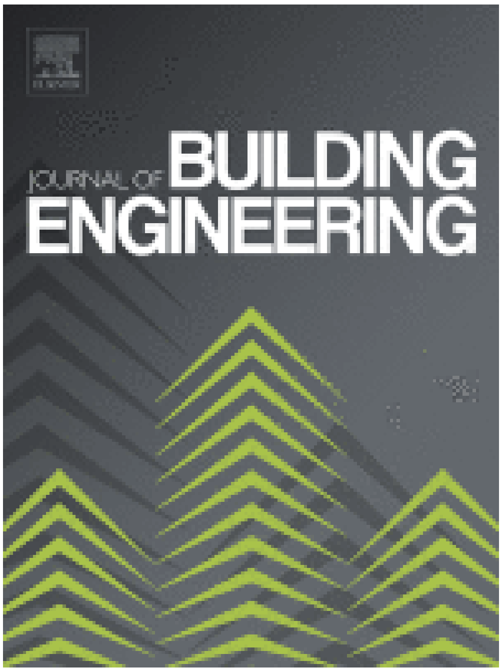
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Xiupeng Yao, Yang Han, Lei Shen, De Zhu
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Combining use of natural ventilation, external shading, cool roof and thermal mass to improve indoor thermal environment: Field measurements and simulation study

Yongcai Li, Xiaohan Tao, Yaqin Zhang, Wuyan Li
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Visual comfort and energy savings in classrooms using surveillance camera derived HDR images for lighting and daylighting control system

Aris Budhiyanto, Yun-Shang Chiou
Article 108841

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Degradation mechanisms of concrete cold joint surfaces under sulfate cycles and varying pouring intervals

Wenzhe Ji, Yuan Qin, Xianwei Zhang, Heng Zhou, Da Liang
Article 108882

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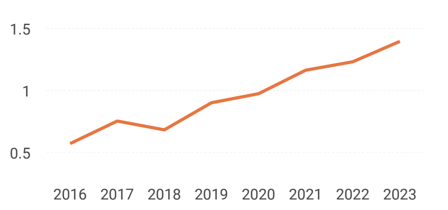

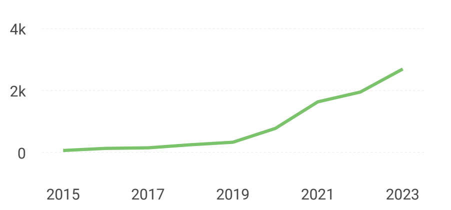

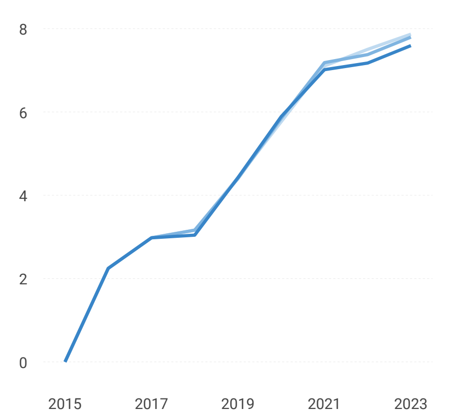

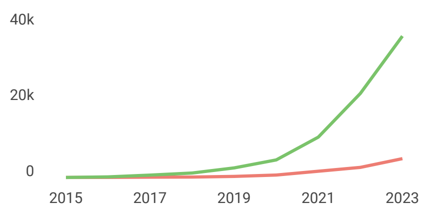

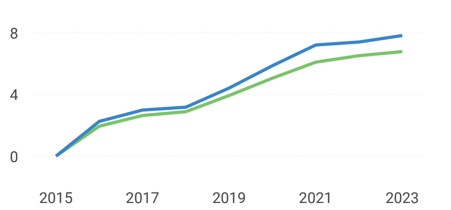

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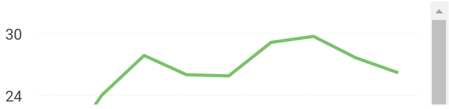

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Visual comfort and energy savings in classrooms using surveillance camera derived HDR images for lighting and daylighting control system

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ABSTRACT

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%–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.

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 (cd/m^2)
LCS	Lighting control system

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HSLDCS	HDRi surveillance lighting and daylighting control system
UGR	Unified glare rating
θ_B	Angle of bottom window blinds (°)
θ_T	Angle of top window blinds (°)

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 100–300 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 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 high-resolution luminance data across a wide field of view, a feat unattainable with a luminance meter. Nevertheless, to ensure absolute validity, 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 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 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 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 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) 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.

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 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 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 7th 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 at a height of 1 m above the floor. The window-to-wall ratio was 32% (Fig. 1).

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.

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

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.

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

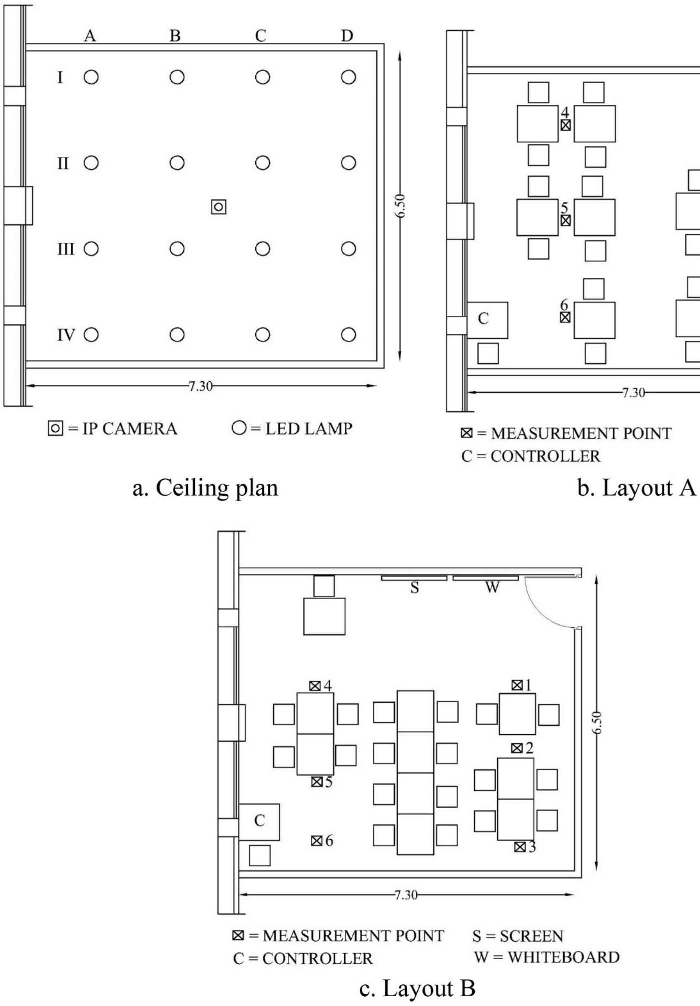


Fig. 2. The ceiling plan (a) and classroom seating layout for group discussion and/or self-study (b) and for slideshow (c).

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 1 min. 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)).

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

where L represents the pixel luminance value (cd/m^2); R, G, and B represent the spectrally weighted radiance values of the pixel (W/m^{2}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. 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 range of 5–23% [39], which was deemed acceptable for measurements using commercial products [27,37].

$$y = \text{-5E-12}x^4 + \text{7E-09}x^3 - \text{3E-06}x^2 + 0.0005x + 0.9895 \tag{2}$$

Since the IP camera takes 1 min 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-min interval is implemented to produce an HDRi, ensuring another 1-min 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^2. 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^2. 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 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.

Four control rules were established based on selected learning activities (slideshow, group discussion and/or self-study) and the

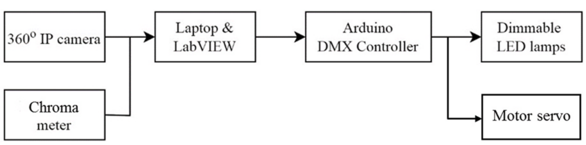


Fig. 3. Control system framework.

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 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 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 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^2) [40], and when the illuminance falls below 500 lux (approximately 200 cd/m^2), the blinds open and/or the lamp brightness increases [9]. The luminance levels for these classrooms ranged between 100 and 200 cd/m^2. Control rule 1 is defined as follows:

Part 1

$$X = \begin{cases} \theta_B + 45^\circ, \text{if } L_4 \vee L_5 \vee L_{62} > 200\ \text{cd}/\text{m}^2 \wedge \theta_B < 90^\circ \\ \theta_B - 45^\circ, \text{if } L_4 \vee L_5 \vee L_{62} < 100\ \text{cd}/\text{m}^2 \wedge \theta_B < -45^\circ \\ \theta_T + 45^\circ, \text{if } L_1 \vee L_2 \vee L_{32} > 200\ \text{cd}/\text{m}^2 \wedge \theta_T < 90^\circ \\ \theta_{T^\circ} - 45^\circ, \text{if } L_1 \vee L_2 \vee L_{32} < 100\ \text{cd}/\text{m}^2 \wedge \theta_T < -45^\circ \end{cases} \tag{3}$$

Part 2

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

Part 3

$$X = \begin{cases} BL_A \wedge BL_D + 10\%, \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_{6\,2} < 100\ \text{cd}/\text{m}^2 \\ BL_B \wedge BL_C + 10\%, \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_6 < 100\ \text{cd}/\text{m}^2 \wedge BL_C < BL_D \wedge BL_B < BL_A \end{cases} \tag{5}$$

where θ_B denotes the bottom blind angle, θ_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 (θ_B and θ_T). If any value of L_4 to L_6 is greater than 200 cd/m^2 and θ_B is less than 90°, θ_B is increased by 45°. However, if any value of L_4 to L_6 is less than 100 cd/m^2 and θ_B is less than -45°, θ_B is decreased by 45°. If any value of L_1 to L_3 is greater than 200 cd/m^2 and θ_T is less than 90°, θ_T is increased by 45°. However, if any value of L_1 to L_3 is less than 100 cd/m^2 and θ_T is less than -45°, θ_T is decreased by 45°.

Each iteration or loop takes 2.5 min because the IP camera needs 1 min 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 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 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 cd/m^2, or approximately 300 and 750 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

$$X = \begin{cases} \theta_B + 45^\circ, \text{if } L_4 \vee L_5 \vee L_{6\,2} > 150\ \text{cd}/\text{m}^2 \wedge \theta_B < 90^\circ \\ \theta_B - 45^\circ, \text{if } L_4 \vee L_5 \vee L_{6\,2} < 60\ \text{cd}/\text{m}^2 \wedge \theta_B < -45^\circ \\ \theta_T + 45^\circ, \text{if } L_1 \vee L_2 \vee L_{3\,2} > 150\ \text{cd}/\text{m}^2 \wedge \theta_T < 90^\circ \\ \theta_{T^\circ} - 45^\circ, \text{if } L_1 \vee L_2 \vee L_{3\,2} < 60\ \text{cd}/\text{m}^2 \wedge \theta_T < -45^\circ \end{cases} \tag{6}$$

Part 3

$$X = \begin{cases} BL_A \wedge BL_D + 10\%, \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_{6\ 2} < 60\ \text{cd/m}^2 \\ BL_B \wedge BL_C + 10\%, \text{if } L_1 \vee L_2 \vee L_3 \vee L_4 \vee L_5 \vee L_6 < 60\ \text{cd/m}^2 \wedge BL_C < BL_D \wedge BL_B < BL_A \end{cases} \tag{7}$$

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 cd/m^2 and θ_B is less than 90°, θ_B is increased by 45°. On the other hand, if any value of L_4 to L_6 is less than 60 cd/m^2 and θ_B is less than -45°, θ_B is decreased by 45°. The same conditions are applied to θ_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 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 cd/m^2) for the first seats, 200 lux (approximately 40 cd/m^2) for the middle seats, and 300 lux (approximately 60 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 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 cd/m^2, 100 cd/m^2, and 200 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 cd/m^2 and close if the luminance value exceeds 50 cd/m^2. Control rule 3 is defined as follows:

Part 1

$$X = \begin{cases} \theta_B + 45^\circ, \text{if } L_{42} > 50\ \text{cd/m}^2 \wedge \theta_B < 90^\circ \\ \theta_B - 45^\circ, \text{if } L_4 < 20\ \text{cd/m}^2 \wedge \theta_B < -45^\circ \\ \theta_T + 45^\circ, \text{if } L_{12} > 50\ \text{cd/m}^2 \wedge \theta_T < 90^\circ \\ \theta_{T^*} - 45^\circ, \text{if } L_{12} < 20\ \text{cd/m}^2 \wedge \theta_T < -45^\circ \end{cases} \tag{8}$$

Part 2

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

Part 3

$$X = \begin{cases} BL_{IV} + 10\%, \text{if } L_3 \vee L_{6\ 2} < 60\ \text{cd/m}^2 \\ BL_{III} + 10\%, \text{if } L_2 \vee L_5 < 40\ \text{cd/m}^2 \\ BL_{II} + 10\%, \text{if } L_1 \vee L_{4\ 2} < 20\ \text{cd/m}^2 \\ BL_{CI} \wedge BL_{DI} + 10\%, \text{if } L_w \neq 0 \wedge L_w < 30\ \text{cd/m}^2 \end{cases} \tag{10}$$

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. θ_B is increased by 45° if L_4 is greater than 50 cd/m^2 and θ_B is less than 90°. Conversely, if L_4 is less than 20 cd/m^2 and θ_B is less than -45°, θ_B is decreased by 45°. Similarly, θ_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 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 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 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 cd/m^2. Considering that the measured luminance value of the projector screen or TV used in the classrooms is approximately 90–120 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°, 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 cd/m^2 for the front seats, 25–60 cd/m^2 for the middle seats, and 40–150 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):

$$X = \begin{cases} BL_{IV} + 10\%, \text{if } L_3 \vee L_{6\ 2} < \ 30 \text{ cd/m}^2 \\ BL_{III} + 10\%, \text{if } L_2 \vee L_5 < \ 25 \text{ cd/m}^2 \\ BL_{II} + 10\%, \text{if } L_1 \vee L_{4\ 2} < \ 15 \text{ cd/m}^2 \\ BL_{CI} \wedge BL_{DI} + 10\%, \text{if } L_w \neq 0 \wedge L_w < \ 30 \text{ cd/m}^2 \end{cases} \tag{11}$$

In control rule 4, L_3 and L_6 are examined first. When either L_3 or L_6 is less than 30 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 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 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 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 cd/m^2 (illuminance = 1000 lux), as recommended by IESNA [41], 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 F2.8210° 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 m, 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.

2.5. Questionnaire survey

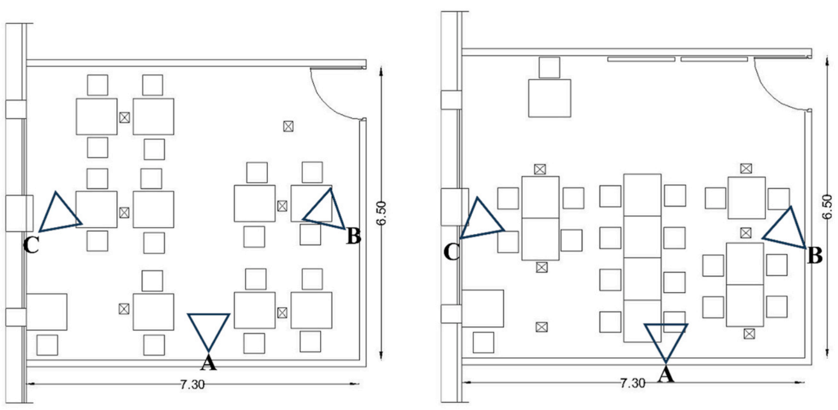
Considering the limitation of the IP camera as HDR vision sensor, a four-part questionnaire survey was conducted to assess the students' learning performance and visual comfort in the classrooms [4]. To ensure inclusivity for respondents who primarily use Mandarin Chinese as their language, Chinese translations 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 dry eyes, heavy eyes, strained and sore eyes, slight headache, continuous blinking, and a dazzled feeling. While physical symptoms do not always indicate discomfort [4,42], 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. 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: 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



a. Layout A b. Layout B

Fig. 4. The positions of capturing HDRi photographs.

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 20 min depending on daylight conditions—the mode values of the recorded data were used. As the mode represents the most frequently occurring value in the dataset, it provides a measure of central tendency for the data [43]. 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 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 [44]. The false color false images were used to provide visual representations of the luminance distribution in the classrooms, and a 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 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 UGR is the CIE glare index specifically designed for indoor lighting, making it more suitable for such environments [4,45]. Table 3 presents the degrees of DGP and UGR [46].

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 [40]. 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).

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 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 60–150 cd/m^2, except for L_5, which exceed 150 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, the luminance values of the front, middle, and rear areas were mainly observed to be

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

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

within the ranges of 20–40 cd/m^2, 40–70 cd/m^2, and 60–100 cd/m^2, respectively. For classrooms implementing control rule 4, the luminance values of the front, middle, and rear areas were primarily within the ranges of 15–25 cd/m^2, 25–60 cd/m^2, and 50–70 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 a luminance value of approximately 30 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_4, L_5, and L_6 (near the windows) were noticeably greater than L_1, L_2, and L_3 (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_1, L_2, and L_3 were slightly greater than L_4, L_5, and L_6. 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_3 was higher than L_6. 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^2 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.

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 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 min, while those used for slide show presentations required an average adjustment time of 30 min.

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, and the brightness levels of the lamps are the same (Fig. 7h).

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° and 45°, 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° and 45°, 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).

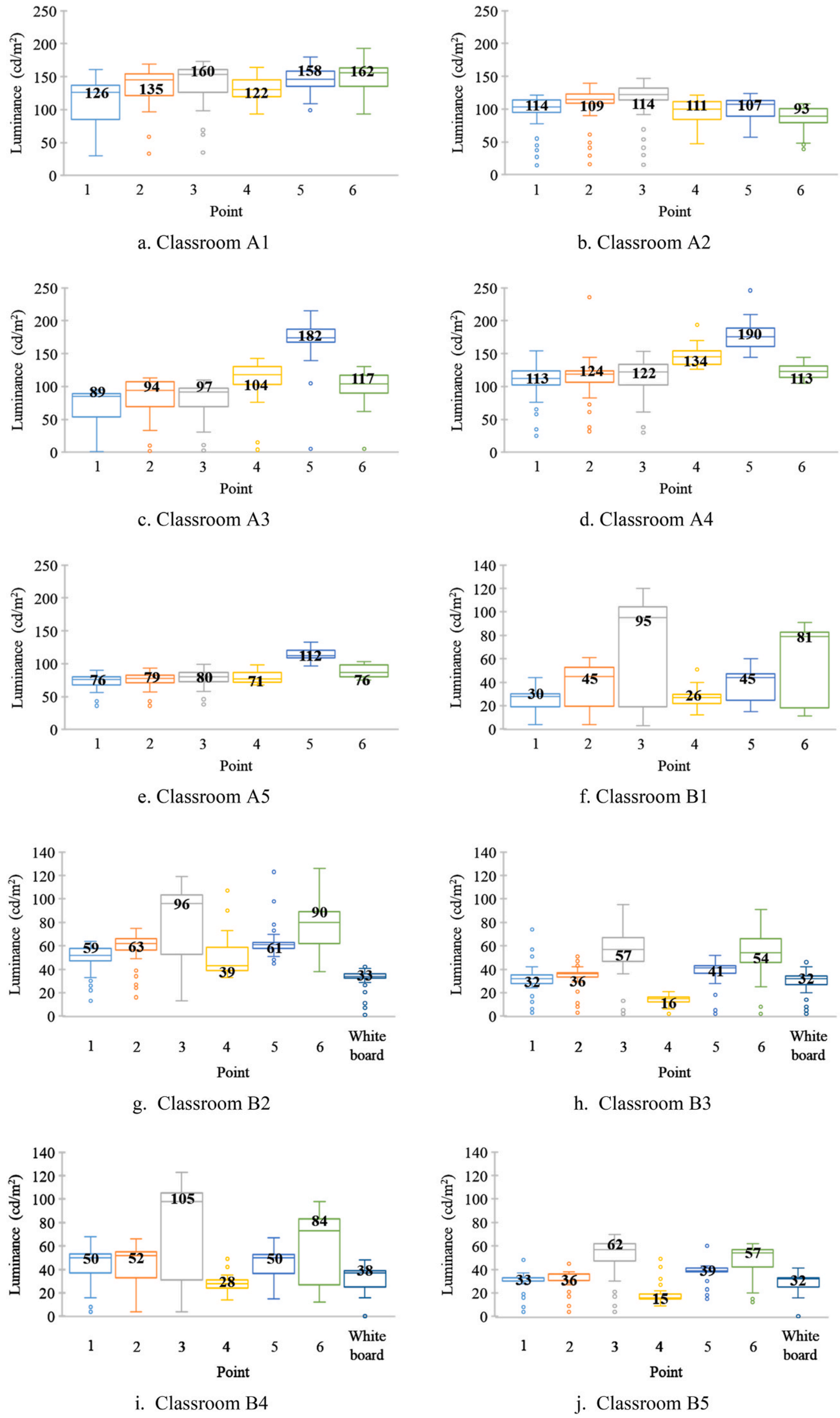


Fig. 5. The luminance and mode value of measurement points of each classroom.

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

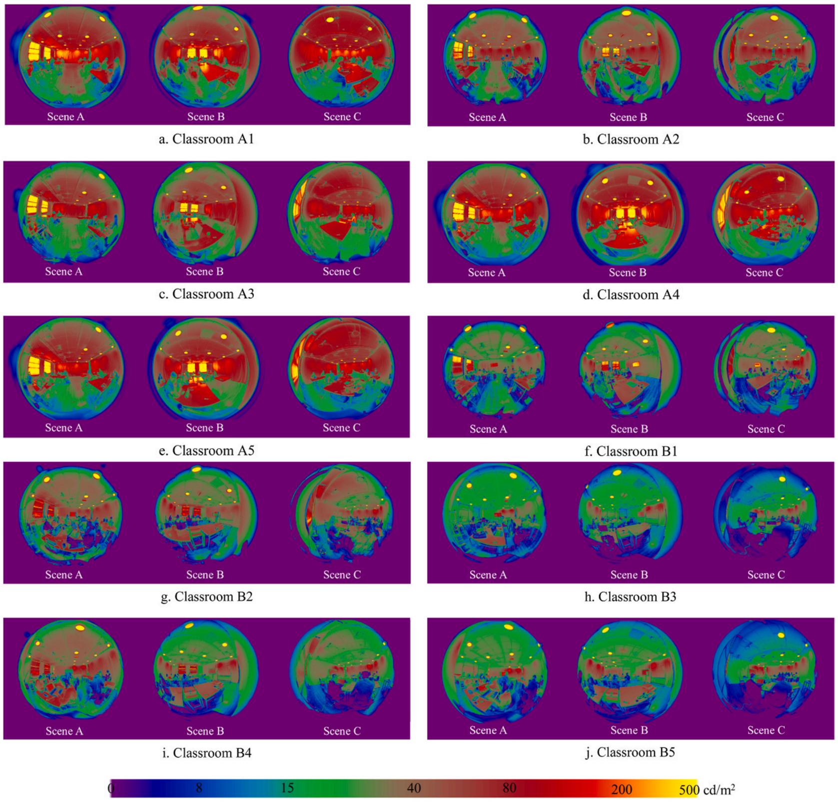


Fig. 6. The false color images of each classroom in scales 500 cd/m^2 for three different scenes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

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

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).

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.

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,

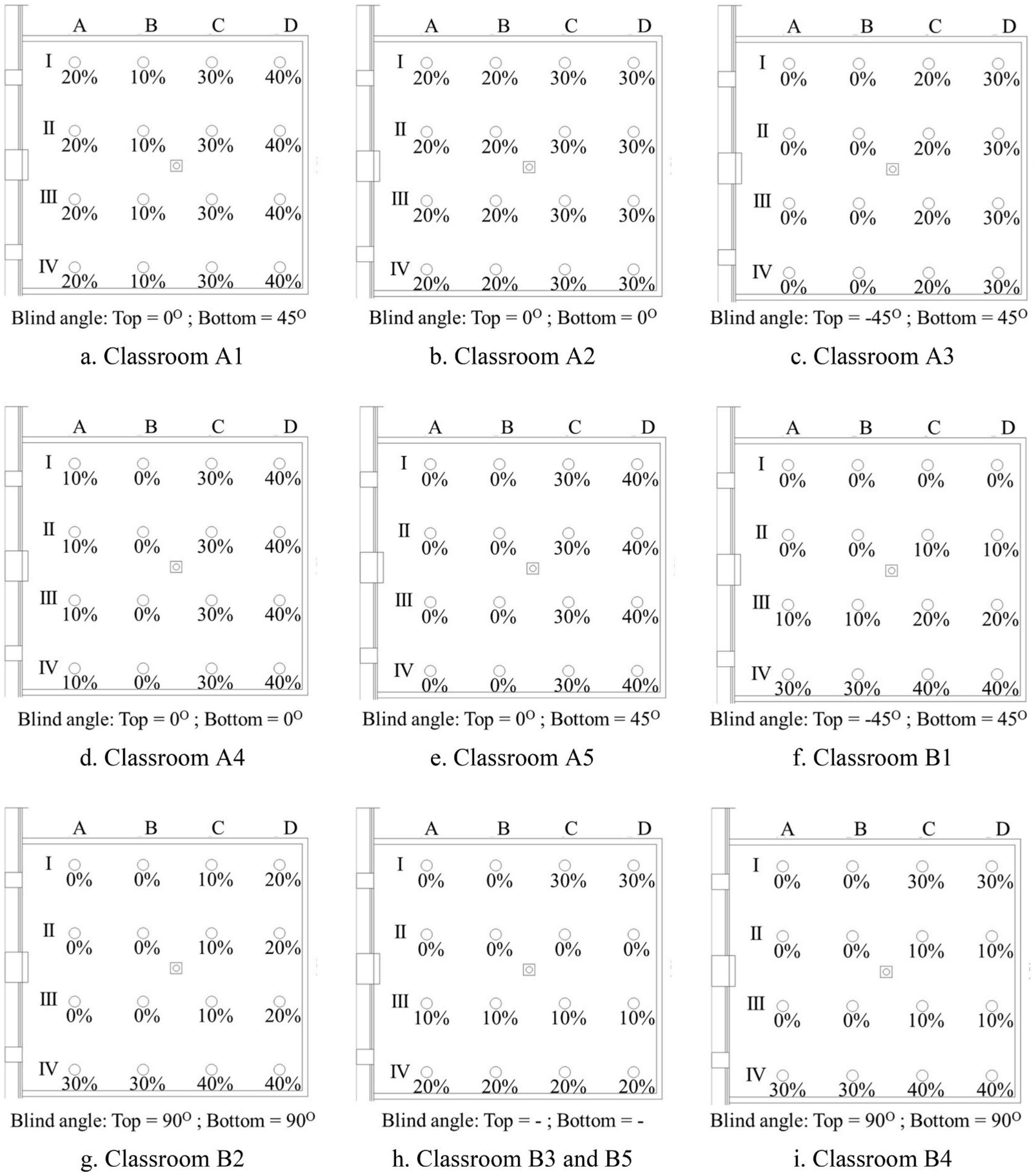


Fig. 7. The brightness level of the lamps and angles of window blinds in each classroom.

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.

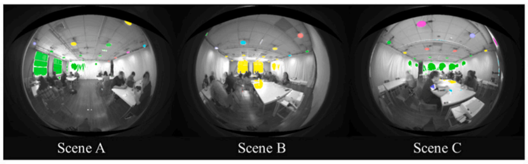
3.4.2. Part B. Visual annoyance and task performance

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.

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.

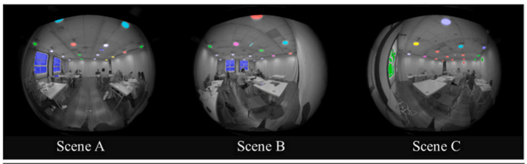
3.4.3. Part C. Student perception

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



	Scene A	Scene B	Scene C
DGP	0.22	0.22	0.11
UGR	22.85	24.18	21.20

a. Classroom A1



	Scene A	Scene B	Scene C
DGP	0.06	0.05	0.07
UGR	21.23	15.69	19.62

b. Classroom A2

	Scene A	Scene B	Scene C
DGP	0.15	0.21	0.04
UGR	23.32	24.53	12.9

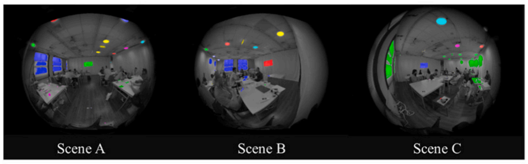
c. Classroom A3

	Scene A	Scene B	Scene C
DGP	0.18	0.24	0.09
UGR	22.57	25.12	14.2

d. Classroom A4

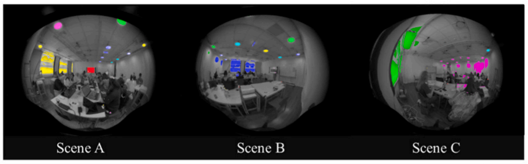
	Scene A	Scene B	Scene C
DGP	0.22	0.23	0.04
UGR	24.26	24.52	11.93

e. Classroom A5



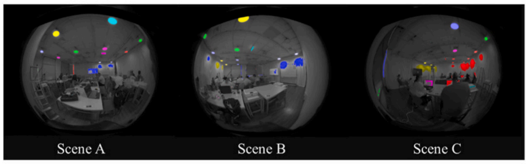
	Scene A	Scene B	Scene C
DGP	0.01	0.01	0.01
UGR	13.46	16.5	16.28

f. Classroom B1



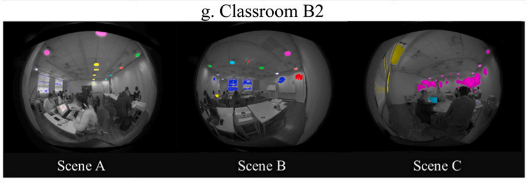
	Scene A	Scene B	Scene C
DGP	0.06	0.05	0.01
UGR	16.26	14.92	11.11

g. Classroom B2



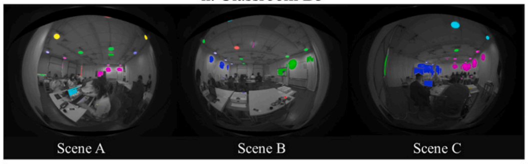
	Scene A	Scene B	Scene C
DGP	0.01	0.01	0.01
UGR	17.8	16.65	14.7

h. Classroom B3



	Scene A	Scene B	Scene C
DGP	0.04	0.01	0.01
UGR	17.37	16.4	11.46

i. Classroom B4



	Scene A	Scene B	Scene C
DGP	0.02	0.01	0.01
UGR	16.66	15.45	14.61

j. Classroom B5

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

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

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

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 Classrooms 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).

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.

The main parameters causing discomfort were identified as the angle of the window blinds, approximately 47% in Classrooms A1 to

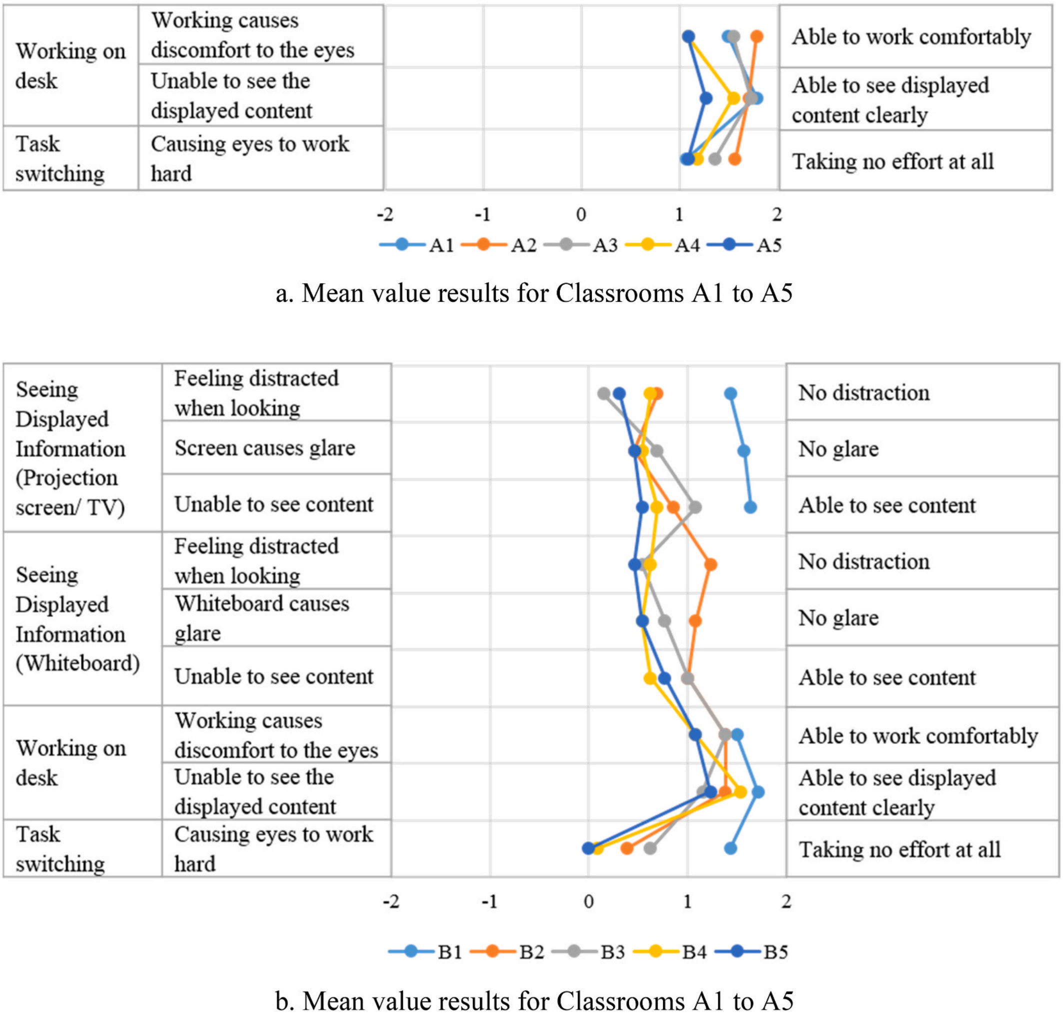


Fig. 10. Mean value results of Classrooms A1 to A5 (a) and Classrooms B1 to B5 (b) for visual annoyance and task performance a. Mean value results for Classrooms A1 to A5 b. Mean value results for Classrooms A1 to A5.

A5, and 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).

4. Discussion

4.1. HSLDCS performance and energy savings

The analysis of the recorded luminance values (Figs. 5 and 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 to 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 the correlation between subjective judgments and vertical illuminance at eye level [46].

Several limitations should be considered. First, the control system requires 2.5 min for the IP camera to generate an HDRi and produce luminance values. Subsequently, an additional 20–30 min are required to adjust the angle of the window blinds and 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. [47] 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 [48]. This approach also allows continuous adjustment of window blind angles and improves responsiveness to daylight fluctuations.

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

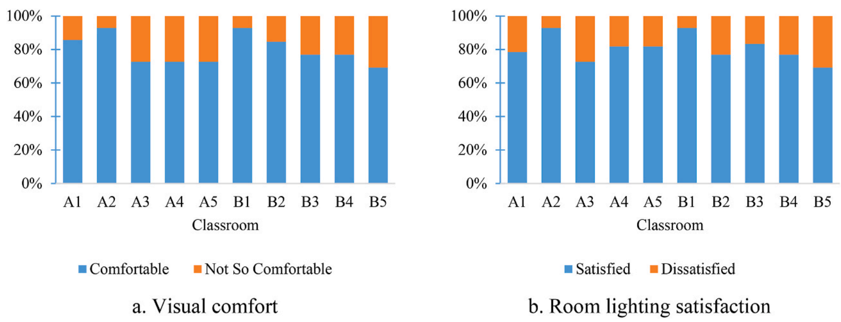


Fig. 12. Overall comfort level and HSLDCS implementation satisfaction feedback from the users.

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

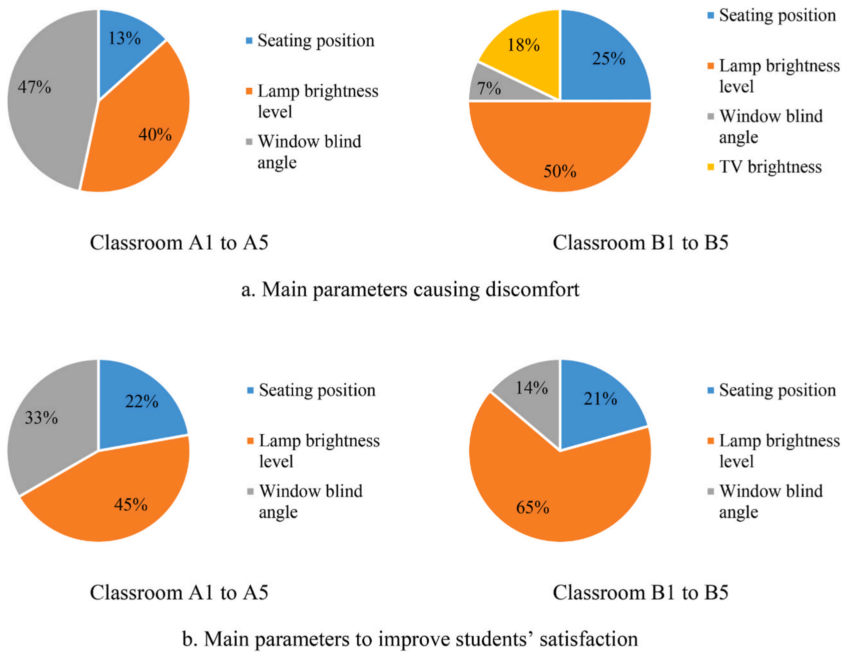


Fig. 13. Main parameters causing discomfort (a) and those that can improve the students' satisfaction according to them (b).

in discussion and/or self-study activities (Fig. 9). Although the class duration was relatively short, ranging from 1 to 2.5 h, these results are consistent with the findings of Leccese et al. [42], 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^2 (approximately 300 lux) was slightly dark. In comparison, a luminance level higher than 100 cd/m^2 (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) [49].

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 [42]. 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 (Figs. 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 [50,51].

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%–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-min time requirement for producing an HDRi, which impacts 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.

CRediT authorship contribution statement

Aris Budhiyanto: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yun-Shang Chiou:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2024.108841.

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