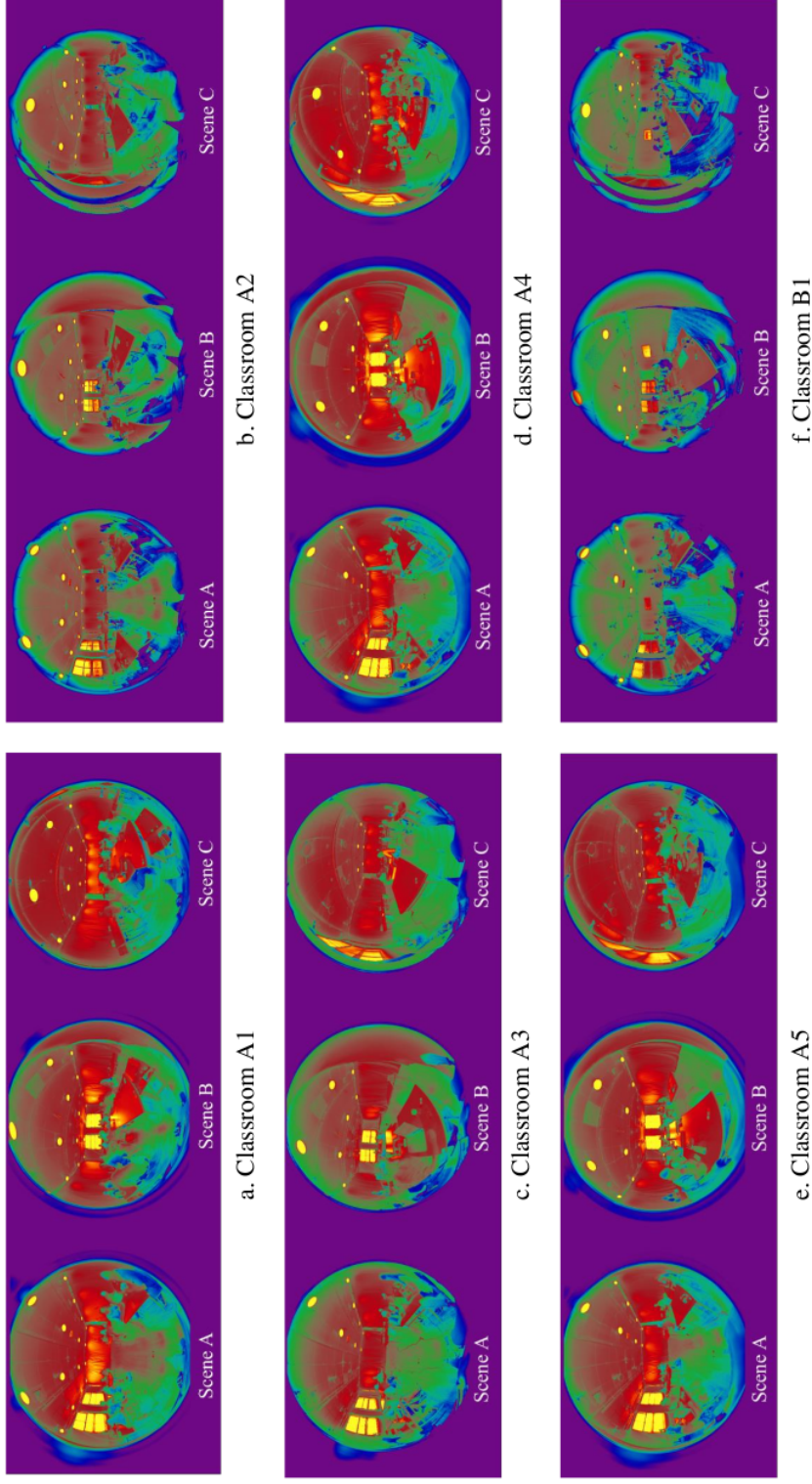


Fig. 6. The false color images of each classroom in scales 500 cd/m<sup>2</sup> for three different scenes.

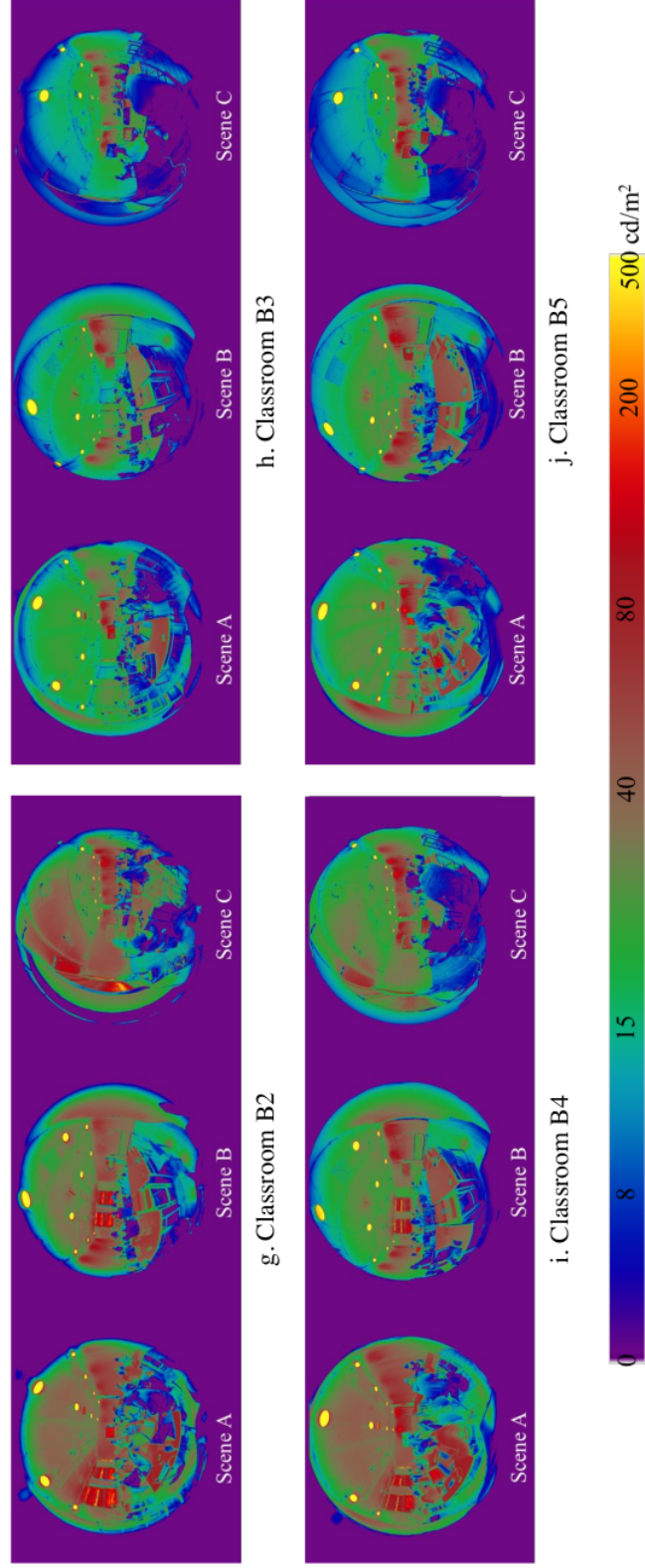


Fig. 6. The false color images of each classroom in scales 500  $\text{cd}/\text{m}^2$  for three different scenes (continued).

As the classroom faces southeast, it receives more daylight in the morning than in the afternoon under clear-sky conditions. In the morning, the daylight intensity gradually increases until it reaches its peak at approximately 11:45, after which it gradually decreases in the afternoon. The angles of the window blinds and <sup>1</sup> brightness levels of the lamps are adjusted to optimize the control of daylight conditions. Consequently, diverse classroom schedules and sky conditions affect both blinds and lamps, as well as the adjustment time for these elements. The adjustment time for each classroom is outlined in Table 5. The average adjustment time for classrooms utilized for discussion and/or self-study was 20 minutes, while those used for slide show presentations required an average adjustment time of 30 minutes.

Table 5. The adjustment time in each classroom.

Classroom	Adjustment time (minutes)
A1	25
A2	25
A3	20
A4	23
A5	14
B1	32
B2	38
B3	24
B4	35
B5	24

Fig. 7 shows the brightness levels of the lamps on the ceiling plan and the angles of the top and bottom window blinds after adjustment. These values remained consistent throughout the class duration. In Classrooms B3 and B5, the windows are blocked using existing shading devices, and only artificial lighting is used in these classrooms; therefore, window blind angles are not applicable, <sup>1</sup> and the brightness levels of the lamps are the same (Fig. 7h).

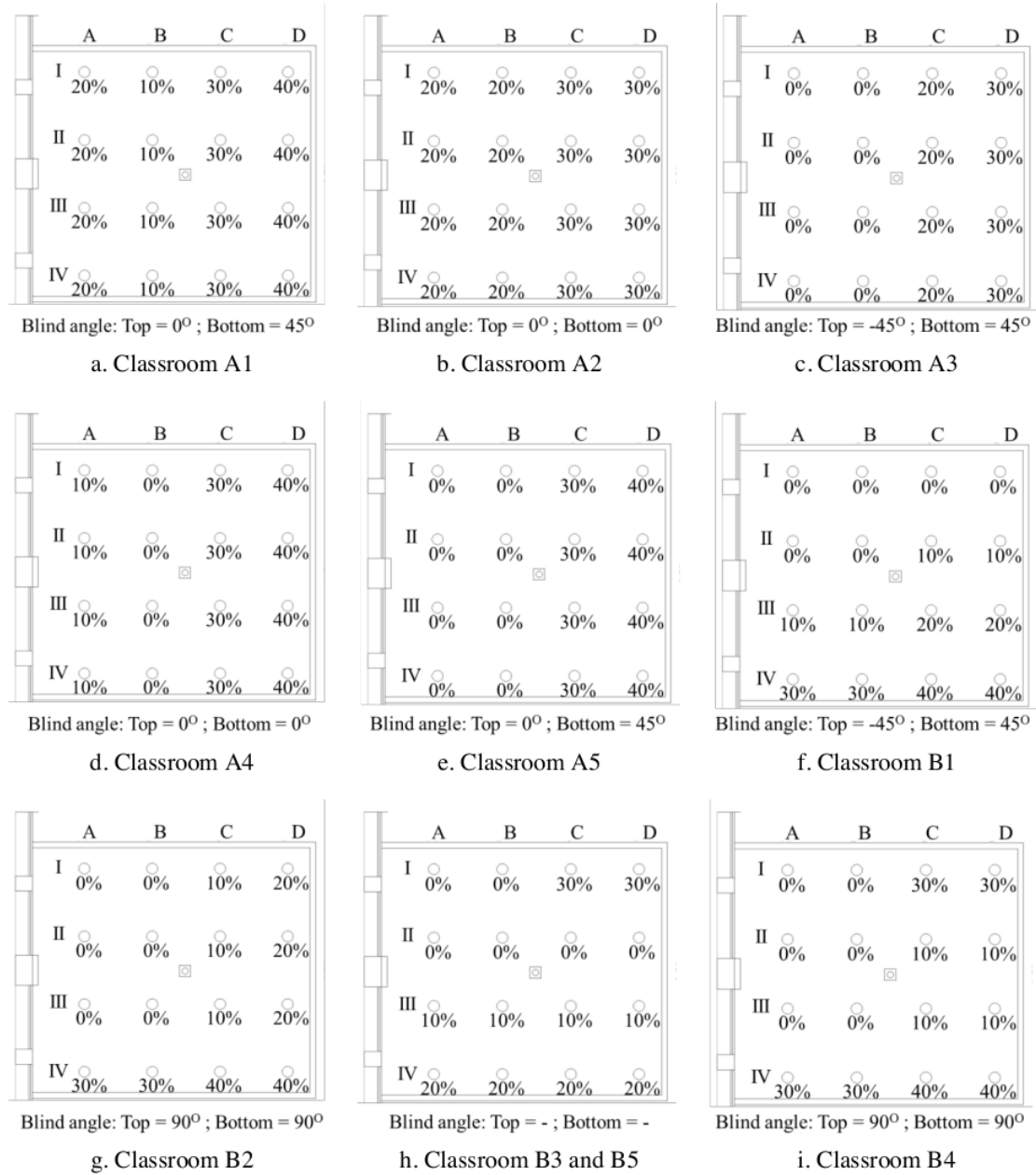


Fig. 7. The brightness level of the lamps and angles of window blinds in each classroom.

In Classrooms A1 and A4, which were designed for discussion and/or self-study and implemented the same control rule, variations were observed based on different

schedules and sky conditions. In Classroom A1, the class begins with half-closed bottom window blinds due to abundant daylight near the windows (Fig. 7a). The brightness of the lamps near the window surpasses that of Classroom A4 (Fig. 7d) because the sky is not clear, and the daylight intensity gradually decreases. Classroom A4, scheduled in the morning, starts with fully open window blinds, resulting in initially lower lamp brightness near the windows. However, the luminance values near the window gradually increase over time, although they do not exceed the specified requirements.

In classrooms implementing control rule 2, Classrooms A2 and A3 had the same schedule but different sky conditions. For Classroom A2, the sky is overcast during the class, leading to fully open window blinds and lamps on columns A and B turning on at a 20% brightness level (Fig. 7b). In Classroom A3, the angles of the top and bottom window blinds are  $-45^{\circ}$  and  $45^{\circ}$ , respectively; at the beginning of the class, the sky is cloudy. However, it suddenly changes to clear, resulting in the lamps on columns A and B remaining turned off (Fig. 7c). In Classroom A5, which was scheduled in the morning, the bottom part of the window blinds was half closed, and the lamps near the windows were turned off due to the high-intensity daylight in that area (Fig. 7e).

In classrooms designated for slide show presentations, Classrooms B2 and B4 share nearly similar settings for window blinds and lamp brightness levels, as both top and bottom window blinds are closed to avoid the excessive daylight (Fig. 7g and i). Although both Classrooms B1 and B4 are scheduled in the afternoon, Classroom B1 operates under the overcast sky conditions, resulting in differing angles for the top and bottom window blinds, set at  $-45^{\circ}$  and  $45^{\circ}$ , respectively (Fig. 7f). For Classrooms B3 and B5, which rely solely on artificial lighting, the brightness levels of the lamps remain consistent across both classrooms (Fig. 7h).

### 3.2 Glare analysis

The results of the glare analysis, represented by DGP and UGR, are presented in Fig. 8. . In Classrooms A1 to A5, all DGP values are less than 0.25, indicating imperceptible daylight glare. Some scenes exhibit very low DGP values, particularly scene C, indicating low vertical illuminance and potential underestimation of glare sources. The UGR values in scenes A and B ranged from 22 to 28, suggesting that the artificial lamps caused a disturbing glare. However, Classroom A2 had lower UGR values (13-22), indicating lower glare perception. Only scene C in Classrooms A3 and A5 had UGR values less than 13, indicating imperceptible glare (Fig. 8a-e). In Classrooms B1 to B5, all DGP values are less than 0.02, indicating no significant daylight glare. The UGR values generally indicate perceptible glare caused by artificial lighting, except for scene C in Classrooms B2 and B4, where the UGR values are less than 13, indicating imperceptible glare (Fig. 8f-j).

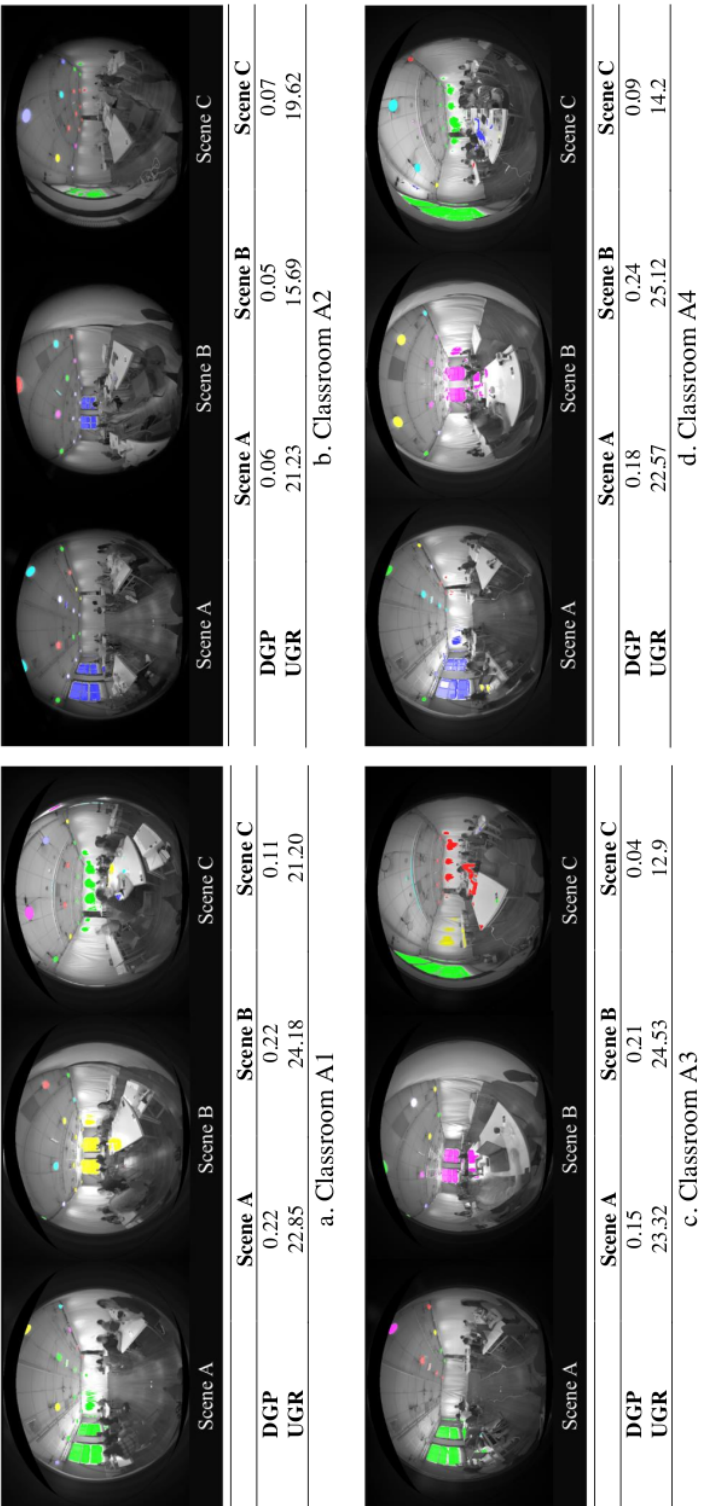
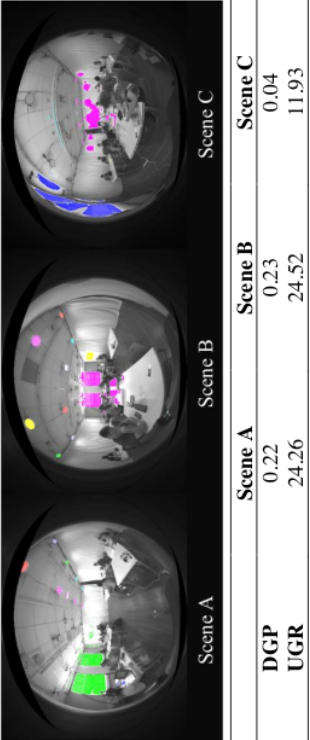
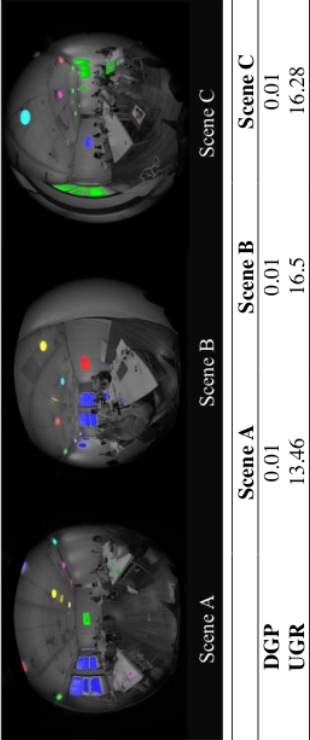


Fig. 8. Glare analysis of each classroom for three different scenes.

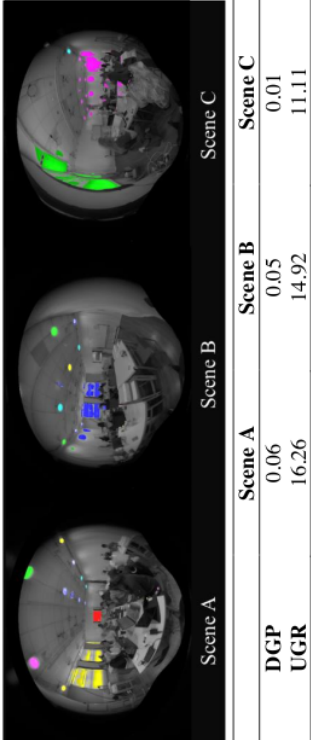




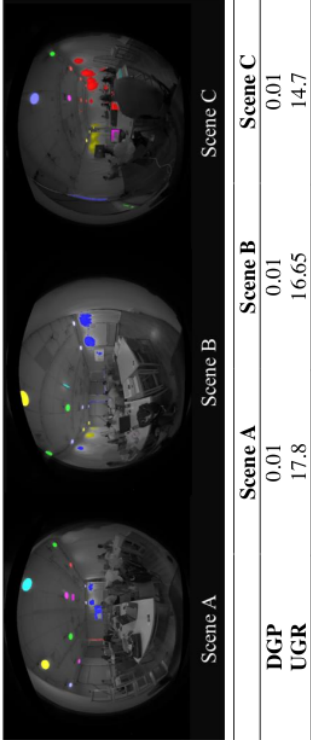
e. Classroom A5



f. Classroom B1



g. Classroom B2



h. Classroom B3

Fig. 8. Glare analysis of each classroom for three different scenes (continued).

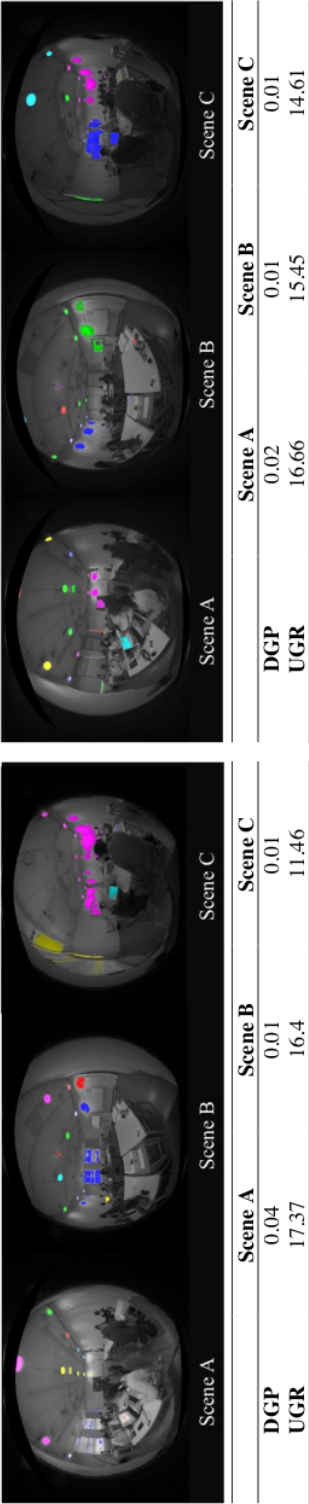


Fig. 8. Glare analysis of each classroom for three different scenes (continued).

### 3.3 Energy savings

Table 6 presents the energy savings achieved by implementing the HSLDCS in each classroom. After the HSLDCS is implemented, energy savings ranging from 43.10% to 63.28% are achieved, depending on daylight availability and the specific control rule used.

Table 6. The energy savings of the classroom by implementing HSLDCS

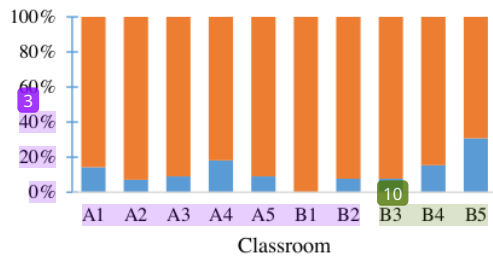
Classroom	Duration (hour)	HSLDCS (kWh)	Baseline (kWh)	Energy saving (%)
A1	1.5	330	580	43.10
A2	1.5	322	580	44.48
A3	1.5	213	580	63.28
A4	1.5	250	580	56.90
A5	1.5	226	580	61.03
B1	1	110	290	62.07
B2	2.5	345	720	52.08
B3	2.5	317	720	55.97
B4	1.5	205	435	52.87
B5	1.5	160	435	63.22

### 3.4 Questionnaire analysis

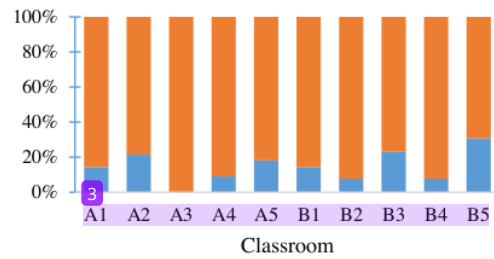
#### 3.4.1 Part A. Physiological Symptoms

The results of Part A of the questionnaire are presented in Fig. 9. The highest percentage of students who reported dry eyes and heavy eyes was 30% (in Classroom B5) (Fig. 9a and b), the highest percentage of students who reported eyestrain was 25% (in Classroom B5) (Fig. 9c), and the highest percentage of students who reported constant blinking was 45% (in Classroom A1) (Fig. 9e). Headaches and dazzled feelings were reported by less than 10% and 20% of the students, respectively, of the students (Fig. 9d and f). Among classrooms with different brightness levels that were attended by the same groups of students, in classrooms set for discussion, those set for discussion had a greater percentage of students experiencing dry eyes, eye strain, and

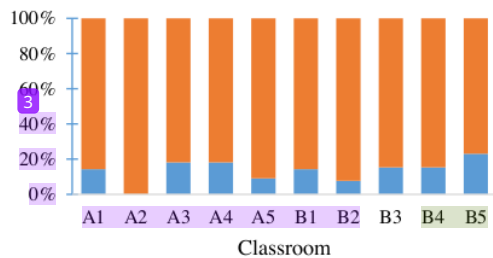
increased blinking in brighter environments. Conversely, in classrooms designated for slide presentations, the percentage of students reporting eye strain is lower in brighter settings. Across all classrooms, students generally tend to feel heavier eyes in darker environments.



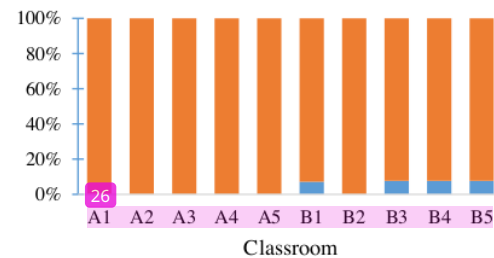
a. Dry eyes



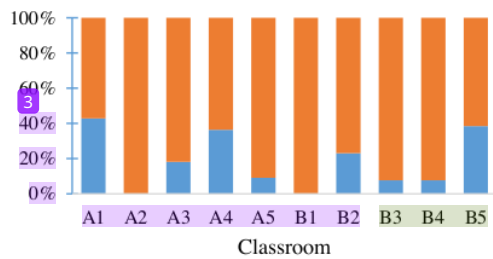
b. Heavy eyes



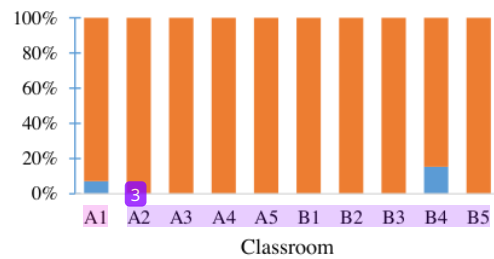
c. Eyestrain



d. Headache



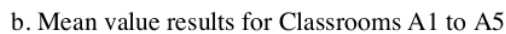
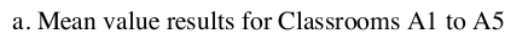
e. Constant blinking



f. Dazed

Fig. 9. The percentage of students that feel physical symptoms during the class.

The resulting mean values, ranging from -2 to 2, are shown in Fig. 10. The mean values for each task were  $> 0$ , indicating that the students tended to be comfortable while achieving satisfactory task performance.



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The question regarding how students adjust their laptops/mobile phones/tablets during class was eliminated from the analysis because some students mentioned that their devices automatically adjusted their brightness levels based on the surrounding environment, providing comfortable brightness levels for their eyes and eliminating the need for manual adjustment.

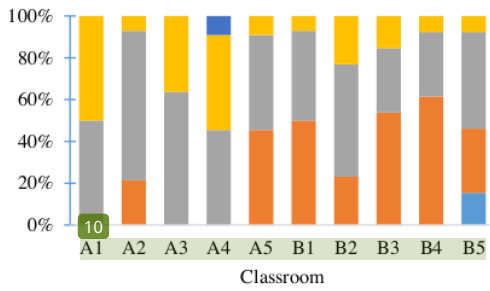
### 3.4.3 Part C. Student perception

In Part C of the questionnaire, students' preferences and opinions were assessed (Fig. 11). Students in Classrooms B1 to B5 felt that the classrooms were slightly darker than those in Classrooms A1 to A5. Among the classrooms with different brightness levels, students noted that Classrooms A1, A4, B2, and B4 were brighter than Classrooms A2, A5, B3, and B5. In Classroom A1, half of the students felt that the classroom was slightly bright, whereas in Classroom A2, only 5% of the respondents felt that the classroom was slightly bright, and approximately 20% felt that the classroom was slightly dark. Similarly, approximately 20% of the students in Classroom B2 felt that the classroom was slightly bright; however, this percentage decreased to 15% in Classroom B3, while the proportion of students who felt that the classroom was slightly dark increased from approximately 20% in Classroom B2 to more than 50% in Classroom B3 (Fig. 11a). For classrooms utilizing projection screens/TVs, more than 50% of the students felt neutral regarding the brightness of the screen/TV. Approximately 10% of the students in Classrooms B1, B2, and B4 reported that the classroom was too bright, while other students (less than 20%) felt that the classroom was slightly dark, except in Classroom B5 (Fig. 11b).

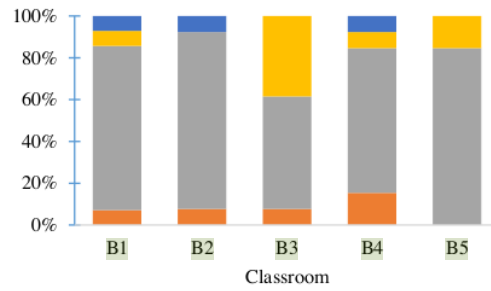
In terms of room lighting satisfaction, all the students in Classrooms A2 and A3 felt neutral and satisfied. Less than 30% of the students felt slightly dissatisfied in Classrooms A1, A4, A5, B1, and B2. In Classroom B3, 40% of the students felt

dissatisfied, while in Classroom B4, the dissatisfaction rate was 20%, and in Classroom B5, it was 60%. The highest number of students who reported feeling dissatisfied was in Classroom B5, while the highest number of students who reported feeling satisfied was in Classroom A3, with over 70% of the students feeling satisfied (Fig. 11c).

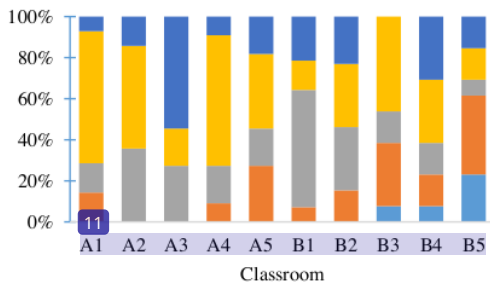
Regarding window blinds and lamp control, more than half of the respondents accepted window blind settings without changing them, except for students in Classrooms A4 and B5. A similar proportion of students accepted the lamp settings in Classrooms A1 to A4 and B1 to B2. Moreover, in Classrooms A1 and A4, which had higher brightness levels due to the HSLDCS, 20% and 10% of the students, respectively, tended to dim from the lights. Conversely, 35% of the students wanted to increase the brightness levels of the lamps in Classroom A2 and 55% in Classroom A5. A similar tendency was observed in Classrooms B3 and B5. In Classroom B3 the number of the students wanting bright lamps was 23% higher than in Classrooms B2 and in Classrooms B5 the number of the students wanting brighter lamps was 8% higher than Classroom B4 (Fig. 11d and e).



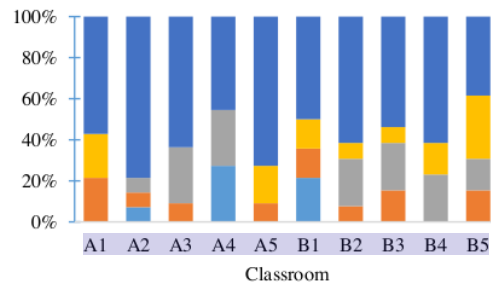
a. Room lighting brightness



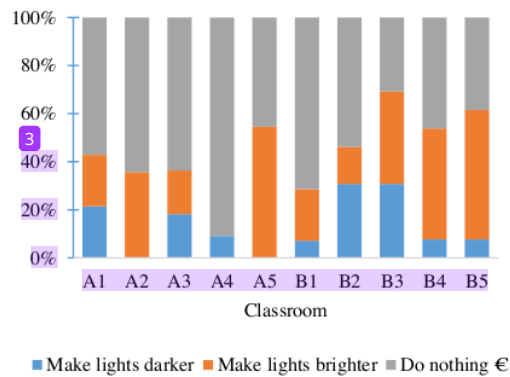
b. Projection screen/ TV brightness



c. Room lighting satisfaction



d. Window blind control



e. Lamp control

Fig. 11. Respondent opinion graph regarding room lighting brightness (a), projection screen brightness (b), room lighting satisfaction (c), and their preferences (d and e).



### 3.4.4 Part D. Overall student experience

The results of Part D of the questionnaire are presented in Fig. 12. Over 70% of the students in each classroom reported feeling comfortable and satisfied with the HSLDCS implemented in the classrooms. Additionally, all the students expressed the importance of visual comfort and satisfaction in supporting the learning process.

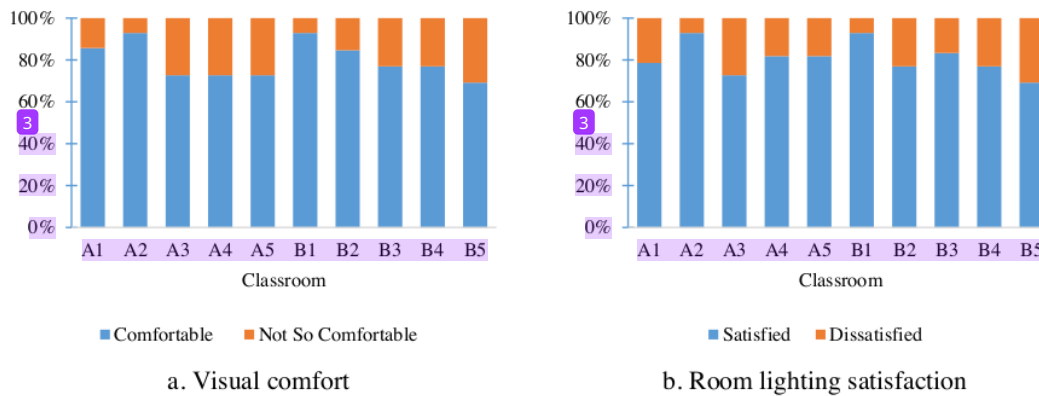
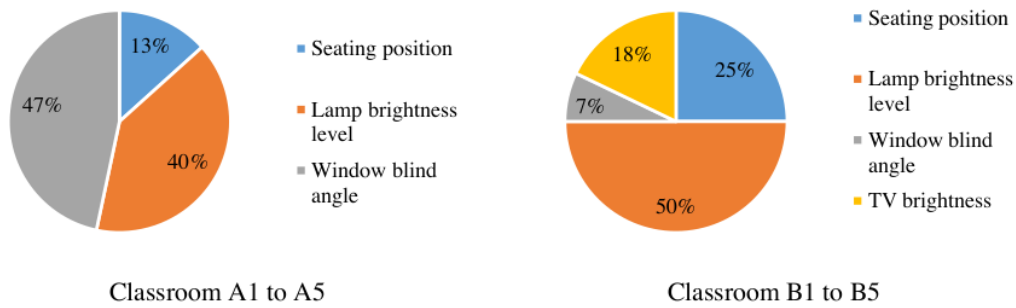
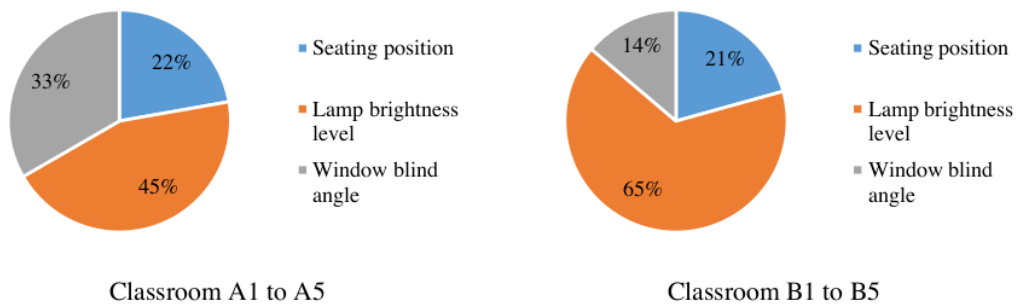


Fig. 12. Overall comfort level and HSLDCS implementation satisfaction feedback from the users.

The main parameters causing discomfort were identified as the angle of the window blinds, approximately 47% in Classrooms A1 to A5, and <sup>1</sup>the brightness levels of the lamps, around 50% in Classrooms B1 to B5. The respondents in all the classrooms reported that changing the brightness levels of the lamps improved their satisfaction with the room lighting and control system. The seating position did not substantially impact students' comfort or satisfaction in small classrooms (Fig. 13).



a. Main parameters causing discomfort



b. Main parameters to improve students' satisfaction

Fig. 13. Main parameters causing discomfort (a) and those that can improve the students' satisfaction according to them (b).

## 4 Discussion

### 4.1 HSLDCS performance and energy savings

The analysis of the recorded luminance values (Fig. 5 and Fig. 6) demonstrated that the HSLDCS effectively maintain appropriate lighting conditions in the classrooms. By adjusting the window blinds and lamp brightness levels based on sky conditions and daylight presence (Fig. 7), energy savings ranging from 43-63% are achieved (Table 6). While window blinds effectively reduce daylight glare, artificial lighting remains a significant source of glare (Fig. 8). Despite the presence of perceptible glare, most

students reported feeling comfortable (Fig. 12), supporting <sup>5</sup> the correlation between subjective judgments and vertical illuminance at eye level [45].

Several limitations should be considered. First, the control system requires 2.5 minutes for the IP camera to generate an HDRi and produce luminance values. Subsequently, an additional 20 to 30 minutes are required to adjust the angle of the window blinds and <sup>1</sup> the brightness levels of the lamps to achieve the required luminance level depending on the sky conditions and daylight availability, which may initially lead to discomfort. Second, the areas near and far from the windows tend to have different luminance values, despite the control rules in part 2 aiming to achieve similar luminance levels in these areas. To address these issues, Plorer et al. [46] suggested implementing a zoning system instead of a centralized system. By separating the control rules for areas near windows, primarily focusing on controlling the angle of window blinds, and on areas farther from windows, primarily focusing on artificial lighting conditions, the luminance discrepancy can be minimized [47]. This approach also allows continuous adjustment of window blind angles and improves responsiveness to daylight fluctuations.

#### 4.2 Visual comfort assessment

The questionnaire results indicate that over 70% of students do not report physical symptoms except for constant blinking. Interestingly, in classrooms with brighter environments, students tend to experience physical symptoms more frequently, particularly in discussion and/or self-study activities (Fig. 9). Although the class duration was relatively short, ranging from 1 to 2.5 hours, <sup>27</sup> these results are consistent with the findings of Leccese et al. [41], who reported that students may experience visual fatigue in bright environments during prolonged class sessions.

Respondents noted the different light levels in the classrooms with lower brightness setting. Since most students worked using laptops/tablets, they found that a luminance level of approximately 60 cd/m<sup>2</sup> (approximately 300 lux) was slightly dark. In comparison, a luminance level higher than 100 cd/m<sup>2</sup> (approximately 500 lux) was slightly brighter (Fig. 11). In the classrooms used for slideshow presentations, although illuminance levels below 100 lux are not comfortable for either paperwork or computer work, but due to the utilization of projection screens/TVs, the screen brightness levels and the surrounding environment differ to ensure that students can see the content displayed on the screen. These findings indicate that student perceptions and preferences regarding lighting conditions differ based on the classroom type (discussion/self-study vs. slideshow) and the specific tasks being performed (paperwork vs. computer work) [48].

Visual comfort analysis indicated that over 70% of the students in each classroom felt comfortable with the brightness level and were satisfied with the HSLDCS implemented in the classrooms (Fig. 12). This percentage reflects a significantly higher satisfaction rate compared to previous studies in university classrooms, where only approximately 50% of students reported satisfaction with their classroom lighting [4–7]. Moreover, the students performed well, as the mean values indicate a positive learning outcome across all the classrooms (Fig. 10). This observation can be explained by the fact that most respondents used laptops/tablets with adjustable brightness, allowing them to adjust the screen brightness to provide contrast with the surrounding environment and maintain their visual comfort, as mentioned previously [41]. According to Freewan and AlDalala [10], visual comfort can be determined by uniformity and diversity, with brightness contrast playing an important role. In classrooms used for discussion and/or self-study, the brightness contrast is

approximately equal across the classrooms, regardless of the brightness level applied in the classrooms. On the other hand, in classrooms used for slideshow presentations, the brightness contrast differs between each seating row and between the TV screen and the whiteboard.

While over 70% of the students in each classroom feel comfortable and satisfied (Fig. 12), 78% of the students express a desire to change the settings of window blinds and lamps in Classrooms A1 to A5, and 79% of the students want to do so in Classrooms B1 to B5 (Fig. 13). This finding is consistent with the tendency observed among people to seek control and influence over building systems. However, this desire for control does not necessarily imply that the existing systems are not performing well [49,50].

## 5 Conclusion

This study provides an innovative solution by using HSLDCS as an alternative LCS to address the suboptimal lighting in education and adapt to diverse learning contexts and activities. The findings effectively proved that the HSLDCS has the ability to maintain optimal lighting conditions, mitigating daylight glare, and achieving energy reduction of approximately 43% to 63%. In ten classrooms, over 70% of the students in each classroom were comfortable with the brightness levels and were satisfied with the implementation HSLDCS. Furthermore, the students demonstrated positive performance, indicating favorable learning outcomes in all classrooms.

The limitation of this study lies on the use of an IP camera is limited by the 2.5-minute time requirement for producing an HDRi, which impacts <sup>2</sup>the adjustment time for window blinds and lamps in response to daylight variations. To address the issue, further research suggesting the implementation of a zoning system is proposed to enhance the HSLDCS's adaptability to fluctuations in daylight.

Taking of consideration of the modern learning activities, reducing the brightness level of the classroom emerges as a viable option for conserving energy. Rather than relying solely on measured illuminance levels, future research of the lighting system in the classroom should prioritize uniformity and diversity in brightness or brightness contrast based on the specific activities taking place.

### **Acknowledgments**

<sup>1</sup> This research was funded by the Taiwan Ministry of Science and Technology (Project No.: NSTC 112-2221-E-011-061- ) and by the Taiwan Ministry of Education. The authors would like to thank Ben-Cheng Guo for assisting the HDRi processing using a 360° IP camera, Ronaldo Gabe Manik for assisting the Arduino Uno utilization, and Joan S.G. Elizalde and Bryan R.F. Guerrero for feedback in the writing-up of the research article.

### **Data availability**

Data will be made available on request.

### **Author contributions**

<sup>9</sup> **Aris Budhiyanto:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing - Review & Editing, Visualization, Project administration. **Yun-Shang Chiou:** Conceptualization, Resources, Supervision, Project management, Funding Acquisition.

### **Appendix**

Appendix A. The condition of the classrooms



a. Classroom A1



b. Classroom A2



c. Classroom A3



d. Classroom A4



e. Classroom A5



f. Classroom B1



g. Classroom B2



h. Classroom B3

Fig. A1. The condition of each classroom.





i. Classroom B4



j. Classroom B5

Fig. A1. The condition of each classroom (continued).

## Appendix B. Visual comfort assessment questionnaire

### VISUAL COMFORT ASSESSMENT QUESTIONNAIRE 視覺舒適度評估問卷

Thank you for agreeing to take part in this survey measuring human visual comfort level in a typical classroom setting. Please pay attention to the lecture, then fill in the questions according to how you actually feel.

22 謝謝您同意填寫本問卷，在一般教室環境進行視覺舒適程度測試。請先專心上課，再依照您的真實感覺回答下列問題

### GENERAL INFORMATION 基本資訊

Gender (M/F) 性別: \_\_\_\_\_ Age 年齡: \_\_\_\_\_ 28 Seating Number 教室座位: \_\_\_\_\_

Should you wear any kind of corrective lenses? 平常是否有戴眼鏡、隱形眼鏡或任何調整型鏡片的需求?

☐ Yes ☐ No

Are you wearing them right now? 是否正佩戴著眼鏡、隱形眼鏡或任何調整型鏡片?

☐ Yes ☐ No

### PART A - PHYSICAL SYMPTOMS 生理狀況

Please pick an answer (yes/no) according to how you physically feel during the whole lecture  
請根據自己在課堂中的生理狀況選擇是或否

1. My eyes feel dry 我的眼睛感覺乾燥  
☐ Yes 是 ☐ No 不是
2. My eyes feel heavy 我的眼睛有點睜不開  
☐ Yes 是 ☐ No 不是
3. I feel a strain and sore in my eyes 我感覺眼周很緊、眼睛很酸  
☐ Yes 是 ☐ No 不是
4. I feel a slight headache 我感覺有輕微頭痛  
☐ Yes 是 ☐ No 不是
5. I tend to blink a lot 我會一直想眨眼  
☐ Yes 是 ☐ No 不是
6. I feel dazzled 我感覺有點目眩（眼花）  
☐ Yes 是 ☐ No 不是



# **PART B – VISUAL ANNOYANCE AND TASK PERFORMANCE 視覺干擾及測試表現**

Please read the statement and fill in the voting scale using a (✓) according to which one is closer to your feeling when you're attending the lecture. (-2 being the least comfortable, 0 being neutral, and 2 being the most comfortable) 請閱讀下列描述，並依上課狀況勾選最符合您感受的分數，負 -2 分代表最不舒服，正 2 分代表最舒服

No	Statement	Voting Scale					Statement		
		-2	-1	0	1	2			
<b>Seeing Displayed Information (Projector/ TV) 看電視/投影布幕上顯示的資訊</b>									
*note: if your class doesn't use projector/ TV, skip this part! *如果您的課堂沒有使用電視/投影機，請略過此部分*									
1	Feel distracted when looking at the projector/ TV 看螢幕會讓我分心						Feel no distraction at all 看螢幕不會讓我分心		
2	Feel that the screen causes glare to the eye 照射在螢幕上的強光會讓我部分看不見						Feel no glare at all 螢幕上沒有刺眼的強光		
3	Unable to see text and numbers 我看不見螢幕上顯示的資訊						Able to see displayed content clearly 我能夠清楚看見螢幕上顯示的資訊		
<b>Seeing Displayed Information (Whiteboard) 看白板上顯示的資訊</b>									
*note: if your class doesn't use whiteboard, skip this part! *如果您的課堂沒有使用白板，請略過此部分									
4	Feel distracted when looking at the screen 看白板會讓我分心						Feel no distraction at all 看螢幕不會讓我分心		
5	Feel the whiteboard causes glare to the eye 照射在白板上強光會造成部分看不見						Feel no glare at all 螢幕上沒有刺眼的強光		
6	Unable to see text and numbers 我看不見螢幕上顯示的資訊						Able to see displayed content clearly 我能夠清楚看見螢幕上顯示的資訊		
<b>Reading, Writing on Desk/ Paper-based Task 桌上閱讀、寫作/紙質任務</b>									
*note: if you don't work using paper, skip this part! *如果你不使用紙張，請略過此部分									
7	Reading, writing makes me uncomfortable 我無法舒服的寫字，書寫						I can write, read, work comfortably 我可以很自在的寫字，書寫		
8	Unable to see text and numbers/ displayed content 我看不見螢幕上顯示的資訊						Able to see displayed content clearly 我能夠清楚看見螢幕上顯示的資訊		
<b>Reading, Writing, Working using Laptop/ Mobile Phone 在桌面/筆記本電腦/手機上閱讀、書寫、工作</b>									
*note: if you don't work using laptop/ mobile phone, skip this part! *如果您不使用筆記本電腦/手機工作，請略過此部分									
9	Reading, writing makes me uncomfortable 我無法舒服的寫字，書寫						I can write, read, work comfortably 我可以很自在的寫字，書寫		
10	Unable to see text and numbers/ displayed content 我看不見螢幕上顯示的資訊						Able to see displayed content clearly 我能夠清楚看見螢幕上顯示的資訊		

**Task Switching 轉移目光焦點** - When you move your eyes from TV screen to your desk/ laptop/ mobile devices

當您將視線從電視屏幕移到辦公桌/筆記本電腦/移動設備時

11	Switching between task causes my eyes to work hard 將目光從桌子上轉移到螢幕上，我的眼睛會需要一些時間適應						I can switch between task with no effort 我可以很自在轉移目光焦點
----	--	--	--	--	--	--	---

20  
12. If you use laptop/ tablet/ mobile phone, do you adjust your device' s brightness? 如果你使用筆記本電腦/平板電腦/手機，你會調整設備的亮度嗎？

☐Yes 是

☐No 不是

**PART C - PREFERENCE 喜好**

Please pick **only one answer for each question**. Pick **the** one that represents **how you actually feel** about the setting of the classroom. 請針對教室環境並依照自己的感受，挑選最符合自己的答案，每題請只勾選一個答案

1. How do **you** feel about the room' s lighting? 請問您對於教室亮度的感覺？

☐Too Dark 太暗

☐Slightly Dark 有點暗

☐Neutral 沒意見

☐Slightly Bright 有點亮

☐Too Bright 太亮

2. How do you feel about the TV/ projector' s brightness? 請問您對於電視/ 投影機亮度的感覺？

\*note: if your class doesn't use TV/ projector, skip this part! \*如果您的課堂沒有使用電視/投影機，請略過此部分

☐Too Dark 太暗

☐Slightly Dark 有點暗

☐Neutral 沒意見

☐Slightly Bright 有點亮

☐Too Bright 太亮

3. Please mark your satisfaction about the room' s lighting condition 請打分您對房間的採光情況是否滿意

☐Very Dissatisfied 太不滿意

☐Slightly Dissatisfied 有點不滿意

☐Neutral 沒意見

☐Slightly Satisfied 有點滿意

☐Very Satisfied 太滿意

4. If **you** have the control over the curtains (window blinds) in the room, what would you like to do? 如果您可以隨意調整教室的窗簾，請問您會想？

☐Close it all 全部關上

☐Only close the upper part 才關上上面的部分

☐Only close the lower part 才關上下面的部分

☐Open it all 全部打開

☐Do nothing 沒做什麼

5. If you have the control over the lamps in the room, what would you like to do? 如果您可以隨意調整教室的燈光，請問您會想？

☐Make lights brighter 讓燈光更亮

☐Make lights darker 讓燈光變暗

☐Do nothing 沒做什麼

**PART D - CONCLUSION 結論**

1. In general, how do you feel about the visual comfort in this classroom? 整體來說，您覺得教室的視覺環境是否舒服？

☐Comfortable 舒服

☐Not Comfortable 不是很舒服

\*if you answered COMFORTABLE in the first question, skip number 2 \*如果您第一題回答舒服，請略過 2 號

2. According to you, what is the main parameter that cause discomfort to your eyes? 根據您個人感受，請問什麼原因容易造成您的眼睛不舒服？
- ☐Lighting Quality 照明品質
- ☐Projector/ TV Quality 電視/投影機品質
- ☐Seating position and distance to screen 座位位置及和螢幕的距離
- ☐Window blind condition 百葉窗狀況
- ☐Others, please state it 其他，請說明\_\_\_\_\_
3. Do you think that visual comfort is important during your learning process in the classroom? 請問您是否認為舒適的視覺環境對課堂中的學習很重要？
- ☐Not That Important 不是很重要 ☐Important 重要
4. In general are you satisfied with the room' s lighting condition? 整體來說，您對房間的照明條件是否滿意？
- ☐Satisfied 滿意 ☐Dissatisfied 不是很滿意
- \*if you answered SATISFIED in the first question, skip number 5 \*如果您第一題回答滿意，請略過 5 號
5. According to you, what can improve your satisfaction? 根據您個人感受，請問什麼可以提高您的滿意度？
- ☐Change the lamp brightness, either increase or decrease it 改變燈泡亮度，增加或減少它
- ☐Change the window blind position, either close or open it 更改百葉窗位置，關閉或打開它
- ☐Move to another seating position 移動到另一個座位
- ☐Others, please state it 其他，請說明\_\_\_\_\_
6. Do you think that satisfaction of the room lighting is important during your learning process in the classroom? 請問您認為在您的課堂學習過程中，房間照明的滿意度重要嗎？
- ☐Not That Important 不是很重要 ☐Important 重要

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