Evaluation of visual and non-visual effects of daylighting in healthcare patient rooms using climate-based daylight metrics and melanopic metrics

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Abstract

Daylight access in healthcare facilities is essential for creating comfortable ambiance conditions for the patients during their accommodation in a hospital. The aim of this paper is to investigate how the window size, the location (Paralimni in Cyprus and Brussels in Belgium), the room orientation and patients' gaze direction have an impact on visual and non-visual effects. This research focuses on hospitals' most typical patient room: the double room (3.50m * 5.50m). The building parameters under study are eight orientations and three window sizes. Moreover, other parameters are the timing (season and hour in a day), the patient placement inside the room, and the patient gaze directions. For this study, computer simulations are used for daylight assessment using climate-based daylight metrics and CIE S026 melanopic metrics for non-visual effects. Research findings show that it is possible to examine design options through a comprehensive investigation of climate-based daylight metrics and CIE S 026 melanopic metrics for optimised performance for visual and non-visual effects.

Introduction

It is widely known that in the 21st century, people are spending about 90% of their time in indoor environments. (World Health Organization, 2014) The COVID-19 pandemic has shown the significant impact that indoor environments play on the health and well-being of people. (Gloster *et al*., 2020)(D'alessandro et al., 2020) Due to the emerging concerns for people's health and well-being during lockdown periods, some studies focused on window views of the external environment and the psychological impact of confinement in indoor spaces. (Batool et al., 2021)

Moreover, there is an increased research interest in studying how buildings affect human physiology and psychology. With the WELL Building Standard publication, more architects and designers have used those guidelines for healthier buildings. (*The WELL Building Standard V1*, 2014) Furthermore, studies show some of the essential points for healthy houses, including the availability of good air quality, daylight, and exposure to sunlight, while also presenting 'five ways to well-being'. (Baker & Steemers, 2019) Overall, more research focuses on the impact of daylight and sunlight since this is known to be the main 'zeitgeber' for human circadian rhythm.

Background

Daylight performance in buildings

Daylighting has been studied mainly in office buildings and educational facilities. Boubekri et al. (2014) studied the impact of daylight exposure on office workers' sleep quality and subjective well-being. They found that workers in spaces with higher daylighting levels had better overall sleep quality and longer sleep duration. Zomorodian & Tahsildoost (2019) used static and dynamic metrics to assess the visual comfort in educational buildings while also using questionnaires and field surveys. They observed a correlation between the Useful Daylight Illuminance metrics and the occupant responses. Michael & Heracleous, (2017) investigated the daylighting conditions in schools in Cyprus and proposed design strategies that could improve the visual comfort of students such as shading devices and blinds. Overall, studies in office and educational buildings show the importance of good daylighting performance and the impact on occupants.

A study by Joarder and Price (2013) used field studies and statistical methods to show that when patients in hospitals are exposed to daylight, it could reduce their length of stay. Moreover, a study by Walch et al. (2005) associated the exposure of patients to natural sunlight with improved mood, reduced mortality, and reduced length of hospitalisation. At the same time, the use of analgesic medications was reduced; hence the medication costs were also reduced. Studies on daylight access in hospitals show the impact on patients' health; however, more studies are needed to evaluate the daylight performance in healthcare facilities compared to building design parameters. Previous studies by the authors investigated natural lighting performance in healthcare facilities for typical hospital rooms, various window-to-wall ratios, building orientations, glazing visible transmittance, and implementation of shading devices. Those studies used static and dynamic metrics to evaluate patients' visual comfort. (Englezou & Michael, 2018) (Englezou & Michael, 2021) Shading devices have improved daylight performance in the South orientation and, more importantly, when the window-to-wall ratio is more than 35%. (Englezou & Michael, 2020)

For the purposes of daylighting assessments in healthcare facilities LEED proposes the use of annual metrics, Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE), based on the methodology of the LM-83-12. (IESNA, 2012) The requirement for sDA is to have at least 75% or 90% of the room's area achieving a minimum of 300 lux for at least 50% of the occupied hours. In addition, ASE, which presents the exposure to direct sunlight with more than 1000 lux for 250 hours per year, should not be more than 10% of the room's area. Moreover, LEED proposes to analyse illuminance levels using static metrics and skies with a minimum limit of 300 lux and a maximum of 3000 lux. (USGBC, 2019) BREEAM also proposes guidelines for daylight assessment, suggesting using static metrics and CIE skies. (BRREAM, 2016) Climate-based metrics have been widely used in the last decades since they use climatic data from weather files.

Evaluation and measurement of non-visual effects of lighting

Since discovering the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs) in the mammalian retina, more research has focused on the non-visual effects of lighting. The ipRGCs cells contain a photopigment called 'melanopsin' which is sensitive to short-wavelength light. (Berson, 2007) Various studies used as markers the melatonin response, pupil constriction, and circadian phase-shifts under various lighting conditions to identify the sensitivity of melanopsin. (Thapan et al., 2001) (Brainard et al., 2001) Based on those studies, it was found that the peak sensitivity for the melanopsin response is at the short-wavelength part of the visible spectrum, around 459nm up to 498nm, and a spectral sensitivity curve was designed. (Lucas et al., 2014) Lucas *et al.* (2014) proposed using metrics calculated based on the spectral sensitivity function of each of the five photoreceptors in the mammalian retina. The Commission Internationale de l'Éclairage (CIE) adopted this method and published the CIE S026:2018 standard for the metrology of the optical radiation of the ipRGCs. (Commission International de l'Éclairage, 2018) It should be noted that the difference between the two methodologies is that the method proposed by Lucas *et al*. uses an equi-energy source illuminant while the CIE method uses the CIE standard illuminant D65.

The increased interest in this interdisciplinary field and lighting assessments focusing on the non-visual effects have raised awareness of having a standard template for different research approaches. (de Kort, 2019) (Commission International de l'Éclairage, 2020) Parameters considered essential for such studies include environmental factors such as seasonality, timing, location, weather patterns, and other person-related factors such as chronotype, age, eye photosensitivities, and more. Finally, it is advised to include information about the light source, intensity, timing, duration of exposure, and spectral properties.

Brown *et al.* (2022) have proposed recommendations for providing proper light at the proper time. More specifically, based on the metrics proposed by the CIE, they recommend having a melanopic EDI of at least 250 lux throughout the day. (Brown et al., 2022). For evening hours, the recommendation is to have a melanopic EDI of 10 lux for at least three hours before bedtime and a melanopic EDI of no more than 1 lux during the sleeping period. Moreover, the certification scheme WELL building standard proposes guidelines for circadian lighting for daylight and electric lighting. (*The WELL Building Standard V1*, 2014)

Research by Kenny P. (2021) investigated the variability of real sky conditions' intensity and spectral properties and the impact of design parameters such as color finishes using circadian and melanopic metrics. More research is needed to understand if there are any intersections between using static or dynamic metrics for daylight assessments for visual effects and using melanopic metrics for the non-visual effects of daylighting.

Methodology

This study evaluates natural lighting performance in a typical hospital patient room (3.50m*5.50m), as seen in figure 1. Three different window-to-wall ratios and eight orientations (South, North, East, West, South-East, South-West, North-East, North-West) are under study. In addition, the analysis includes an investigation of two locations; Brussels in Belgium (Lat. 50.85° N, Long. 4.36° E) and Paralimni in Cyprus (Lat. 35.05° N, Long. 33.99° E). For this study, computer simulations are carried out using climate-based daylight metrics for the visual effects and CIE S026 melanopic metrics for the non-visual effects.

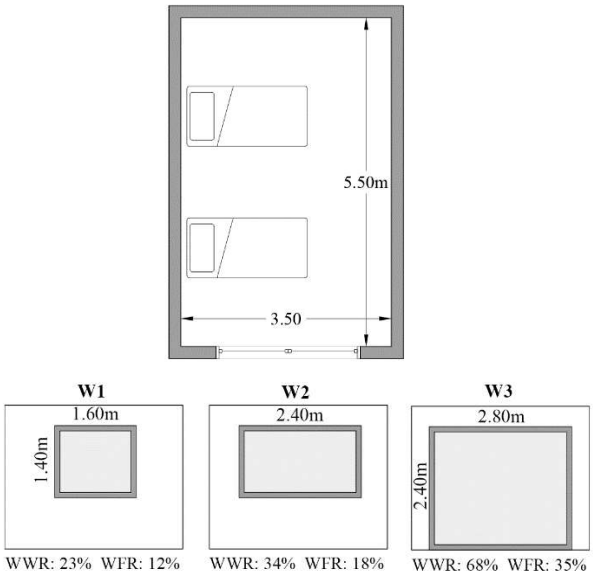

*Figure 1. Plan view of the typical hospital patient room (3.50m*5.50m) and the three window-to-wall ratios (W1-23%, W2-34%, W3-68%)*

Computer simulations for climate-based daylight metrics

The investigation of daylight performance for the visual effects was carried out using computer simulations. For the purposes of this study, the software Climate Studio version 1.7.8 in Rhinoceros 7 was used, which implements the Radiance simulation engine. Radiance uses a backward ray-tracing method to calculate the contribution to lighting levels. Dynamic metrics, also known as climate-based daylight metrics, were used to evaluate daylight performance since these metrics use the climatic data of solar irradiance for calculations. The dynamic metrics used are the Useful Daylight Illuminance (four categories), the Spatial Daylight Autonomy, and the Annual Sunlight Exposure. The 3D models for the rooms were designed as shown in figure 1. The simulations were carried out using weather files of Typical Meteorological Year for the locations of Paralimni and Brussels. The visible transmittance for the glazing was set to 70% for a double glazing window. The working plane height was set at 0.85m above the finished floor level, the usual height of a patient's bed. The Radiance parameters used for the simulations are shown in Table 1, and the surface reflectances for the walls, ceiling, and floor are shown in Table 2. Calculations for climate-based daylight metrics were done for a total of 48 case studies to examine the daylight performance of the spaces.

Table 1. Simulation Parameters used in software Climate Studio and ALFA

Software	Ambient bounces (-ab)	Limit weight (-lw)	Ambient divisions (-ad)
Climate Studio	6	0.0001	1
ALFA	6	0.000001	-

Table 2 Properties of surface reflectances used in the software Climate Studio and ALFA

	Reflectance	Specular	Roughness
Wall	80%	0.40%	0.20
Ceiling	82%	0.45%	0.20
Floor	20%	1.25%	0.20
Window frame	44%	2.95%	0.10
External Ground	18%	0.25%	0.20

Computer simulations for melanopic metrics

Additional computer simulations were carried out for the non-visual effects of daylighting conditions using the ALFA software in Rhinoceros 7. The ALFA software uses the Radiance simulation engine with 81-colour spectra channels for spectral calculations using different types of skies. (*ALFA - Solemma*, 2022) The spectral properties of skies were precomputed using the libradtran library, which is used for radiative transfer calculations. (Emde et al., 2016) Two studies have evaluated the software ALFA in terms of validation methods using the values of spectral irradiance from field measurements and simulations. (Pierson et al., n.d.)(Balakrishnan & J.Jakubiec, 2020) These studies showed that the ALFA software could have relative errors of less than 30% when building geometries, outdoor environment, and more are accurately modelled. However, simulation software for non-visual effects still have some limitations which can not be avoided at the moment.

For this study, only the Clear and Overcast skies were used to evaluate the brightest and darkest daylighting conditions for the two locations in three seasons (December 21st, June 21st, March 21st) and five hours during each day (7 a.m., 9 a.m., 12 p.m., 3 p.m., 5 p.m.). Since the typical room under study is the double room, the investigation included four placements of the patient, and for each placement, three gaze directions were evaluated, as seen in figure 2. The height of the gaze directions was set at 1.30m above the finished floor level, which is the height of a seating person's eyes on a hospital bed. The same materials were used for the glazing (spectral characteristics for a clear glazing) and wall, ceiling, floor surfaces as in climate-based simulations. The parameters used for the simulations are shown in Table 1, and the surface reflectances are shown in Table 2. It should be noted that ALFA takes into account the spectral properties for the materials and glazing used as these were measured using a spectrophotometer. (*ALFA - Solemma*, 2022)

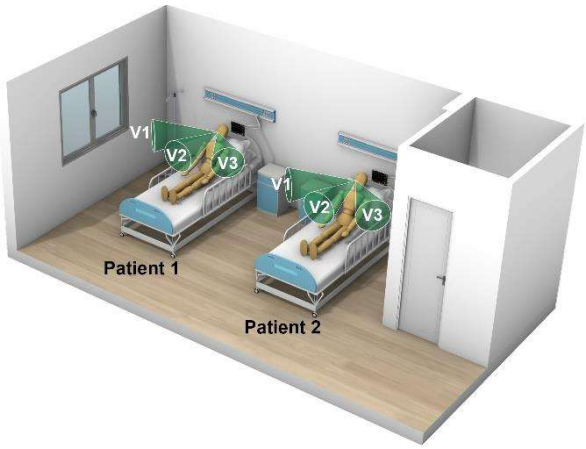

Figure 2. Patient placement in a patient double room and the three gaze directions

Calculations were done for a total of 10752 cases for the location of Paralimni and 9985 cases for the location of Brussels. Since the software calculates the Melanopic/Photopic ratio (M/P ratio) and the Equivalent Melanopic Lux (EML) by Lucas *et al.*, the results were converted to the metrics of melanopic DER and melanopic EDI, as seen in Equations (1) and (2). (CIE Central Bureau, 2021)

$$Melanopic\ EDI = 0.9058\ x\ EML \quad (1)$$

$$Melanopic\ DER = \frac{Melanopic\ EDI}{Photopic\ illuminance} \quad (2)$$

Results

Results for climate-based daylight metrics

Figure 3 shows the results of Useful Daylight Illuminance (UDI) for Brussels and Paralimni, the three window-to-wall ratios, and the eight orientations. The results are shown in four categories; UDI less than 100 lux, UDI from 100 to 300 lux, UDI from 300 to 3000 lux and UDI more than 3000 lux. The UDI from 300 to 3000 lux shows the percentage of the rooms' area with acceptable illuminance levels. It should be noted that the hours analysed are only the hours from sunrise until sunset for each location, a total of 4373 hours for Paralimni and 4388 for Brussels throughout a year.

Overall, Brussels and Paralimni have more than 58% for the category UDI 300-3000 lux for all the cases presented. It is evident that the fluctuations in this category are due to the orientation of the room. The North orientation in Brussels for W1 has 58% UDI 300-3000 lux, while the South orientation has 63%, and the West and East orientations have around 60%. When the window-to-wall ratio is bigger such as W3, the North orientation has 76% UDI 300-3000 lux while the South orientation has 58%, and the West and East orientations have about 65%. This is because when the window-to-wall ratio is small, the North orientation has a higher percentage of the UDI categories with less than 300 lux, meaning electric lighting is needed. On the contrary, with a higher window-to-wall ratio, the South orientation is more susceptible to direct sunlight; hence larger area near the window will have more than 3000 lux. Moreover, when comparing the results for the two locations, they are similar because the analysed hours are from sunrise to sunset for each location, while at the same time, the UDI is an annual dynamic metric that does not show the seasonal effect.

Figure 4 shows the results for Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). For most cases, the sDA is up to 100%, meaning that 100% of the room's area has 300 lux for more than 50% of the analysed hours. Furthermore, the ASE shows the percentage of the area with more than 1000 lux of direct sunlight. The LEED v4 certification scheme proposes to have a maximum of 10% of the rooms' area with more than 1000 lux for more than 250 hours per year. (USGBC, 2019) The findings show that the North orientation always has 0% of ASE for all the cases since direct sunlight exposure does not exceed the 250 hoursin a year. The North-East and North-West orientations have ASE of 1.76% and 3.53%, respectively, for the location of Brussels with W1, while for W3 the ASE goes up to 10% for both orientations. For Paralimni, the ASE is less than 10% only for the orientations North, North-East, and North-West for W1. The rest orientations have higher than 10% of ASE, which means that shading devices could be beneficial in reducing the glare probability or excessive solar heat gains.

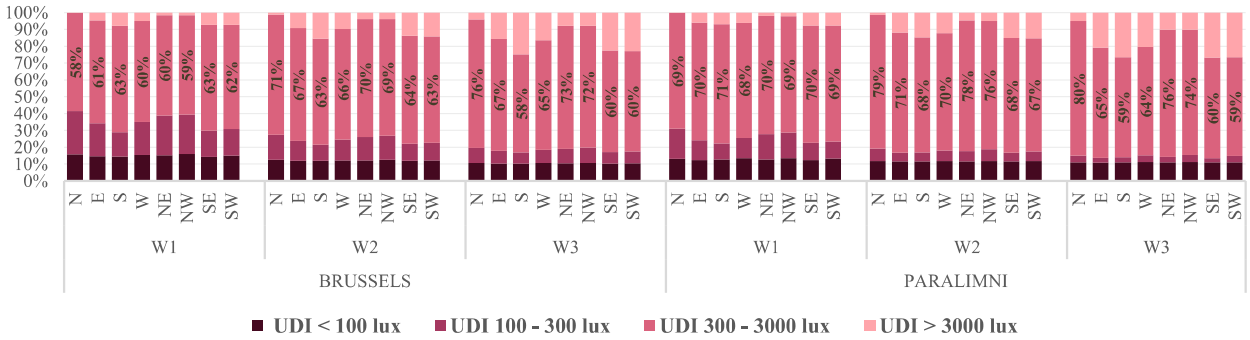

Figure 3. Useful Daylight Illluminance (four categories) for Brussels and Paralimni, the three window-to-wall ratios, and eight orientations.

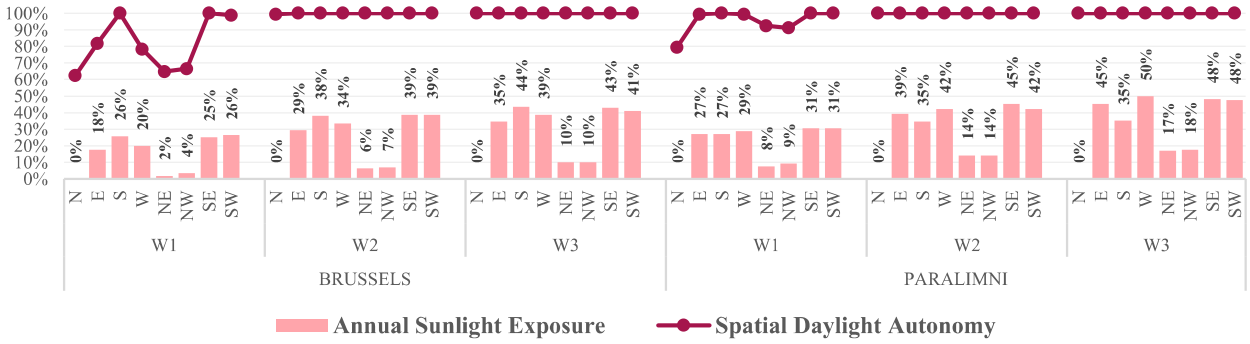

Figure 4. Spatial Daylight Autonomy and Annual Sunlight Exposure for Brussels and Paralimni, the three window-to-wall ratios, and eight orientations.

Results for melanopic DER and melanopic EDI

Figure 5 shows the results for the melanopic DER and the melanopic EDI for both locations, the three window-to-wall ratios, eight orientations, four patient placements and three gaze directions. The graphs show with a red dashed line the equivalent melanopic DER for the CIE standard illuminant D65 with a CCT of 6500K, and with a grey dashed line the minimum recommendation for a proper light during the daytime for comparison purposes. It is clear that there is a great variability for occasions with a clear sky with a melanopic DER ranging from 0.45 up to 1.22 and a melanopic EDI ranging from 10 lux up to 40000 lux depending on the time of the day, orientation, and more. On the other hand, the cases with an overcast sky seem to have a melanopic DER ranging from 0.8 up to 1.0 and melanopic EDI from 50 lux up to 10000 lux. However, some cases for 7 a.m. and 9 a.m. have a melanopic DER of more than 1.0 and a melanopic EDI of less than 250 lux, which is the recommendation for exposure during the day. For Clear sky, it is shown that the cases with melanopic EDI less than 250 lux are again during morning hours.

Figure 6 shows a histogram with the frequencies of melanopic DER for Brussels and Paralimni, comparing the two types of skies for each season (March, June, and December.

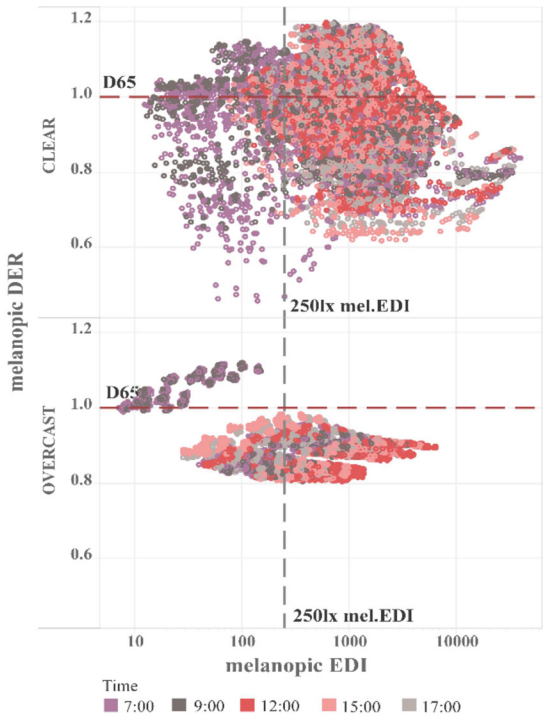

Figure 5. Melanopic DER and Melanopic EDI results for the locations of Brussels and Paralimni, the three window-to-wall ratios, eight orientations, patient placements, and gaze directions.

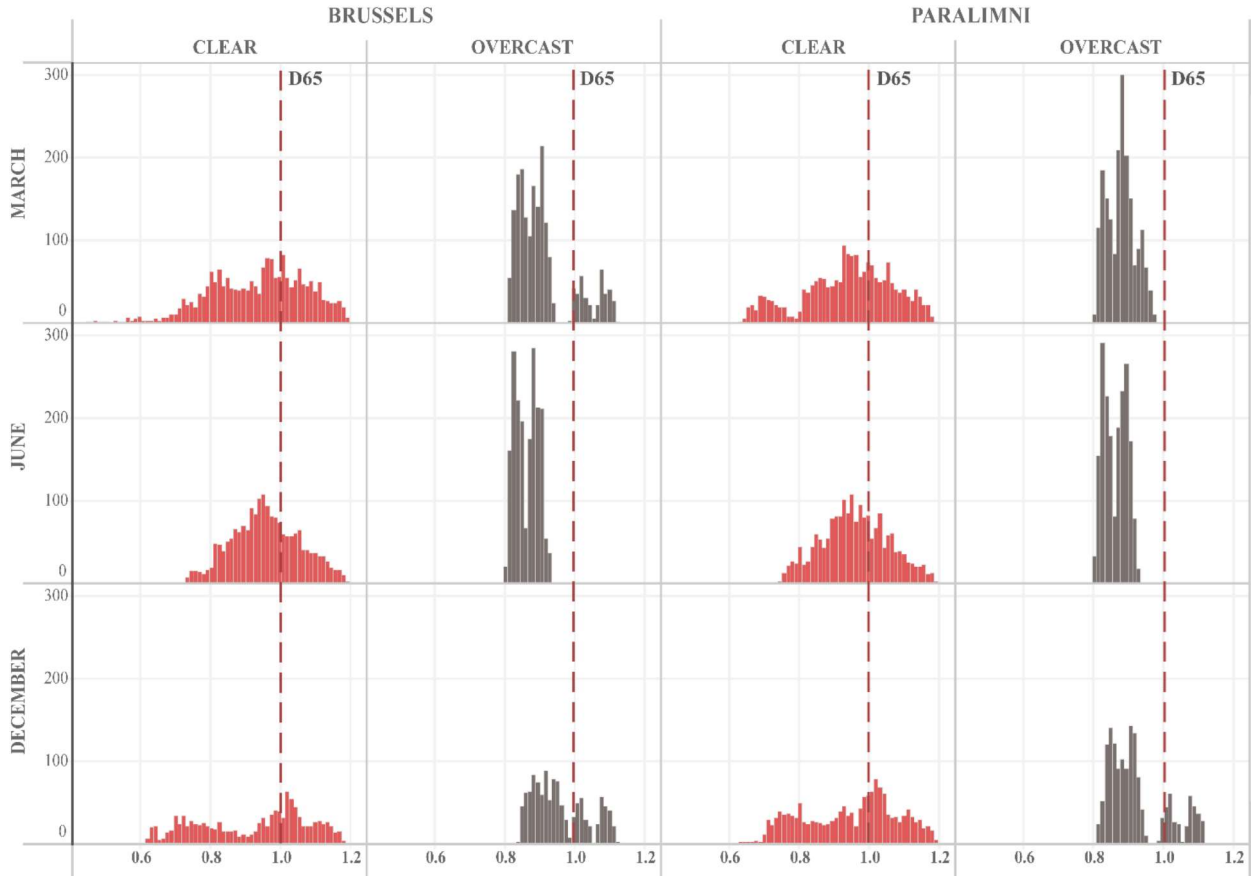

Figure 6. Comparing Melanopic DER results for the locations of Brussels and Paralimni. The data set includes results for the three window-to-wall ratios, eight orientations, four patient placements, and three gaze directions.

The findings for the clear sky in Brussels range from 0.47 up to 1.20 for March, 0.73 up to 1.20 for June, and 0.62 up to 1.20 for December. For Paralimni, the melanopic DER ranges from 0.64 up to 1.17 in March, 0.74 up to 1.20 in June, and 0.60 up to 1.20 in December. It seems that during March and mainly in December, the melanopic DER has higher variability due to the orientation and the low sun angles depending on the timing.

Moreover, the results for an overcast sky show higher frequencies with melanopic DER less than 1.0. More specifically, for Brussels in March, the melanopic DER ranges from 0.81 up to 1.11, in June from 0.80 up to 0.92, and in December from 0.83 up to 1.12. For Paralimni, the melanopic DER in March ranges from 0.80 up to 0.97, in June from 0.80 up to 0.92, and in December from 0.81 up to 1.11. It should be noted that the histogram presents three small clusters for occasions of an overcast sky during March and December in Brussels and during December in Paralimni, which have melanopic DER of more than 1.0 while melanopic EDI is less than 200 lux. These cases are for morning timings at 7 a.m. and 9 a.m., with low sun angles and low daylight intensities. Despite that, it is evident that with an overcast sky, not many occasions exceed a melanopic DER of more than 1.0, indicating a blue-enriched light source.

Figure 7 shows the results for the location of Paralimni only for a clear sky. The data are presented in a matrix to compare the effect of different window-to-wall ratios and the room orientation on the melanopic DER and melanopic EDI.

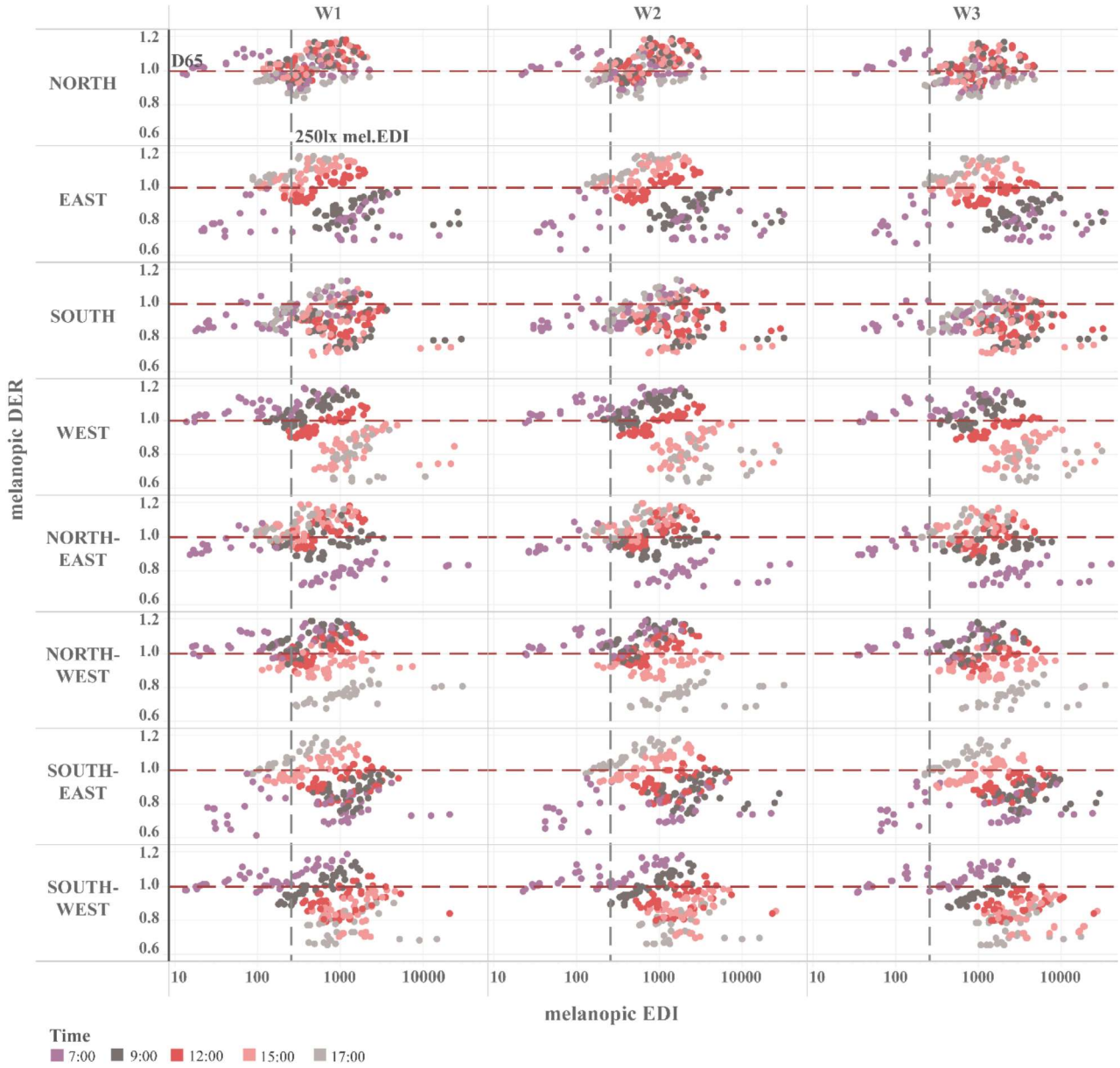

Figure 7. Comparing Melanopic DER and Melanopic EDI results for the location of Paralimni. The data set includes results for the three window-to-wall ratios, eight orientations, four patient placements, and three gaze directions.

The main parameters that affect the melanopic metrics are the orientation and the timing during the day. The window-to-wall ratio has an impact only for South, South-West, and South-East orientations, which have direct sunlight exposure, and the higher window-to-wall ratio increases even further the melanopic EDI. However, all the occasions with direct sunlight exposure have a melanopic DER less than 1.0.

When comparing the orientations for W1, it is shown that the North orientation has more than 70% of the cases with melanopic EDI of more than 250 lux and 57% of cases with melanopic DER of more than 1.0. The South orientation has 82% of cases with melanopic EDI more than 250 lux and 17% of cases with melanopic DER more than 1.0. The East orientation has 80% of cases with melanopic EDI more than 250 lux and 42% of cases with melanopic DER more than 1.0. The West orientation shows similar results to the East orientation, with some cases being reversed based on the timing during a day. Overall, it is clear that the melanopic DER and melanopic EDI are affected by the sun's position (altitude and azimuth) depending on the timing of the day; hence the results show differences for each room orientation.

Conclusion

This research investigated the daylight performance in a typical patient room in healthcare facilities focusing on the visual and non-visual effects of daylight. The study included parameters such as the window-to-wall ratio, orientation of the room, placement of the patient inside the room, patient gaze directions, and location. Overall, the results show that there are possibilities to achieve sufficient lighting levels inside the rooms while maintaining low possibilities for glare or solar heat gains. The North, North-East, and North-West orientations show the highest percentage in the UDI 300 – 3000 lux category and the lowest in UDI with more than 3000 lux and the ASE.

Moreover, the investigation of the melanopic DER and melanopic EDI show that the non-visual effects can be significantly influenced based on the orientation of the building and the timing of a day. In addition, the direct sunlight exposure inside a room seems to increase the melanopic EDI while at the same time producing a melanopic DER of less than 1.0. The weather conditions of the sky also significantly affect the melanopic EDI and melanopic DER for both locations. Depending on the orientation, North has more cases with melanopic DER higher than 1.0, which is related to more blue-enriched lighting, while at the same time, those cases have melanopic EDI of more than 250 lux. In addition, healthcare facilities operate 24 hours/day; hence proper lighting conditions should be provided with melanopic EDI less than 10 lux for 3 hours before the usual bedtime for patients and a melanopic EDI less than 1 lux during the evening.

In conclusion, it is impossible to directly correlate the climate-based and melanopic metrics to find the best optimisation techniques for improved visual and non-visual effects. However, this study shows that a comprehensive investigation of all those metrics can provide insights for achieving good results for visual and non-visual effects on patients.

Authors' contributions

M. Englezou performed the conceptualisation, methodology, computer simulations, formal analysis, investigation, data curation, visualisation, writing-original draft, writing-review, and editing. A. Michael performed reviews and supervision.

References

ALFA - Solemma. (2022). https://www.solemma.com/alfa

Baker, N., & Steemers, K. (2019). *Healthy Homes - Designing with light and air for sustainability and wellbeing* (1st ed.). RIBA Publishing.

Balakrishnan, P., & J.Jakubiec, A. (2020). Spectral Rendering with Daylight: A Comparison of Two Spectral Daylight Simulation Platforms. *Proceedings of Building Simulation 2019: 16th Conference of IBPSA*, *16*, 1191–1198. https://doi.org/10.26868/25222708.2019.211158

Batool, A., Rutherford, P., McGraw, P., Ledgeway, T., & Altomonte, S. (2021). Window Views: Difference of Perception during the COVID-19 Lockdown. *LEUKOS*, 1–11. https://doi.org/10.1080/15502724.2020.1854780

Berson, D. M. (2007). Phototransduction in ganglion-cell photoreceptors. *Pflugers Archiv European Journal of Physiology*, *454*(5), 849–855. https://doi.org/10.1007/s00424-007-0242-2

Boubekri, M., Cheung, I. N., Reid, K. J., Wang, C.-H. H., & Zee, P. C. (2014). Impact of windows and daylight exposure on overall health and sleep quality of office workers: A case-control pilot study. *Journal of Clinical Sleep Medicine*, *10*(6), 603–611. https://doi.org/10.5664/jcsm.3780

Brainard, G. C., Hanifin, J. P., Greeson, J. M., Byrne, B., Glickman, G., Gerner, E., & Rollag, M. D. (2001). Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor. *Journal of Neuroscience*, *21*(16), 6405–6412. https://doi.org/10.1523/jneurosci.21-16-06405.2001

Brown, T. M., Brainard, G. C., Cajochen, C., Czeisler, C. A., Hanifin, J. P., Lockley, S. W., Lucas, R. J., Münch, M., OHagan, J. B., Peirson, S. N., Price, L. L. A., Roenneberg, T., Schlangen, L. J. M., Skene, D. J., Spitschan, M., Vetter, C., Zee, P. C., & Wright, K. P. (2022). Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. *PLOS Biology*, *20*(3), e3001571. https://doi.org/10.1371/JOURNAL.PBIO.3001571

BRREAM. (2016). *BREEAM International New Construction 2016 - Technical Manual*. BRE.

CIE Central Bureau. (2021). *CIE S 026:2018 Tutorial*.

Commission International de l'Éclairage. (2018). *CIE S 026/E:2018 - CIE System for metrology of optical*

radiation for ipRGC-influenced responses to light. CIE.

Commission International de l'Éclairage. (2020). What to document and report in studies of ipRGC-influenced responses to light. In *CIE TN 011:2020 Technical Note*. https://doi.org/10.25039/TN.011.2020

D'alessandro, D., Gola, M., Appolloni, L., Dettori, M., Fara, G. M., Rebecchi, A., Settimo, G., & Capolongo, S. (2020). COVID-19 and Living space challenge. Well-being and Public Health recommendations for a healthy, safe, and sustainable housing. *Acta Bio Medica : Atenei Parmensis*, *91*(9-S), 61. https://doi.org/10.23750/ABM.V91I9-S.10115

de Kort, Y. A. W. (2019). Tutorial: Theoretical Considerations When Planning Research on Human Factors in Lighting. *LEUKOS - Journal of Illuminating Engineering Society of North America*, *15*(2–3), 85–96. https://doi.org/10.1080/15502724.2018.1558065

Emde, C., Buras-Schnell, R., Kylling, A., Mayer, B., Gasteiger, J., Hamann, U., Kylling, J., Richter, B., Pause, C., Dowling, T., & Bugliaro, L. (2016). The libRadtran software package for radiative transfer calculations (version 2.0.1). *Geoscientific Model Development*, *9*(5), 1647–1672. https://doi.org/10.5194/GMD-9-1647-2016

Englezou, M., & Michael, A. (2020). Assessment of daylight performance and the impact of shading devices for typical in-patient rooms in healthcare facilities in Cyprus. *Procedia Manufacturing*, *44*, 277–285. https://doi.org/10.1016/j.promfg.2020.02.232

Englezou, M., & Michael, A. (2018). Assessment of natural lighting performance of typical in-patient rooms of healthcare facilities in Cyprus. *Proceedings of 6th International Conference on Renewable Energy Sources & Energy Efficiency*, 139–148.

Englezou, M., & Michael, A. (2021). Investigation of various window sizes and glazing systems in terms of daylight performance and their impact on solar heat gains in typical healthcare patient rooms. *Proceedings of 16th Conference on Sustainable Development of Energy, Water and Environmental Systems*, 1–385.

Gloster, A. T., Lamnisos, D., Lubenko, J., Presti, G., Squatrito, V., Constantinou, M., Nicolaou, C., Papacostas, S., Aydın, G., Chong, Y. Y., Chien, W. T., Cheng, H. Y., Ruiz, F. J., Garcia-Martin, M. B., Obando-Posada, D. P., Segura-Vargas, M. A., Vasiliou, V. S., McHugh, L., Höfer, S., … Karekla, M. (2020). Impact of COVID-19 pandemic on mental health: An international study. *PLOS ONE*, *15*(12), e0244809. https://doi.org/10.1371/JOURNAL.PONE.0244809

IES. (2012). Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). In *Illuminating Engineering Society of North America*. https://www.ies.org/product/ies-spatial-daylight-autonomy-sda-and-annual-sunlight-exposure-ase/

Joarder, A. R., & Price, A. (2013). Impact of daylight illumination on reducing patient length of stay in hospital after coronary artery bypass graft surgery. *Lighting Research and Technology*, *45*(4), 435–449. https://doi.org/10.1177/1477153512455940

Kenny, P. (2021). Characterising the Melanopic / Spectral Microclimate of Indoor Spaces. PhD Dissertation [Loughborough University]. In *Loughborough University*. https://doi.org/https://doi.org/10.26174/thesis.lboro.15104814.v1

Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., Figueiro, M. G., Gamlin, P. D., Lockley, S. W., O'Hagan, J. B., Price, L. L. A., Provencio, I., Skene, D. J., & Brainard, G. C. (2014). Measuring and using light in the melanopsin age. *Trends in Neurosciences*, *37*(1), 1–9. https://doi.org/10.1016/j.tins.2013.10.004

Michael, A., & Heracleous, C. (2017). Assessment of natural lighting performance and visual comfort of educational architecture in Southern Europe: The case of typical educational school premises in Cyprus. *Energy and Buildings*, *140*, 443–457. https://doi.org/10.1016/J.ENBUILD.2016.12.087

Pierson, C., Aarts, M., & Andersen, M. (n.d.). *Validation of Spectral Simulation Tools for the Prediction of Indoor Daylight Exposure École Polytechnique Fédérale de Lausanne (EPFL), Lausanne , Switzerland Eindhoven University of Technology (TU / e), Eindhoven , The Netherlands Abstract Key Innova*.

Thapan, K., Arendt, J., & Skene, D. J. (2001). An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. *Journal of Physiology*, *535*(1), 261–267. https://doi.org/10.1111/j.1469-7793.2001.t01-1-00261.x

The WELL Building Standard v1. (2014). International Well Building Institute.

USGBC. (2019). *LEED v4 for Building Design and Construction* (Issue July). https://www.usgbc.org/resources/leed-v4-building-design-and-construction-current-version

Walch, J. M., Rabin, B. S., Day, R., Williams, J. N., Choi, K., & Kang, J. D. (2005). The effect of sunlight on postoperative analgesic medication use: A prospective study of patients undergoing spinal surgery. *Psychosomatic Medicine*, *67*(1), 156–163. https://doi.org/10.1097/01.psy.0000149258.42508.70

World Health Organization. (2014). Combined or multiple exposure to health stressors in indoor built environments. In Sarigiannis; D.A.; (Ed.), *Combined or multiple exposure to health stressors in indoor built environments* (Issue October).

Zomorodian, Z. S., & Tahsildoost, M. (2019). Assessing the effectiveness of dynamic metrics in predicting daylight availability and visual comfort in classrooms. *Renewable Energy*, *134*, 669–680. https://doi.org/10.1016/J.RENENE.2018.11.072