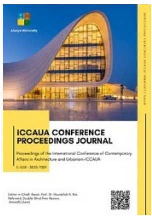

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Harnessing The Power of Healthy Rhythmic Daylight: A Simulation-based Approach in Healthcare Environments

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Abstract

This research aims to examine and evaluate the presence and quality of rhythmic daylight in healthcare facilities, particularly in patients' rooms. The study evaluates whether the natural lighting design within these rooms simulates and mimics rhythmic patterns found in natural daylight. Using computer simulation tools, such as VELUX Daylight Visualizer and Rhino with ALFA, this research evaluates key daylight performance metrics, including daylight illuminance, color temperature, daylight factor, daylight availability, and the melanopic/photopic ratio in selected patient rooms at King Abdullah University Hospital (KAUH) in Irbid City. Results indicate that current daylight conditions fail to provide adequate exposure to rhythmic daylight cycles, potentially disrupting patients' circadian regulation. This study emphasizes the need for evidence-based daylighting strategies that integrate circadian-supportive design principles into healthcare architecture. These strategies aim to create environments that promote better health outcomes and well-being in healthcare settings.

Keywords: Rhythmic daylight; Circadian health; Simulation; Healthcare settings.

Introduction

1.1 Background and Context

Daylight within built environments profoundly impacts occupants' overall health, especially in contexts requiring healing or recovery (Alzoubi & Al-Rqaibat, 2014; Jafarifiroozabadi et al., 2022). For patients in Hospital rooms, well-designed daylight facilitates access to the natural light cycle, enhancing recovery and psychological well-being (Ferrante & Villani, 2022). In line with the broader movement of biophilic design, which emphasizes strategies that promote emotional and physical well-being through connections with nature, integrating effective daylighting becomes critical in healthcare settings (Al-azzawi et al., 2024; Almusaed, 2010). Various studies have proven that daylight has a positive impact on patient well-being and recovery rates, as well as staff productivity in healthcare environments. Both windows and daylighting are considered highly desired natural elements, playing a crucial role in health and well-being (Knoop et al., 2019). This effect stems from humans' innate connection to nature, including light and views from windows (Jafarifiroozabadi et al., 2022). Research indicates that access to natural light not only facilitates recovery but also enhances cognitive health (Yin et al, 2023). Moreover, the presence of natural light and green spaces in healthcare environments is associated with improved attention restoration and better concentration, underscoring the multifaceted benefits of integrating such elements (Richardson et al., 2013). That is why Healthcare facilities that incorporate natural elements such as daylight achieve better health outcomes for patients (Jafarifiroozabadi et al., 2022).

1.2 Problem Statement and Research Gap

Lighting has become a fundamental element in designing a 'healthy healing environment' for patients, especially the concept of rhythmic daylight design (Amleh et al., 2022). Exposure to natural light enhances mood, productivity, comfort, and health (Morales-Bravo & Navarrete-Hernandez, 2022) and is linked to circadian rhythms that regulate essential physiological functions (Lockley, 2010). Daylight can also alleviate stress, shorten hospital stays, and improve visual activities (Alzoubi & Al-Rqaibat, 2014; Salonen et al., 2013), in addition to aiding in pain relief and accelerating healing (Ferrante & Villani, 2022). From an architectural viewpoint, naturalistic elements in design increase place attachment and contribute to a more positive experience for occupants (Cole et al., 2021; Afara et al. 2024; Amen, Afara, and Muhy-Al-din 2024) while also improving subjective well-being (Krols et al., 2022; Yasminingrat et al., 2023). Moreover, constant exposure to natural light in an indoor environment has been found to enhance the perceived ambiance of patients' rooms, enhancing their quality and having a positive impact on patients' psychological health (Salland et al., 2020).

The presence of rhythmic daylight in healthcare environments has a significant impact on fostering healing settings. Rhythmic daylight significantly fosters recovery, boosts optimism, and energizes staff while promoting healing. Despite these known benefits, traditional healthcare settings often neglect the dynamic nature of natural light. Most of the previous studies have focused on static metrics such as daylight factor or general illuminance, and have ignored the rhythmic variations of light throughout the day and across seasons. This rhythmic pattern is crucial for maintaining a healthy circadian system, which often lacks optimized daylight design, limiting natural light exposure and negatively impacting circadian rhythms. This study addresses these gaps by evaluating the quality and presence of rhythmic daylight in patient rooms, using simulation-based metrics that account for both visual and circadian-relevant factors. The findings aim to inform the development of innovative architectural design strategies that optimize health-centered daylight design in healthcare environments. Therefore, assessing rhythmic daylight quality in patients' rooms is vital for innovative architectural design that focuses on incorporating rhythmic daylight to address these issues and improve patient well-being.

1.3 Objectives and Hypotheses

This study aims to investigate and evaluate the presence of rhythmic daylight in healthcare facilities using simulation methods, specifically by examining how the openings' design, including their size, orientations, and configuration, can influence the quality of natural light and its rhythmic pattern. The importance of achieving a harmonious connection between built environments and nature for health matters further supports the need for this analysis (Al-azzawi et al., 2024). The study was conducted at King Abdullah University Hospital (KAUH) in Irbid, where different rhythmic daylight scenarios were analyzed and assessed inside different room typologies with varying opening designs.

This study is guided by the hypothesis that existing patient rooms do not sufficiently support circadian lighting requirements due to inadequate exposure to rhythmic daylight. It is expected that rooms featuring larger windows and higher window-to-floor area ratios will demonstrate greater dynamic daylight availability and achieve more favorable melanopic-to-photopic (M/P) ratios. Additionally, south-facing rooms or those with optimized window orientations are anticipated to perform better in delivering circadian-effective lighting. Seasonal variations are also hypothesized to play a significant role in daylight performance, with winter conditions producing the lowest levels of illuminance and M/P ratios.

1.4 Significance and Structure of the Paper

This study addresses a critical need for architectural design strategies that prioritize rhythmic daylight integration in healthcare environments. By optimizing window-to-wall ratios, refining opening configurations, incorporating shading elements, and employing high-performance glazing, designers can enhance indoor daylight conditions that align with natural light cycles—thereby supporting patients' circadian rhythms and psychological well-being. The findings also highlight the importance of integrating biophilic design principles in healthcare architecture. Previous studies, such as those by Zhong et al. (2022) and Al-Azzawi et al. (2024), demonstrate that exposure to natural rhythms not only supports physical health but also enhances emotional connection, identity, and sense of place. The integration of simulation results and image-based analysis in this study strengthens the case for daylight as both a functional and therapeutic design element.

The significance of this paper lies in its systematic exploration of how architectural daylight strategies affect patient health outcomes. By systematically evaluating the performance of various design parameters across different room typologies and seasonal conditions, the study offers empirical evidence linking daylight quality with circadian support and healing potential.

The paper begins with an introduction that establishes the relevance of natural light in healthcare design and identifies existing gaps in current practices. The literature review synthesizes research on daylight's psychological and physiological effects and outlines the theoretical framework, emphasizing the dynamic, rhythmic nature of natural light and its relevance to circadian health.

The methodology section details the simulation-based design and the use of a mixed-methods approach to assess daylight metrics across room typologies and seasonal conditions. The results present quantitative and qualitative findings that reveal the influence of daylight rhythms on patient comfort and recovery. The discussion connects these findings to prior research, addresses study limitations, and proposes actionable design recommendations.

Finally, the conclusion summarizes the study's contributions and implications for future research and healthcare design practice.

Literature Review

2.1 The Quality of Healthy Daylight

Numerous research studies show that the amount, form, and quality of light exposure daily can significantly impact human emotional and physical well-being (Konis, 2018). Several studies emphasize that to achieve a healthy environment in healthcare settings, patients should receive adequate light levels at the appropriate time of day with a complete natural rhythmic cycle (Riva et al., 2022). Otherwise, daylight alone is insufficient for promoting health and well-being (Münch et al., 2020); this underscores a significant gap in the current literature addressing healthy daylight design. Patients need to experience the natural daylight pattern, characterized by dynamicity and rhythmicity, to avoid adverse health effects from insufficient exposure (Wirz-Justice et al, 2021; Nagare et al., 2021). Much like the environmental factors impacting liveability, insufficient daylight exposure can adversely affect patient recovery and satisfaction (Nwachukwu et al., 2023; Haruna et al., 2023). This calls for the importance of prioritizing the integration of healthy rhythmic daylight to foster healing environments for patients.

2.2 The Visual Perception of Light

Light can be understood not only as radiant energy but also as a physical phenomenon perceived through visual sensation (Schreuder, 2008). In built environments, light transcends mere physicality, engaging the mind and enhancing well-being (Nilsson & Smolka, 2021; Salland et al., 2020). Its visual qualities can affect mood and productivity, adding a therapeutic aspect to architectural spaces (Madsen, 2006). Thus, architectural daylight design should consider light's visual language and its effects on perception (Nilsson & Smolka, 2021). This requires an in-depth understanding of the link between design, natural light, and health to create effective daylighting in architecture.

From an architectural perspective, design influences how natural light is integrated, and several strategies optimize its penetration for health benefits (Aguilar-Carrasco et al., 2023; Alkhatatbeh & Asadi, 2021). Features like large windows, skylights, and light shelves improve daylight quality, positively impacting occupants (Morales-Bravo & Navarrete-Hernandez, 2022). Also, the spatial arrangement and orientation of rooms also affect daylight availability, necessitating strategic positioning for optimal exposure (Rockcastle & Andersen, 2014). Therefore, understanding the design-daylight relationship is crucial for developing strategies that promote healthy environments.

2.3 Theoretical framework

2.3.1 Rhythmic Daylight as a Design Principle for Health

Unlike other elements found in nature, light is visually perceived and is highly dynamic and undergoes continual changes within and across days, as well as throughout the seasons. This creates rhythmic light patterns in terms of intensity, direction, brightness, contrast, color, diffuseness, and view (Knoop et al., 2019). In recent years, there has been increasing recognition of the need for rhythmic daylight that mimics natural light, in addition to the concept of 'naturalistic design' (Al-azzawi et al., 2024), especially in healing environments. Research indicates that direct experiences of nature in built environments enhance health outcomes, promoting physical activity and healing (Sari et al., 2023), while indirect nature experiences, such as simulated natural environments, are linked to psychological benefits like reduced anxiety (Chang & Chen, 2005).

To thoroughly investigate rhythmic daylight, it is important to assess both the visual and non-visual effects of natural light over a full daytime cycle (Song et al., 2022). This approach reveals insights into how daylight patterns affect patients both physiologically and perceptually.

The literature identifies several light metrics to assess the quality of healthy daylight, which include (1) Light intensity, measuring available light in a space (Beemer et al., 2021), (2) Color temperature, defining the appearance of light sources (Dai et al., 2018; Konis, 2018), (3) Color Rendering Index (CRI), indicating how accurately a light source reproduces colors compared to natural light (Dai et al., 2018; Hoof et al., 2009), (4) Luminance, reflecting the amount of light emitted per unit area (Aristizabal et al., 2021; Huisman et al., 2018), (5) Uniformity, measuring the evenness of light distribution (Riva et al., 2022; Huisman et al., 2018), (6) Sensitivity, describing variations in light intensity (Huisman et al., 2018; Mardaljevic et al., 2013), and (7) Directionality, indicating the emitted light's direction and angle spread (Mardaljevic et al., 2013; Dai et al., 2018). Despite the complexities in studying the interplay between daylight dynamics and human responses (Knoop et al., 2019), utilizing these metrics can provide valuable insights into the rhythmic nature of daylight and its potential health impacts on patients.

2.3.2 Natural Daylight Rhythms and Patterns

Based on the literature review, this section examines variations in natural light illuminance and color temperature through the Kruithof curve developed by Arie Anders Kruithof (Van Bommel, 2016). The curve illustrates the illuminance and color temperature levels that create visually appealing environments, serving as a reference for daylight values that mimic natural conditions (Ashdown & Eng, 2015), with each color temperature linked to a specific illuminance level, as presented in Figure 1. The data presents the dynamic rhythmic pattern of natural light throughout the daytime cycle.

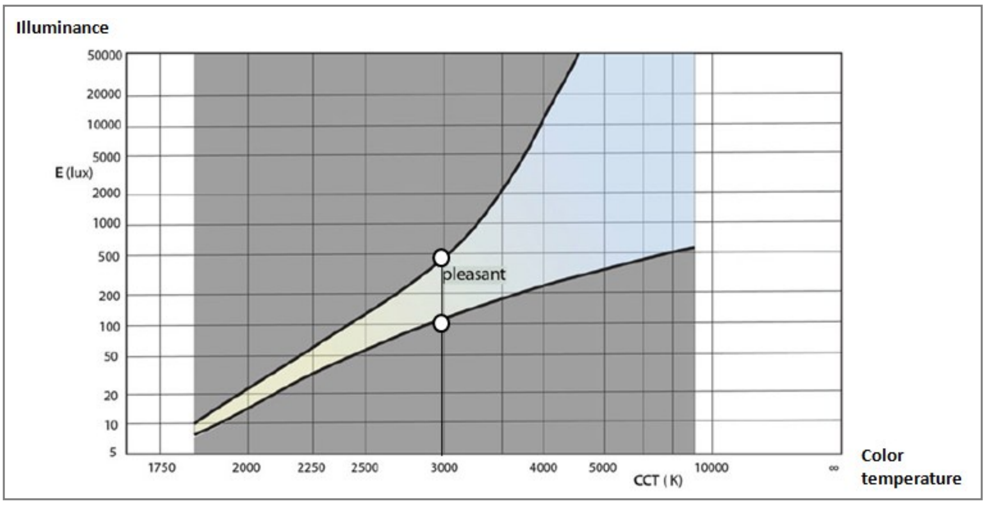
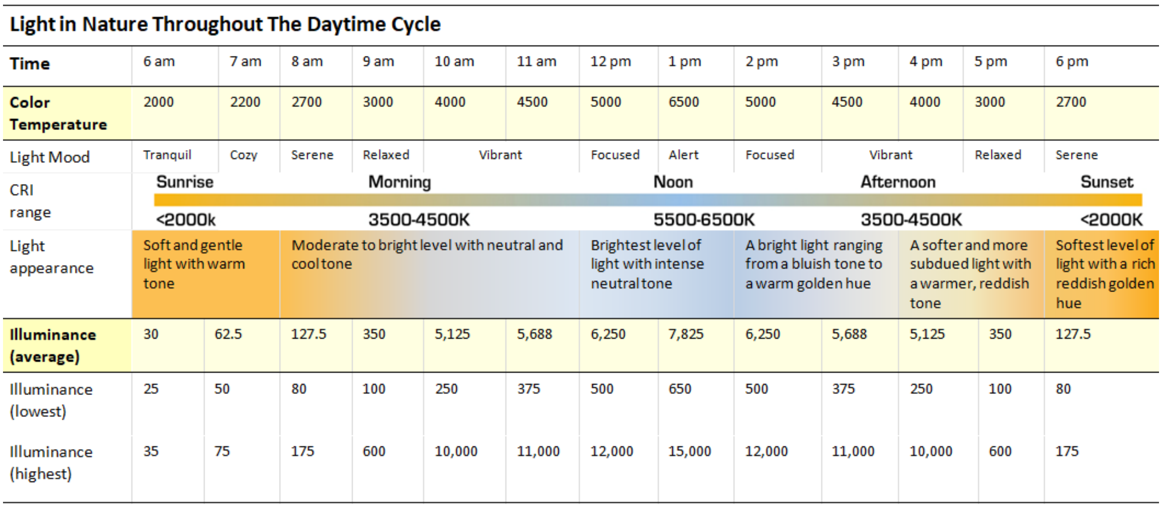


Figure 1. Kruithof's graph illustrating pleasant and natural combinations of illuminance levels (E) and color temperature (CCT).

The curve illustrates light values from lowest (early and late hours) to highest (peak), linking color temperature to specific illuminance levels. For instance, 3000 k is associated with 100 lux (lowest), 350 lux (average), and 600 lux (highest). 3000 k corresponds to 100 lux (lowest), 350 lux (average), and 600 lux (highest). Light illuminance and color temperature were extracted and analyzed based on the Kruithof curve, as shown in Figure 2, which highlights the dynamic rhythm of natural light throughout the daytime cycle.

At sunrise, illuminance starts at 30 lux with a warm color temperature of 2000k, increasing to 127 lux and 4000k by morning. At noon, the peak occurs at 6250 lux with a color temperature of 5000 K. In the afternoon, illuminance declines to 30 lux by sunset, with color temperatures between 4000 and 2000 K, creating a relaxed mood. In winter, illuminance averages between 25 and 650 lux. Statistical analysis reveals a prominent rhythmic pattern, with significant variability in natural illumination values—9147483 variance on summer days versus 38804 on winter days, as shown in Figure 3. The appearance of light in nature and the light color temperature correspond to these variations. Light variations show that sunrise features soft, warm light, transitioning to moderate to bright intensity with cool tones throughout the day, and becoming softer with a reddish hue at sunset. During the evening, the light becomes softer and more subdued with a reddish hue, peaking at sunset with a softer, golden, reddish light and a vibrant atmosphere.

These rhythmic indicators should be central to daylight design in patient rooms. In summary, the analysis confirms that natural light follows a clear rhythmic pattern, crucial for both visual and non-visual characteristics. Literature underscores the vital role of natural light in health and well-being, regulating physiological and psychological responses. Consequently, this study uses lighting values in nature as a foundational reference in evaluation, as they represent the normal, healthy situation that patients need.



Light in Nature Throughout The Daytime Cycle

Time	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm
Color Temperature	2000	2200	2700	3000	4000	4500	5000	6500	5000	4500	4000	3000	2700
Light Mood	Tranquil	Cozy	Serene	Relaxed	Vibrant		Focused	Alert	Focused	Vibrant		Relaxed	Serene
CRI range	Sunrise <2000k			Morning 3500-4500K				Noon 5500-6500K		Afternoon 3500-4500K			Sunset <2000K
Light appearance	Soft and gentle light with warm tone		Moderate to bright level with neutral and cool tone				Brightest level of light with intense neutral tone		A bright light ranging from a bluish tone to a warm golden hue		A softer and more subdued light with a warmer, reddish tone		Softest level of light with a rich reddish golden hue
Illuminance (average)	30	62.5	127.5	350	5,125	5,688	6,250	7,825	6,250	5,688	5,125	350	127.5
Illuminance (lowest)	25	50	80	100	250	375	500	650	500	375	250	100	80
Illuminance (highest)	35	75	175	600	10,000	11,000	12,000	15,000	12,000	11,000	10,000	600	175

Figure 2. Rhythmic Pattern of Light in Nature Throughout the Daytime Cycle.

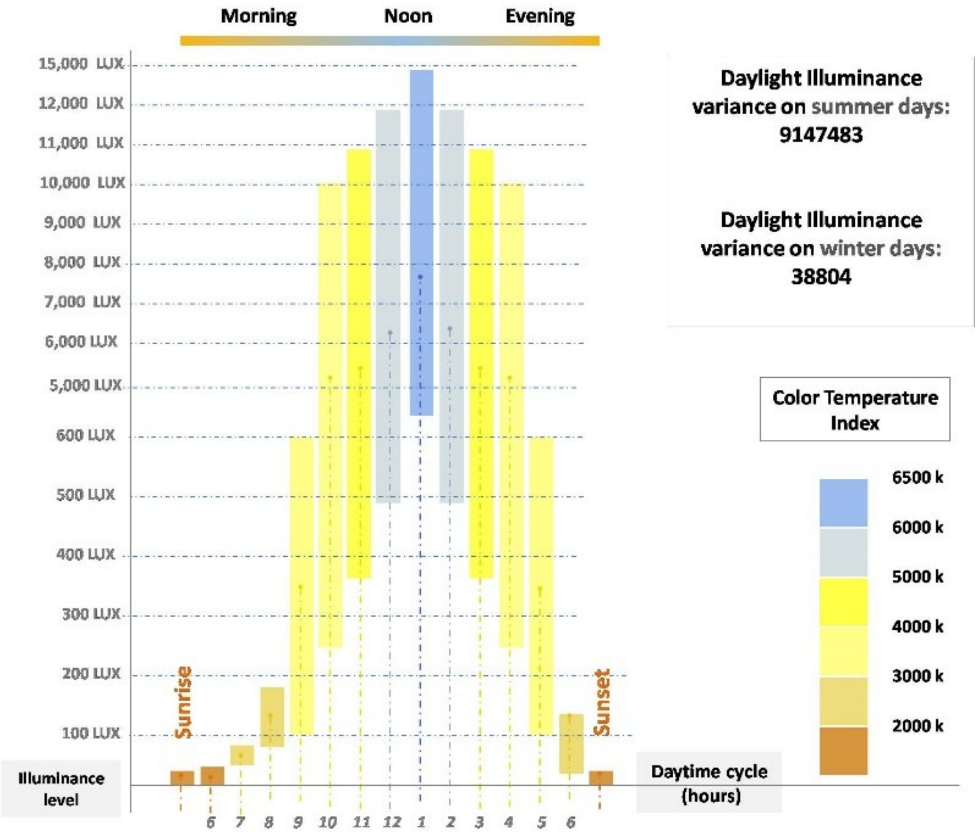


Figure 3. Range and Average Daylight Illumination from Sunrise to Sunset.

3. Research Method

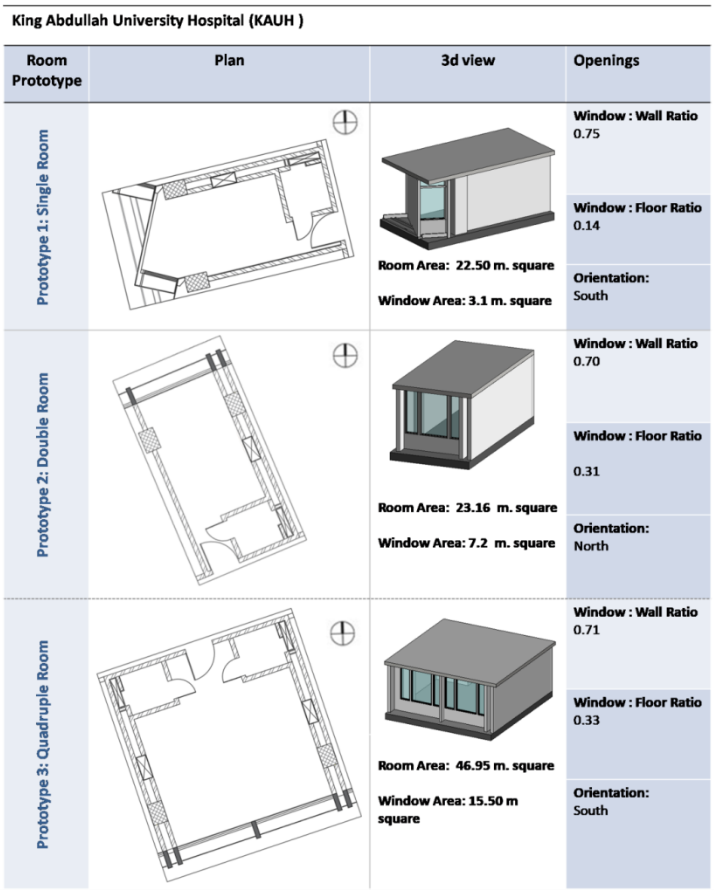
This study investigates the quality and presence of rhythmic natural daylight in patient rooms at King Abdullah University Hospital (KAUH) in Irbid, Jordan. Three typical inpatient room types—single, double, and quadruple—were selected for simulation-based analysis. To evaluate the effectiveness of daylight design in supporting circadian rhythms, comfort, and visual perception, the study employed a combination of simulation tools: Rhino 7, VELUX Daylight Visualizer, and ALFA. These tools were used to assess key daylight performance metrics critical for designing a healthy rhythmic daylight design, including daylight illuminance, color temperature, daylight factor, daylight availability, and daylight (Melanopic/Photopic) ratio. Each metric provides significant insights into the quality of rhythmic daylight experienced and perceived inside the three rooms' prototypes. The three-room prototypes were simulated across different seasonal conditions—March 21, June 21, and December 21—with metrics analyzed throughout the day from sunrise to sunset. The study compared simulation results with recommended rhythmic light patterns found in nature to provide recommendations for improving daylight quality in healthcare settings.

3.1 Deriptive analysis: The (KAUH)

KAUH is located near the Jordan University of Science and Technology in northern Jordan. The hospital comprises a 15-story building with a total area of 95,583 m² for inpatient services and three low-rise buildings for outpatient clinics. The hospital's high-rise section is divided into four interconnected wings with patient rooms located on the fourth to sixth and ninth to twelfth floors.

Rooms in Wings A and C face south and north, while those in Wings B and D face east and west, affecting daylight exposure. The research focuses on single, double, and quadruple room types, analyzing south-facing single rooms, north-facing double rooms, and south-facing quadruple rooms. The sizes and dimensions of rooms vary by wing, with smaller rooms in Wings B and D. Additionally, opening characteristics vary inside patient rooms, with Wing A featuring large windows, and differences in window dimensions impact daylight entry and distribution. As for the materials, the patient rooms' construction includes pre-cast concrete walls, ceilings, and regular 6-mm glass windows with a 25% transmittance factor. These materials have a direct effect on the quality and intensity of daylight penetration into the rooms. Table 1 shows the selected room prototypes for the analysis, along with their main design characteristics.

Table 1. The three analyzed room Prototypes with their design characteristics.



King Abdullah University Hospital (KAUH)

Room Prototype	Plan	3d view	Openings
Prototype 1: Single Room		Room Area: 22.50 m. square Window Area: 3.1 m. square	Window : Wall Ratio 0.75 Window : Floor Ratio 0.14 Orientation: South
Prototype 2: Double Room		Room Area: 23.16 m. square Window Area: 7.2 m. square	Window : Wall Ratio 0.70 Window : Floor Ratio 0.31 Orientation: North
Prototype 3: Quadruple Room		Room Area: 46.95 m. square Window Area: 15.50 m square	Window : Wall Ratio 0.71 Window : Floor Ratio 0.33 Orientation: South

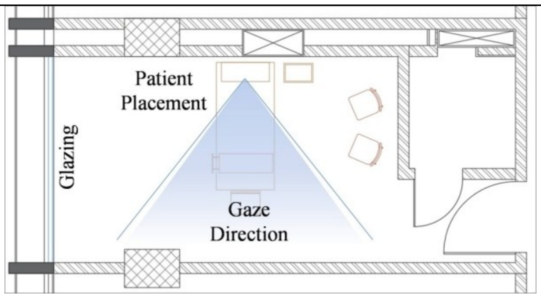
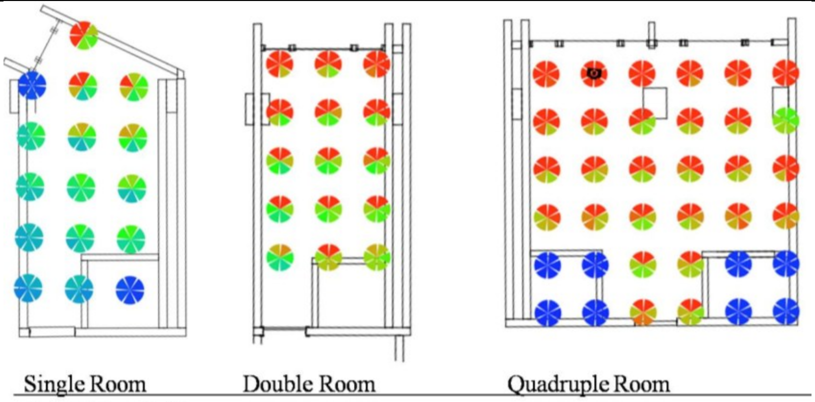
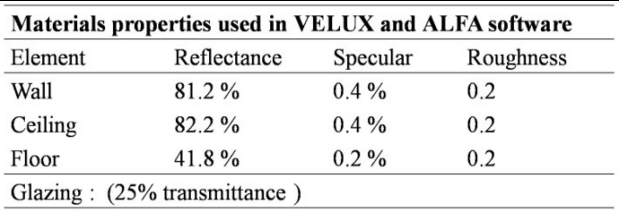
3.2 Simulation tools

The VELUX Daylight Visualizer software (version 3) was used to analyze horizontal daylight illuminance and daylight factor. This tool calculates available daylight, visualizes luminance and daylight distribution, and generates false color images (VELUX, 2022). Simulations reflected various daylight hours across the year, using climatic data to simulate light conditions during different seasons: sunny skies on June 21 and overcast skies on March 21 and December 21. The Daylight factor was calculated under overcast conditions. Regular simulations occurred on these three days from 6 a.m. to 6 p.m. at 7-hour intervals.

The ALFA software in Rhinoceros 7 analyzed non-visual daylight effects using the melanopic-photopic metric.ALFA software, a lighting engine that considers circadian lighting principles, high-resolution rendering across an 81-color spectrum, and spectral calculations, precisely simulates the effect of daytime sky conditions (Solemma, 2020). In this study, simulation settings were configured to evaluate daylight levels under clear and overcast skies on March 21, June 21, and December 21, with simulations run similarly to the VELUX assessments at 7-hour intervals.

The analysis adopted the general gaze direction in relation to the patient's position adjacent to the openings and facing the wall. To ensure comprehensive coverage of the patient's field of view, the setting is set to 6 directions. The gaze direction height was set to match the eye level of a seated patient on the bed, set at 1.2 meters above the floor. To ensure realistic results, ALFA software accounted for the transmission and reflection properties of the materials and glazing. The simulation setup overveiw are shown in Table 2.

Table 2. Simulation Setup Overview: Patient Positioning, Sensor Grid, and Material Properties in ALFA and VELUX Software.

<table>
<tr><th>Component</th><th>Description / Visualization</th></tr>
<tr><td>Patient placement in the room and the gaze direction.</td><td>
</td></tr>
<tr><td>Grid setup settings for the three rooms in ALFA Software.</td><td>
Single Room Double Room Quadruple Room
Grid Setup Settings
Spacing: 1.2 meter
Directions: 6
Radius: 0.3 meter</td></tr>
<tr><td>Properties used for materials in the simulation Software</td><td>
<table>
<tr><th colspan="4">Materials properties used in VELUX and ALFA software</th></tr>
<tr><th>Element</th><th>Reflectance</th><th>Specular</th><th>Roughness</th></tr>
<tr><td>Wall</td><td>81.2 %</td><td>0.4 %</td><td>0.2</td></tr>
<tr><td>Ceiling</td><td>82.2 %</td><td>0.4 %</td><td>0.2</td></tr>
<tr><td>Floor</td><td>41.8 %</td><td>0.2 %</td><td>0.2</td></tr>
<tr><td colspan="4">Glazing : (25% transmittance)</td></tr>
</table></td></tr>
</table>

To complement the simulation-based findings and enhance methodological validity, this study references field measurements conducted by Alzoubi and Al-Rqaibat (2014) at the same hospital (KAUH). Their empirical research used light sensors to record daylight illuminance in patient rooms across various orientations and seasonal conditions. The results revealed that many rooms failed to meet the recommended daylight thresholds (e.g., 300 lux), especially in north-facing rooms and during winter, due to poor window design and limited exposure. These measurements substantiate the simulation outcomes presented in this study, reinforcing the conclusion that current architectural configurations inadequately support rhythmic daylight cycles necessary for promoting circadian health and visual comfort.

4. Results

4.1 Daylight inside Patients' Rooms

Daylight is crucial for maintaining health and well-being in healthcare settings, as it significantly impacts circadian rhythms and psychological responses. This section evaluates daylight conditions in patient rooms, focusing on illuminance levels, daylight factor (DF), daylight availability, and light absorbed by patients. By analyzing these conditions in relation to natural light patterns, the study assesses whether the current lighting design supports the creation of a healthy and rhythmic daylit environment, essential for patient recovery and comfort.

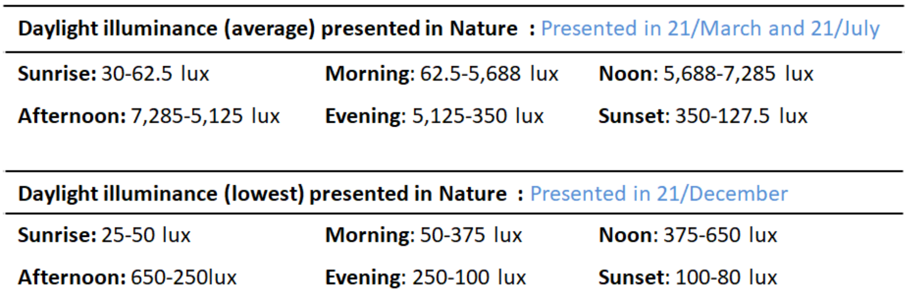
4.1.1 The Daylight Illuminance.

Recognizing the impact of lighting values in nature, which follow a clear rhythmic pattern, on visual perception and physiological responses, this study relies on the natural pattern of light as a basic reference for evaluation. As represented in **Error! Reference source not found.**, natural illuminance values range from 30 to 7285 lux in spring and summer, and 25 to 650 lux in winter. The data shows average indoor illumination values should be higher on March 21 and June 21, with lower values on December 21 to create a well-lit environment. The analysis reveals that all three rooms exhibit significant disparities in illuminance compared to natural levels, particularly in winter.

The results for each room across the three days of the daytime cycle are presented in **Error! Reference source not found.**. For Room 1, with a W.W.R of 0.75, illuminance levels vary from 14 to 2101 lux in spring, and 44 to 1528 lux in summer, while winter shows minimal variation, from 21 to 2101 lux. Room 2, with a W.W.R of 0.7, illustrates a broader range, with illuminance from 18 to 913 lux in spring and 61 to 1005 lux in summer, maintaining lower variances. Room 3, also facing south, shows the highest variances, ranging from 43 to 2234 lux in spring and 96 to 2893 lux in summer, with winter values from 32 to 724 lux. Overall, illuminance levels in all rooms remain below the required natural values due to factors such as orientation and window design.

Table 3. Comparative Analysis of Natural and Simulated Daylight Illuminance Across Seasonal Conditions.

The illumination values on March 21, June 21, and December



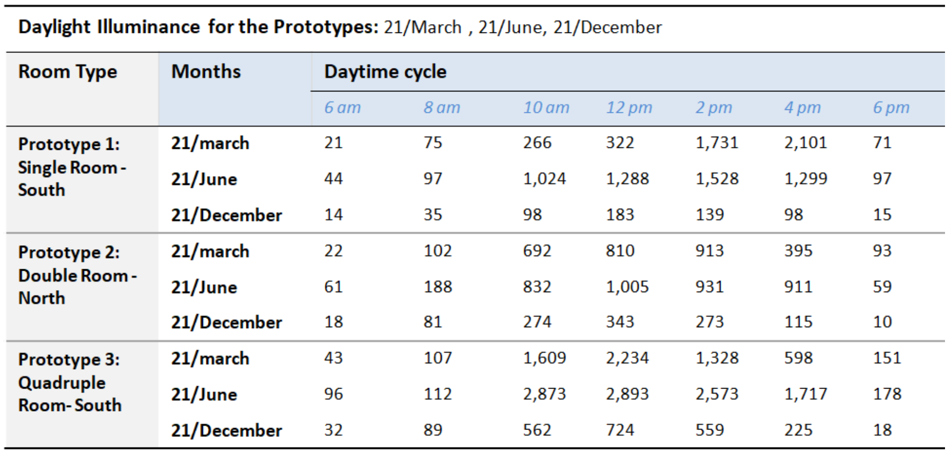
Daylight illuminance (average) presented in Nature : Presented in 21/March and 21/July

Sunrise: 30-62.5 lux
Morning: 62.5-5,688 lux
Noon: 5,688-7,285 lux
Afternoon: 7,285-5,125 lux
Evening: 5,125-350 lux
Sunset: 350-127.5 lux

Daylight illuminance (lowest) presented in Nature : Presented in 21/December

Sunrise: 25-50 lux
Morning: 50-375 lux
Noon: 375-650 lux
Afternoon: 650-250lux
Evening: 250-100 lux
Sunset: 100-80 lux

The illumination values for the three rooms on March 21, June 21, and December 21.



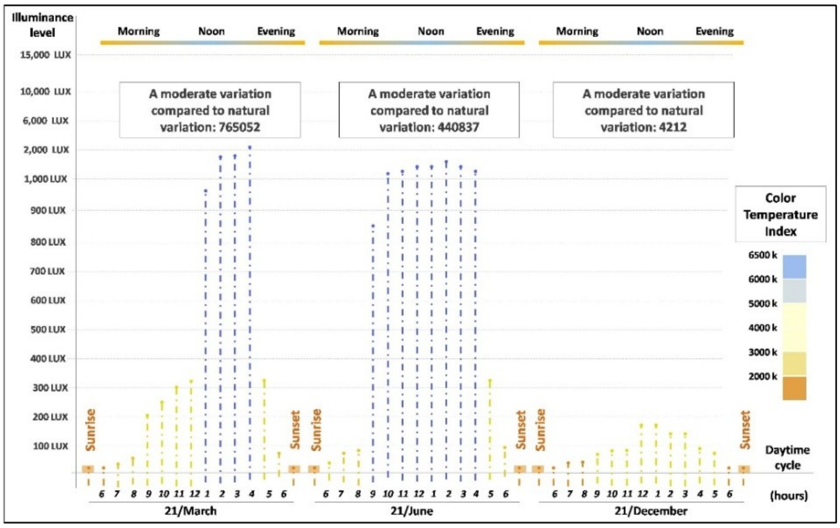
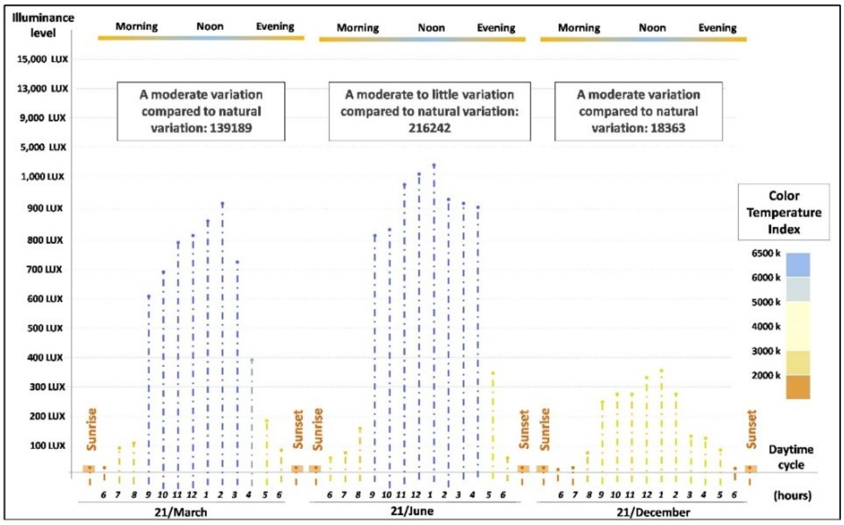
Daylight Illuminance for the Prototypes: 21/March , 21/June, 21/December

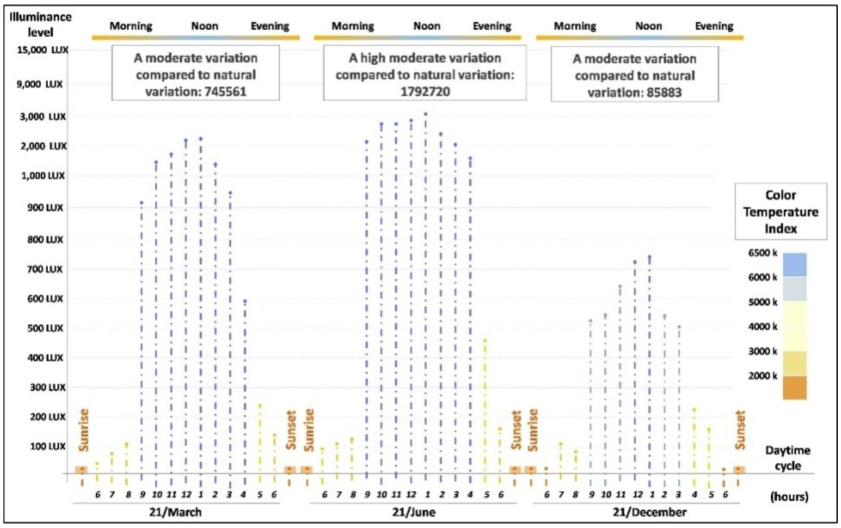
Room Type	Months	Daytime cycle						
		6 am	8 am	10 am	12 pm	2 pm	4 pm	6 pm
Prototype 1: Single Room - South	**21/march**	21	75	266	322	1,731	2,101	71
	21/June	44	97	1,024	1,288	1,528	1,299	97
	21/December	14	35	98	183	139	98	15
Prototype 2: Double Room - North	**21/march**	22	102	692	810	913	395	93
	21/June	61	188	832	1,005	931	911	59
	21/December	18	81	274	343	273	115	10
Prototype 3: Quadruple Room- South	**21/march**	43	107	1,609	2,234	1,328	598	151
	21/June	96	112	2,873	2,893	2,573	1,717	178
	21/December	32	89	562	724	559	225	18

In terms of illumination variability across the daytime cycle, the rooms lack the necessary range and variability, hindering the creation of the healthy rhythmic pattern of daylight essential for patients' well-being. Room 1 (south-facing, W.W.R 0.75) has spring illuminance levels ranging from 14 to 2101 lux with a variance of 765052, and summer levels from 44 to 1528 lux with a variance of 440873; winter shows minimal variation with values between 21 and 2101 lux. Room 2 (north-facing, W.W.R 0.7) displays stronger ranges—18 to 913 lux in spring (variance: 139189) and 61 to 1005 lux in summer (variance: 216242)—but remains mostly between 274 and 1005 lux in winter, resulting in a steady but arrhythmic atmosphere. Room 3 (south-facing, W.W.R 0.75) shows the highest variance, with spring levels from 43 to 2234 lux, summer levels from 96 to 2893 lux, and winter levels from 32 to 724 lux, primarily fluctuating between 562 and 2893 lux. Table 4 visualizes the rhythmic fluctuations in daylight illuminance levels and associated color temperatures throughout the daytime cycle for each room across three seasonal conditions.

Overall, all three rooms consistently record illuminance levels below natural requirements due to factors such as orientation and opening design. While Room 3 exhibits slight rhythmicity, Rooms 1 and 2 do not, potentially undermining patient well-being in these environments. It is evident from the analysis that these rooms fail to provide the variance and rhythmicity needed for optimal dynamic daylight in the healthcare environments; instead, they provide more stable, controlled environments with low illuminance levels that may be less conducive to patient well-being.

Table 4. Daylight Illumination Profiles for Patient Rooms Across Seasonal Cycles.

Room	**Description**
Room 1	
Room 2	

Room 3	

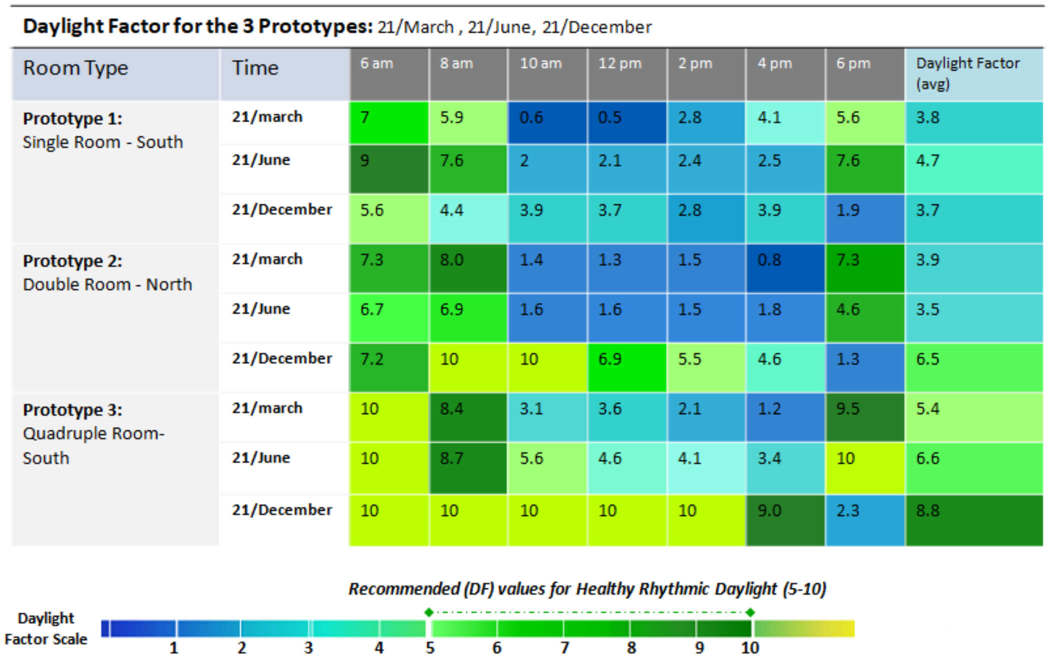
4.1.2 The Daylight Factor (DF)

The daylight factor (DF) serves as a crucial metric for measuring indoor to outdoor illuminance, with optimal values ideally fluctuating between (5-10) from sunrise to sunset to support effective rhythmic daylight.. Furthermore, the (DF) analysis helps assess the quantity, distribution, and uniformity of natural light through multiple metrics, including average (DF), median (DF), and uniformity ratio (DF). These metrics are of significant importance for evaluating the contribution of daylight to patients' well-being, comfort, and visual performance. Within the three patient rooms, evaluations for (DF) values were conducted along the daytime cycle (see Table 5) and across the space (see Figure 4). The measurements were taken every 2 hours on March 21, June 21, and December 21 (see Table 5). The findings revealed that DF values predominantly fell below 4, indicating insufficient natural light levels.

Generally, the only good values of (DF) were recorded during the early and late hours across the three days, while most values fell below 4, which is far from the recommended healthy range. December 21, however, recorded the highest measurements, particularly in Room 3, which consistently demonstrated satisfactory daylight conditions. In contrast, Room 1 exhibited considerable variability; it peaked at a DF of 4 at 9:00 a.m. on June 21 but dropped to 0.5 during midday on March 21. Room 2, while achieving a maximum DF of 10.0 on December 21, suffered a decline to 0.8 on June 21. Notably, Room 3 maintained DF values above 5, averaging 6.9, signifying robust daylight penetration that positively impacts patient comfort.

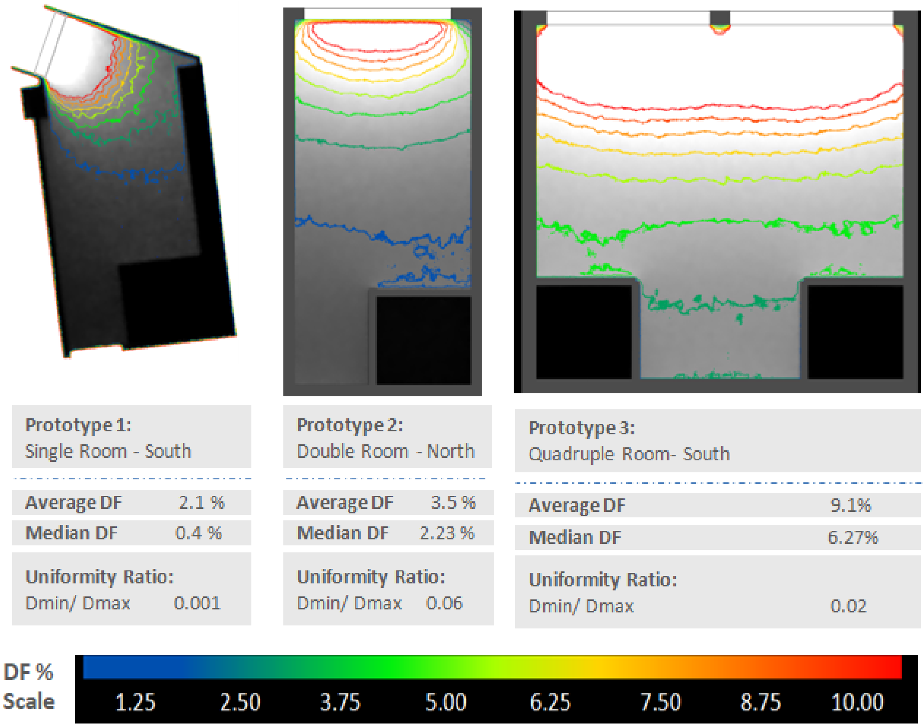
Further insights gained from simulations using the Velux daylight visualizer provided a clearer picture of DF across the spaces in terms of daylight quantity, distribution, and uniformity. The simulation was run for the rooms at the same hour (12:00 p.m.) on June 21. The ISO contour plans for each room are presented in Figure 4, illustrating the average (DF), median (DF), and uniformity ratio (DF). Room 1 recorded an average DF of 2.1% and a median of 0.4%, while Room 2 fared slightly better with an average of 3.5% and a median of 2.23%. In stark contrast, Room 3 excelled with an average DF of 9.1% and a median of 6.27%, highlighting its superior daylight quality. The uniformity ratios also favored Rooms 2 and 3, demonstrating more consistent daylight distribution, which is essential for enhancing patient comfort and visual performance.

Table 5. The (DF) Values in the Three Rooms Across the Daytime Cycle on March 21, June 21, and December 21.



Daylight Factor for the 3 Prototypes: 21/March , 21/June, 21/December

Room Type	Time	6 am	8 am	10 am	12 pm	2 pm	4 pm	6 pm	Daylight Factor (avg)
Prototype 1: Single Room - South	**21/march**	7	5.9	0.6	0.5	2.8	4.1	5.6	3.8
	21/June	9	7.6	2	2.1	2.4	2.5	7.6	4.7
	21/December	5.6	4.4	3.9	3.7	2.8	3.9	1.9	3.7
Prototype 2: Double Room - North	**21/march**	7.3	8.0	1.4	1.3	1.5	0.8	7.3	3.9
	21/June	6.7	6.9	1.6	1.6	1.5	1.8	4.6	3.5
	21/December	7.2	10	10	6.9	5.5	4.6	1.3	6.5
Prototype 3: Quadruple Room-South	**21/march**	10	8.4	3.1	3.6	2.1	1.2	9.5	5.4
	21/June	10	8.7	5.6	4.6	4.1	3.4	10	6.6
	21/December	10	10	10	10	10	9.0	2.3	8.8



Prototype 1:
Single Room - South
Average DF 2.1 %
Median DF 0.4 %
Uniformity Ratio:
Dmin/ Dmax 0.001

Prototype 2:
Double Room - North
Average DF 3.5 %
Median DF 2.23 %
Uniformity Ratio:
Dmin/ Dmax 0.06

Prototype 3:
Quadruple Room- South
Average DF 9.1%
Median DF 6.27%
Uniformity Ratio:
Dmin/ Dmax 0.02

Figure 4. The ISO contour plans represent the DF values in the three rooms at noon on June 21.

Given the strong relationship between uniform daylight and visual ergonomics, as well as the support it provides for circadian rhythms, it is evident that improvements should be made. Therefore, new design recommendations are highly needed for improving healthy daylight design in the three rooms. Collectively, these recommendations should be designed to optimize the quality of rhythmic natural light, its cycle and patterns, and, ultimately, the well-being of patients.

4.1.3 Daylight availability - Perceptual Properties.

The percentage of daylight availability indicates the amount of natural light inside the room compared to the outdoor illuminance level. It serves as a crucial indicator for evaluating overall lighting conditions. For the analysis, the daylight availability on June 21 is calculated based on the illuminance level and daylight factor. June

21 has the longest daylight period across the years, offering insights into the maximum potential for daylight inside the room. The results are shown in Figure 5.

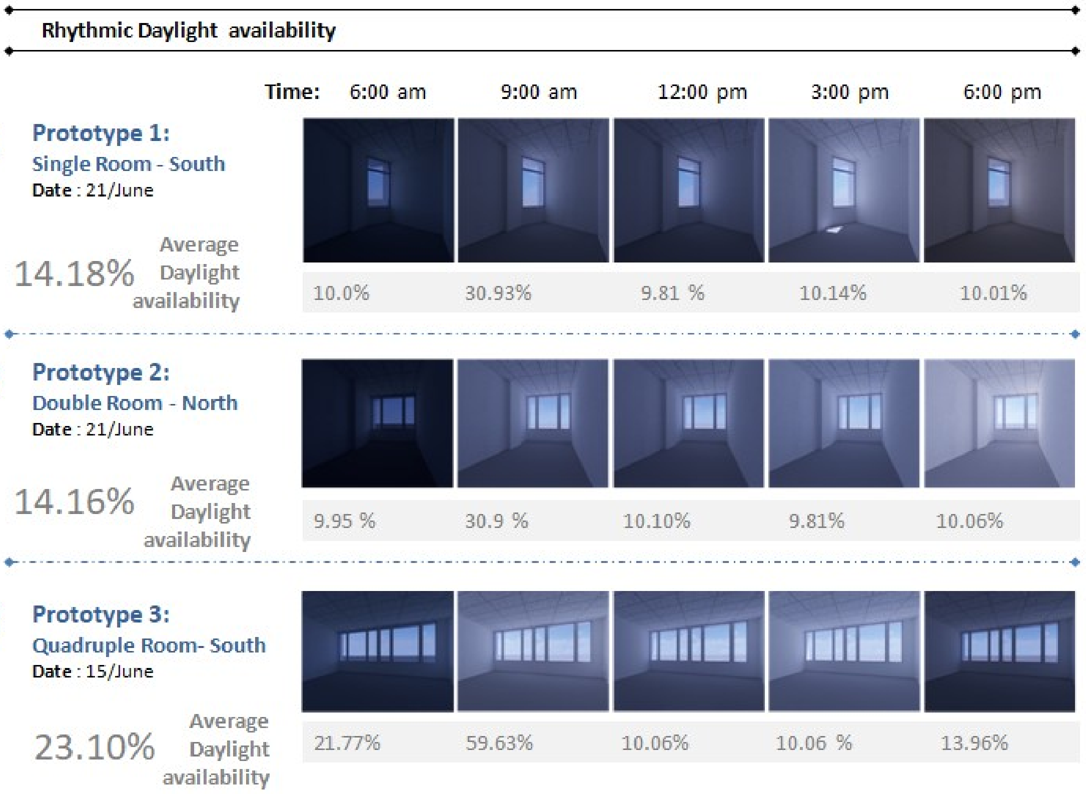


Figure 5. Daylight Availability in the Three Rooms at 12:00 p.m. on June 21.

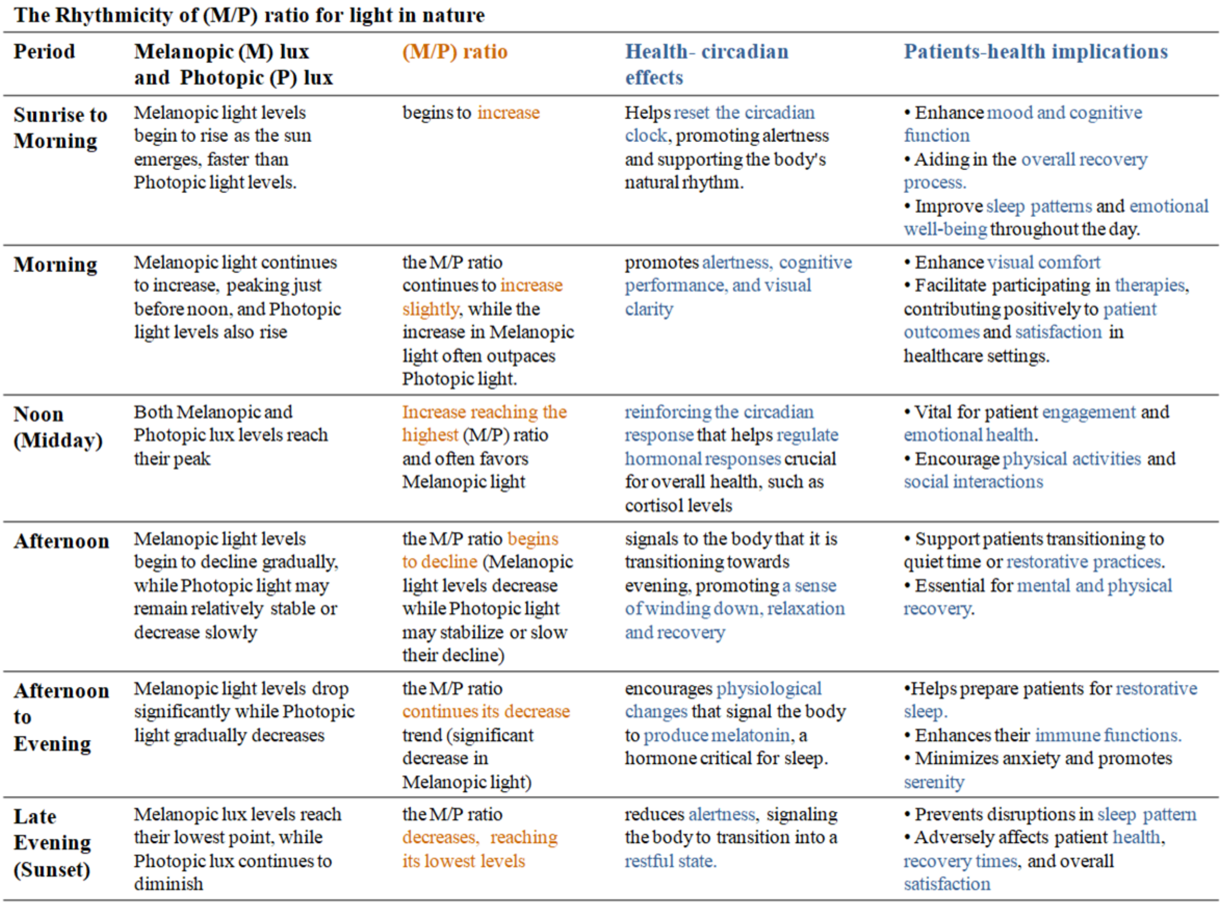
On June 21, the Rhythmic daylight availability inside the three rooms ranged from 14% to 23%. Notably, the lowest percentage was recorded from noon to evening, while morning time showed slightly better availability. Room 3 achieved the highest percentage of rhythmic daylight availability (59.63%) in the morning time, while Room 1 recorded the lowest percentage (9.81%) during noon, and Room 2 registered the lowest (9.81%) in the afternoon. For March 21 and December 21, the potential range of daylight availability is considerably lower (below 23.10%), emphasizing limited access to natural light and the absence of a rhythmic pattern within the rooms.

In conclusion, Room 3 exhibited the highest availability (23.10 %) compared to Rooms 1 and 2, which 2 showed similar lower levels (14.18% and 14.16 %, respectively), indicating insufficient natural light availability to create a rhythmic, healthy atmosphere for patients.

4.1.4 The Circadian-Health effects of daylight: Melanopic (M), Photopic (P), (M /P) Ratio.

The circadian health of patients is significantly influenced by types of daylight: Melanopic light enhances physiological health, while Photopic light improves visual comfort. The Melanopic/Photopic (M/P) ratio is vital for assessing these effects, with a higher ratio indicating stronger circadian influences. The ideal daylight condition that replicates the natural pattern of melanopic and photopic light, in addition to the associated health-circadian effects and patients' health implications from this pattern and changes, is shown in **Error! Reference source not found.**. Replicating this rhythmic pattern within patient rooms is crucial for maintaining good health.

Table 6. Rhythmic Changes in Melanopic Light, Photopic Light, and M/P Ratio During the Daytime Cycle, in addition to the associated health-circadian effects and implications.



The Rhythmicity of (M/P) ratio for light in nature

Period	Melanopic (M) lux and Photopic (P) lux	(M/P) ratio	Health- circadian effects	Patients-health implications
Sunrise to Morning	Melanopic light levels begin to rise as the sun emerges, faster than Photopic light levels.	begins to increase	Helps reset the circadian clock, promoting alertness and supporting the body's natural rhythm.	• Enhance mood and cognitive function • Aiding in the overall recovery process. • Improve sleep patterns and emotional well-being throughout the day.
Morning	Melanopic light continues to increase, peaking just before noon, and Photopic light levels also rise	the M/P ratio continues to increase slightly, while the increase in Melanopic light often outpaces Photopic light.	promotes alertness, cognitive performance, and visual clarity	• Enhance visual comfort • Facilitate participating in therapies, contributing positively to patient outcomes and satisfaction in healthcare settings.
Noon (Midday)	Both Melanopic and Photopic lux levels reach their peak	Increase reaching the highest (M/P) ratio and often favors Melanopic light	reinforcing the circadian response that helps regulate hormonal responses crucial for overall health, such as cortisol levels	• Vital for patient engagement and emotional health. • Encourage physical activities and social interactions
Afternoon	Melanopic light levels begin to decline gradually, while Photopic light may remain relatively stable or decrease slowly	the M/P ratio begins to decline (Melanopic light levels decrease while Photopic light may stabilize or slow their decline)	signals to the body that it is transitioning towards evening, promoting a sense of winding down, relaxation and recovery	• Support patients transitioning to quiet time or restorative practices. • Essential for mental and physical recovery.
Afternoon to Evening	Melanopic light levels drop significantly while Photopic light gradually decreases	the M/P ratio continues its decrease trend (significant decrease in Melanopic light)	encourages physiological changes that signal the body to produce melatonin, a hormone critical for sleep.	•Helps prepare patients for restorative sleep. • Enhances their immune functions. • Minimizes anxiety and promotes serenity
Late Evening (Sunset)	Melanopic lux levels reach their lowest point, while Photopic lux continues to diminish	the M/P ratio decreases, reaching its lowest levels	reduces alertness, signaling the body to transition into a restful state.	• Prevents disruptions in sleep pattern • Adversely affects patient health, recovery times, and overall satisfaction

The melanopic/ photopic ratio serves as a crucial metric for assessing the impact of light on circadian health, as a higher M/P ratio indicates a greater potential circadian effect of daylight.. Typical daylight ratios range from 1.00, representing a neutral balance between M and P, to 1.05, indicating a good balance, to 1.10, indicating a perfect balance, with values slightly favoring melanopic over photopic to ensure healthy circadian effects.

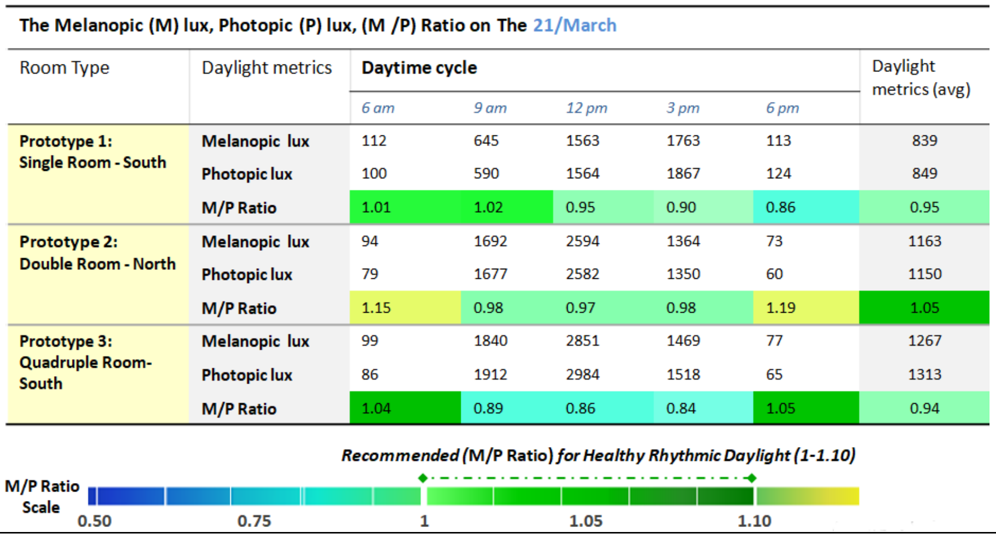
On March 21, M/P ratios ranged from 0.84 to 1.05, with Room 2 meeting the optimal ratio of 1.05, while others failed to provide adequate Melanopic and Photopic light levels. On June 21, promising trends were noted except for Room 2 during early and late hours, and Room 1's values rose in the afternoon, disrupting circadian health. Most rooms did not achieve the recommended M/P ratio of 1.00 to 1.10, with Room 3 providing the closest values, particularly in the early morning and evening. The results for December 21 showed M/P averages of 0.99 for Rooms 1 and 2 and lower values for Room 3. Room 1 maintained ratios from 0.95 to 1.01 across all days, suggesting a healthy daylight level, while Room 2 ranged from 0.95 to 1.07, indicating potential deficiencies. Room 3 consistently fell below recommended levels, signaling a need for improvement to support patient well-being.

The M/P ratio analysis reveals that while some rooms, particularly Room 2, achieved the recommended values on specific dates, consistent deficiencies in Melanopic and Photopic light levels across other rooms highlight the need for ongoing improvements to support optimal patient well-being and circadian health. Table 7 shows the recorded M/P ratios across March, June, and December for the analyzed patient rooms.

Table 7. Melanopic and Photopic Illuminance Levels and M/P Ratios in Patient Rooms on March 21, June 21 and December 21.

Section	Description

March 21st

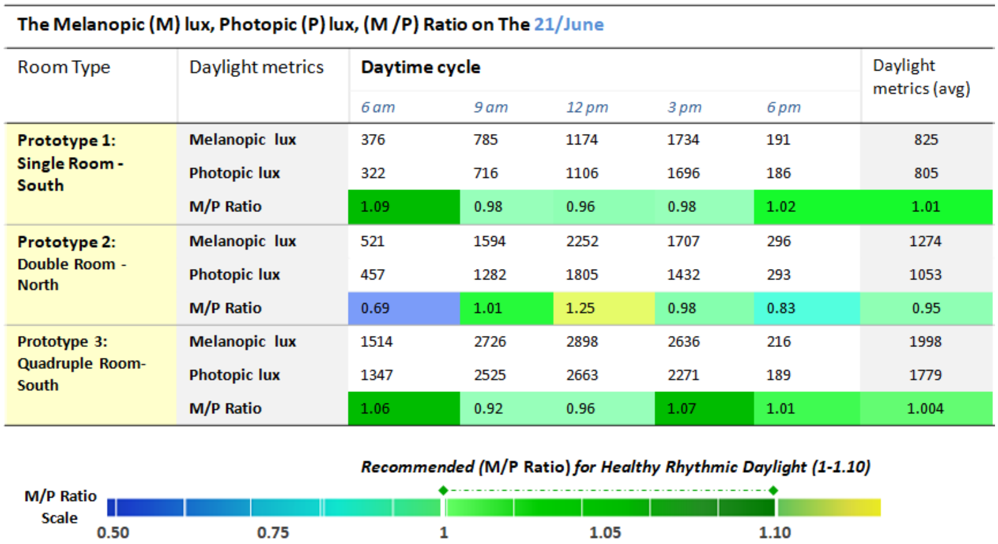


The Melanopic (M) lux, Photopic (P) lux, (M /P) Ratio on The 21/March

Room Type	Daylight metrics	Daytime cycle					Daylight metrics (avg)
		6 am	*9 am*	*12 pm*	*3 pm*	*6 pm*	
Prototype 1: Single Room - South	**Melanopic lux**	112	645	1563	1763	113	839
	Photopic lux	100	590	1564	1867	124	849
	M/P Ratio	1.01	1.02	0.95	0.90	0.86	0.95
Prototype 2: Double Room - North	**Melanopic lux**	94	1692	2594	1364	73	1163
	Photopic lux	79	1677	2582	1350	60	1150
	M/P Ratio	1.15	0.98	0.97	0.98	1.19	1.05
Prototype 3: Quadruple Room-South	**Melanopic lux**	99	1840	2851	1469	77	1267
	Photopic lux	86	1912	2984	1518	65	1313
	M/P Ratio	1.04	0.89	0.86	0.84	1.05	0.94

Recommended (M/P Ratio) for Healthy Rhythmic Daylight (1-1.10)

June 21

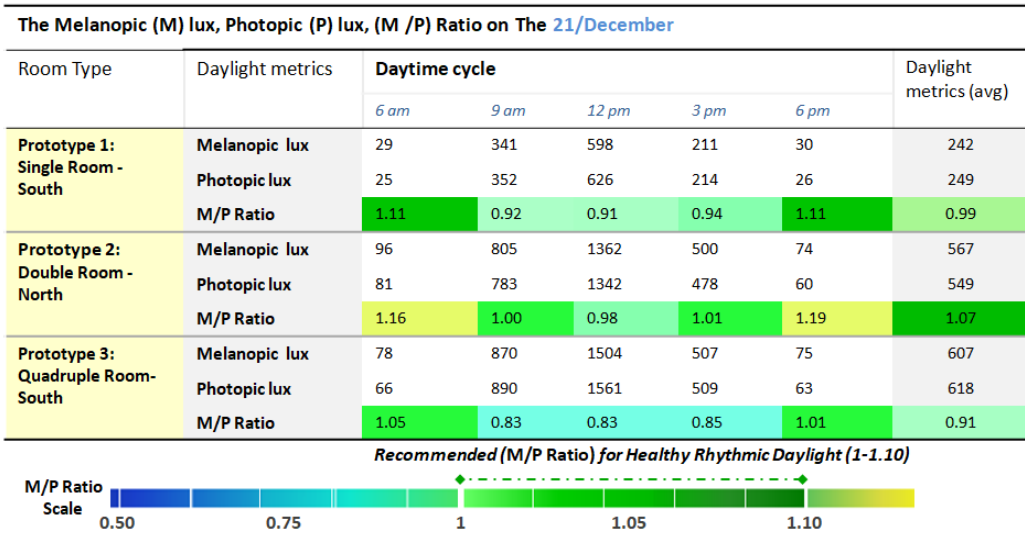


The Melanopic (M) lux, Photopic (P) lux, (M /P) Ratio on The 21/June

Room Type	Daylight metrics	Daytime cycle					Daylight metrics (avg)
		6 am	*9 am*	*12 pm*	*3 pm*	*6 pm*	
Prototype 1: Single Room - South	**Melanopic lux**	376	785	1174	1734	191	825
	Photopic lux	322	716	1106	1696	186	805
	M/P Ratio	1.09	0.98	0.96	0.98	1.02	1.01
Prototype 2: Double Room - North	**Melanopic lux**	521	1594	2252	1707	296	1274
	Photopic lux	457	1282	1805	1432	293	1053
	M/P Ratio	0.69	1.01	1.25	0.98	0.83	0.95
Prototype 3: Quadruple Room-South	**Melanopic lux**	1514	2726	2898	2636	216	1998
	Photopic lux	1347	2525	2663	2271	189	1779
	M/P Ratio	1.06	0.92	0.96	1.07	1.01	1.004

Recommended (M/P Ratio) for Healthy Rhythmic Daylight (1-1.10)

December 21



The Melanopic (M) lux, Photopic (P) lux, (M /P) Ratio on The 21/December

Room Type	Daylight metrics	Daytime cycle					Daylight metrics (avg)
		6 am	*9 am*	*12 pm*	*3 pm*	*6 pm*	
Prototype 1: Single Room - South	**Melanopic lux**	29	341	598	211	30	242
	Photopic lux	25	352	626	214	26	249
	M/P Ratio	1.11	0.92	0.91	0.94	1.11	0.99
Prototype 2: Double Room - North	**Melanopic lux**	96	805	1362	500	74	567
	Photopic lux	81	783	1342	478	60	549
	M/P Ratio	1.16	1.00	0.98	1.01	1.19	1.07
Prototype 3: Quadruple Room-South	**Melanopic lux**	78	870	1504	507	75	607
	Photopic lux	66	890	1561	509	63	618
	M/P Ratio	1.05	0.83	0.83	0.85	1.01	0.91

Recommended (M/P Ratio) for Healthy Rhythmic Daylight (1-1.10)

4.1.5 The Light Absorbed by Patients' Eyes and the Change in the Light Spectrum.

Using Alfa software, the amount of light absorbed by an observer's eye and spectrum changes were quantified, focusing on light on June 21. Figure 6 Illustrates the light-receiver points, indicating that Melanopic light, Photopic light, and the (M /P) ratio.

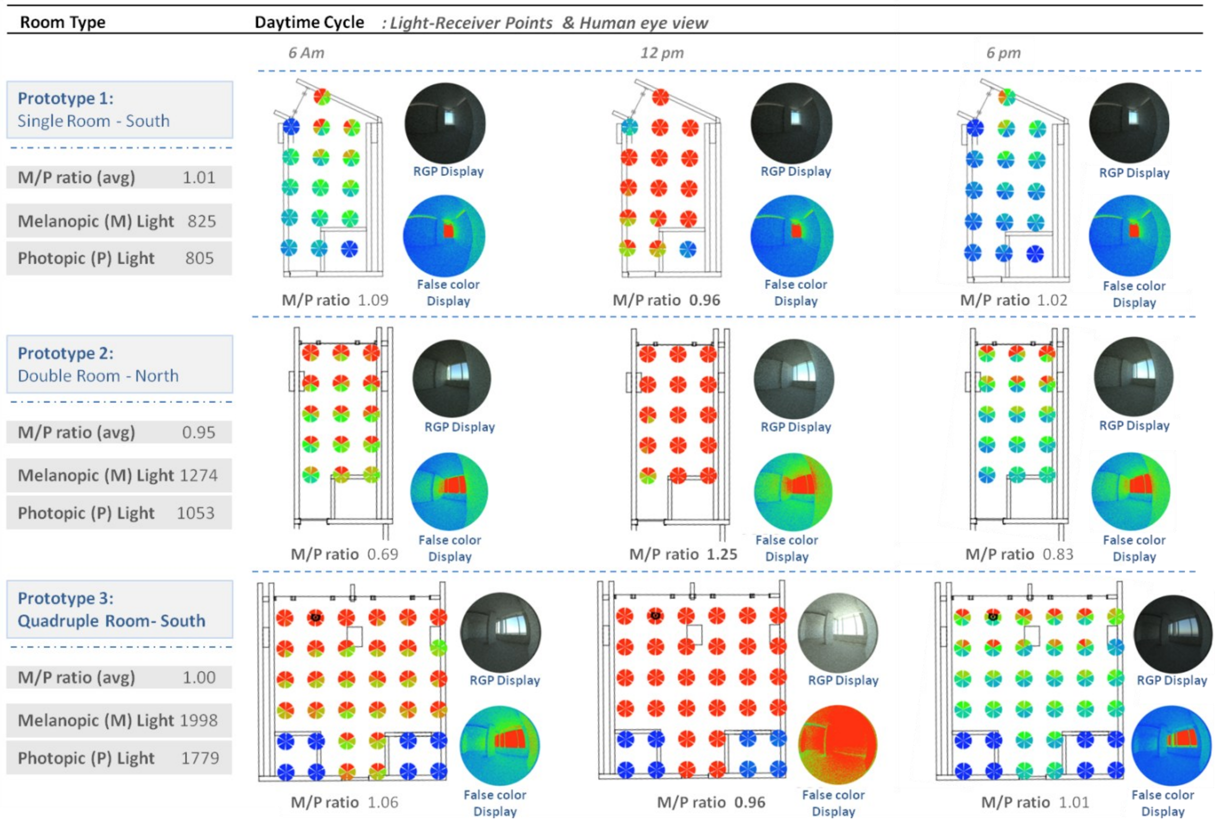


Figure 6. Light-Receiver Points for Each Room Plan Representing the Melanopic and Photopic Light Values and M/P Ratio Along the Daytime Cycle for June 21.

Light-receiver point analysis indicated that early and late hours showed optimal Melanopic, Photopic values, and M/P ratios within the recommended range of 1.0 to 1.10. However, midday values were inadequate. Room 1 maintained an M/P ratio of 1.01, suggesting consistent circadian impacts, albeit with lower overall light levels. Room 2 fluctuated between 0.69 and 1.25, with higher Melanopic levels during midday, potentially benefiting circadian health. Room 3 exhibited superior Melanopic and Photopic values, averaging an M/P ratio around 1.004, making it the most conducive environment for patient well-being compared to the other rooms.

5. Discussion

This study provides a detailed investigation of the impact of different opening designs and seasonal changes on illuminance levels in patient rooms at KAUH. The findings highlight significant variations in illuminance levels and patterns, demonstrating that south-facing rooms (Rooms 1 and 3) receive higher and more variable light levels than north-facing rooms. This observation supports Farivar and Teimourtash's (2023) conclusion that window areas meeting a 60% floor area ratio can achieve healthy daylight. Room 3's larger window-to-floor ratio (75%) aligns with A. Maleki & N. Dehghan's (2021) recommendation for a minimum WWR of 30%; thus, it reinforces the premise that optimal window design is vital for maximizing daylight exposure.

Moreover, the analysis of seasonal variations in illuminance levels complements the broader guidelines found in existing literature. Costa et al. (2024) found that UDI values can significantly vary based on window orientation. This aligns with our study's observations that different window orientations not only influence daylight distribution but also the variability of illuminance levels. Comparatively, other studies emphasize the importance of window design in achieving optimal daylight performance. For example, Farivar and Teimourtash (2023) highlight that windows in higher positions, especially horizontal ones, can yield Useful Daylight Illuminance (UDI) values reaching up to 59%. They also note that increasing the window-to-floor area ratio, as seen in Room 3, can improve daylight availability but may decrease UDI if illuminance levels surpass 3000 lux. This aligns with the main research findings that larger windows and higher window-to-wall and window-to-floor ratios can enhance daylight levels and potentially lead to higher variance. This offers a nuanced understanding of the complexities involved in daylight optimization. Notably, the daylight factor (DF) metric is explicitly explored in other studies. Acosta et al. (2015) and Phillips (2004) suggest that window shape and orientation critically affect DF, with square and high-angled windows performing better. This is aligned with the findings of this research, as Room 3, with south-oriented openings and a higher window-to-floor ratio, has the highest DF value, falling within the recommended range for optimal circadian-health outcomes.

In conclusion, this study's findings highlight significant daylight-related challenges across the three patient rooms examined. Notably, Prototype 1's deficiencies in daylight illuminance and variability potentially compromise its potential for supporting circadian health, while Prototype 2's inconsistent daylight availability raises concerns about its ability to foster a rhythmic atmosphere conducive to patient recovery. Meanwhile, Prototype 3, although promising, still falls short in maintaining optimal Melanopic/Photopic ratios. These discrepancies in overall daylight quality underline the critical role that design characteristics play in enhancing health outcomes for patients, as the quality of daylight can influence both physiological and psychological well-being.

The strengths of this study include its detailed empirical data on specific room conditions and its comprehensive analysis of seasonal and hourly fluctuations in daylighting inside patient rooms. Importantly, it provides detailed insights into exploring the impact of design characteristics on the presence and quality of rhythmic daylight patterns and how these patterns strongly affect patients' circadian health. This deepens our understanding of the optimal quality of daylight required in hospital settings. However, limitations must be acknowledged, such as the study's focus on a single geographic location, as well as the challenges associated with data collection methodologies, particularly those related to patient health outcomes. Future research efforts should aim to examine a broader range of site variations and the relationship between rhythmic daylight exposure and patient health outcomes, enhancing our understanding of the implications of circadian daylighting design in healthcare settings. Ultimately, these findings align with the established principles in the literature, emphasizing the importance of window size, area, positioning, and orientation in achieving optimal daylight conditions. Aligning with the principles of this research on healthy rhythmic daylight design in healthcare environments, Akande (2021) posits that for optimal health outcomes, building design must integrate key elements such as strategic orientation for natural daylight capture, thoughtful fenestration placement, effective shading to prevent overheating, and the incorporation of landscaping. With these insights, healthcare architects and designers can create environments that not only facilitate healing but also promote overall circadian health. This paves the way for further research into the synergistic role of the rhythmic natural light cycle in improving patient care outcomes. However, this study provides more detailed data on specific room conditions and seasonal and hourly variations, in addition to the rhythmic daylight pattern, offering a comprehensive understanding of the quality of healthy rhythmic daylighting in patient rooms.

6. Conclusion

This research employs simulation techniques to investigate and evaluate the existence of rhythmic daylight in patients' rooms in KAUH. Specifically, it studies how window design might affect the natural light and rhythmic pattern. This research emphasizes the importance of incorporating rhythmic daylight in healthcare environments, particularly in patients' rooms, in order to enhance well-being and promote healing. The analysis revealed that the studied patient rooms often fall short in providing optimized daylight design, which does not adequately support the natural circadian rhythms essential for patient recovery and well-being. While Room 3 showed some potential, all rooms require significant improvements to meet the recommended levels of daylight illuminance, color temperature, daylight factor, daylight availability, and the M/P ratio.

The study's findings emphasize the need for innovative architectural design strategies that prioritize incorporating rhythmic daylight into the patients' rooms. These strategies should include increasing the window-to-wall ratios, redesigning openings, using adjustable blinds or curtains, employing high-performing glazing materials, and employing daylight redirection techniques to improve daylight distribution. Additionally, optimizing the orientation and design of windows can help create a more dynamic lighting environment that better mimics the natural rhythmic patterns of daylight.

Future research should explore advanced design strategies that integrate rhythmic daylight into patient rooms, as supported by both this study and current literature. The findings highlight the need for a shift in healthcare facility design, moving beyond static lighting solutions toward dynamic daylight systems that align with patients' circadian rhythms. Such an approach can enhance patient comfort, improve mood, and support faster recovery. Future investigations should focus on optimizing key architectural variables, including window orientation, size, spatial layout, and exposure to dynamic natural light. By embedding these considerations into the design process, healthcare environments can become more therapeutic, ultimately promoting better health outcomes.

Declaration of interests

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

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