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PARAMETRIC SIMULATION OF ARTIFICIAL LIGHT EFFECTS ON VERTICAL ILLUMINANCE FOR CIRCADIAN STIMULUS IN OPEN-PLAN OFFICE

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ABSTRACT

Lighting contributes not only to visual performance but also to the regulation of human circadian rhythms. One of the key parameters in evaluating circadian-effective lighting is vertical illuminance at eye level, which represents the amount of light reaching the human eye. Based on circadian lighting principles, appropriate levels of vertical illuminance are required to support alertness and biological rhythm alignment during daytime. This study investigates the effects of interior surface reflectance and correlated color temperature (CCT) on vertical illuminance in an open-plan office environment. A parametric simulation was conducted using DIALux evo, based on a fixed layout of office space and luminaires. Two CCT conditions representing daytime lighting were applied: 6500 K (08:00–12:00) and 5000 K (12:00–16:00). Interior surface reflectance values for ceiling, walls, and floor were systematically varied to evaluate their impact. The simulation excludes daylight contribution to isolate the effects of artificial lighting parameters. The results show that the average vertical illuminance ranges from 381 lux to 571 lux across all scenarios. High-reflectance scenarios produce illuminance levels exceeding 500 lux, indicating strong circadian stimulation but potential overlighting conditions. In contrast, low-reflectance scenarios fall within the recommended range of 250–500 lux, providing more balanced circadian-effective lighting. These findings indicate that interior surface reflectance has a significant influence on vertical illuminance, while the effect of CCT is not significant under the studied conditions. Therefore, reflectance can be considered a critical design parameter in achieving circadian-supportive lighting environments in office spaces.

KEYWORDS: circadian lighting, human-centric lighting, interior reflectance, office lighting simulation, vertical illuminance

Pencahayaan tidak hanya berperan dalam mendukung kenyamanan visual, tetapi juga memengaruhi ritme sirkadian manusia. Salah satu parameter yang digunakan untuk mengevaluasi pencahayaan yang mendukung sistem sirkadian adalah vertical illuminance pada tingkat mata, yang merepresentasikan jumlah cahaya yang diterima oleh mata. Penelitian ini bertujuan untuk menganalisis pengaruh reflektansi permukaan interior dan correlated color temperature (CCT) terhadap nilai vertical illuminance pada ruang kantor open-plan. Penelitian dilakukan menggunakan metode simulasi parametrik dengan perangkat lunak DIALux evo berdasarkan satu layout ruang dan konfigurasi lampu yang sama. Dua skenario CCT diterapkan untuk merepresentasikan kondisi pencahayaan siang hari, yaitu 6500 K pada periode pagi dan 5000 K pada periode siang. Nilai reflektansi permukaan interior pada plafon, dinding, dan lantai divariasikan dalam rentang standar untuk menganalisis pengaruhnya terhadap distribusi vertical illuminance. Hasil simulasi menunjukkan bahwa nilai rata-rata vertical illuminance berkisar antara 420 lux hingga 571 lux. Berdasarkan ambang batas pencahayaan sirkadian, sebagian skenario berada pada rentang 250–500 lux yang menunjukkan stimulasi sirkadian yang efektif. Hasil penelitian menunjukkan bahwa reflektansi interior memengaruhi nilai vertical illuminance, sementara variasi CCT tidak memberikan pengaruh signifikan terhadap nilai iluminansi.

KATA KUNCI: *circadian lighting, human-centric lighting, reflektansi interior, simulasi pencahayaan, vertical illuminance*

INTRODUCTION

Light exposure at the eye, commonly represented by vertical illuminance, has a great impact on human circadian rhythms, which are involved in important physiological processes such as sleep–wake cycles, hormone secretion, and alertness. In indoor environments, vertical illuminance is not only determined by lighting systems but also by interior surface reflectance, which influences how light is distributed and reflected within a space. Light perception through intrinsically photosensitive retinal ganglion cells (ipRGCs) relays signals to the central clock within the brain. These cells contain melanopsin photoreceptors that play an important role in circadian phototransduction (Lucas et al., 2019).

Conventional lighting design, which focuses on horizontal illuminance at task surfaces, cannot adequately reproduce the retinal stimulation that drives circadian entrainment, where vertical illuminance is the illuminance falling on a vertical plane at eye level that has become a more relevant measure for circadian effects of lighting (Jalali et al. 2024).

Vertical illuminance is an important consideration in that it better captures the effective light exposure that presents to the retina. Recent circadian lighting studies also emphasize melanopic-based metrics, such as melanopic equivalent daylight illuminance (mel-EDI), to evaluate biologically effective light exposure (CIE, 2018). Recent developments in integrative lighting have further emphasized the importance of considering both visual and non-visual effects of light in building design (CIE, 2020). Both daylight and electric lighting systems have shown significant effects on vertical melanopic illuminance and circadian-effective light exposure, with daylight often being the dominant contributor to biologically relevant light levels in indoor environments (Sanchez-Cano et al., 2024; Huang et al., 2024).

For instance, studies in office and educational environments have shown that variations in spectral power distribution, correlated color temperature (CCT), luminaire configuration, and daylight availability can significantly influence vertical illuminance and circadian-effective lighting metrics under similar spatial conditions (Jalali et al., 2024; Sanchez-Cano et al., 2024).

Although circadian lighting studies have advanced, there is a lack of available literature that explains how idealistic and practical vertical illuminance targets are created and measured, and the way they are accomplished in the actual built environment. While existing metrics (mel-EDI, circadian stimulus (CS)) have matured from theory to action in design guidance and standard protocols, this area is growing more rapidly, as a group of researchers seeks more precise, evidence-backed thresholds and measurement procedures that incorporate sensor position, sense of orientation, and timing (Huang et al. 2024; Jalali et al. 2024).

Additionally, empirical studies have shown that recommended circadian lighting targets are not consistently achieved in real-world environments, particularly when daylight availability is limited or when lighting systems are not specifically designed to support circadian-effective illumination (Brown et al., 2022; Jalali et al., 2024).

Collectively, these findings suggest a clear research need for systematic studies that assess vertical illuminance under different artificial lighting conditions and identify the primary design factors influencing circadian lighting performance in indoor environments (Huang et al., 2024; Jalali et al., 2024).

Filling this gap is vital for achieving a balance between laboratory-derived circadian theory and the practicalities of building environments, and improving human-centred lighting strategies that can optimally optimize the visual comfort, biological performance, and energy performance of these resources. Hence, this research explores the association between different lighting system configurations and temporal levels to different vertical illuminance thresholds for circadian lighting evaluation. We (1) quantify vertical illuminance at normal eye positions subject to controlled but artificial lighting structures (including various CCT and luminaire locations), (2) investigate which factors (CCT, luminaires, surface reflectance, time of the day) best affect the achievement of established circadian thresholds, and (3) discuss implications for design practice and standards application in academic studio contexts. The growing understanding of non-visual biological responses to light has increased the importance of evaluating lighting performance beyond conventional visual criteria (van Bommel, 2020).

METHODS

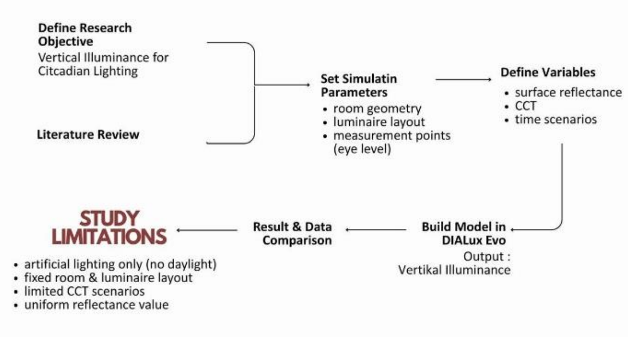


Figure 1. Research Workflow
(Source: Author's Document, 2026)

The diagram illustrates the overall research process, including variable definition, simulation procedures, and data analysis. Model validation was conducted by verifying the accuracy of input parameters, including room geometry, surface reflectance values, and luminaire specifications based on manufacturer data. The simulation results were further evaluated by comparing the obtained vertical illuminance values with typical office lighting ranges and findings from previous studies to ensure consistency and reliability.

In addition, the study acknowledges several limitations, including the use of artificial lighting conditions without daylight contribution, a fixed spatial layout, and simplified reflectance values. These constraints may affect the generalizability of the results, but allow for a more controlled assessment of the selected variables.

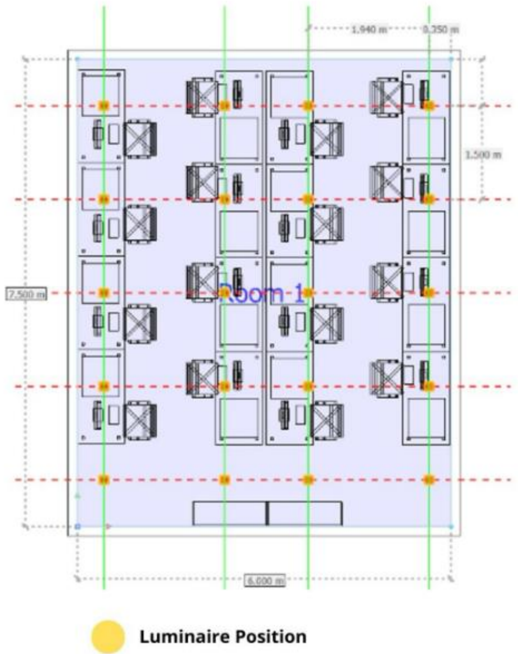


Figure 2. Layout simulation
(Source: Author's Document, 2026)

Figure 2 shows the layout used for the lighting simulation. The yellow points represent the luminaire positions, which are arranged to align with the desk layout. This configuration ensures that each workstation receives adequate illumination and reflects a realistic lighting design approach.

The luminaires are evenly distributed across the space to avoid areas that are too bright or too dim, creating a more balanced lighting condition overall. This setup is intended to resemble a typical office environment, where lighting is planned to support daily activities and visual comfort. By keeping the layout consistent in all scenarios, the simulation can more clearly show how changes in factors such as CCT and surface reflectance influence the resulting vertical illuminance.

Simulation Model

In this work, we use parametric lighting simulation to investigate vertical illuminance at the eye level of occupants as a performance optimization parameter for circadian lighting in a working environment. The simulated room symbolizes the open office style, which is popular in today's workplaces, with the advantage of enhanced space efficiency and supporting the co-working environment (Appel-Meulenbroek et al., 2021).

The office model was designed based on spatial configurations proposed by Meek and Van Den Wymelenberg (2014) with spatial dimensions of 6 m × 7.5 m × 3 m. The lighting configuration corresponds to the layout of the workstation to maximize light distribution in the working area and to support visual comfort among the occupants. This approach reflects common lighting design practice in open-plan offices where luminaire placement is coordinated with workspace organization (Boyce, 2014; CIBSE, 2015).

Daylight contribution is excluded from the simulation to isolate the effect of artificial lighting. Figure 2. The open-plan office layout used in the simulation shows workstation arrangement and luminaire locations. The luminaire placement follows the workstation configuration to ensure appropriate light distribution across the working area and to maintain visual comfort for occupants. Aligning luminaires with the layout of the work area is a common lighting design practice in open-plan offices because lighting performance is closely related to the spatial organization of tasks and occupants (Boyce, 2014; CIBSE, 2015; Meek & Van Den Wymelenberg, 2014).

Lighting Simulation and Evaluation Method

Simulations of lighting are performed after establishing the horizontal illuminance on the work plane with DIALux evo at approximately 500 lux in accordance with the recommended lighting level for office tasks as indicated in EN 12464-1 (2021). A dimmable electric lighting system is used for time-based circadian lighting in this study. Two correlated color temperature (CCT) conditions are used to represent different periods of the working day: 6500 K in the morning (08:00–12:00) under conditions to facilitate alertness and circadian stimulation; and 5000 K in the afternoon hours (12:00–16:00), within a context to promote visual performance and cognitive focus and to minimize excessive circadian stimulation (Brown et al., 2022; Jalali et al., 2024).

Table 1. Reflectance Threshold for Simulation in DIALux Evo

Surface	Reflectance
Ceiling	0.70-0.90
Wall	0.50-0.80
Floor	0.20-00.40

Table 2. Lighting Scenarios

Scenario	CCT (K)	Reflectance
S1	6500	Higher Reflectance for each surface : Ceiling = 0,9 Wall = 0,8 Floor = 0,4

Scenario	CCT (K)	Reflectance
S2	5000	Higher Reflectance for each surface : Ceiling = 0,9 Wall = 0,8 Floor = 0,4
S3	6500	Mid Reflectance for each surface : Ceiling = 0,8 Wall = 0,7 Floor = 0,3
S4	5000	Mid Reflectance for each surface : Ceiling = 0,8 Wall = 0,7 Floor = 0,3
S5	6500	Low Reflectance for each surface : Ceiling = 0,7 Wall = 0,5 Floor = 0,2
S6	5000	Low Reflectance for each surface : Ceiling = 0,7 Wall = 0,5 Floor = 0,2

In the parametric analysis, the interior surface reflectance value is manipulated as the major design aspect because reflectance has a major effect in shaping the light distribution in the room and the vertical illuminance. The reflectance values are within suitable office light ranges with ceiling reflectance about 0.80, wall reflectance about 0.60, and floor reflectance approximately 0.25 (CIBSE, 2015).

During a parametric simulation, interior surface reflectance values are also varied as the major design parameter because reflectance has a significant effect on the distribution of light in a space and thereby the vertical illuminance. Reflectance scenarios are specified according to commonly recommended ranges in lighting designs in office areas, based on lighting design guidelines (CIBSE, 2015; SLL, 2022). Table 1 summarizes the reflectance values applied in the simulation.

This analysis uses parametric simulation scenarios to determine the reflection of correlated color temperature (CCT) in both room space and interior surface reflectance trends. For office settings, the ceiling, walls, and floor reflectance values for these spaces have been adjusted into typical ranges that are widely accepted to see the effect of those values on the level of vertical illuminance. Each set of scenarios preserves the spatial layout of the office and the arrangement of luminaires to separate the influence of interior surface reflective properties upon the ensuing lighting conditions. Vertical illuminance is assessed at seated eye level, about 1.2 m above the floor level, on a vertical plane facing the primary viewing direction toward the work desk. This orientation is typical of upright-facing posture faced by occupants while the work is carried out on the desk.

This is discussed with respect to widely used circadian lighting recommendations, suggesting that daytime vertical illuminance levels of 250–500 lux at eye level provide adequate support for effective circadian stimulation in indoor contexts (Brown et al., 2022).

Table 3. Circadian Lighting Boundary (Approximate Vertical Illuminance)

Vertical Illuminance at Eye Level	Circadian Interpretation
<100 lux	Insufficient circadian stimulation
100–200 lux	Low circadian stimulus
200–500 lux	**Effective daytime circadian stimulation**
> 500 lux	Strong circadian stimulus

By reference data, the vertical illuminance thresholds given in Table 3 are used to determine the circadian effectiveness potential of the simulated lighting conditions. Light going directly to the eye is critical to the human circadian system, according to previous studies. Vertical illuminance is thus widely accepted as a convenient indicator for biologically relevant light exposure in indoor settings. Values less than approximately 100 lux are usually regarded as not triggering the circadian system, and eye-level levels between 200 and 500 lux are frequently found to confer good daytime circadian stimulation that enhances alertness and cognitive performance. These thresholds are based on existing circadian lighting studies and recommendations of indoor lighting exposure (Rea & Figueiro, 2018; Brown et al., 2022).

Data Collection

The lighting instrument of the simulation was generated from the lighting database available on DIALux evo. The luminaire variants were first discussed and selected for photometric properties, and in an ideal office lighting installation. The last luminaire chosen for the simulation is an LED light downlight (MPE DLT12-9/3C), a color temperature variable with tunable correlated color temperature.

The luminaire has a capability to be lit in various CCT configurations (6500 K, 5000 K, 4000 K), which enables the generation of a dynamic lighting scenario for a circadian lighting system. Using photometric data found with the DIALux database, the luminaire shows luminous flux of approximately 2835 lm, 27 W power consumption, 105 lm/W luminous efficacy, and the simulation model uses a total of 20 luminaires. So the luminaire positions are oriented along the workstation layout of the open-plan office, to ensure that the light is evenly distributed through the working space. This layout mirrors a typical lighting layout for the office, where luminaire placement is based on the arrangement of workstations in the space.

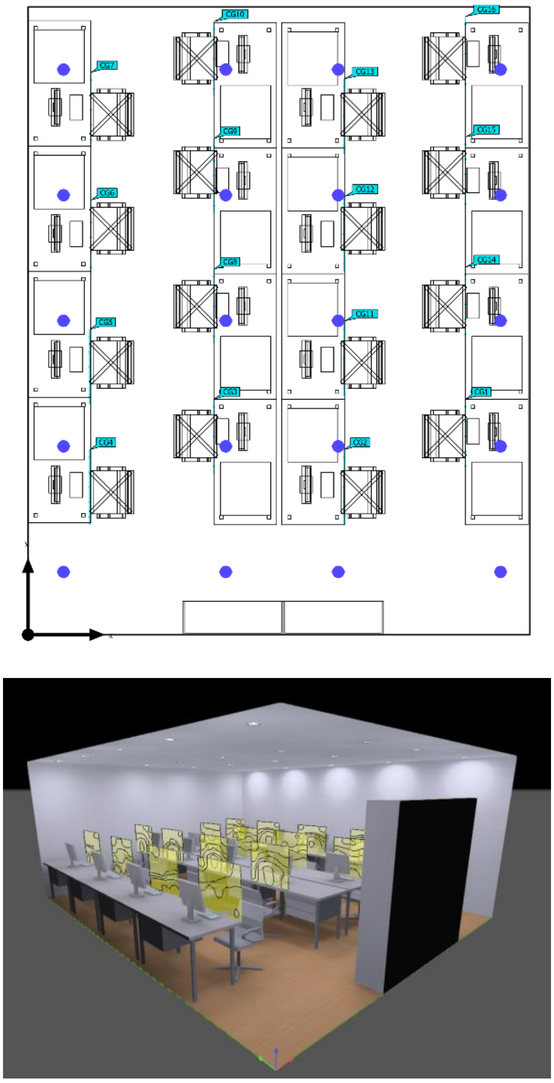


Figure 3. Luminaire Placement for Vertical Illuminance Simulation
(Source: Author's Document, 2026)

The Lamp Placement for measurement points used to collect vertical illuminance data in the simulation model. The blue markers are the calculation points located at seated eye level (1.2 m above floor) of a desk at each workstation to represent the typical user seating position. For interpretation, the results were set into two context regions by applying correlated CCT, with 6500 K (morning) and 5000 K (afternoon) for each case.

RESULTS AND DISCUSSION

Table 4 presents values of vertical illuminance from the simulation. A total of sixteen measurement points (CG1–CG16) were used for occupant positions for the open-plan office layout. Vertical illuminance values were taken at each point and the average value for each scenario was calculated to assess the overall lighting condition. For analytical purposes, simulation scenarios are segmented into two segments by used correlated color temperature (CCT). Scenarios 1, 3, and 5 for 6500 K lighting condition, Scenarios 2, 4, and 6 for 5000 K lighting condition. The group composition enables comparison of vertical illuminance performance at two different circadian lighting conditions, depending on interior surface reflectance variations.

Table 4. Result Scenarios

LP	Scenarios S1	S2	S3	S4	S5	S6
CG1	559	559	526	526	362	362
CG2	532	532	491	491	329	329
CG3	615	615	589	589	473	473
CG4	553	553	519	519	395	395
CG5	581	581	548	548	426	426
CG6	592	592	560	560	429	429
CG7	573	573	540	540	394	394
CG8	645	645	619	619	494	494
CG9	638	638	613	613	479	479
CG10	590	590	562	562	410	410
CG11	543	543	505	505	350	350
CG12	540	540	504	504	348	348
CG13	527	527	491	491	299	299
CG14	570	570	538	538	339	339
CG15	564	564	532	532	330	330
CG16	514	514	481	481	241	241

Table 5. Threshold Range Vertical Illuminance for Circadian Lighting (200-500lux)

Range	Interpretation	Implication for Circadian Lighting
<200 lux	Below threshold	Insufficient for effective circadian simulation
200-500 lux	Recommended range	Adequate for Circadian Stimulation and visual comfort
>500 lux	Above the recommended threshold	Strong stimulation, potentially excessive

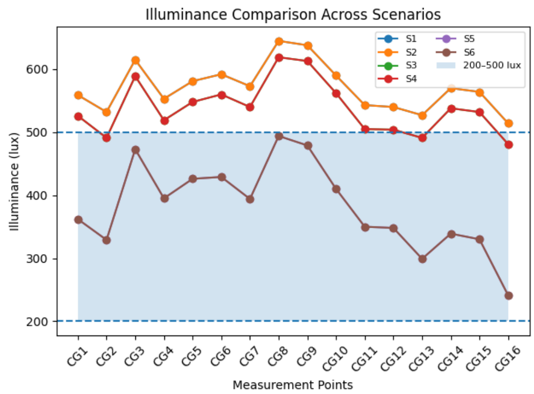


Figure 4. Simulation Result Within Threshold (200-500lux)
(Source: Author's Document, 2026)

The simulation results indicate that several scenarios produce identical values. Specifically, S1 and S2, S3 and S4, as well as S5 and S6 show the same vertical illuminance at all measurement points.

Therefore, the analysis is discussed based on three groups: S1–S2, S3–S4, and S5–S6.

Vertical illuminance is classified into three ranges: below 200 lux (insufficient), 200–500 lux (recommended), and above 500 lux (potentially excessive). This classification is used to evaluate the effectiveness of each scenario in supporting circadian stimulation.

Scenarios S1–S2 show the highest values (527–645 lux), with all points above 500 lux, indicating strong but potentially excessive stimulation. Scenarios S3–S4 range from 481 to 619 lux, with values distributed between the recommended and above-threshold ranges, suggesting a more balanced condition. In contrast, scenarios S5–S6 range from 241 to 494 lux, with most values within the recommended range, although some approach the lower limit.

Overall, vertical illuminance decreases from S1–S2 to S5–S6. Among the scenarios, S3–S4 provide the most balanced performance, as they achieve adequate circadian stimulation without excessive illumination.

Correlated Color Temperature (CCT) Result

According to the simulation results, the correlated color temperature (CCT) does not significantly affect vertical illuminance values. This is evident from the comparison between scenarios with different CCT settings but identical interior reflectance conditions, where Scenario 1 (6500 K) and Scenario 2 (5000 K) both yield an average vertical illuminance of 571 lux. Similarly, Scenario 3 (6500 K) and Scenario 4 (5000 K) produce 539 lux, while Scenario 5 (6500 K) and Scenario 6 (5000 K) result in 420 lux.

This occurs because illuminance calculations are based on photometric quantities, such as luminous flux and luminous intensity distribution, which are independent of spectral characteristics like CCT. This consistency assumes that the luminaires maintain identical luminous flux and photometric distribution (IES data) across different CCT settings. However, despite identical numerical values, variations in CCT may still influence visual perception, as higher CCT is generally perceived as brighter and can enhance contrast on vertical surfaces. Therefore, the differences in vertical illuminance observed between scenarios are primarily attributed to variations in interior surface reflectance, which significantly affect light reflection, inter-reflection, and overall light distribution within the space.

Reflectance Result

The average vertical illuminance of the simulated data ranges from 381 lux to 571 lux across the six scenarios. Based on the circadian lighting thresholds presented in Table 3, varying levels of circadian stimulation can be identified.

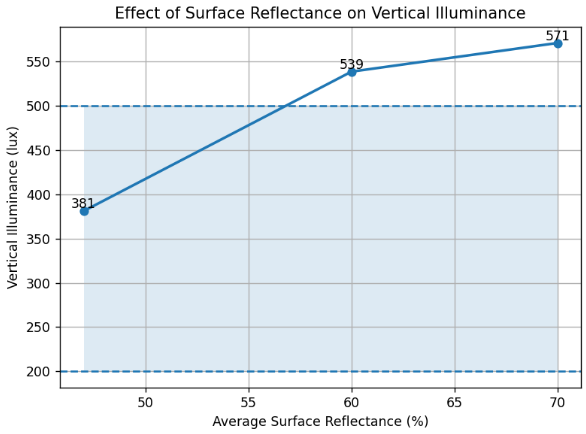


Figure 5. Simulation Result Within Threshold (200-500lux) (Source: Author's Document, 2026)

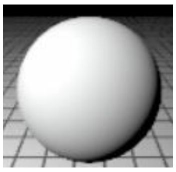
Scenarios S1 and S2 produce the highest average vertical illuminance (571 lux), followed by S3 and S4 (539 lux). These values exceed the upper threshold of 500 lux, indicating strong circadian stimulation. However, such conditions may also suggest potential overlighting, which could lead to visual discomfort or excessive stimulation if not properly controlled.

In contrast, Scenarios S5 and S6 yield lower average vertical illuminance values of 381 lux, which fall within the recommended range of 250–500 lux. This range is generally considered effective for supporting daytime alertness and circadian activation, indicating a more balanced lighting condition.

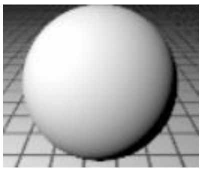
The reflectance-based chart further clarifies this relationship by showing a consistent trend between surface reflectance and vertical illuminance. Higher reflectance levels (as in S1–S2) result in increased illuminance due to stronger inter-reflections, while lower reflectance levels (as in S5–S6) help reduce excessive light and maintain values within the recommended range.

These findings highlight that interior surface reflectance not only influences the magnitude of vertical illuminance but also plays a critical role in determining the quality of circadian lighting. While higher reflectance can enhance light distribution, it may lead to excessive illumination. Conversely, lower reflectance contributes to more controlled lighting conditions, although it must be carefully balanced to ensure sufficient illumination across the space. Similar findings have been reported in previous lighting studies, where interior surface reflectance was identified as an important factor influencing indoor lighting performance and illuminance distribution (Boyce, 2014; CIBSE, 2015). In addition to its quantitative impact, reflectance also affects the visual quality of the interior environment. Higher reflectance is typically associated with lighter surface finishes that enhance brightness, whereas lower reflectance corresponds to darker materials that absorb more light. These variations are visually represented in the differences shown in the figure below.

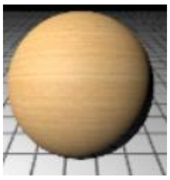
Real Used Material S1-S2



Ceiling: Traffic White Reflectance: 88%



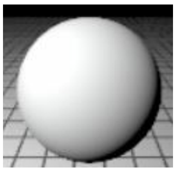
Wall: Traffic White Reflectance: 80%



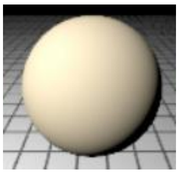
Floor: Light Oak Reflectance: 46%

Figure 6. Lighting Simulation S1-S2
(Source: Author's Document, 2026)

Real Used Material S3-S4



Ceiling: Traffic White Reflectance: 80%

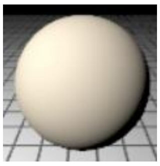


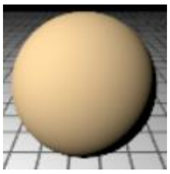
Wall: Cream Reflectance: 75%

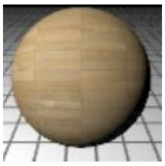
Floor: Oak Wood Grey Reflectance: 34%

Figure 7. Lighting Simulation S2-S3
(Source: Author's Document, 2026)

Real Used Material S5-S6







Ceiling: Ivory Reflectance: 70%

Wall: Beige Reflectance: 49%

Floor: Oak Wood Reflectance: 26%

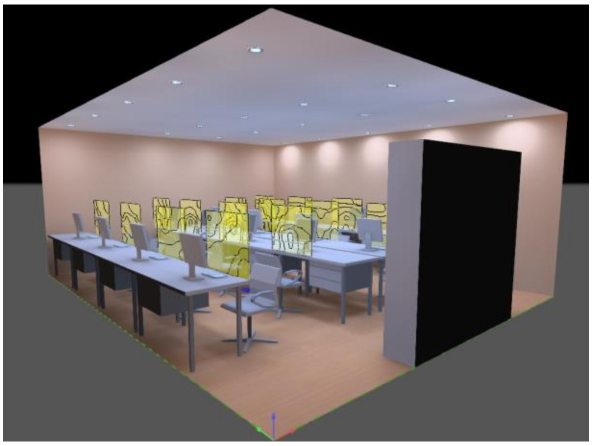


Figure 8. Lighting Simulation S5-S6
(Source: Author's Document, 2026)

CONCLUSION

Using a fixed office layout and luminaire arrangement, this study assessed vertical illuminance at eye level under the application of interior surface reflectance and correlated color temperature (CCT) scenarios. The simulation results indicate that the average vertical illuminance ranges between 420 lux and 571 lux for the scenarios. According to the applied circadian lighting thresholds, Scenarios S5 and S6 are within the effective circadian stimulation range (250–500 lux), while Scenarios S1–S4 exceed 500 lux, indicating stronger circadian stimulation. The findings demonstrate that interior surface reflectance significantly affects vertical illuminance; in addition, variations in CCT do not significantly change the illuminance values. High-reflectance surfaces reflect more light within the space and increase vertical illuminance, while lower reflectance surfaces reduce reflected light and thus decrease illuminance. Prior studies of circadian lighting have shown that light received at the eye is a critical factor in modulating circadian processes and supporting alertness, sleep quality, and overall well-being in office environments (Rea & Figueiro, 2018; Figueiro & Rea, 2021; Brown et al., 2022). Peak daytime vertical illuminance of approximately 250–500 lux is associated with improved alertness and circadian activation in indoor environments. Therefore, interior surface reflectance should be considered a critical design parameter for achieving circadian-supportive lighting conditions in office environments.

However, this study is limited by the use of controlled artificial lighting conditions without daylight integration, the reliance on vertical illuminance as the primary evaluation metric without considering spectral aspects, and the use of a fixed spatial layout. These factors may affect the generalizability of the findings to more complex real-world environments.

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