MSA Engineering Journal
MSA Engineering Journal (ekb.eg)
ISSN 2812-5339 (print); ISSN 2812-4928 (online)
E-mail: jzus@msa.edu.eg

Improving Circadian Light Exposure Through Architectural Daylighting Design in School Classrooms

May Adel Ebaid[1*]

[1*]Architecture Systems Engineering Department, Faculty of Engineering, October University for Modern Sciences and Arts, Giza, Egypt. maebaid@msa.edu.eg

Abstract

Recent studies reveal light exposure in architectural spaces impacts human biological functions and overall health including circadian rhythms, functions, sleep quality, and alertness. These non-visual effects go beyond what frequent studies associate with visual lighting. Hence, understanding circadian responses is becoming increasingly important in spaces like schools where performance and alertness are critical. However, effective architectural daylighting design guidelines targeting circadian needs remain underdeveloped. This study aims to improve Daylight-driven circadian lighting aligned with visual requirements in schools through an architectural approach. by modifying five architectural features in school classrooms located in Helwan, Egypt, and investigating their impact on indoor daylight characteristics. The study conducted simulations to analyze daylight illuminance and the circadian effect of light during their occupancy hours across the year, using Design Builder v7. Results are based on a comparative analysis between base case classrooms and proposed circadian-architecture modifications case simulations. Initial base-case simulations revealed illuminance values and Equivalent melanopic lux outside the recommended range; indicating visual and circadian discomfort. The adaptive circadian approach improved light distribution, minimized glare, and enhanced dark zones illumination during critical working hours, with an average improvement from 21% in the morning to 93% in the afternoon. Overall, this study highlights the importance of architectural features for circadian lighting wellness in classroom design, to enhance student well-being and productivity.

Keywords: Day Lighting Design; Circadian wellness; Architecture Adaptation; Classrooms.

1 Introduction

In recent decades, there has been notable advancement in comprehending the way humans respond to light exposure within architectural space. Traditional lighting research and design standards focused primarily on meeting visual acuity needs. However, recent evidence clearly shows that light also has impacts on users' biological functions, and overall health [1,2]. Specifically, how light influences aspects such as regulating our circadian rhythms, functions of the neuroendocrine system, sleep quality, levels of alertness, and cognitive performance [3]. These interconnected effects go beyond the aspects of visual lighting and are often referred to as non-visual responses. There has been an increasing focus on studying the effect of daylight over these non-visual aspects, mainly in places like workplaces and schools where staying alert, being productive, and performing are crucial, aiming to find ways to synchronize our circadian alignment with the daylight while also considering factors like visual needs, energy efficiency, productivity levels, and overall well-being [4]. While daylight and electric sources meet users' visual needs, indoor exposure to artificial lighting often fails to provide the light intensity and spectral content needed to properly stimulate circadian functioning [5]. Natural daylight has dynamic qualities in terms of intensity, spectral composition (SPD), and angle over the course of the year [6]. This inherent inconsistency makes daylight ideally suited as a light source for activating the circadian system, to deliver appropriate spectrum and intensity at appropriate times over the daytime [7]. Prior studies found that populations reliant solely on daylight enjoy improved sleep quality. while, windowless, low daylight exposures are associated with disrupted circadian rhythms and impaired sleep outcomes [8]. These outcomes align with users' augmented preference for daylight access in the architectural space design [9,10].

Natural light exposure in built environments is widely acknowledged as a crucial element; as it has the potential to greatly affect students' and instructors' general productivity and well-being [11]; as it has a greater impact on circadian rhythms in kids and teenagers compared to adults. underscoring the high value of classroom lighting design for healthy circadian alignment in students, design strategies in classrooms should account for both the visual and circadian benefits afforded through the judicious integration of natural illumination in their architectural plans [12]. Thus, comprehending the interactive aspects between light and architectural spaces is essential for creating such built environments. Yet, accurately determining architecture's contribution to non-visual light effects and quantifying the influence of specific architectural parameters such as (orientation, window size, surface optical properties, internal finishing, etc.) on modulating daylight remains challenging.

Research Problem: Indoor educational spaces frequently lack lighting that meets both the visual tasks and the biological needs of users. This Inadequate daylight design in classrooms can lead to insufficient illuminance for reading and writing. Furthermore, it will not provide the light intensity spectrum and duration to support student's circadian rhythms for regulating sleep patterns, and other functions that affect well-being and academic performance.

Research Aim: This study therefore aims to develop an architectural approach strategy for improving the integration of daylight illumination in school classrooms to concurrently meet the visual lighting needs for educational tasks as well as the non-visual circadian lighting ones. It focuses on identifying key architectural features that can be optimized to enhance circadian daylighting in classroom spaces.

Research Significance: while visual needs have been the focus of architectural lighting design standards, there is an increasing demand to incorporate non-visual circadian lighting considerations. This study aims to bridge this gap by studying architectural features that allow for circadian-effective daylighting. This can provide evidence-based design guidelines for upgrading existing classrooms and developing new circadian-centric school designs, enhancing human performance and user experience.

2 Research Methodology

The study utilized a mixed-method approach, starting with a qualitative approach through a comprehensive review of existing literature to identify potential architectural design features for enhancing circadian-effective daylighting in educational environments. A Simulation-based comparative analysis approach was employed to enable systematic evaluation of selected design parameters under various environmental conditions. The methodology involved modeling and evaluating the performance impacts of key architectural features using lighting simulation software on a case study.

Data Collection Methods: Data collection relied on building performance simulations. Two existing classroom case studies in Cairo, Egypt were first modeled, and secondary data of the case study were collected including sun exposure, location, geometry, openings, glass features, interior finishes, lighting systems, and occupancy schedules; this served as as a reference point, to establish base-case conditions daylighting performance. Five key architectural variables were modified including internal wall color /reflectance, window-to-wall ratio, window glazing color, and shading devices.

Daylighting simulation: Annual Daylighting simulations were performed using the Radiance engine in Design Builder V7, a verified and reliable simulation engine of modern thermal and visual simulation tools. Climate data for Cairo, Egypt, allowed the modeling of realistic sky conditions using the Perez model. Running Simulations captured daylighting illuminance under various seasonal and lighting conditions during the summer and winter seasons.

Evaluation Metrics: Calculations of standard Daylight illuminance quantified visual daylighting performance, at 1.1 m work plane height to evaluate visual performance. The circadian lighting potential was assessed using the Equivalent Melanopic Lux (EML) metric. EML values weight photopic illuminance

(R) by unitless melanopic ratio acquired on the weighting of the light source spectrum that regulates the circadian system.

Data Analysis: Spatial maps of simulated daylight illuminance and EML values were analyzed to compare the daylighting and circadian lighting distribution for the base-case classrooms and the proposed design features at various time points. Statistical analysis indicated the improvements in circadian lighting while maintaining recommended visual illuminance levels.

This research methodology based on simulations and comparative analysis provided insights that allowed for a data-driven exploration of how modifying architectural features could enhance the incorporation of natural daylight, in classrooms to better align with students' circadian systems.

3 Importance of Circadian Lighting in Classroom Spaces

Exposure to light plays an important part in stimulating and regulating the human circadian system, which is crucial for optimizing health and performance [13]. The circadian system not only controls the 24-hour sleep/wake cycle but also influences hormones, body temperature, cognitive functions, and other biological processes, as shown in Figure 1. Circadian lighting forms an important pillar of the broader framework of the human-centric approach to lighting design. Effective human-centric lighting aims to meet the needs of both comfort and tasks. It also supports the synchronization of our body's rhythms by adjusting the light spectrum. Accordingly, these two concepts work together harmoniously as HCL takes into account the impact of lighting, on our rhythms ultimately promoting overall human well-being, and performance to enhance users' experiences while considering architecture [14]. Natural daylight provides the intensity and spectral composition needed to maintain a strong circadian function [15]. However, people spend over 90% of their time indoors under static electric lighting, which puts them at risk of disrupting their circadian rhythms due to inadequate or inappropriate lighting conditions. This can have short and long-term consequences such as poor sleep quality and an increased risk of diabetes, obesity, and even cancer [16,17].

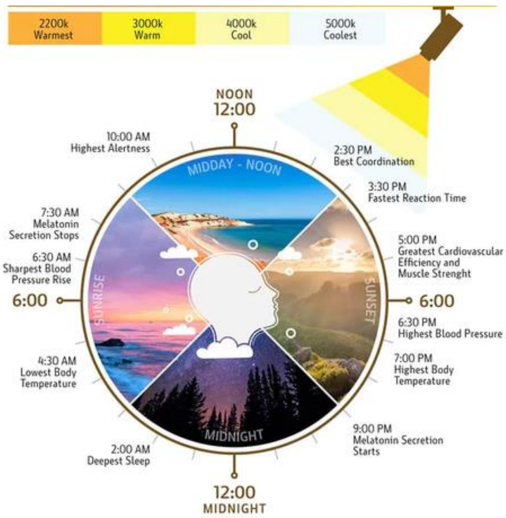


Figure 1. Light impact on the Circadian System[18].

Among the population groups that are particularly susceptible to the negative effects of improper circadian stimulation are students. This is because light exposure during their ages significantly influences their sleep patterns [19]. Creating indoor learning environments requires consistent, non-distracting lighting and glare control, especially in sunlight-inducing areas. However, studies show that over half of US and European schools fail to meet the minimum illuminance level of 300 lux [20], and Middle Eastern schools often exceed the maximum illuminance near openings of 3000 lux. An exhaustive approach is needed for optimal student learning experiences.

Strategies that focus on enhancing daylight quantity and distribution could provide nonvisual lighting benefits but are currently underutilized in both existing schools and new construction projects [21].

Daylight would improve their productivity, and cognition performance, and reduce absence rates. To ensure that students can effectively engage in tasks such, as writing and reading at study tables, and whiteboards; it is essential to have adequate lighting in the classroom. Poor quality lighting in a classroom can have an impact on students' physiological well-being, Hinder their ability to learn, as well as cause eyestrain leading to difficulties in absorbing information and increased levels of stress.

4 Architecture Parameters Impact on Circadian Lighting

Historically, architectural lighting design - encompassing both electric and natural daylighting - has prioritized visual needs alone [22]. However, emerging research recognizes that the built environment and associated illumination also potentiate non-visual facets of occupant well-being [23]. Qualities modulating circadian entrainment, including light intensity and spectral distributions, are substantially shaped by architectural parameters [21]. Comprehending the complex interplay between lighting and buildings is therefore fundamental to perceive spaces promoting visual and non-visual comfort.

Hraska (2015) proposed that a holistic approach attending to the interplay between lighting sources, interior design elements, architectural plans, and site layout holds the potential to yield environments fulfilling both visual and non-visual lighting prerequisites [24]. In 2021, Vas and Inanici assessed how architecture influences daylight's visual and non-visual (i.e. circadian) potency in interior spaces, Their simulation results concluded that, while daylight can fulfill circadian requirements, six architectural factors were proposed to enable such effectiveness. Key guidelines proposed include: assessing site context for obstructing elements limiting daylight access, avoiding shading devices blocking sky views as horizontal blinds mitigating glare showed minimal circadian impact, and orienting seating zones >20ft from windows towards the nearest aperture to maximize daylight stimulation [25]. Changing the window view had a 58% effect on circadian potential. Fundamentally, architects should proactively examine and integrate dynamics between buildings and available daylight, starting from initial design, to render natural light a viable circadian-effective resource.

A review by Alkhatatbeh, B.J, and Asadi in 2021 examined how architectural design impacts indoor lighting qualities that influence the circadian system, for both natural and artificial light. studies investigated architecture's effect on non-visual light effects are grouped based on the architectural factor explored, including window attributes, window shades and outdoor impediments, surface colors and reflectivity, internal space proportions, and glazing/glass characteristics [26]. For instance, Light-colored internal walls have improved circadian light compared to darker ones [27], The use of shading panels enhances both the intensity and spread of luminance. Horizontal shading has caused further effects compared to vertical ones, texture and color of shading panels have an impact on light illumination. [28]. If the openness between panels is reduced it increases the influence of shading panels on circadian daylight. Acosta et al. (2019) found a direct relationship between window wall area and circadian stimulus, showing a 14% increase for 45% WWR when compared to small windows [29]. Aguilar-Carrasco et al. (2021) revealed that 40% WWR improved circadian potential by 50% compared to the 30% WWR, and 30% provided adequate CS near windows, where lower percentages were not effective [30].

In summary, architectural design and daylighting share a reciprocal relationship, with each factor imposing constraints upon the other [31]. The intrinsic restrictions of daylight as an illumination source - its variability, diffuseness, etc. - shape architectural considerations such as floor depths, building forms, glazing properties, and other design parameters. Understanding these complex interdependencies between daylighting adequacy and the built environment warrants an integrated approach to reconciling lighting needs, programmatic functions, and regulatory contexts when designing a space. Further research elucidating these dynamics may reveal optimized design strategies balancing daylighting provision, architectural intent, and policy frameworks for sustainable buildings promoting human habitation.

5 Lighting metrics in spaces

5.1 Daylight Metrics

Different metrics have been recognized to calculate daylight levels and investigate indoor daylighting comfort, as concise in Table 1. Daylight Autonomy (DA) measures the percentage of time that illumination meets a threshold [32]. Illuminance (lux) is a measurement of the quantity of light that reaches a surface. It is commonly used in indoor light performance assessments, small grid calculations are always more accurate than the average methods. To determine the lighting levels for tasks requiring visual clarity it is typical to measure the amount of light on the horizontal surface at desk level. For office and administrative work it is generally recommended to have an illuminance range of 300-500 lux and lighting systems are designed accordingly. While horizontal illuminance alone doesn't provide an assessment of visual quality it is commonly used as a reference point. Calculating illuminance across points on the horizontal plane can be done in various ways using a continuous grid focusing on specific zones or areas of interest or pinpointing task-specific locations. Daylight Illuminance has been used in the study; as it corresponds to typical daylight levels that stimulate our circadian receptors.

Another metric is Useful Daylight Illuminance which keeps track of how daylight provides illuminances that are beneficial for users, acceptable ranges are established between 100 and 2000 lux. however, there are concerns regarding the upper threshold as it causes glare, overlit, and overheating [27]. The ratio of indoor to outdoor illumination is known as the daylight factor metric. It can be calculated from Illuminance levels, using the formula $DF = 100 \times (Ein/Eout)$ where Ein is indoor illuminance level and Eout is outdoor, which is dynamic according to the climatic data [33].

Table 1: Day Lighting Metrics [34].

Day Lighting Metrics	Daylight autonomy (DA)
	work plane daylighting Radiance Illuminance (E)
	Useful daylight illuminance (UDI)
	Daylight factor (DF)

5.2 Circadian Lighting Metrics

There are primarily two methods for measuring the non-visual or circadian effectiveness of light, The first is through assessing the anticipated suppression of melatonin, known as Circadian Stimulus (CS). The CS is calibrated to predict the equivalent nocturnal melatonin suppression, ranging from 0 to 0.7 on a scale where 0.3 suffices for circadian entrainment, where 233 lux from daylight or 575 lx from fluorescent lamp FL11 are equivalent to this threshold. A Daysimeter, a head-worn instrument, can measure it at eye level. Determination of CS first weights spectral irradiance by the sensitivity of retinal photoreceptors into a measure called Circadian Light (ClA). This CLA value is then adjusted by the following equation (1) model to yield the Cs value [25].

$$Cs = 0.7 - \frac{0.7}{1+\left(\frac{CLA}{355.7}\right)^{1.1026}} \quad (1)$$

Another metric involves calculating Equivalent Melanopic Lux (EML) based on the sensitivity of users' eyes photoreceptors [6]. The EML model thereby provides a photometric evaluation correlating light exposure to non-visual biological impacts. As shown in Equation (2), EML is calculated by multiplying vertical illuminance in lux by a unitless melanopic ratio acquired on the weighting of the light source spectrum, ranging from 0.45 to 1.70. This ratio compares the source’s melanopsin-weighted irradiance versus a reference illuminant, thereby indicating its relative efficacy in stimulating circadian responses linked to melatonin suppression [29].

$$EML = E * R \ (2)$$

The Equivalent Melanopic Lux metric differentiates light sources with equivalent visual brightness based on circadian stimulation [15]. For example, luminous light providing 200 lux yields 108 EML, while equal daylight illumination produces 220 EML.

The International WELL Building Institute adopted the EML metric to estimate the effectiveness of circadian light designs within its certification program, WELL certified projects exhibit enhanced illumination per these non-visual criteria as it focuses on spanning intensity, timing, and duration for circadian entrainment [17]. To calculate the EML, we need to know the Melanopic lux ratio for the daylight source at a Correlated Color Temperature (CCT) of 6500K, which is typically used to represent daylight [35]. According to the table provided in the WELL building standard, As shown in Table 2, the Melanopic lux ratio for daylight is 1.1.

Table 2: Light sources and corresponding Melanopic Ratio [17]

Correlated Colour Temperature -CCT(K)	Light source	Melanopic ratios
2800	Incandescent	0.54
4000	LED	0.76
6500	Daylight	1.10

Recent versions mandate at least 200 EML daily between 9 am-1 pm at 75% of workstations, attainable via daylight, electric lights, or both; alternatively, 150 EML minimum from electrical sources and at least 125 EML for a three-quarter of learning area desks for four hours daily [17,36].

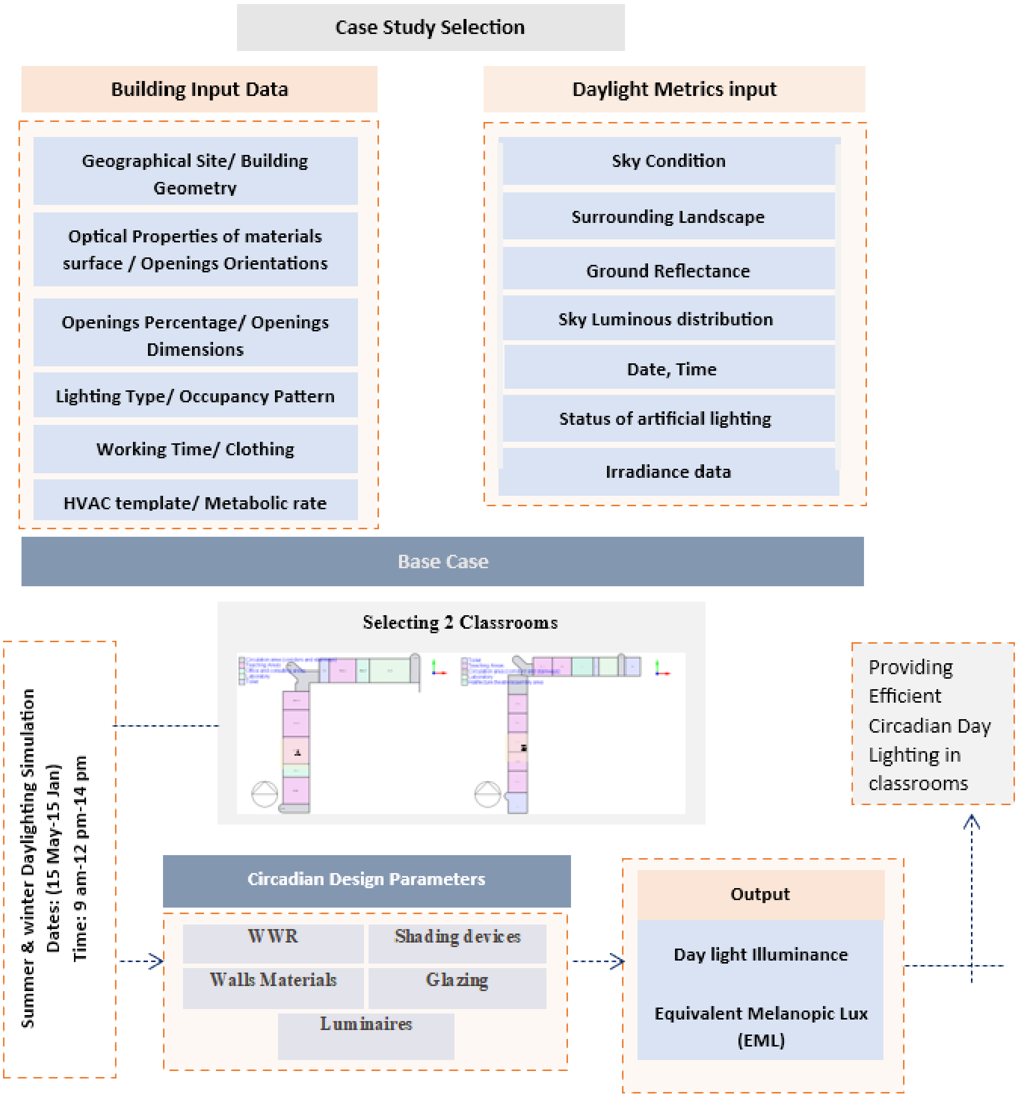
Studies showed that illuminance values below 300 lux indicate insufficient lighting requiring supplemental electric sources, while values exceeding 3000 lux signify potential glare and visual discomfort. According to the WELL, sustained exposure to ≥240 Equivalent Melanopic Lux (EML) over 4 hours fully suppresses melatonin, shifting the circadian rhythm [17]. These thresholds guided the study simulation assessments comparing computed photopic and Melanopic illuminance. So, starting 240 and exceeding 960 EML is considered the healthy range for circadian stimulus.

6 Empirical study

6. 1 Methodology Adopted for simulation

The lighting simulation follows a specific approach as shown in Figure 2. First, a school building was selected to analyze the impact of design parameters on daylighting to improve circadian efficiency. followed by establishing the base case model for simulation, and entering the case study parameters into Design Builder; including the geometry, materials, fenestration details, lighting systems, and occupancy profiles of the school building, based on its existing conditions. Then the base case daylighting simulations were performed during summer and winter for 3 different hours. configuring outputs such as Daylighting illuminance levels then calculating the Melanopic Lux values as a human circadian metric. This helps generate daylight profiles for the existing class design parameters. For the second phase simulation; architecture parameters like wall color, window-to-wall ratios, glazing type, and shading dimensions/reflectance/openness were modified; to improve daylight provision. Finally, we compare the lighting performance of the base and modified case by analyzing the results of simulated daylight availability, and illuminance levels, in addition to EML circadian metric. This helps us quantify and assess the effect of classroom architecture features on circadian daylighting in space.

Fig. 2: Methodology Adopted for Simulation.



6. 2 Criteria for Selecting Case Study

The key criteria used for selecting the experimental case study classrooms; were the school typology as a prototype sustainable educational facility. The school was established as the first formal public sustainable school in cooperation with the General Authority for Educational Buildings and the Union of Egyptian Banks, serving as a governmental prototype model to be implemented across different locations in Egypt. The primary design objective was improving students' well-being, which aligns with the stated aim of this study to explore daylight and circadian lighting in educational buildings. The selected case study is a representative of common educational spaces in the region. The school's physical parameters, including dimensions, orientation, window properties, interior finishes, and lighting systems, provided a realistic base-case condition for testing proposed architectural modifications through simulation models. This allowed assessing retrofit strategies on classes facing daylighting performance issues under the local climate.

6. 3 Case Study Investigations

The selected case study in this research is Hewayatna School, a public school located in Helwan, Egypt. Where the climate is classified as a hot desert climate [37]. The number of sunshine hours in Cairo varies from 6 hours and 23 minutes per day in December up to 11 hours and 54 minutes of sunshine on days in July [38], where It is sunny around 80% of daylight hours. The school comprises a nursery, middle school, and high school. This four-story building includes classrooms, facilities, and eco-friendly features as the implemented solar power plant, it is surrounded by a swimming pool area, green spaces, and other facilities, covering an area of 8,600 square meters.
For the analysis, the focus was on two identical middle school classrooms on the third floor of the L-shaped building wings as shown in Figure 3. where students and instructors spend most of their time and reported issues with a lack of adequate lighting. They were selected based on their locations, identicality in size, windows, orientation, finishes, and lighting systems. The classrooms measure 8.30 x 8.30 meters with 4-meter ceilings and have single-glazed windows on the west façade.

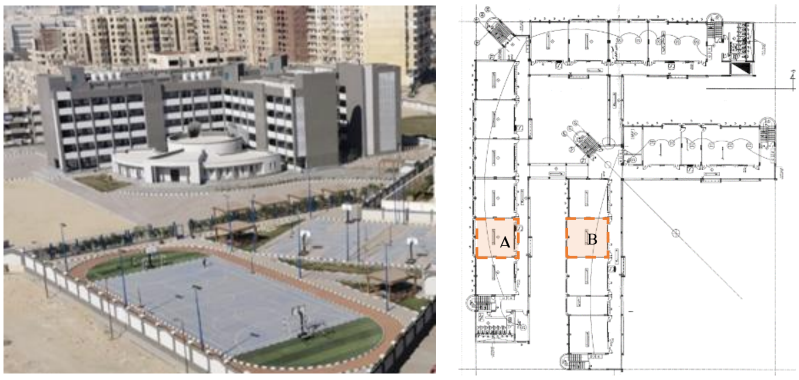


Fig. 3: Case study building view, and Architecture plan highlighting Class A and B.

6. 4 Daylighting Simulation Process

The simulation study was performed using the Radiance daylight simulation engine in Design-builder V7. The method used to simulate lighting in classes was Daylight Illuminance (E) of the west façade, it was calculated under realistic sky and sun conditions derived from Cairo's climate data, Egypt (30°N 31°E). The sun's altitude at noon varies from 36.6° to 83.4° over the year. The simulation working plane height was set at 0.9-1.2m to match the average student's eye height. Other classroom space inputs are depicted in Table 3.

Table 3: Building Input parameters for daylighting simulation.

Simulation Properties		Daylighting Simulation Time	Sky Methods
Work plane height	1.1 m	Summer on 15 May	Perez method (Direct normal irradiance: measured direct normal and diffuse horizontal irradiance data)
Ground plane extension	30 m		
Grid spacing	1.0 m x 1.0 m	Winter on 15 December (9 am, 12 pm, 14 pm)	
Luminaire type	Surface mount		

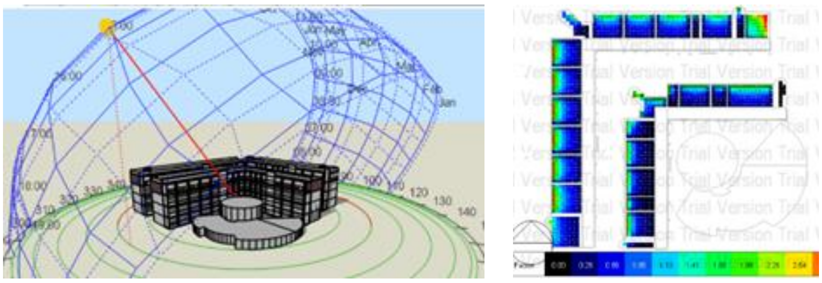
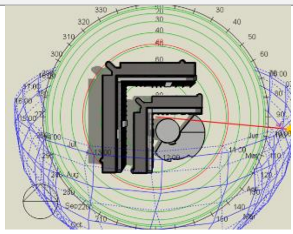
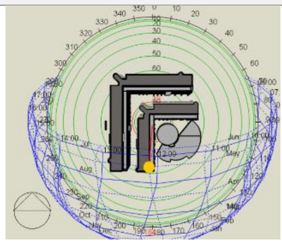
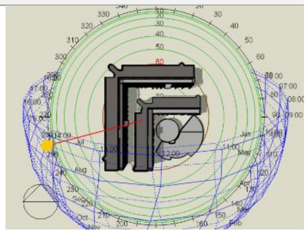
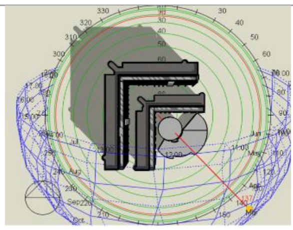
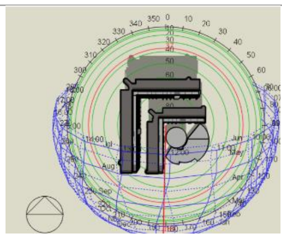
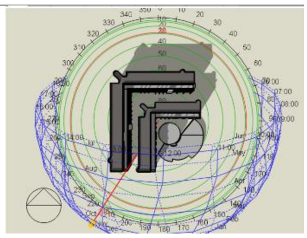


Fig. 4: On the left is design-build Modelling, On the right, is base case simulation.

We conducted interviews with teachers to determine the best simulation times that fit their schedule, conducting simulations twice a year during summer and winter seasons at 9 am, 12 pm, and 14 pm.
To accurately depict the variations in daylight within the space we utilized sky conditions using the Perez method. Our goal was to capture lighting conditions during periods by focusing on extreme solar angles. As shown in Table 4, daylighting differences between Classrooms A and B are apparent for both seasons, with higher summer sun angles enabling deeper light penetration and more shadows, especially at 14 pm (afternoon) as the sun directly projected into classrooms. Accordingly, horizontal shading like architectural louvers is most effective in the south Facade. while vertical fins are more effective for east and west.

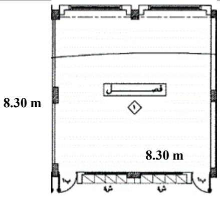
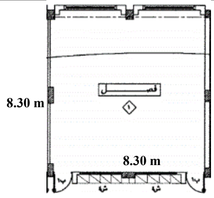
Table 4: case study Sun path diagrams of Summer and Winter seasons.

Time	Morning Sun path	Noon Sun path	Afternoon Sun path
Summer			
Winter			

6. 5 Proposed Adaptation Architecture parameters to obtain a Circadian System:

According to the literature review and best practices, The climate in which the classroom is located must be carefully considered before beginning any daylighting project. For this reason, several authors concentrated on the room's geometrical layout and orientation. However, in this work, Given that the building already existed, the aim was to come up with an alternative plan that could be implemented, with minimal modifications and costs. The goal was to propose improvements that could be easily executed in class without the need for changes or costly disruptions. So the class geometry is a constant parameter, however, the adaptation parameters included internal Walls (Color), window wall ratio, glazing type, shading device, and Luminaires. Table 5 shows the Architecture Parameters for the base case and the proposed modifications for the circadian parameters in classrooms; to improve the circadian efficiency [16,17].

Table 5: Current and Proposed class Design parameters to improve Circadian lighting.

Architecture Features	Property	Base Case	Circadian case
Space dimensions [25]	depth (Constant)		
Walls/internal surface [26,27]	Color	Painting walls with light brown	Painting walls with neutral colors, such as white, to increase CS
	Reflectance (Light Reflectance Value)	40-56%	70-90%
Windows [26,28,29]	Window-to-wall ratio	30%	40% Greater WWR improves circadian
	Orientation	West Facade	West Facade
	Window Head Height	1.0	1.2 More daylight penetration via windows with higher head heights.
Window Glass [25,26]	Color	Transparent	Blue-tinted glazing for better CS
	Transmittance	0.898 Calculated Values Total solar transmission (SHGC) Direct solar transmission Light transmission U-value (ISO 10292/ EN 673) (W/m2-K) **U-Value (W/m2-K)**	0.578 Calculated Values Total solar transmission (SHGC) 0.569 Direct solar transmission 0.409 Light transmission 0.578 U-value (ISO 10292/ EN 673) (W/m2-K) 1.831 **U-Value (W/m2-K) 2.130**
	Type	Single clear glazing	Electrochromic glazing (EC) (EC glazing stabilities light illuminance)
Shading devices [28]	Type	No shading devices	Use shading devices: vertical + horizontal louvers, time-based at 14 pm (4 blades with 0.3 vertical spacing at an angle of 15 degrees).
	Color	×	Blue
	Reflectance	×	Matt
	Orientation	×	The influence of vertical shading panels on light illuminance is greater
	Openness	×	Vertical shade panels' effects on daylight are amplified when there is less openness between panels.
Luminaires [25]	Luminaire technique	Using just direct	Stepped control

7 Results & Discussion

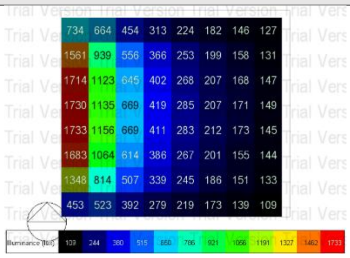
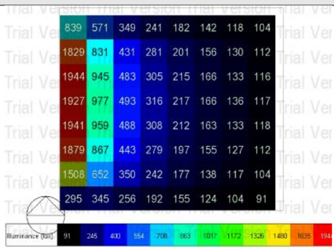
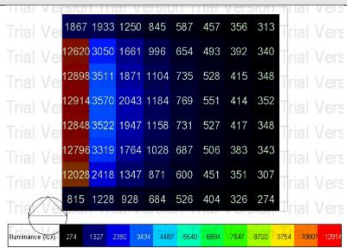
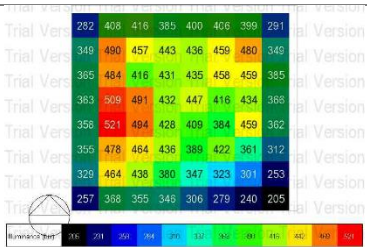
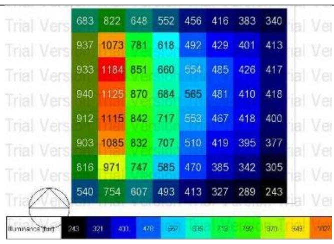
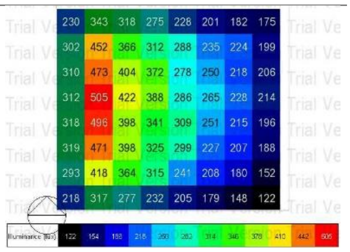
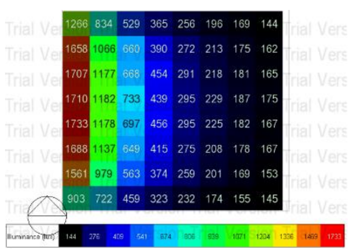
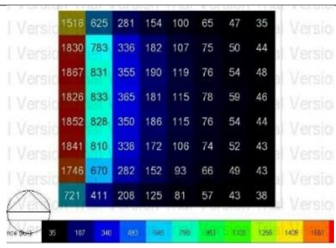
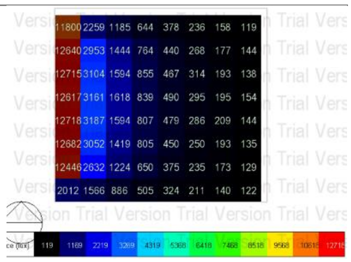
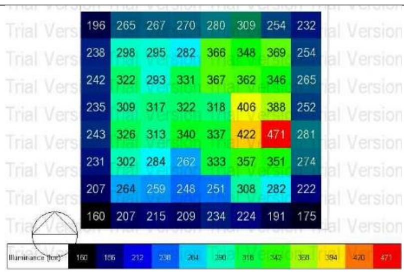
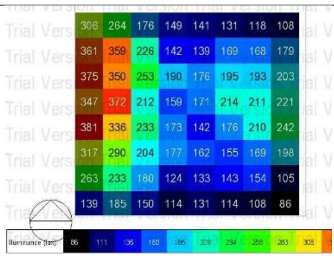
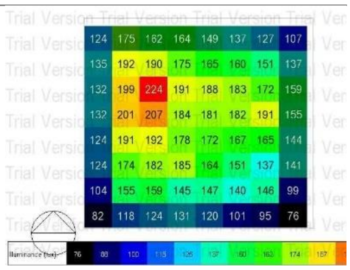
The simulation results of the natural Daylighting illuminance metric for the two classes (A & B), were simulated under different lighting conditions, times, and seasons, in two phases; the base case and the modified case. Quantitative simulation results were presented as colored grids of area 1.0 m^2, that show the daylighting readings for Daylight illuminance (lux); to calculate the equivalent melanotic lux (EML).

7.1 Summer Daylight Simulation Results.

Primary results in summer for both classrooms showed that maximum daylight illuminance values are out of the visual comfort range, where 35% of the area classrooms received poor daylighting, under the recommended values, accompanied by excessive glare, registering more than 1000 lux, around the window zones. For instance; the base case in classroom A at 9 am showed average minimum and maximum illuminance of 151.35 lux and 1156.42 lux respectively, and for classroom B, 169.25 lux and 1182.78 lux. Yet, Results after implementing the architecture modifications, showed improved levels, and light uniformity in both rooms, as illuminance ranged from 301.2 to 521.83 lux for class A, while class B recorded a range of 248.16 to 471.9 lux at the same time. Simulations at noon indicated that the base case of Classroom A had an uneven daylight distribution, ranging from just 117.59 lux to a maximum of 977.24 lux, with notable improvement in maximum values with the proposed modifications, illumination became higher and uniformly distributed by natural illuminance of range 342.5-1184.8 lux. similarly, modified Classroom B performed better than the base case, achieving a good daylighting profile from 124.37 lux to 372.44 lux.

Later in the same day at 14 pm, original simulations for both Classroom A and B witnessed excessive illuminance of up to 3570.21 lux, leading to excessive glare for students and a disturbing indoor environment. After adaptation, Classroom A presented illuminance of 180.69 – 505.99 lux and Classroom B registered 137.76 – 224.2 lux, indicating significant improvements in uniformity and minimizing the glare in this time of the day. The following Table 6, shows the summer simulation output from the daylighting grid which indicates the average Minimum and Maximum daylight Illuminance (lux).

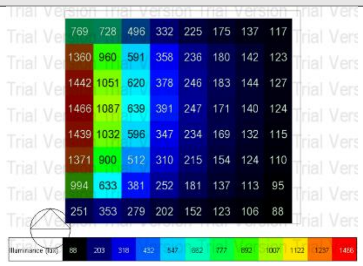
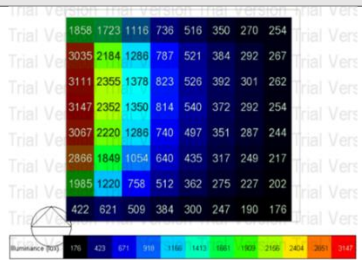
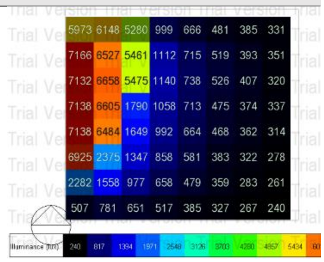
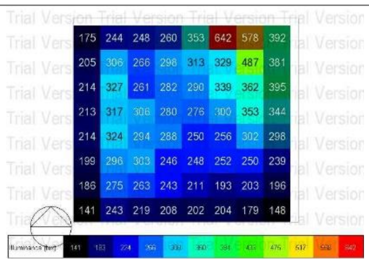
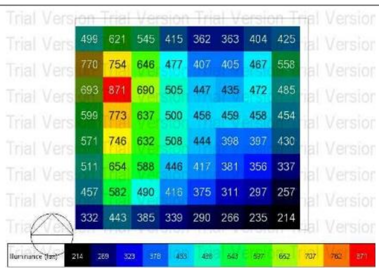
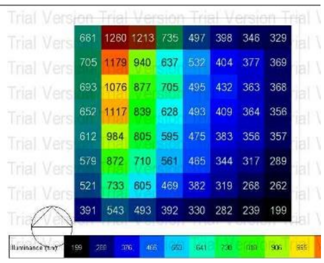
Table 6: Daylighting Simulation of the Base Case & proposed Circadian Case on Summer Season.

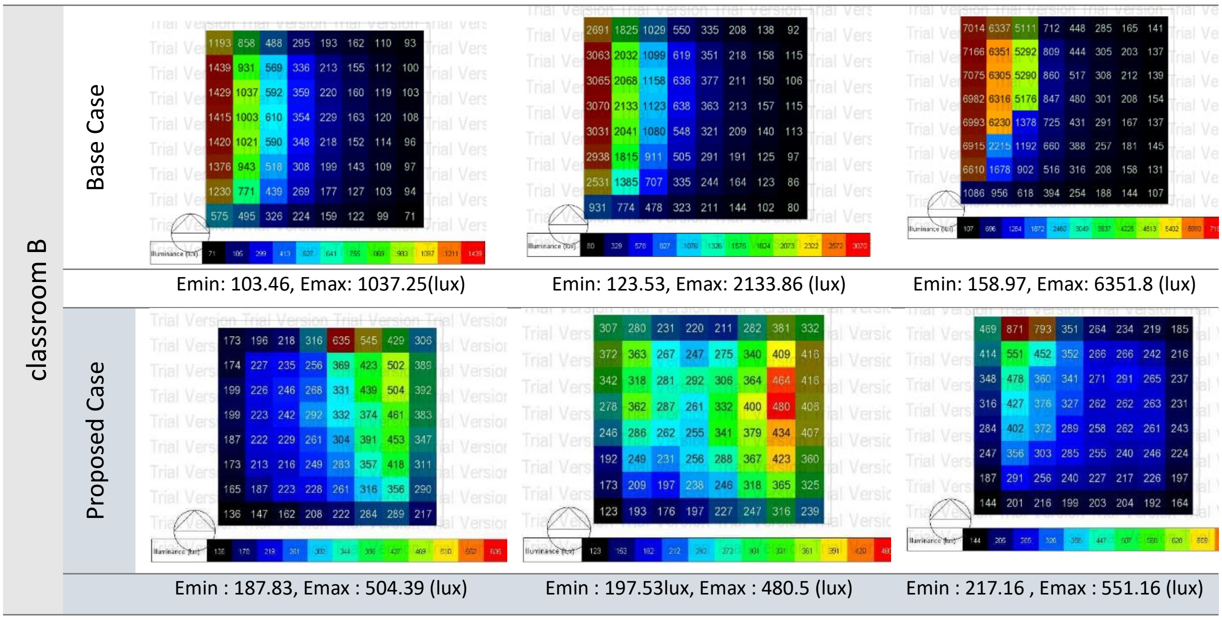
Summertime Daylighting Simulation Results				
Time/ Space		Morning (9 am)	At Noon (12 pm)	Afternoon (14 pm)
Classroom A				
		E_{min}:151.35, E_{max}: 1156.42 (Lux)	E_{min}: 117.59, E_{max}: 977.24 (Lux)	E_{min}: 351.6l, E_{max} 3570.21 (lux)
	Proposed case			
		E_{min}: 301.2, E_{max}: 521.83 (lux)	E_{min}: 342.5, E_{max}: 1184.8 (Lux)	E_{min}: 180.69, E_{max}: 506 (lux)
classroom B				
		E_{min}: 169.25, E_{max}: 1182.78 (lux)	E_{min}: 49.45, E_{max}: 833.19 (lux)	E_{min}: 173.18, E_{max}:3187.39(lux)
	Modified Case			
		E_{min}: 248.16L, E_{max}: 471.9 (Lux)	E_{min}: 124.37, E_{max}: 372.44 (lux)	E_{min}: 137.76, E_{max}: 224.2 (lux)

7.2 Winter Daylighting Simulation Results

On December 15th, the initial readings for the base cases indicated the same challenges as in summer. Morning daylight illuminance for classroom A ranged from 103 lux to 1087 lux, indicating nonuniform light distribution, While Simulations after modification techniques resulted in balanced illumination distribution. Minimum and maximum values in classroom A improved to 193.03 lux and 487.15 lux, avoiding the aforementioned glare. Concurrently, classroom B experienced an improvement with illumination levels ranging from 187.83 lux to 504.39 lux, particularly benefiting areas that were previously poorly lit.
At noon, high levels of illumination were recorded in both classrooms under the base case scenario; Classroom A peaked at a high level of brightness with a measurement of 2355.24 lux while Classroom B ranged from 123.53 lux to 2133.86 lux during that period. The implementation of circadian lighting proved effective in enhancing both adequacy and comfort of illumination in the classrooms mentioned above as measurements indicated more desirable ranges; Classroom A ranged from 297.34 to 871.67 lux while Classroom B recorded illuminance between197.53lux and 480.5lux.
Peak levels of illumination were observed at 14 pm in both classrooms, under base case conditions; both classroom results were the most uncomfortable, where Classroom A experienced excessively high illuminance ranging at 6658.39 lux while comparable highs were reached in Classroom B measuring 6351.8lux. However, the implementation of the circadian modifications technique substantially improved the illuminance to within targeted ranges and much better uniformity. Where Classroom A measured 1179.53 lux while Classroom B recorded 551.16 lux. Winter season simulation results are depicted in Table 7.

Table 7: Daylighting Simulation Results on Winter Season.

Wintertime Daylighting Simulation Results				
Time/Space		Morning (9 am)	At Noon (12 pm)	Afternoon (14 pm)
Classroom A	Base Case	 Emin : 113.37 lux, Emax : 1087.16	 Emin : 227.01 lux, Emax : 2355.24 lux	 Emin : 284 lux, Emax : 6658.39
	Proposed Circadian	 Emin : 193.03lux, Emax : 487.15 lux	 Emin : 297.34 lux, Emax : 871.67 lux	 Emin : 268.09 lux, Emax : 1179.53



In summary, The daylighting performances of the classrooms, according to the occupation timings of the school across the year for base-case models revealed illuminance values outside the recommended range of 300-1000 lux, indicating visual discomfort. However, an adaptive circadian approach improved light distribution, minimized glare, and enhanced illumination in previously dark zones during critical working hours.

7.3 Investigating the Circadian Lighting Comfort Results

To assess circadian comfort, the Equivalent Melanopic Lux (EML), has been calculated using equation (2), where the Melanopic ratio of daylight is around 1.10 based on the datasheet provided by WELL building guidelines, where a healthy circadian stimulus requires an EML range of 240-2000 lux, The latest standard minimum requirement is 200 EML between morning and noon at eye level for at least three-quarters of the space[17,36]. In the base case, around 40% of the Classroom A area had inadequate EML that did not meet the WELL targets for all simulated timings. However, after implementing the architectural modifications to enhance circadian comfort, we were able to achieve the recommended EML levels for 75% of the simulated times. The improvements included a reduction of EML for classroom A from 7324 to 1297 at 14 pm in winter, and from 3297 to 556 lux in summer. Results for Classroom B revealed that the modified case achieved much better EML values than the base case, all over the year, where the most improvement was achieved at 14 pm with a reduction in EML with approximately 6300 lux in winter, and 3250 lux in summer. This reduction transformed the class circadian value range from inadequate to adequate by 100% in winter, and 60% adequate in summer, as shown in Table 6,7.

Table 8: Equivalent Melanopic lux Change percentage.

Class	class A						class B					
Time/	winter			Summer			winter			Summer		
Change Percentage	9:00 AM	12:00 PM	14:00 pm	9:00 AM	12:00 PM	14:00 pm	9:00 AM	12:00 PM	14:00 pm	9:00 AM	12:00 PM	14:00 pm
Min EML Change %	71.2	30.8	-5.8	101.4	192.1	-48.5	82.8	60.9	37.3	46.8	153.3	-20.5
Max EML Change %	-55.2	-63.0	-82.4	-54.9	21.3	-85.8	-51.3	-77.5	-91.3	-60.1	-55.3	-93.0

Table 8 shows the percentage change in EML values between the base case and the proposed circadian case for the classrooms across different times. Classroom A was improved in winter by 55% at 9 am, 63% at 12 pm, and 82% at 14 pm, while in summer reduced by 54%, 21%, and 86% respectively. Classroom B, a reduction in winter of 51%, 77%, and 91% respectively, while for summer reduction was by 60%, 55%, and 93% respectively, this shows that the adaptation of the circadian case highest effect change was at 14 pm, with a slight reduction occurring at noon, The following chart demonstrates the EML improvement for both cases, highlighting the effectiveness of the circadian approach in improving lighting conditions inside Classrooms.

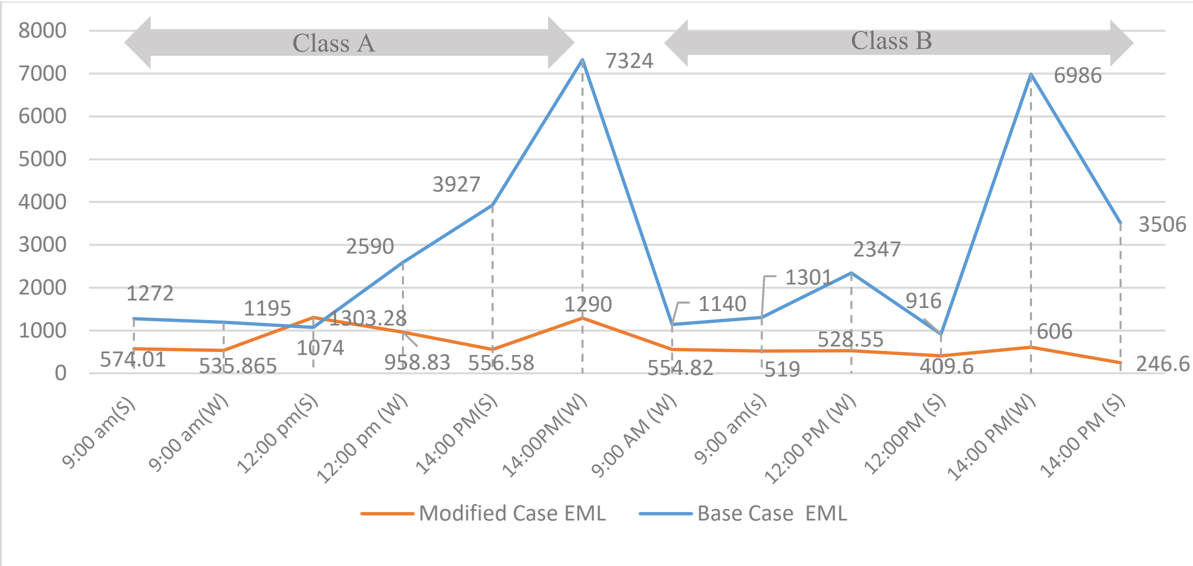


Fig. 5: Equivalent Melanopic Lux Improvement Chart.

Conclusion

This study aimed to create indoor educational lighting spaces that effectively correspond with students' circadian systems, considering both the visual and circadian benefits of light, through an architectural approach. simulation testing with the proposed architectural modifications enabled comparative analysis between the base case classrooms and the circadian-enhancing architectural techniques; conducting simulations of 2 classrooms, on two seasonal days at three key times of day, allowed us to comprehensively assess daylighting performance under a wide range of sun positions.

Initial simulations of the base-case models revealed illuminance values outside the recommended illuminance range of 300-500 lux, indicating visual and circadian discomfort. However, architectural feature adaptations improved light distribution, minimized glare, and enhanced illumination in previously dark zones during critical working hours. Post- modifications, over 97% of areas met/exceeded the 240 EML, except for Classroom B at 14 pm in summer, despite the daylight illuminance improvement.

Sky conditions significantly impacted circadian potential, where classroom B experienced limited daylight penetration due to an obstructing building, this problem can be addressed by integrating step-control artificial lighting with sensors in deep areas. Overall, Morning EML was reduced by 21-70%, and afternoon EML was reduced up to 93% at 14 pm, obtaining effective circadian exposure levels for students in classrooms during the daytime, and supporting their health and learning performance goals.

These study results align with previous research, by Altenberg Vaz, (2021), Alkhatatbeh, (2021), and Bellia, (2021), confirming that architectural features play a great role in space's visual appeal and the user's circadian system. yet, the weight of each design element is still unspecified [25,26,23].

Based on the simulation results, The study concluded the following Architectural Design Guidelines for educational spaces.

Windows: Maximizing the window wall ratio up to 40% is recommended for an evenly distributed daylight and Equivalent Melanopic lux, thus enhancing circadian-effective light inside classrooms.

Shading Devices: Simulations showed the addition of exterior vertical shading elements (10cm) combined with overhang louvers (1m) was effective in controlling glare and excessive illumination near windows during times of peak solar exposure in the afternoon, the configuration was 6 horizontal blades at 15° angle with 0.3m spacing verified ideal to minimize glare without reducing overall classroom EML levels. However, continuous overhang and horizontal blinds weren't as effective in the circadian effect if turned off, it only reduced high illuminance at this time to avoid glare near windows.A shading system that can be automatically or manually operated during peak hours is preferable to improve circadian daylighting while increasing visual comfort.

Glazing Properties: The results showed that the electrochromic glass, blue-tinted glazing, compared with clear glass improved the penetration of circadian light in space as well as reducing the illuminance levels and glare near window areas.

Internal walls: Brighter interior surfaces, painted with reflectance levels exceeding 80% showed better distribution of light and higher EML levels in the deep corners of the classroom away from the windows.

In Conclusion, this study highlights the importance of considering architectural features for circadian lighting comfort in classroom design; to enhance student well-being and productivity. Daylight remains the optimum light source for stimulating our circadian system. Moving forward, further research is required to operationalize this framework and; provide guidelines for evidence-based built environments that effectively promote circadian functioning. Future research can incorporate other architectural design features that contribute to circadian wellness in different building typologies. It would also be valuable to investigate the impact of design factors on both direct and indirect light sources along with emerging innovative technologies such as nanomaterials, smart glass, and clear photovoltaic glazing.

Recommendations

Overall this study recommends that while designing educational buildings, we should prioritize circadian wellness in the classroom, this can be achieved with the following :

- Applicable modifications for retrofitting can enhance the circadian effect of light and create a more comfortable learning environment in existing buildings.
- Schools should consider optimizing light levels, minimizing glare, and enhancing dark area's illumination during working hours, by modifying simple architectural features such as windows, skylights, light shelves, and interior finishes
- Integrating non-visual lighting design strategies better starts from the beginning stage; to enhance students' health well-being and focus.
- Perform simulations and analysis at various times of day and seasons to indicate the variations in light exposure, over time for comprehensive understanding before construction.
- Implementing dynamic shading and lighting controls that can be modified according to changing sky conditions and classroom requirements is beneficial.
- Educating different Stakeholders such as architects, designers, educators, and facility managers, By raising awareness and providing training on circadian lighting principles, to guarantee that everyone engaged shares circadian health objectives.

- Schools should frequently monitor and evaluate the efficiency of circadian lighting solutions in educational buildings. By collecting feedback from students and staff, or actual field measurements using head-worn Daysimeter for students, schools can identify areas for improvement and make adjustments to enhance the overall well-being and productivity of building occupants

Limitation

The research study focuses on the case of Cairo, Egypt, and its weather conditions.

References

[1] Vetter, C.; Morgan Pattison, P.; Houser, K.; Herf, M.; Phillips, A.J.K.; Wright, K.P.; Skene, D.J.; Brainard, G.C.; Boivin, D.B.; Xiao, H., Cai, H., & Li, X. (2021). Non-visual effects of indoor light environment on humans: A review☆. Physiology & Behavior, 228, 113195.

[2] Glickman, G. A Review of Human Physiological Responses to Light: Implications for the Development of Integrative LightingSolutions. Leukos 2021, 18, 387–414. [CrossRef]

[3] Neberich, M., & Opferkuch, F. (2021). Standardizing melanopic effects of ocular light for ecological lighting design of nonresidential buildings—an overview of current legislation and accompanying scientific studies. *Sustainability*, *13*(9), 5131.

[4] Chen, X.; Zhang, X.; Du, J. The potential of circadian lighting in office buildings using a fibre optics daylighting system in Beijing. Build. Environ. 2020, 182, 107118. [CrossRef]

[5] Konis, K. (2017). A novel circadian daylight metric for building design and evaluation. *Building and Environment*, *113*, 22-38.

[6] Figueiro, M.; Rea, M. Office lighting and personal light exposures in two seasons: Impact on sleep and mood. Light. Res. Technol. 2014, 48, 352–364.

[7] Figueiro, M. A proposed 24 h lighting scheme for older adults. Light. Res. Technol. 2008, 40, 153–160.

[8] Boubekri, M.; Cheung, I.N.; Reid, K.J.;Wang, C.-H.; Zee, P.C. Impact of windows and daylight exposure on overall health and sleep quality of office workers: A case-control pilot study. J. Clin. Sleep Med. 2014, 10, 603–611.

[9] Boyce, P.R. (2003). Human Factors in Lighting (2nd ed.). CRC Press. https://doi.org/10.1201/9780203426340

[10] Heerwagen, J. H., & Heerwagen, D. R. (1986). Lighting and psychological comfort. *Lighting Design and Application*, *16*(4), 47-51.

[11] Acosta, I.; Campano, M.; Leslie, R.; Radetsky, L. Daylighting design for healthy environments: Analysis of educational spaces for optimal circadian stimulus. Sol. Energy 2019, 193, 584–596

[12] Figueiro, M.G.; Rea, M.S. Office lighting and personal light exposures in two seasons: Impact on sleep and mood. Light. Res. Technol. 2016, 48, 352–364. [Google Scholar] [CrossRef]

[13] Jarboe, C., Snyder, J., & Figueiro, M. G. (2020). The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use. *Lighting Research & Technology*, *52*(2), 167-188.

[14] Di Nicolantonio, M., Rossi, E., Deli, A., & Marano, A. (2020). The human centric lighting approach for the design of Age-Friendly products. *Theoretical Issues in Ergonomics Science*, *21*(6), 753-772.

[15] Price, L. L., Udovičić, L., Behrens, T., Van Drongelen, A., Garde, A. H., Hogenelst, K., ... & Wolska, A. (2019). Linking the non-visual effects of light exposure with occupational health. *International journal of epidemiology*, *48*(5), 1393-1397.

[16] Ebaid, M. A. (2023). A framework for implementing biophilic design in cancer healthcare spaces to enhance patients' experience. *International Journal of Sustainable Building Technology and Urban Development*, *14*(2), 229-246.

[17] Standard, W. B. (2018). International WELL Building Institute.

[18] Tunable white LED lighting: TILLUME 24V DC CRI90 leds, TILLUME. Available at: https://tillumelight.com /collections/tunable-white-led-lighting (Accessed: 10 December 2023).

[19] Hagenauer, M. H., & Lee, T. M. (2013). Adolescent sleep patterns in humans and laboratory animals. *Hormones and behavior*, *64*(2), 270-279.

[20] Sleenhoff, S., van Zoest, V., & Sturm, J. (2015). Daylight requirements for the school environment: Visual and nonvisual parameters that support health and learning. In CIE x042: 2015 Proceedings of the CIE Midterm Meeting in Paris (France), May 21–23, 2017 (Vol. 52). Vienna: Commission Internationale de l'Eclairage.

[21] Widiastuti, K., Susilo, M. J., & Nurfinaputri, H. S. (2020). How Classroom Design Impacts for Student Learning Comfort: Architect Perspective on Designing Classrooms. *International Journal of Evaluation and Research in Education*, *9*(3), 469-477.

[22] Jarboe, C., Snyder, J., & Figueiro, M. G. (2020). The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use. *Lighting Research & Technology*, *52*(2), 167-188.

[23] Bellia, L., & Fragliasso, F. (2021). Good places to live and sleep well: A literature review about the role of architecture in determining non-visual effects of light. *International journal of environmental research and public health*, *18*(3), 1002.

[24] Hraska, J. Chronobiological aspects of green buildings daylighting. Renew. Energy 2015, 73, 109–114.
[25] Altenberg Vaz, N., & Inanici, M. (2021). Syncing with the sky: daylight-driven circadian lighting design. *Leukos*, *17*(3), 291-309.
[26] Alkhatatbeh, B. J., & Asadi, S. (2021). Role of architectural design in creating circadian-effective interior settings. *Energies*, *14*(20), 6731.
[27] Potočnik, J., & Košir, M. (2020). Influence of commercial glazing and wall colours on the resulting non-visual daylight conditions of an office. Building and Environment, 171, 106627.
[28] Parsaee, M., Demers, C. M., Lalonde, J. F., Potvin, A., Inanici, M., & Hébert, M. (2020). Human-centric lighting performance of shading panels in architecture: A benchmarking study with lab scale physical models under real skies. Solar Energy, 204, 354-368.
[29] Acosta, I., Leslie, R. P., & Figueiro, M. G. (2017). Analysis of circadian stimulus allowed by daylighting in hospital rooms. *Lighting Research & Technology*, *49*(1), 49-61.
[30] Aguilar-Carrasco, M. T., Domínguez-Amarillo, S., Acosta, I., & Sendra, J. J. (2021). Indoor lighting design for healthier workplaces: natural and electric light assessment for suitable circadian stimulus. *Optics Express*, *29*(19), 29899-29917.
[31] Tregenza, P.; Mardaljevic, J. Daylighting buildings: Standards and the needs of the designer. Light. Res. Technol. **2018**, 50, 63–79.
[32] Lm, I., 2013. Approved method: IES spatial Daylight autonomy (sDA) and annual sunlight exposure (ASE). Illuminating Engineering Society. https://www. ies. org/product/ies-spatial-daylight-autonomy-sda-and-annual-sunlight-exposure-ase.
[33] Nabil, A., & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and buildings*, *38*(7), 905-913.
[34] Lee, J., Boubekri, M., & Liang, F. (2019). Impact of building design parameters on daylighting metrics using an analysis, prediction, and optimization approach based on statistical learning technique. *Sustainability*, *11*(5), 1474.
[35] Lowry, G. D. (2018, April). A comparison of metrics proposed for circadian lighting and the criterion adopted in the WELL Building Standard. In CIBSE Technical Symposium, Stretching the Envelope. CIBSE.
[36] American National Standards Institute and Illuminating Engineering Society of North America. American National Standard Practice on Lighting for Educational Facilities. New York, NY: Illuminating Engineering Society of North America; 2013. RP-3-13.
[37] Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific data, 5(1), 1-12.
[38] Egyptian Meteorological Authority website, (2024), Available at: http://ema.gov.eg/ .