Exploring the Impact of Spatial Factors on Circadian Daylight Distribution

Neda Ghaeili[1]
Julian Wang[1 *]
Shevvaa Beiglary[1]
Ying-Ling Jao[2]

1. Department of Architectural Engineering, Pennsylvania State University
2. Ross and Carol Nese College of Nursing, Pennsylvania State University

* Corresponding author

https://doi.org/10.52202/077496-0015

Abstract

Lighting strongly influences indoor well-being, yet existing metrics like "Daylight Autonomy" and "Annual Solar Exposure" overlook circadian light. Research highlights circadian light's significant impact on human performance, creating a need to explore spatial factors affecting its distribution. This study examines the influence of surface reflectance, proximity to windows, windows' optical properties, and gaze direction on circadian light. Using the Lark Plugin for Grasshopper, simulations were conducted in a box-model room with ten glazing systems varying in visible transmittance. The results show that windows with a visible transmittance below 0.3 fail to provide adequate circadian light unless the gaze is perpendicular. Among surface reflectance factors, wall reflectance proved more critical than ceiling reflectance in optimizing circadian light exposure.

Keywords: circadian light, spatial factors, window, wellbeing, daylight

1. Introduction

The impact of circadian light on the well-being of humans has been recently recognized. Several studies have investigated the effects of circadian light on human well-being, highlighting its significance and the consequences of insufficient exposure. For instance, some researchers have noted that circadian rhythm sleep-wake disorders are common in people suffering from mental disorders and that lighting therapy can help regulate this disorder (Blume, Garbazza, & Spitschan, 2019). Other research has proven that circadian cycles govern cellular functions and tissue processes by regulating gene expression and protein interactions (Grey & Koeffler , 2007). Disruption of these cycles may influence cancer susceptibility, highlighting the importance of circadian genes in tumor suppression. The impact of natural light on cognitive performance, physical activity, and alertness in students and workers has been discussed in the study (Shishegar & Boubekri, 2016). The study was done by Jao et al. (2022) also indicated that the ambient indoor lighting condition has positive influences on behavioral and psychological symptoms in people with dementia (Jao, et al., 2022). It is evident that indoor lighting is crucial for human well-being, given that Americans spend approximately 90% of their time indoors (Dodge, Daly, Huyton, & Sanders, 2012).

The intensity and duration of circadian daylight exposure received indoors depend on several factors, as outlined by Ghaeili, Ardabili et al. (2023). These factors encompass four key nodes:

- Node 1: Daylight source
- Node 2: Optical and morphological characteristics of windows
- Node 3: Optical properties of interior spaces

- Node 4: Occupant posture and gaze direction

Nodes 1 and 4 represent factors beyond the direct control of engineers and architects. However, for Node 2, in the context of glazing performance, optical characteristics encompass light transmittance, reflectance, and absorption, while morphological characteristics involve physical attributes such as window size, design, and glazing configuration. Node 3, on the other hand, emphasizes the importance of indoor surface light reflectance. Consequently, it is essential for professionals to thoroughly address all relevant aspects of Nodes 2 and 3 to effectively mitigate potential challenges posed by Nodes 1 and 4 in worst-case scenarios.

Regarding Node 2, various studies have examined this node from different perspectives. In most studies concerning the optical properties of windows, spectral transmittance has been the primary focus. For example, a study found no linear correlation between circadian stimulus and circadian light transmittance (Hraska, 2015). Similarly, others have suggested that windows could effectively meet indoor health standards for glazing systems with a visible transmittance (Tvis) above 0.5 (Ghaeili, Beiglary, Wang, & Jao, 2023). For glazing with Tvis below 0.5, spectral transmittance weighted by circadian sensitivity provides a precise assessment of window performance.

On the other hand, architectural factors such as window-to-wall ratio (WWR), window orientation, and shading have been studied regarding the morphological properties of windows. For instance, some researchers have found that north windows require a higher WWR than south ones (Zeng, Sun, & Lin, 2021). Additionally, others noted that north-facing windows are less affected by changes in sky type compared to south-facing windows (Song, Jiang, & Cui, 2022). Concerning the impact of shading systems, research suggests that as long as the shading system does not obstruct the view of the sky from the window, it does not significantly impact the circadian performance of windows (Altenberg Vaz & Inanici, 2019). These studies focus on Node 2, and they all confirm that the impact of these variables is not independent; instead, there is an interconnected correlation among the variables that also affect the level of transmitted circadian light.

As noted elsewhere, a similar interconnected correlation exists among the parameters of Node 3 and Node 4, ultimately influencing the occupants' exposure to circadian light within a room (Ghaeili Ardabili, Wang, & Wang, 2023). Node 3, which examines interior architecture, surface reflectance, and spatial distance from the window, contributes to the fluctuation in the level and intensity of circadian daylight. Similarly, factors such as gaze direction and cornea height from Node 4 also impact the amount of exposure to circadian light. For instance, a study has demonstrated that when the gaze direction faces the window, there is a more significant reduction in circadian light as the distance from the window increases (Konis, 2018). Conversely, when the gaze is away from the window, there is less fluctuation in the reduction of circadian light exposure. Research indicates that wall reflectance is a key factor in determining exposure to circadian light

https://doi.org/10.52202/077496-0015

(Potočnik & Košir, 2021).This is not the case when the observer's gaze is perpendicular to the window.

This study aimed to explore the correlation between gaze direction, distance from the window, interior surface reflectance, and window Tvis. To achieve this, we utilized a box-modeled room simulated in Rhino, and the LARK plugin was employed to simulate various combinations of these variables. This approach allowed us to assess the impact of these variables and their correlation with circadian light exposure.

2. Methodology

This study involved the consideration of 10 windows selected from the International Glazing Data Base (IGDB), chosen based on their Tvis values. The objective was to select one glazing system from each 0.1 interval within the 0 to 1 Tvis range. The selected windows' spectral transmittance curves are presented in Fig. *1*.

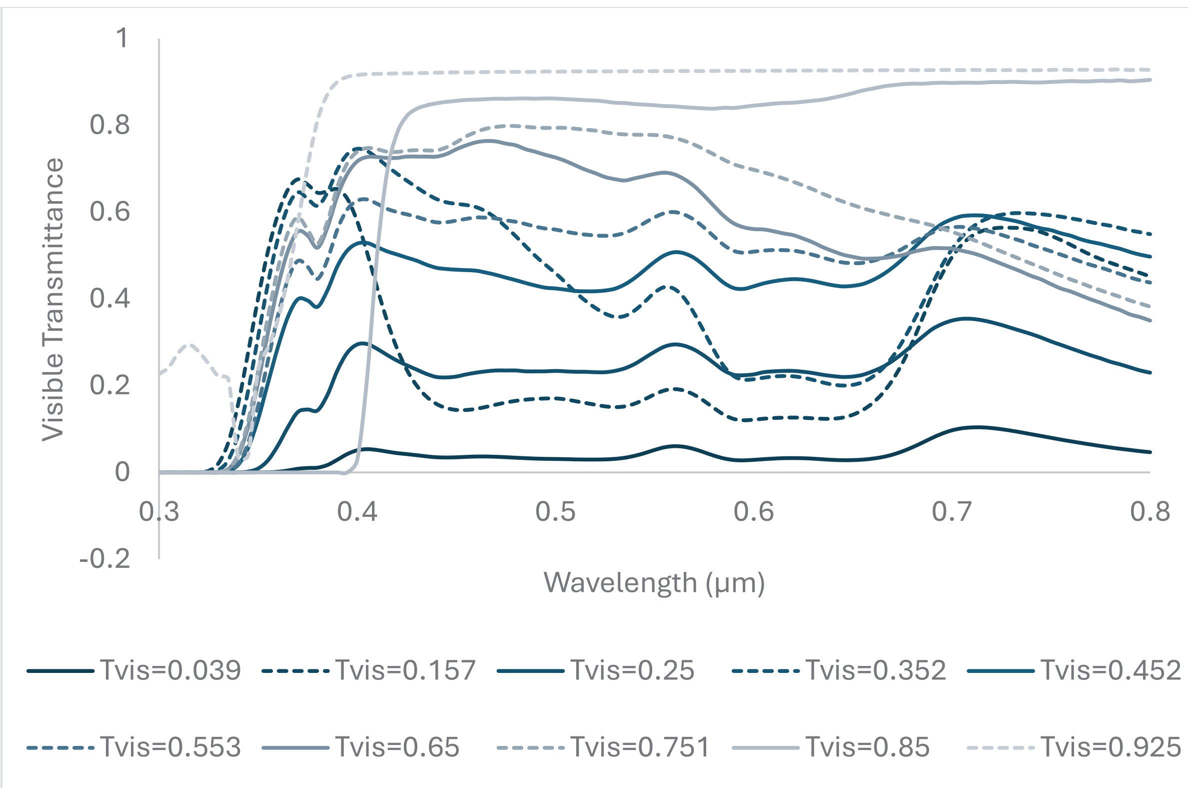


Fig. 1. Spectral transmittance of the selected glazings.

Regarding interior surface reflectance, ASHRAE recommendations were followed. The surface reflectance for ceilings ranged between 70% and 85%. For walls, it was between 50% and 70%. For floors, it was 20%. These ranges and values were also adopted for this research, with a 5% step interval for ceilings and a 10% step interval for walls to provide various scenario combinations.

This analysis was conducted using the LARK Plugin for Grasshopper. A box model measuring 7*7*3m^3 was used, with a window featuring a 30% WWR on the model's south façade. The simulation was conducted in ASHRAE climate zone 4 in Denver, Colorado. As part of our simulation, we considered the noon fall equinox.

A grid measuring six by six, spaced 0.5 m away from the room walls, was employed for simulation. Four gaze directions were considered at each point on the grid: perpendicular to the window, parallel to the window (facing west and east walls), and away from the window. These gaze directions are denoted as S, W, E, and N, respectively.

The grid consists of 36 points, numbered from 1 to 36, for ease of reference in the paper. Fig. *2* illustrates the location and designation of these points and the four-gaze directions.

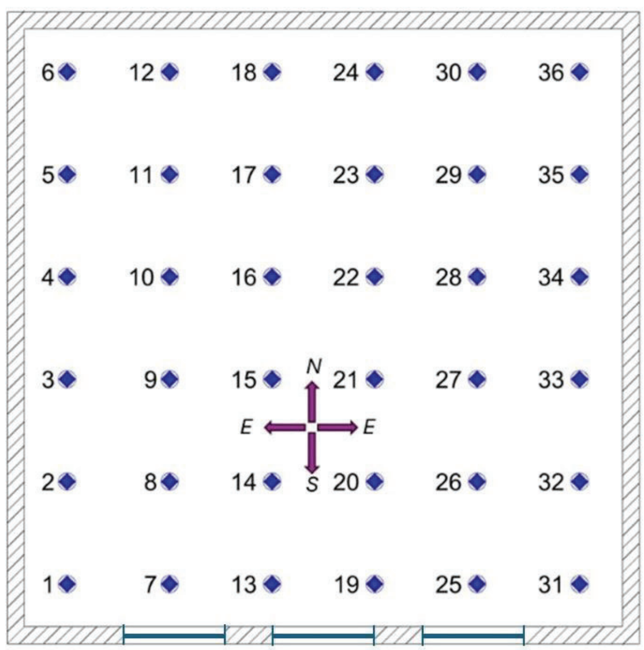


Fig. 2. Plan view: 36 sensors evenly spaced at 1m intervals in a 7×7m^2 room, 0.5m from walls.

3. Results

The level of circadian light, represented by m_EDI (melanopic Equivalent Daylight Illuminance), was simulated for each point on the sensor grid and across four gaze

https://doi.org/10.52202/077496-0015

directions by adjusting wall and ceiling reflectance and window visible transmittance. The simulated values were analyzed using a decision tree regression to assess the impact of each variable on m_EDI levels. The decision tree predicts m_EDI by iteratively splitting the data into smaller subsets based on the most significant feature at each step. It chooses the feature (such as wall reflectance, ceiling reflectance, or window transmittance) and a threshold value that best separates the data, reducing the variance of m_EDI within each new subset. By minimizing the variance, the tree ensures that the resulting subsets contain data points that are more similar in terms of their m_EDI values, leading to more accurate predictions. At each "split," the tree focuses on improving how well the model can predict m_EDI, ultimately breaking the data into groups that best explain the relationship between the variables and circadian light levels.

As depicted in Fig. *3*, the gaze direction is the most influential parameter, followed by Tvis, in determining the condition of whether the space meets the required m_EDI levels. In cases where the gaze direction is perpendicular to the window, regardless of Tvis value, exposure exceeds the 250 melanopic lux standard established by the WELL Building Standard (Circadian Lighting Design, 2022). However, if the gaze direction deviates from the perpendicular and Tvis falls below 0.301, circadian light exposure is below the threshold at 86.4 Lux.

Moreover, for points numbered above 30 that are positioned adjacent to the wall, a gaze direction parallel to the window facing the west wall yields higher circadian light compared to other directions. This may be due to the wall's obstruction of the south gaze direction, which makes the west direction a superior option. For finer adjustments, considering a southwest direction may offer even better results.

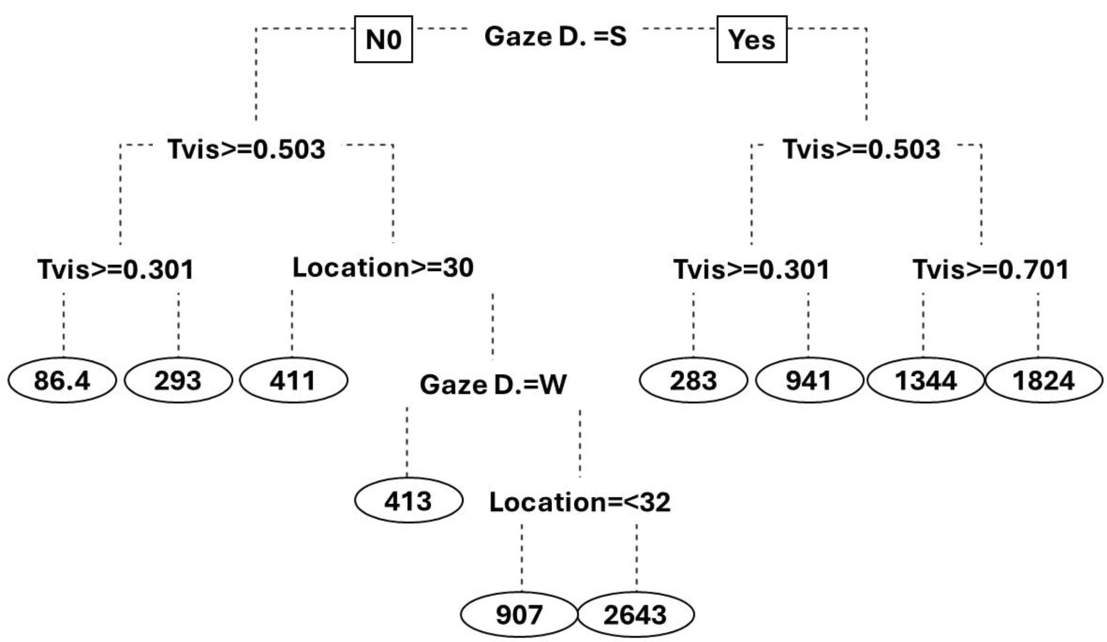
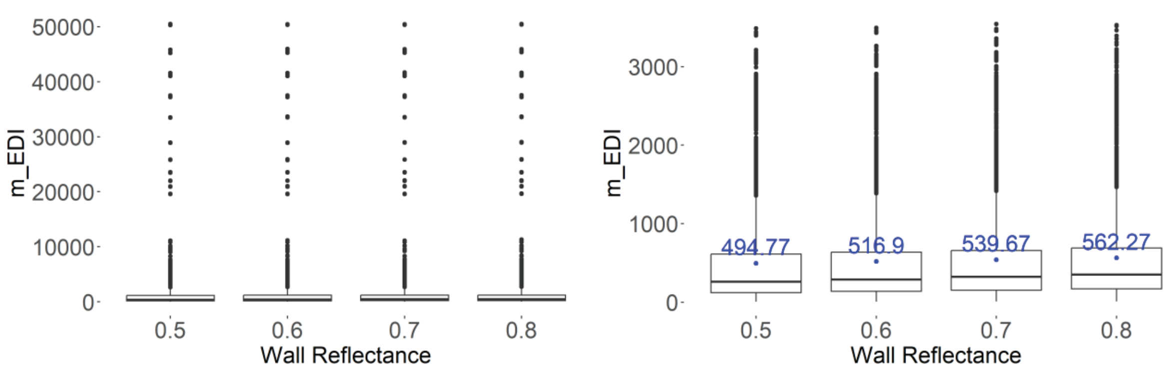


Fig. 3. Using Decision Tree Regression to assess the influence of variables on the level of m_EDI.

Since surface reflectance did not appear in the decision tree plot, it indicates that surface reflectance has a minimal effect on the amount of m_EDI. To provide a clearer understanding of m_EDI variations across different wall and ceiling reflectance groups, side-by-side box plots were generated. Figures 4a and 4c show that the impact of surface reflectance on m_EDI distribution is limited, and there are a series of outliers. Most outliers in the upper whisker of the plot are due to sensor points located in rows adjacent to the window. Consequently, data from the first three rows of the sensor grid were excluded to analyze further and check the impact of surface reflectance on circadian light in the deeper part of the room.

In Figures 4b and 4d, despite removing the first three rows, some outlier data points remain, especially when looking directly at the window. However, the reflectance of the walls becomes a significant factor in various scenarios, such as in areas far from the window and when the gaze direction is not perpendicular. A notable trend indicates that for every 10% increase in wall surface reflectance, there is approximately a 9% increase in m_EDI levels. In contrast, ceiling reflectance exhibits less pronounced effects on m_EDI levels.

Table 1 presents a more detailed examination of the impact of surface reflectance variation on the second half of the room.



[a] [b]

 https://doi.org/10.52202/077496-0015

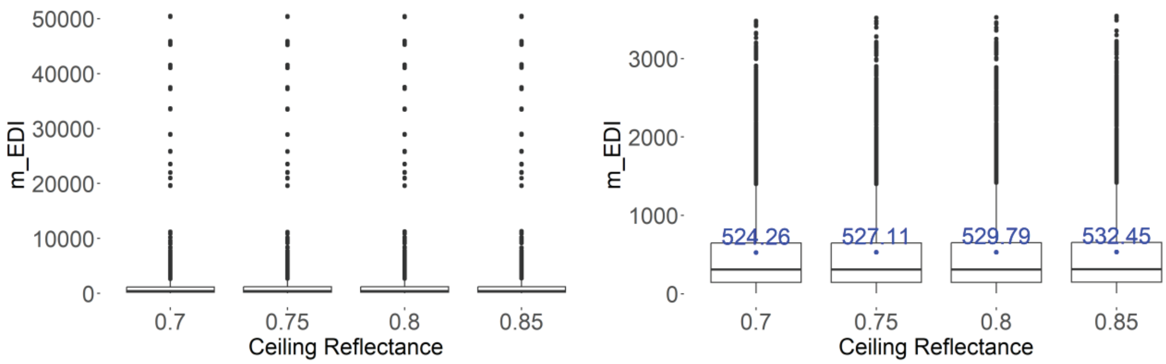


Fig. 4. The m_EDI values distribution for different sensor points in simulation grids: a) all sensor points according to the wall reflectance, b) 18 sensor points in the second half of the room according to the wall reflectance, c) all sensor points according to the ceiling reflectance, d) 18 sensor points in the second half of the room according to the ceiling reflectance.

Table 1. Summary statistics of m_EDI by surface reflectance

Surface conditions		**m-EDI values**			**Percentage variance (relative to lowest reflectance)**
Type	Reflectance	Mean	Std Dev	Variance	
Wall	50%	494.7713	601.8083	362173.2	-
	60%	516.8984	603.9540	364760.5	4.47
	70%	539.6673	607.9916	369653.8	9.07
	80%	562.2699	611.9694	374506.6	13.64
Ceiling	70%	524.2582	602.5969	363123.0	-
	75%	527.1096	605.3231	366416.0	0.54
	80%	529.7859	608.8238	370666.4	1.05
	85%	532.4531	611.0561	373389.5	1.56

The decision tree classification assessed the importance of various spatial variables, focusing on room depth and its influence on circadian light distribution. The analysis concentrated on the second half of the room, applying a 250 melanopic lux threshold to categorize data. Measurements below this threshold were labeled as 0 (insufficient light), and those equal to or above were labeled 1 (sufficient light). The decision tree plot visually distinguished these categories, with white nodes representing sufficient light and black nodes indicating insufficient light. Node percentages indicated how conditions met the threshold; for instance, 90.78% of cases with Tvis above 0.301 and a gaze direction of east, south, or west met the 250 lux threshold.

https://doi.org/10.52202/077496-0015

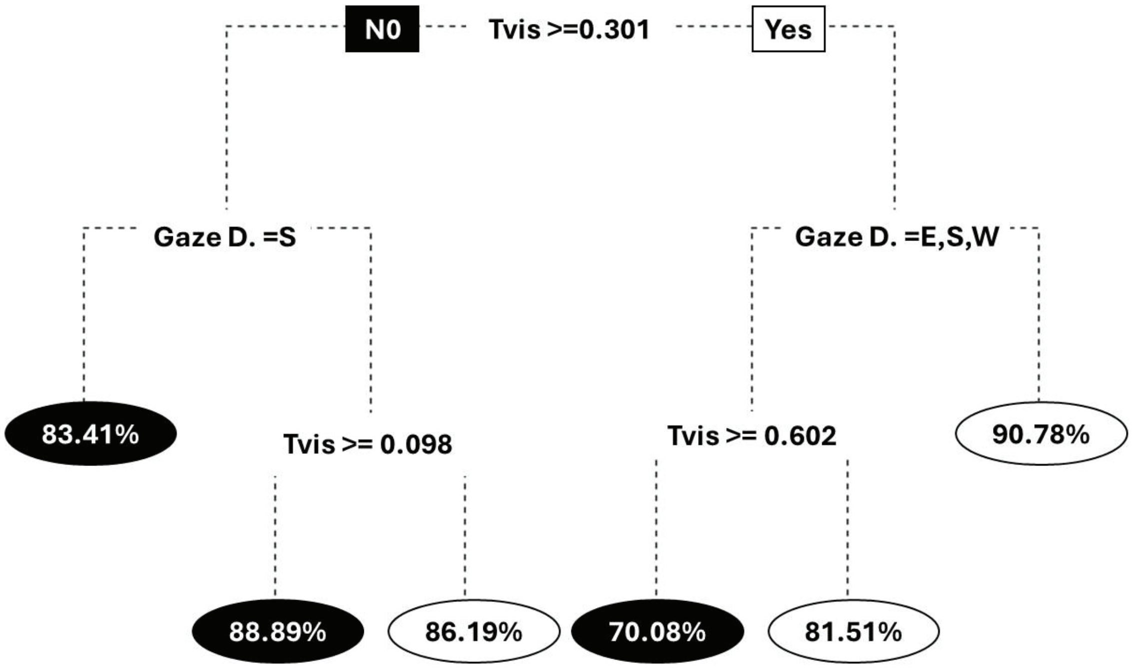


Fig. 5. Using Decision Tree Classification to assess the influence of variables on the level of m_EDI in the second half of the room.

As illustrated in Fig. *5*, Tvis emerges as the most influential variable. In 83.41% of instances where Tvis falls below 0.301, and the gaze direction is non-perpendicular to the window, the exposure to circadian light remains below 250 Lux. Furthermore, when the gaze direction is away from the window, and Tvis exceeds 0.602, the threshold is met in 81.51% of cases. Furthermore, for cases where Tvis is above 0.301, and the gaze direction is not opposite the window, the windows meet the threshold for 90.78% of cases.

4. Conclusion

The exploration of circadian daylight encompasses a multitude of interconnected parameters, reflecting the complexity of indoor circadian lighting dynamics. There is an urgent need for a standardized metric to measure indoor circadian light distribution and ensure healthy indoor environments. This study simulated circadian light exposure levels within a room using a limited set of glazing samples and varying wall and ceiling reflectance.

Our research underscores the significance of gaze direction and window transmittance as essential variables in circadian light distribution. While a previous study has questioned the accuracy of Tvis in assessing circadian performance, our focus was to ascertain the predictive capability of existing properties in this research (Ghaeili, Beiglary, Wang, & Jao, 2023).

https://doi.org/10.52202/077496-0015

Wall reflectance emerged as a noteworthy factor, particularly in the deeper areas of the room, although Tvis and gaze direction overshadowed its impact. Acknowledging that these findings may evolve in more extensive and deeper spaces is important. This highlights the need for ongoing research to comprehensively understand and optimize circadian lighting in indoor environments.

Conflict of Interest

This research was supported by the National Institutes of Health/National Institute of Aging (#1R21AG078544-01) for 'The Effect of Smart Ambient Bright Light for Nursing Home Residents with Alzheimer's Disease and Related Dementias,' and by the National Science Foundation (#2001207 CAREER) for 'Understanding the Thermal and Optical Behaviors of Near Infrared (NIR)-Selective Dynamic Glazing Structures.' All authors declare no conflicts of interest.

References

Altenberg Vaz, N., & Inanici, M. (2019). Syncing with the sky: daylight-driven circadian lighting design. *LEUKOS: The Journal of the Illuminating Engineering Society*, 291-309.

Blume, C., Garbazza, C., & Spitschan, M. (2019). Effects of light on human circadian rhythms, sleep and mood. *Somnologie*, 147-156.

Circadian Lighting Design. (2022). https://v2.wellcertified.com/en/wellv2/light/feature/3

Dodge, R., Daly, A., Huyton, J., & Sanders, L. (2012). The challenge of defining wellbeing. *Int. J. Wellbeing*.

Ghaeili Ardabili, N., Wang, J., & Wang , N. (2023). A systematic literature review: Building window's influence on indoor circadian health. *Renewable and Sustainable Energy Reviews.*

Ghaeili, N., Beiglary, S., Wang, J., & Jao, Y. (2023). Assessment of the window performance from the light provision and circadian light aspects. *Proceedings of the 52nd American Solar Energy Society National Solar Conference 2023* (pp. 43-51).

Grey, S., & Koeffler, H. (2007). The role of circadian regulation in cancer. *Cold Spring Harbor Laboratory Press, 72*, 459-464.

Hraska, J. (2015). Chronobiological aspects of green buildings daylighting. *Renewable Energy*, 109-114. doi:http://dx.doi.org/10.1016/j.renene.2014.06.008

https://doi.org/10.52202/077496-0015

Jao, Y.-L., Wang, J., Liao, Y.-J., Parajuli, J., Berish, D., Boltz , M., Calkins, M. (2022). Effect of ambient bright light on behavioral and psychological symptoms in people with dementia: a systematic review. *Innov Aging*. doi: 10.1093/geroni/igac018.

Konis, K. (2018). Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities. *Building and Environment*, 112-123.

Potočnik, J., & Košir, M. (2021). Influence of geometrical and optical building parameters on the circadian daylighting of an office. *Journal of Building Engineering*.

Shishegar, N., & Boubekri , M. (2016). Natural light and productivity: analyzing the impacts of daylighting on students' and workers' health and alertness. *Int'l Journal of Advances in Chemical Engineering & Biological Sciences (IJACEBS)*.

Song, H., Jiang, W., & Cui, P. (2022). A study on nonvisual effects of natural light environment in a maternity ward of a hospital in cold area. *BioMed Research International*.

Zeng, Y., Sun, H., & Lin, B. (2021). Optimized lighting energy consumption for non-visual effects: A case study in office spaces based on field test and simulation. *Building and Environment*.