RESEARCH ARTICLE Journal of Daylighting 12 (2025) 40-50 doi:10.15627/jd.2025.3

ISSN 2383-8701

Journal of Daylighting

Journal homepage: https://solarlits.com/jd

# Optimisation of Indoor Spatial and Temporal Aspects of Deep Architectural Studio on Visual Comfort

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## Article info

***Article history:***
Received 16 August 2024
Revised 31 October 2024
Accepted 16 November 2024
Published online 5 January 2025

***Keywords:***
Indoor daylighting
Visual comfort
Vertical eye illuminance
Glare sensation

## Abstract

Visual comfort in deep rooms with side lit openings varies by positions and time; thus, interventions are required to provide comfort for all users in a room. This study aims to identify the conditions affecting visual comfort and potential interventions on spatial and temporal aspects of a room. This experiment comprises two layout settings: semi-enclosed studio layout and open studio layout with variables of zone (perimeter and core), viewing direction (north window, east wall, south window, and west wall), and temporal aspect (morning, midday, and afternoon), which determines how each aspect influences visual comfort. In this study, visual comfort is indicated using vertical eye illuminance (Ev) and daylight glare probability (DGP). Field measurements of daylighting performance were taken over five days and three times per day using a light meter to capture Ev and HDR images, which were then processed using Aftab Alpha software to produce DGP values. The results indicate that visual comfort in a deep room sequentially depends on view direction, zone, layout, and time. The value of Ev in deep rooms is significantly influenced by the type of opening, specifically the side lighting, which results in short penetration and does not reach the room core. Additionally, it depends on outdoor conditions. Consequently, the value at the perimeter is much higher than that at the core. By contrast, the glare sensation was not influenced by outdoor conditions during the day. Adjusting the view direction can control the less-than-ideal sitting position to obtain visual comfort. Additionally, correcting the sitting position in the zone can improve visual comfort at various times. Obstruction in the room plays a positive role in controlling glare and plays a negative role when reducing Ev. The period of visual discomfort throughout the day identified that the worst conditions occur in the morning owing to the lack of Ev. The optimum condition occurs during the day in the west wall and south window view direction, south perimeter zone, and semi-enclosed studio layout. Therefore, view direction and zone are effective features for obtaining visual comfort. Nevertheless, the layout type, room surface properties, and obstruction can also enhance visual comfort in various time conditions such as in the morning, afternoon, or evening. Horizontal plane components such as ceilings can expand the effects of Ev and reduce the effects of DGP in the morning or on cloudy days. The findings have implications for the design of deep rooms such as offices, studios, museums, and galleries in arranging the characteristics of horizontal and vertical surfaces of furniture and layout room that can affect the performance of the user.



## 1. Introduction

Natural lighting in buildings remains the main choice among building users because it is more economical, has a positive impact on health, and is preferable to use compared to artificial lighting [1,2]. However, users need to minimise natural lighting problems, such as glare [1,3]. Understanding the interactions between light, space, and humans is important in architecture. This integration produces a space that is suitable for living, namely, one that can fulfil the functional and aesthetic aspects of the space and influence the perception and well-being of the user [4,5]. This aspect is fulfilled through the image-forming process, which involves the processing of light information through the visual system in the eye and transmission to the human brain [6]. Image forming consists of visual performance, which is defined as speed and accuracy in performing visual tasks; visual comfort, which is closely related to glare protection and indoor illuminance; and visual experience, which discusses how light can change the overall impression of a space [6-8].

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Visual comfort is a well-established research topic in lighting research, but experts still find it difficult to define it with a strong consensus [6]. However, visual comfort is often related to glare, namely, 'hindrance to vision by too much light', which can be grouped into disability, discomfort, and dazzling glare [9]. In addition, glare is directly influenced by the size of the window and the brightness of the sky visible through it, while it decreases in relation to the brightness of the room's interior [10]. There are several metrics used by researchers to measure glare, such as Vertical Illuminance, Luminance, daylight glare probability (DGP), daylight glare index (DGI), unified glare rating (UGR), annual sunlight exposure (ASE), and luminance contrast ratios (CR) [11]. Although the DGP showed better accuracy than other glare ratings regarding subjective evaluation [12]. DGP is a function of vertical eye illuminance (Ev), along with the luminance of the glare source, its solid angle, and positional index [13]. The DGP standard used internationally is x>0.35 (comfortable); 0.35>x<0.4 (perceptible); 0.4>x<0.45 (disturbing); and 0.45>x<0.6 (intolerable) [13]. Several researchers have also attempted to create a threshold for DGP, such as research in the USA with the highest threshold being uncomfortable at x>0.25, research in Thailand with disturbing-intolerable at 0.26, and research in Indonesia with disturbing-intolerable at 0.24-0.26 [14,15,16]. However, research has suggested that vertical illuminance can outperform complex glare indices, such as DGP and DGI because of its good correlation with perceived visual comfort [17,18]. Vertical illuminance refers to the illuminance measured on a vertical plane and is expressed in lux [19]. To determine the Ev, the illuminance sensor is positioned vertically at a height of 1.2 meters, parallel to and close to the test subject's eye level [18]. The thresholds used to detect glare under vertical illuminance were x<875 (comfortable), 875>x<1250 (bounded), and x>1250 (uncomfortable) [14]. Additionally, several researchers tried to establish thresholds for Ev, such as two studies in the USA with the highest threshold being discomfort at x>1500 lux or intolerable at x>383.1 lux and research in China with three different thresholds three times, namely intolerable 3500 lux in the morning, 4000 lux in the midday, and 4200 lux in the afternoon [20-22]. The difference in the threshold values for DGP and Ev shows that lighting conditions are influenced by other factors, such as environmental conditions [11].

The deep room is a unique room typology related to the distribution of natural light and glare. These rooms are often associated with low daylight penetration, which causes the space to be uncomfortable and unhealthy for users [23]. Given that natural light can only penetrate to a distance of 1.5 times the height of the window, additional methods are required to address this problem [24]. One method is to divide the light openings into view and daylight windows; however, this treatment requires changes to the building envelope [25]. Changes to the spatial and temporal aspects of space are a step towards overcoming this problem without the need to change the building envelope. The layout, zone, and view direction can influence the lighting conditions in indoor rooms [24]. In deep rooms, it is advisable to avoid using full-height furniture or partitions, especially in zones distant from light openings [24,26]. This is because it reduces natural lighting access to zones distant from light openings, significantly reducing indoor light levels [27]. Nevertheless, attention must be paid to how natural lighting can be assessed to have a glare effect, particularly in the perimeter zone near light openings [28]. To mitigate this glare, it is beneficial to soften the contrast between the perimeter zone and the core [24]. Another method involves sitting in a position slightly away from the window and facing parallel to it [24,29]. This enhances user comfort, as it allows individuals to rest their eyes when facing the light opening while not performing a visual task [30]. However, studies tend to rely on generalised open layout rooms with single window orientations and do not fully explore how factors like partition design, seating position, and view direction may affect various zones throughout the day [29,31]. In bilaterally-lit rooms, it has an advantage in improving daylight uniformity and visual comfort. Still, it leaves an unexplored gap in the application in different zones, especially in deep rooms or semi-enclosed layouts with constraints like walls and partitions [32,33]. Across these studies, it appears that variability in daylight is greatly influenced by view direction and seating position. However, a lack of detailed inquiry remains into how it varies within different zones in open and semi-enclosed layouts, especially across various times of the day. Consequently, while the current literature provides substantial insights into daylight optimisation, there remains a clear research gap in refining DGP and vertical illuminance metrics to account for open-plan and semi-enclosed spatial configurations comprehensively and the temporal dynamics of natural light, which are vital for enhancing visual comfort. Furhermore, it was found that individuals' glare perception increases gradually from morning to afternoon; the later it is in the afternoon, the more tolerant users become to indoor glare [22]. However, users tend to be tolerant of low illuminance levels and sensitive to high illuminance levels [18]. This shows that defining visual comfort using the distribution of Ev and glare sensation (DGP), will provide different thresholds. This study aims to explore the effects of these spatial and temporal conditions on visual comfort, as seen from the distribution metrics of Ev and glare sensation. By examining the differences in the effects of visual comfort on, this study provides architects and designers with a comprehensive understanding of how light affects visual comfort, particularly in room interiors. To address these challenges and assess their impact, this study employs a comprehensive methodological approach. The subsequent section outlines the methodology used to investigate these factors, including the experimental design, data collection procedures, and statistical analysis techniques.

## 2. Methods and materials

The method used in this study was experimental with field measurements. Institut Teknologi Bandung (ITB) Architecture Building is a 6-story building located between a 2-story building with a distance of 8 meters to the south and a 6-story building with a distance of 17 meters to the north. In addition, shading around the building and trees on the south side also block the intensity of light entering the room. Some of the spatial contexts that must be considered are shown in Fig. 1. Field measurements were conducted in the architectural studio room of the ITB which has a room size of 17.85 m x 20.85 m x 2.9 m. The room was on the 4th floor at a height of 12.24 m from the ground floor. The study was conducted in two studio room layouts: semi-enclosed studio layout (SEL) over two days (30 September and 2 October 2020) during sunny weather with 10–40% cloud cover, and open studio layout (OL) over three days (21–23 March 2022) during cloudy weather conditions with cloud cover varying daily between 50–100% (Fig.

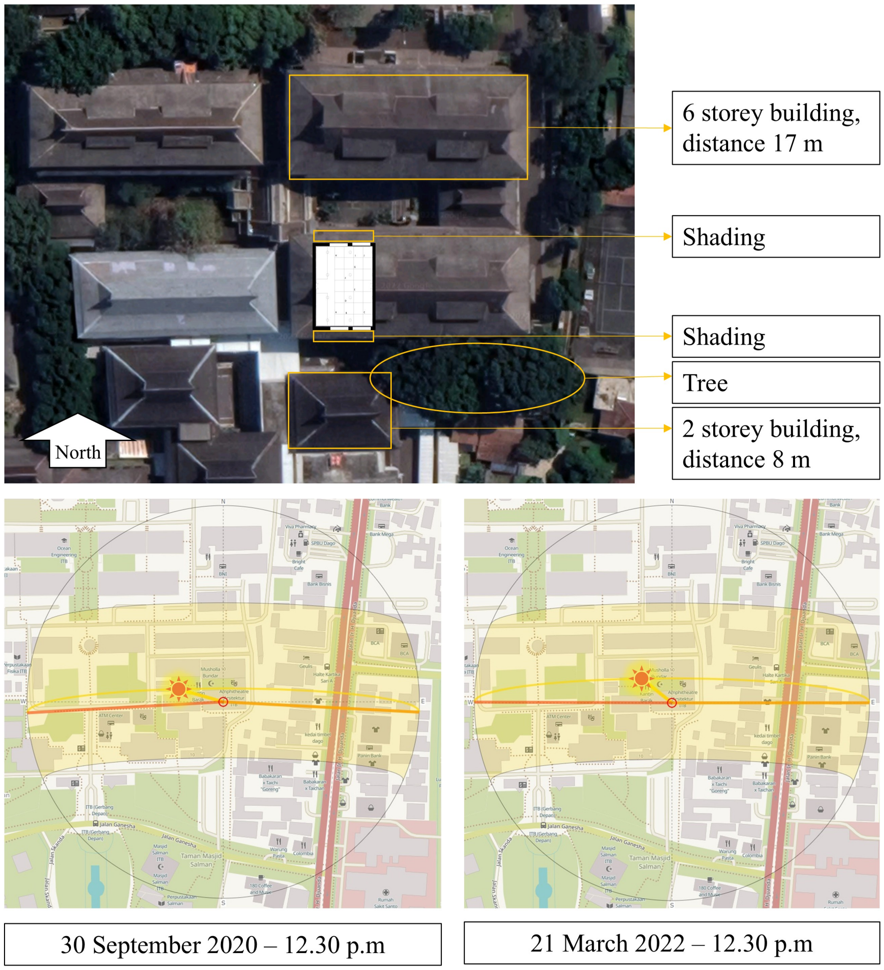



**Fig. 1.** The context of buildings around the study location and two sun positions at the time of field measurements from suncalc.org.

1). These two dates were selected because the sun is directly above the equator, resulting in day and night being nearly equal in length. Measurements conducted in the morning (08.00–09.45), midday (12.30–14.15), and afternoon (14.30–16.15) in natural light condition.

The architecture studio in this study uses acoustic ceilings (80% reflectance), cream-coloured walls (70% reflectance), and cream ceramic floors (80% reflectance) as shown as in Figs. 2(f)-(h). The furniture in the semi-enclosed studio layout is a wooden drawing table with a glass table base (70x120x90 cm), interspersed with a white drawing table (80x110x70 cm), a black iron shelf in the middle of the room (45x120x180), and a wooden iron shelf on the east wall (35x140x230 cm). The furniture in the open studio layout is a wooden drawing table with a glass table base (70x120x90 cm) and a wooden iron shelf on the east wall (35x140x230 cm). At the time of measurement, the iron shelf was empty but is typically used to place models. Figures 2(a) and (d) shows the furniture layout and section in semi-enclosed studio layout, whereas Figs. 2(b) and (e) shows the furniture layout and section in open studio layout. Measurement points for this study were obtained by creating a 3x3 meter grid, and then 10 measurement points (point A-J) were randomly selected to represent each vertical and horizontal line. At each point, 4 Ev and DGP data were taken according to 4 view directions, namely: north window, east wall, south window and west wall. Details regarding the measurement points and view direction are illustrated in Fig. 2(c). Ev measurements were taken using a Lutron LX-1108 Light Meter. HDR imaging was selected for glare measurement because it can capture high dynamic range luminance values, which are crucial for accurately assessing visual discomfort in environments with significant brightness contrasts. HDR images provide a more detailed and precise measurement of luminance, especially in complex lighting conditions, compared to other techniques that may not capture the full range of light intensities. This method aligns well with the study's focus on evaluating glare (DGP) in real-world settings where variations in natural lighting are prevalent. The steps taken to obtain the DGP value are as follows: 1. HDR images were captured using a Canon EOS 5D Mark II camera with a Canon EF 8–15 mm f/4 L USM fish eye; 2. the fish eye lens was calibrated by inputting the luminance value of one measuring point taken using a Konica Minolta LS110 luminance meter in the Aftab Alpha software; 3. the HDR images were then processed using Evalglare and Aftab Alpha software to produce the DGP values [34-36].

Based on the results of the normality assumption test using Shapiro–Wilk goodness of fit on all spatial and temporal aspects, a p-value of $<0.001$ was obtained. This indicates that the normality assumption is not met or not normally distributed. Thus, the

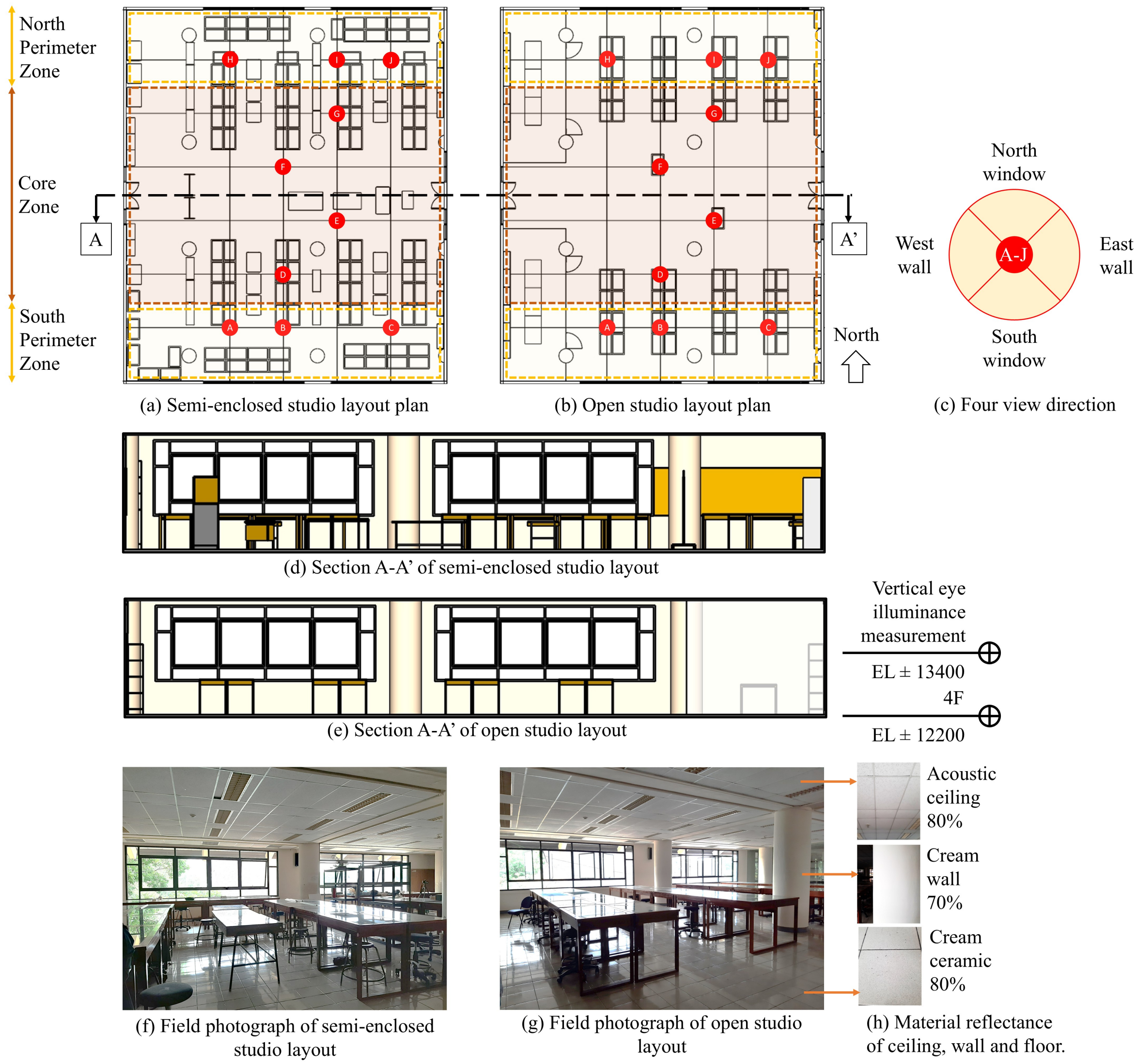



**Fig. 2.** (a) Semi-enclosed studio layout plan; (b) Open studio layout plan; (c) Four view direction for measurement; (d) section A=A' of semi-enclosed studio layout; (e) Section A-A' of open studio layout; (f) Field photograph of semi-enclosed studio layout; (g) Field photograph of open studio layout; (h) Material reflectance of ceiling, wall and floor.

appropriate analysis used is the non-parametric method, namely Kruskal–Wallis. This test determines whether the samples originate from the same distribution and does not assume normality of the random error, although it does require independence of the errors [37]. The Kruskal–Wallis test is used to examine the phenomena associated with each category in spatial and temporal aspects, and a significant difference is determined between the categories (p-value < 0.05). Subsequently, Dunn's test is conducted to identify which groups are significantly different from each other (p-value < 0.05). Furthermore, the research is continued by conducting optimisation studies to get the maximum results from the user's visual comfort. The prediction profiler enables researchers to examine the relationship between multiple factors and multiple responses which are displayed in a matrix plot [38]. A row of plots show the conditional relationship between dependent and independent variables. Desirability functions can also be used to get optimisation values from multiple responses. The subsequent section presents the results sequentially, according to the data analysis method to address the research questions. It begins with the Kruskal–Wallis test on the spatial and temporal aspects, followed by the visual comfort optimisation study with prediction profiler.

## 3. Results and discussion

In this study, the quality of visual comfort was determined from the distribution of Ev and the presence of glare in the room. To show the difference in measurement range of vertical eye illumination and DGP, three measurement points are selected to represent each zone. Point A represents the south perimeter zone, point G represents the core zone, and point J represents the north perimeter zone. The measured Ev values range from 9.07–1855 lux, which indicates a level between comfortable and

**Table 1.** Differences in daylight glare probability (DGP) at south perimeter, core and north perimeter at certain measurement times, view directions and layouts.

| Sessions (time) | Zone \ View Direction | Semi-enclosed studio layout | | | | Open studio layout | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | North Window (lux) | East Wall (lux) | South Window (lux) | West Wall (lux) | North Window (lux) | East Wall (lux) | South Window (lux) | West Wall (lux) |
| Morning (8 a.m-9.45 a.m) | South Perimeter | 39 | 120 | 638 | 125 | 38 | 204 | 306 | 241 |
| | Core | 110 | 43 | 45 | 62 | 105 | 33 | 29 | 47 |
| | North Perimeter | 244 | 78 | 60 | 147 | 174 | 143 | 39 | 95 |
| Midday (12.30 p.m-2.15 p.m) | South Perimeter | 58 | 196 | 880 | 150 | 99 | 625 | 835 | 232 |
| | Core | 62 | 24 | 24 | 28 | 150 | 26 | 63 | 148 |
| | North Perimeter | 280 | 54 | 50 | 104 | 240 | 151 | 90 | 288 |
| Afternoon (2.30 p.m-4.15 p.m) | South Perimeter | 22 | 91 | 542 | 76 | 46 | 308 | 973 | 240 |
| | Core | 56 | 22 | 22 | 21 | 124 | 37 | 65 | 67 |
| | North Perimeter | 272 | 82 | 66 | 150 | 191 | 94 | 89 | 97 |

Note: Vertical eye illuminance range is x<875 lux=comfortable; 875 lux >x < 1250 lux=bounded; and x>1250 lux=uncomfortable [14].

**Table 2.** Differences in daylight glare probability (DGP) at south perimeter, core and north perimeter at certain measurement times, view directions and layouts.

| Sessions (time) | Zone \ View Direction | Semi-enclosed studio layout | | | | Open studio layout | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | North Window | East Wall | South Window | West Wall | North Window | East Wall | South Window | West Wall |
| Morning (8 a.m.-9.45 a.m.) | South Perimeter | 0.011 | 0.06 | 0.298 | 0.008 | 0.185 | 0.189 | 0.223 | 0.176 |
| | Core | 0.103 | 0.009 | 0.016 | 0.005 | 0.224 | 0.204 | 0.235 | 0.203 |
| | North Perimeter | 0.204 | 0.019 | 0.025 | 0.077 | 0.219 | 0.196 | 0.228 | 0.209 |
| Midday (12.30 p.m.-2.15 p.m.) | South Perimeter | 0.015 | 0.166 | 0.314 | 0.009 | 0.197 | 0.199 | 0.228 | 0.134 |
| | Core | 0.024 | 0.005 | 0.009 | 0.005 | 0.218 | 0.193 | 0.225 | 0.204 |
| | North Perimeter | 0.19 | 0.009 | 0.011 | 0.023 | 0.228 | 0.195 | 0.223 | 0.205 |
| Afternoon (2.30 p.m.-4.15 p.m.) | South Perimeter | 0.007 | 0.035 | 0.316 | 0.005 | 0.214 | 0.206 | 0.245 | 0.195 |
| | Core | 0.023 | 0.005 | 0.018 | 0.004 | 0.235 | 0.187 | 0.231 | 0.208 |
| | North Perimeter | 0.173 | 0.009 | 0.01 | 0.021 | 0.221 | 0.192 | 0.229 | 0.209 |

Note: DGP threshold is 0.21=imperceptible-perceptible; 0.22=perceptible-disturbing; 0.24>x<0.26=disturbing-intolerable [16].

uncomfortable [14]. Conversely, the DGP value ranges from 0.004–0.373, indicating that it can reach a comfortable level (0.35) [13]. However, if the DGP value is adjusted to other studies conducted in tropical areas, it will show that the indoor glare sensation can reach a level between disturbing and intolerable [15,16] As shown in Table 1, the Ev values at points A, G, and J during the semi-enclosed studio layout (30 September 2020) and open studio layout (21 March 2022) measurements were almost at a comfortable level. However, the DGP values (Table 2) showed different trends. In the semi-enclosed studio layout, most of them were at the perceptible level; however, in the south perimeter with a view direction south window, intolerable levels were found in the morning, afternoon, and evening. Furthermore, in the open studio layout, most of them were also at the imperceptible-disturbing level. However, in the south window view direction, the value changed to the intolerable at the south perimeter during the day.

This shows that differences in spatial and temporal aspects can affect the distribution of light and glare sensation in room. To further understand the differences in the effects of spatial and temporal aspects on visual comfort conditions, particularly regarding vertical eye illumination and DGP values, further analysis was conducted using the Kruskal–Wallis test to show differences phenomena between groups (layout, zone, view direction, and temporal).

### *3.1. Study of differences in spatial and temporal aspects*

#### *3.1.1. Spatial context*

The Kruskal–Wallis results for Ev, presented in Fig. 3(a), indicate a significant difference among the groups (p=0.0093), and the Dunn post-hoc test highlights that the open studio and semi-enclosed studio layouts are significantly different from each other (z=-2.60073, p=0.0093). This implies that the semi-enclosed layout has a lower vertical eye illuminance compared to the open studio layout. The same result was found in Kruskal–Wallis results for DGP, presented in Fig. 3(b), which indicate a significant difference among the groups (p<.0001). Additionally, the Dunn post-hoc test highlights that the open studio and semi-enclosed studio layouts are significantly different from each other (z=-15.2203, p<.0001). This suggests a highly significant difference in glare levels between the two layouts, with the semi-enclosed

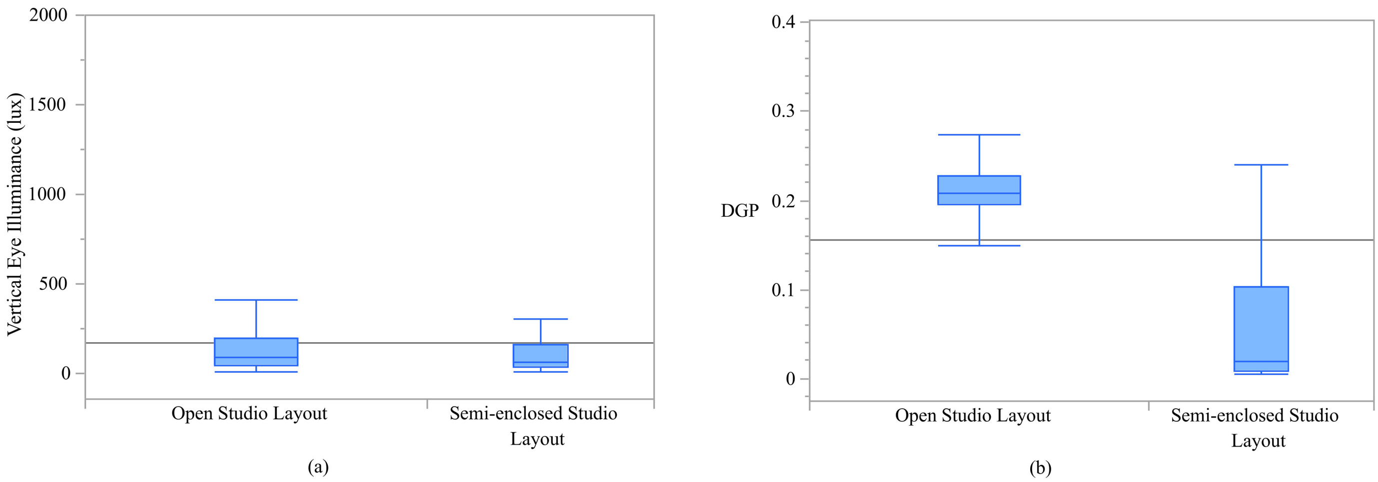



**Fig. 3.** (a) Kruskal–Wallis test for vertical eye illuminance by layout (p=0.0093); (b) Kruskal–Wallis test for DGP by layout (p<.0001).

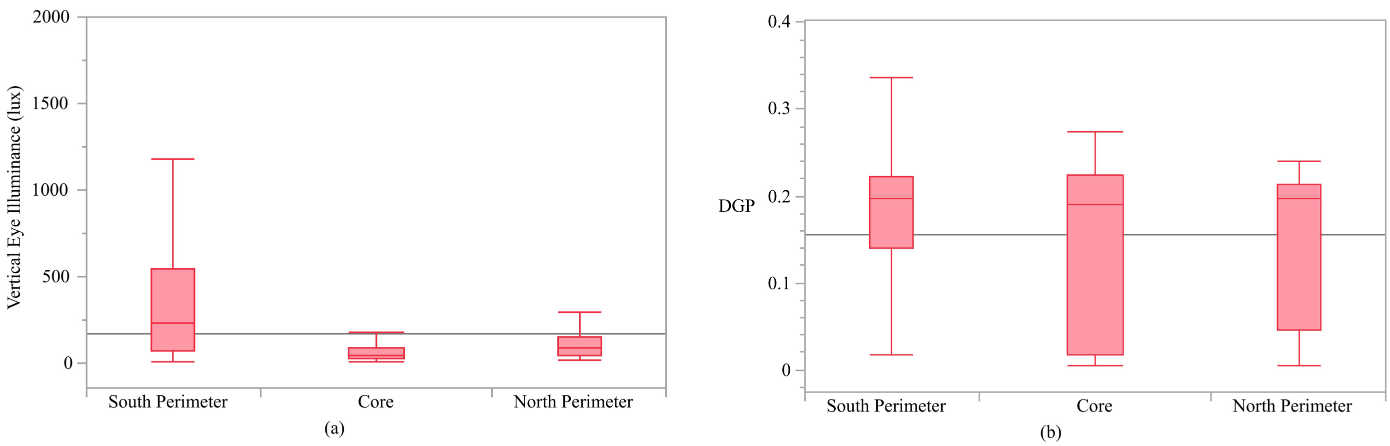



**Fig. 4.** (a) Kruskal–Wallis test for vertical eye illuminance by zone (p<.0001); (b) Kruskal–Wallis test for DGP by zone (p=0.0367).

layout experiencing significantly lower glare probability than the open studio layout.

As shown in Fig. 4(a), the Kruskal–Wallis test for Ev shows that all zones are significantly different from each other (p<.0001). Dunn post-hoc test was conducted on three comparison groups: north perimeter vs core (z=5.3762, p<.0001), north perimeter vs south perimeter (z=-5.8845, p<.0001), and core vs south perimeter (z=-11.6674, p<.0001). It shows that the south perimeter has the highest illuminance, followed by the north perimeter, and the core has the lowest illuminance. Furthermore, as shown in Fig. 4(b), Kruskal–Wallis for DGP shows a statistically significant difference in DGP between the zones; however, the difference is less pronounced than for illuminance (p=0.0367). The Dunn post-hoc test was conducted on three comparison groups: north perimeter vs core (z=0.66421, p=1), north perimeter vs south perimeter (z=-1.74319, p=0.2439), and core vs south perimeter (z=-2.52809, p=0.0344). This indicates that only the core and south perimeter differ significantly in terms of DGP, with the south perimeter having more glare. The north perimeter does not significantly differ from either the core or the south perimeter in terms of glare. These results highlight that glare and Ev behave differently across zones, with Ev showing clearer distinctions than glare. This suggests that while daylight access (Ev) varies significantly across zones, glare control may be more zone-specific, particularly concerning the south perimeter (perimeter that has light openings with direct access to light from the sky).

At each measurement point, four data were obtained for Ev and DGP from four facing directions, namely, south window, west wall, north window, and east wall (Fig. 2(c)). As shown as in Fig. 5(a), Kruskal-Wallis test for eye vertical illuminance show a statistically significant difference in Ev depending on the view direction (south window, north window, east wall, west wall) (p<.0001). The Dunn post-hoc test for six comparison groups: south window vs north window (z=4.43648, p<.0001), south window vs east wall (z=3.94389, p=0.0005), west wall vs north window (z=3.06162, p=0.0132), west wall vs east wall (z=2.56903, p=0.0612), east wall vs north window (z=0.49226, p=1), and west wall vs south window (z=-1.37452, p=1). The south window has significantly higher Ev than the north window and east wall. The west wall also has significantly higher illuminance than the north window, but no significant differences were found between the west wall and the south window or between the east wall and the north window. Finally, the west wall

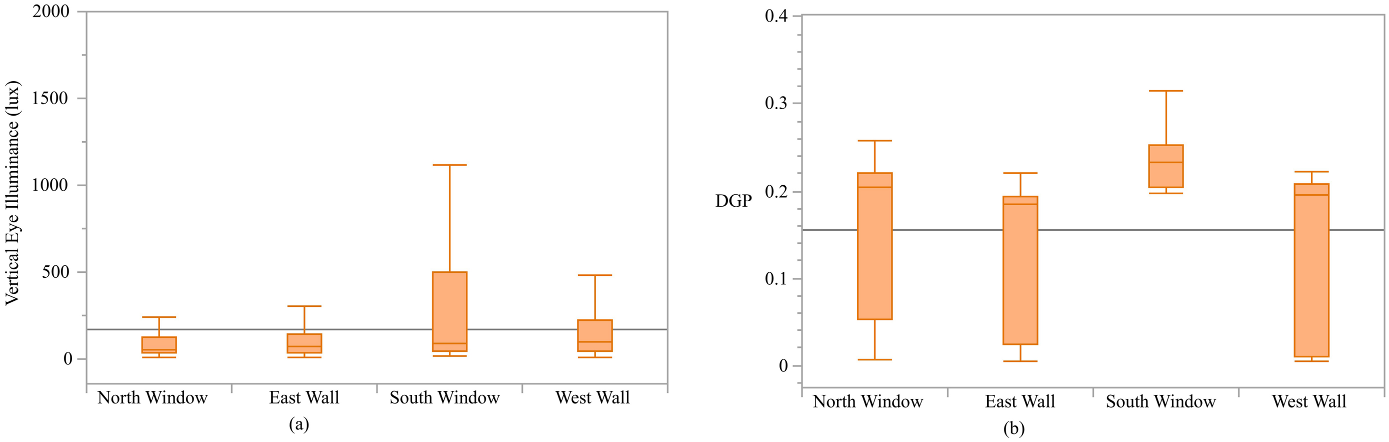



**Fig. 5.** (a) Kruskal–Wallis test for vertical eye illuminance by view direction (p<,0001); (b) Kruskal–Wallis test for DGP by view direction (p<,0001).

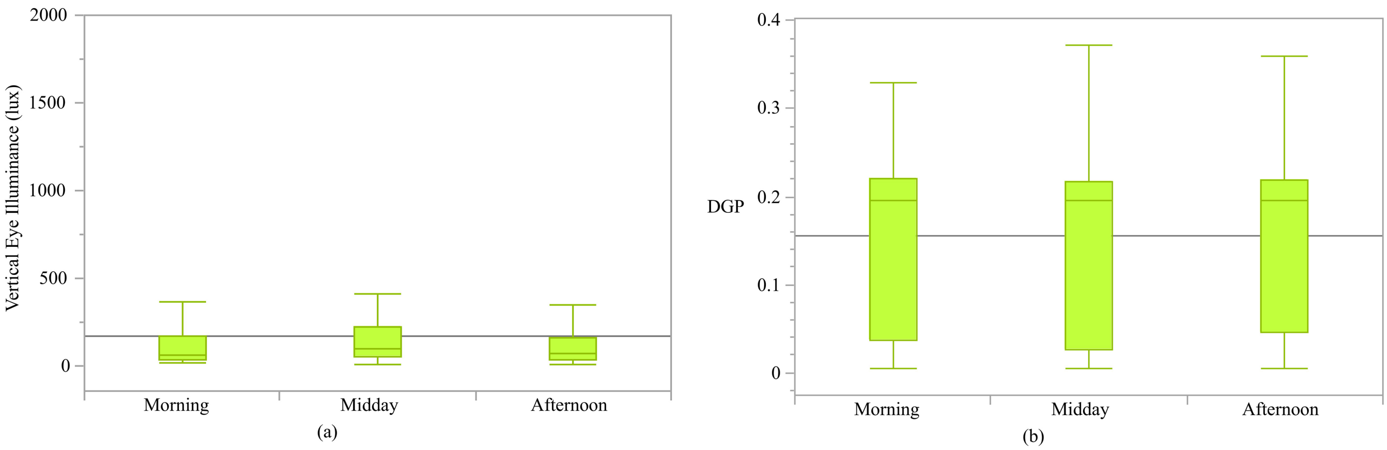



**Fig. 6.** (a) Kruskal–Wallis test for vertical eye illuminance by session (p=0.0003); (b) Kruskal–Wallis test for DGP by session (p=0.9661).

vs east wall is nearly significant, suggesting that they might differ in illuminance but with weaker evidence.

The Kruskal–Wallis for DGP, as shown in Fig. 5(b), shows p<.0001 that indicates a statistically significant difference in DGP depending on the view direction. Furthermore, the Dunn post-hoc test for six comparison groups: south window vs east wall (z=11.1725, p<.0001), south window vs north window (z=5.6075, p<.0001), west wall vs east wall (z=1.7127, p=0.5206), west wall vs north window (z=-3.8516, p=0.0007), east wall vs north window (z=-5.5647, p<.0001), and west wall vs south window (z=-9.4594, p<.0001). The south window has significantly higher DGP than the east wall and north window, but the north window has significantly higher glare than the east and west walls. There is also no significant difference between the west wall and east wall, suggesting similar glare probabilities. Finally, the south window produces much more glare than the west wall. The results indicate that illuminance and glare behave differently across different view directions. Architects should focus on these distinctions, especially when managing natural light from the south window (light opening that gets direct access to light from the sky), which tends to produce higher glare and illuminance.

### *3.1.2. Temporal context*

The Kruskal–Wallis results for Ev, presented in Fig. 6(a), show a p-value of 0.0003. This indicates a statistically significant difference in Ev between the different sessions (morning, midday, afternoon), or at least one session differs significantly from the others in terms of illuminance levels. Furthermore, the Dunn post-hoc test for three comparison groups: midday vs morning (z=3.03852, p=0.0071), afternoon vs morning (z=-0.74373, p=1), and afternoon vs midday (z=-3.78254, p=0.0005). Midday session stands out as the session with the highest illuminance, whereas morning and afternoon are more similar to each other. While the Kruskal–Wallis results for DGP show a p-value of 0.9661, no statistically significant difference is found in DGP between the sessions (morning, midday, afternoon). Therefore, the glare probability remains fairly constant throughout the day, and the session does not have a notable impact on glare. Architects should account for higher illuminance levels at midday when planning lighting strategies in spaces that experience natural light. This could lead to considerations for shading or light diffusion to avoid excessive brightness during the midday hours. As glare does not vary by session, controlling glare may not need to be adjusted throughout the day but should be managed effectively across all times.

Several factors, including temporal and spatial aspects such as layout, zones, and view direction, significantly influence visual comfort in deep rooms. Side lighting openings affect the distribution of natural light in semi-enclosed and open studio layouts, with the highest Ev and DGP values observed near the room's perimeter. This aligns with the optimum daylight penetration rule of thumb, which suggests that light reaches a distance of 1.5 times the window's head height [24,29]. In deep rooms, layout variations have minimal impact on Ev distribution owing to limited light penetration, leading to zones with lower light levels. However, the overall distribution of Ev remains comfortable, which is likely due to the bilaterally lit room [33]. This contrasts with glare sensations, where open layouts, lacking large furniture to block light, can increase DGP values to levels between disturbing and intolerable. Additionally, furniture can reduce indoor lighting levels [27]. However, lighting openings with direct sky access are crucial in deep rooms, as direct and peripheral sky views can significantly raise Ev and glare levels. This effect is particularly pronounced in south window view direction, where direct sky views can elevate glare to uncomfortable levels. The sun's movement throughout the day affects Ev more than DGP values, with the highest illuminance occurring during midday, while DGP values remain relatively stable throughout the day. After understanding the phenomenon from spatial and temporal aspects, an optimization study was conducted.

### *3.2. Study optimisation*

Optimisation study aims to better understand the condition of the room by combining several visual comfort objectives. In this study, visual comfort is shown in the form of eye vertical illuminance and DGP. It was combined to obtain the maximum, minimum, and target results. Table 3 shows that optimisation studies that will be sought are: Ev max - DGP max (scenario one); Ev max - DGP min (scenario two); Ev min - DGP max (scenario three); Ev min - DGP min (scenario four); and Ev target (875<x>1250) - DGP target (x<0.21) (scenario five).

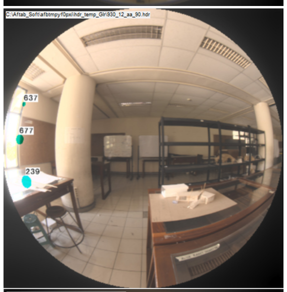
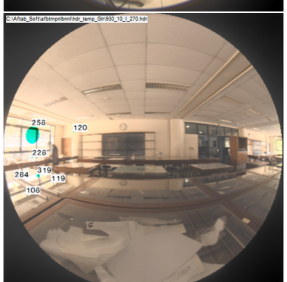
The worst room conditions were identified in scenario one (Evmax-DGPmax), three (Evmin-DGPmax), and four (Evmin-DGPmin). In scenario one (Evmax-DGPmax), where the goal was to find maximum glare conditions, the open layout on the southern perimeter, with view direction to the south window during the day, showed the highest glare potential. This zone near the window provided strong light distribution but also created visual discomfort due to the frontal sitting position, which intensified glare. A simple adjustment—reorienting the seating direction away from the window—can help mitigate this issue. In scenario three (Evmin-DGPmax), the objective was to identify the worst scenario in terms of low Ev and high glare. This was observed in the open layout on the north perimeter, with view direction to the south window in the morning. Here, the room appeared dim overall, whereas the south window was excessively bright, leading to discomfort. Scenario four (Evmin-DGPmin) aimed to pinpoint the darkest room setting without glare, which occurred in the semi-enclosed layout in the core area, with view direction to the east wall in the morning. These situations could be improved by enhancing natural light penetration (e.g., using light shelves) and increasing wall or furniture reflectance to achieve more even light distribution and reduce contrast [31].

The best room conditions were found in scenarios two (Evmax-DGPmin) and five (Evtarget-DGPtarget). In scenario 2 (Evmax-DGPmin), the goal was minimal glare with maximum light distribution, observed in the semi-enclosed layout on the southern perimeter, with view direction to the west wall during the day. The window edge zone proved to be the optimal area for light distribution. Scenario 5, an extension of scenario 2, targeted a specific Ev range (875-1250 lux) and a DGP threshold (below 0.21). This was achieved in the open layout on the southern perimeter, with view direction to the north window during the day. Both scenarios suggest strategies for achieving ideal conditions which is sit near the window for strong light distribution, but adjust seating orientation and use furniture to block direct window access.

Achieving the optimal conditions in deep rooms, which require ideal Ev and glare sensation, depends on several factors. First, morning light tends to be weak, making it challenging to utilise in such rooms. Second, Ev is affected by external factors such as surrounding buildings, reflective surfaces, obstructions, and interior elements such as light shelves or reflectance from floors, walls, and ceilings. Third, increasing and reducing glare sensation in deep rooms can be addressed by changing the distance, facing direction, and sitting position or by changing the layout of the room. These factors must be considered when adjusting layouts or adding light-enhancing features to ensure optimal lighting, especially during low outdoor light conditions. Thus, optimizing visual comfort from an architectural perspective involves several key considerations. First, in deep rooms, lighting is highly sensitive to light openings, requiring careful treatment of side lighting to avoid creating contrast with the room's surfaces (floor, walls, ceilings). Second, ceiling design plays a more significant role than walls, as it is closer to the user. Therefore, using light guides or internal reflections, particularly those that incorporate the ceiling, is more effective. Finally, if light guides are essential for improving light distribution, the floor-to-floor height should be considered to facilitate installation.

This experimental study was conducted in a deep room with two side lighting sources relying on natural light. The findings apply to similar architectural types, such as offices, studios, museums, and galleries. While field measurements can capture real-time phenomena, they are limited to the specific conditions present during the measurement period. Factors such as unpredictable outdoor lighting and interactions with interior furniture may influence indoor light distribution. Future research could utilise more robust methods, such as simulations, to gather year-round data under varying outdoor conditions. Additionally, further exploration is required to maintain optimal visual comfort—ensuring balanced light distribution without glare or excessive contrast—throughout the day, especially considering surface properties in deep rooms. Other topics such as different room types, such as amphitheatres, larger sample sizes, such as comparing several rooms that have the same typology, and different geographic locations, such as in sub-tropical areas, can be explored to gain a deeper understanding of this topic. Other areas for future research include the temporal aspects of lighting and human reactions, such as visual fatigue, circadian rhythms, and user mood. Research on dynamic lighting systems that address these aspects are also gaining traction among scholars.

**Table 3.** Optimisation of scenarios from spatial and temporal aspect interventions for visual comfort.

| No | Scenarios | | | Aims | Optimisation Result | | | | Interpretation |
|---|---|---|---|---|---|---|---|---|---|
| | Photo | Ev (lux) | DGP | | Layout | Zone | View Direction | Session (time) | |
| 1 |  | Max (560) | Max (0.27-intolerable) | Identifying conditions where glare is maximum | Open Studio Layout | South Perimeter | South Window | Midday | Disturbing glare occurs in open layout conditions, especially on the south perimeter and view direction to the south windows during the day. |
| 2 |  | Max (398) | Min (0.07-imperceptible) | Identify low glare conditions with the highest illuminance | Semi-enclosed Studio Layout | South Perimeter | West Wall | Midday | Optimum condition with highest lighting level with the lowest glare level occurs at semi, south perimeter, wall, during the day. |
| 3 |  | Min (228) | Max (0.25-intolerable) | Identify the worst conditions with the lowest illuminance and highest glare | Open Studio Layout | North Perimeter | South Window | Morning | The worst conditions were found in open, north perimeter, and with view direction to the south windows in the morning. |
| 4 |  | Min (0) | Min (0.03-imperceptible) | Identify the darkest conditions without glare | Semi-enclosed Studio Layout | Core | East Wall | Morning | The darkest condition without glare occurs in the middle of the room with a semi-enclosed and view direction to the east wall in the morning. |
| 5 |  | Range: 875-1250 (532) | Threshold: 0.21 (0.13-imperceptible) | Identify conditions where glare is acceptable and the best possible vertical illuminance range can be achieved. | Semi-enclosed Studio Layout | South Perimeter | South Window | Midday | Optimum condition to achieve the expected Ev and DGP targets are obtained in the southern perimeter zone, semi-enclosed layout but view direction to the south window during the day. |

## 4. Conclusion

The average DGP value in both layout rooms was at a perceptible level but could reach a level between disturbing and intolerable in the south window view direction. Conversely, the average Ev value was at a comfortable level. This indicates that visual comfort in a deep room sequentially depends on view direction, zone, layout, and time. The Ev in deep rooms is primarily influenced by the type of opening, specifically side lighting, which results in daylight penetration that fails to reach the room's core and is dependent on outdoor conditions. Consequently, illuminance at the perimeter is significantly higher than at the core. However, the glare sensation remains unaffected by outdoor conditions during the day. Adjusting the view direction can help manage less-than-ideal sitting positions for improved visual comfort, while repositioning within zones enhances comfort across different times of the day. Obstructions within the room play a dual role: positively by controlling glare and negatively by reducing Ev. Throughout the day, visual discomfort is most pronounced in the morning owing to insufficient Ev. Optimal conditions are typically found during the day, especially when facing the west wall or south window, in the south perimeter zone, and in a semi-enclosed studio layout. This highlights that view direction and zone placement are crucial factors in achieving visual comfort, while aspects such as layout, room surface properties, and obstructions can improve at different times of the day. Horizontal plane elements, such as ceilings, can enhance Ev and mitigate glare effects, particularly in the morning or under cloudy conditions. Though field measurements capture real-time phenomena, they are constrained by the specific conditions at the time of measurement. Future research could employ more robust approaches, such as simulations, to collect data across the entire year under diverse outdoor conditions. To optimise visual comfort from an architectural perspective, it is important to consider the contrast between light opening and room surface, ceiling design for internal reflection, and floor-to-floor height to accommodate the light guide intervention. These insights have significant implications for designing deep spaces such as offices, studios, museums, and galleries, where the configuration of horizontal and vertical surfaces, furniture, and layouts can significantly influence user performance.

## Acknowledgement

This study was supported by the Riset Unggulan Institut Teknologi Bandung 2024, contract number 138/IT1. B07.1/TA.00/2024.

## Contributions

Rizky Amalia Achsani: Writing-original draft, writing-review and editing, conceptualisation, methodology, data curation, investigation, formal analysis, visualisation, validation, and resources. Surjamanto Wonorahardjo: Writing–original draft, writing – review and editing, conceptualisation, methodology, data curation, investigation, formal analysis, visualisation, validation, and resources. Sugeng Triyadi: Writing–original draft, writing – review and editing, conceptualisation, methodology, investigation, formal analysis, visualisation, validation, and supervision.

## Declaration of competing interest

The authors declare no conflict of interest.

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