RESEARCH ARTICLE
Journal of Daylighting 9 (2022) 28-47
doi:10.15627/jd.2022.3

ISSN 2383-8701

Journal of Daylighting

Journal homepage: https://solarlits.com/jd

A Daylight Assessment on Visual and Nonvisual Effects of Light Shelves: A Human-centered Simulation-based Approach

Seyedeh Nazli Hosseini,[a] Iman SheikhAnsari[*,b]

[a] *Department of Interior Architecture, Faculty of Architecture & Urbanism, Tehran University of Art, Tehran, Iran*

[b] *Faculty of Architecture and Urbanism, Art University of Isfahan, Isfahan, Iran*

Article info

Article history:
Received 17 December 2021
Revised 10 February 2022
Accepted 10 February 2022
Published online 14 March 2022

Keywords:
Daylight performance
Visual effects
Nonvisual
Human-centric lighting

Abstract

The contribution of daylight to a comfortable environment for occupants has been the subject of studies for years. Light shelves are known as daylight redirecting systems to enhance indoor daylight conditions. Although several research papers have focused on their daylight performance, there is a lack of studies on the performance of light shelves on circadian rhythm. In this context, daylight's biological effects on human beings have been under investigation. Therefore, this paper aims to evaluate the performance of light shelves in terms of visual and nonvisual effects of daylight, including circadian stimulus, visual comfort, and task performance through a multi-criteria human-centric evaluation. To this end, the authors set three following conditions if a model could provide simultaneously, the occupants would be in a comfortable space both visually and non-visually: 75% workstations with Equivalent Melanopic Lux> 250 EML concurrently with Vertical Photopic illuminance < 1500 lux, and Photopic illuminance on working plane > 300 lux. Accordingly, the light shelves with various depths, states, and orientations were simulated by ALFA to evaluate the comfort of occupants in office space over working hours. The results indicated that although applying light shelves impacted the metrics, the enhancements were minor compared to a conventional window, specifically on EML. In detail, inadequate EML levels were observed in all orientations on the simulation days. Besides, changes in the photopic illuminance at the eye and workstations levels were not substantial. Finally, the paper presents a case study that showcases simulation techniques that focus on daylighting and circadian rhythm.

1. Introduction

Over the past two centuries, architectural innovations by computational process and parametric tools [1] have enhanced indoor conditions [2]; therefore, indoor occupational hours have increased to 90% within the indoor space by 2020 [2,3]. Sustainable designs that would promote human health and well-being are currently viewed as one of the future requirements of built environment design. Moreover, extensive investigations have reported significant healthcare issues regarding daylighting quality within indoor space [3,4]. Research in photobiology and neuroscience has revealed that light entrains the human circadian system [5].

Circadian rhythms, the biological clock, is regulated by the Suprachiasmatic Nucleus (SCN) and interrupted by inputs including behavioral (non-photic) and light (photic), such as the timing, intensity, duration, wavelength, and light exposure [6–9].

*Corresponding author.
S.Nazli.Hosseinii@gmail.com (S. N. Hosseini)
ImanSheikhAnsari@gmail.com (I. SheikhAnsari)

Meticulously, light information is captured by the eyes using specialized retinal photoreceptors located in the ganglion cell layer; These Intrinsically Photoreceptive Retinal Ganglion Cells (ipRGCs) contain a novel photopigment called Melanopsin and project directly to the SCN via a dedicated neural pathway, the RetinoHypothalamic Tract (RHT) [10–12]. Therefore, the wavelength of light reaching the retina is an implicit parameter in suppressing melatonin [13,14] as well as the promotion of cognitive health, being more alert [15,16], and interrupting the circadian rhythm [17].

Since light visual and nonvisual impacts on human beings are evident, architects and designers need metrics and guidance to evaluate daylight performance and the nonvisual effects [2,18]. Amundadottir et al. (2017) have worked on a unified framework for evaluating and reporting the spectral effectiveness of light [19]. The currently applied standards specify minimum light intensity levels in Equivalent Melanopic Lx (EML) units, a new measure of light intensity weighted by the sensitivity of Melanopsin containing ipRGCs of the eye [20]. In general, studies categorized

Nomenclature

EML	*Equivalent Melanopic Lx*
SCN	*Suprachiasmatic Nucleus*
ipRGCs	*Intrinsically Photoreceptive Retinal Ganglion Cells*
RHT	*RetinoHypothalamic Tract*
LGS	*light guiding system*
LTS	*light transporting system*
CBDM	*Climate Based Daylight Modeling*
sDA	*Spatial Daylight Autonomy*

the circadian lighting analysis methods into two general approaches: (1) multispectral simulations employing radiance to calculate EML directly [21,22], (2) annual hourly and sub-hourly analysis using Daysim to evaluate melanopic-to-photopic ratio for estimating the level of the circadian light stimulus [23–27].

Furthermore, the International Well Building Institute developed building certification systems to measure and monitor building performance and its impacts on health and well-being. The current WELL requirement for " Melanopic Light Intensity for Work Areas " states the following [28]:

"Light models or light calculations (which may incorporate daylight) show that at least 250 equivalent melanopic lx is present at 75% or more of workstations, measured on the vertical plane facing forward, 1.2 m [4 ft] above finished floor (to simulate the view of the occupant). This light level is present for at least 4 hours per day for every day of the year."

Light shelves are the most common type of redirecting daylight system typically positioned above the eye level of a standing person to maintain the outside view [29–31]. They have the capability of shading, reflecting sunlight, and decreasing direct glare from the sky. Additionally, light shelves serve as the optical treatment of space reduce the total annual electricity for lighting [32]. Therefore, this paper would assess the impacts of light shelves as a redirecting daylight system representative.

Although several studies have evaluated the nonvisual effects of daylight on the entraining circadian system, few researchers have focused on the performance of daylight systems and their nonvisual effects. Given the lack of research, this study mainly focused on a human-centric approach to evaluate redirecting daylight systems in office buildings for nonvisual health potential and visual interest. In detail, human perception of space is a 3-dimensional (3d) luminous scene; however, daylight analysis methods are commonly used to assess light across a two-dimensional (2D) surface (illuminance-based). More precisely, these methods were developed to alleviate discomfort resulting from excessive luminous contrast ratios limited within a fixed view position, particularly related to task areas; therefore, they do not account for the spatial composition of daylight across an occupant's field of view or vertical illuminance captured at the eye [2,33] In addition to these limitations, those methods neglect the health effects of daylight on occupants [2]. Further, the current grid-based method for daylight simulation does not represent human interaction with space but instead simulates the daylight potential of space (even not occupied part). Therefore, the human-centric method employed in this study will evaluate daylight performance of light shelves using a range of view directions from a single view position related to the light received at the eye level and nonvisual health potential [2,34,35].

2. Literature Review

2.1. Daylight and daylight systems

Architects and designers have attempted to effectively apply natural light to improve the indoor condition by various means, including the forms of the building [36,37], characteristics of openings [37–40], and fabric of cities [41,42]. The lighting strategies have improved daylight conditions and responses to physiological and psychological needs. Boubekri asserted that despite the evidence connecting natural light to health issues, neither lighting design guidelines nor the illumination standards discussed the contribution of daylighting to the human's sense of well-being in the previous times [43]. Since then, studies have started to investigate the contribution of daylight systems to health-related issues [43–46] and averting visual discomfort for occupants [47–49].

Littlefair (1996) and Tsangrassoulis (2008) introduced two categories of innovative daylight systems without shading, namely light guiding system (LGS) and light transporting system (LTS) [50,51]. LGS systems reflect and redirect sunlight and daylight indoors, while complex components of LTS provide the opportunity to offer collection, transport, and distribute sunlight within a space. [44,52–54]. Table 1 gives information about the strategies of each system.

2.2. Light shelves

Kontadakis et al. (2017) stated that light shelves as the most common structure among daylight systems [31]. Light shelves are regularly located above the human eye level, resulting in the window division into two parts that serve as a clerestory to redirect sun rays, provide desirable views, and enhance daylight's perceptual effects [30,31,56,73]. Technically, light shelves are a horizontal baffled employed inside and/or outside a window as part of a façade or mounted on it. Room configuration, ceiling height, and the eye level of occupants are parameters that set the

Table 1. Commonly applied daylighting systems without shading.

Daylight systems without shading	
Light Guiding System (LGS)	Light Shelf [31,55–60]
	Anidolic Integrated System [61-63]
	Anidolic Ceiling [61-63]
	Zenith Light-guiding Element with the Holographic Optical Element (HOW) [64]
	Holographic Optical Element (HOE) in the Skylight [64]
Light Transport Systems (LTS)	Heliostat [31,65]
	Light Pipe [66–68]
	Solar Tubes [66–68]
	Fibers [69–72]

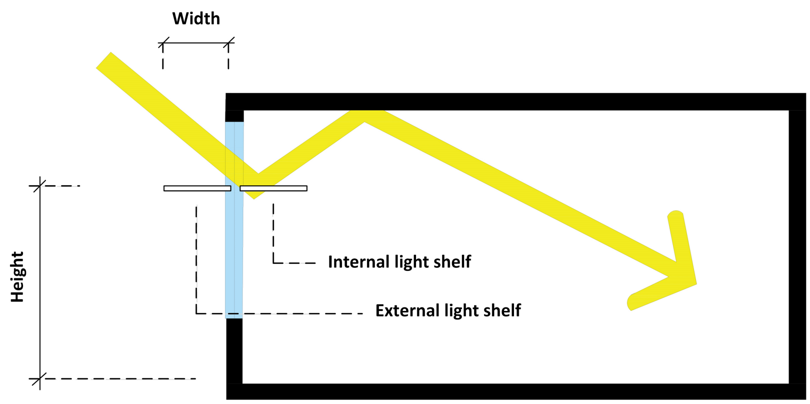


Fig. 1. Light shelves mechanism [84].

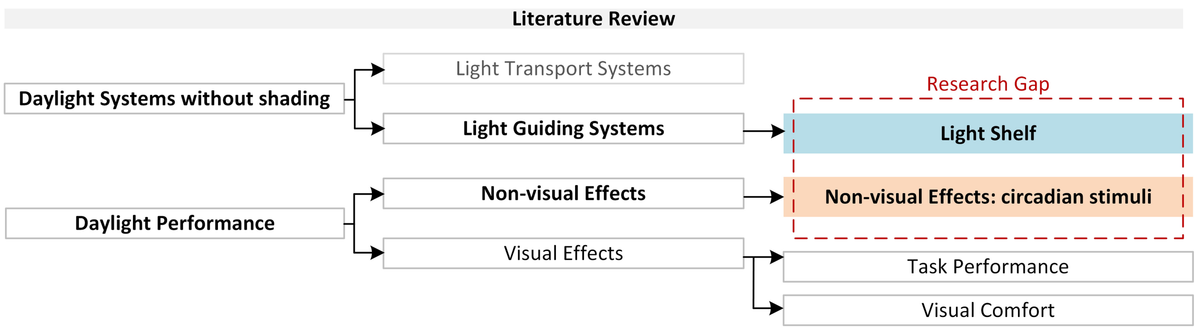


Fig. 2. The literature review process- by authors.

position of light shelves. Besides, the geometry is an essential parameter for the uniform distribution of daylight compared to a non-shaded conventional window. Similarly, external and internal light shelves have different daylight performance regarding changes in the exposure, especially in the vicinity area of the sky zenith (Fig. 1) [29,74].

Physical principles and characteristics of light shelves, including orientation, position in the façade, and depth, fulfill daylight and shading demands. Since the light is reflected to the ceiling, characteristics including surface materials [75–79], shelf geometry [56,80,81], and shelf dimension [55,82] are essential parts of a light shelf system. These parameters should be taken into account concerning glare resulting from the ceiling reflections [29,32,74]. The optical treatment light shelves significantly improved the efficiency and direction of redirected light in conventional light shelves [29,83]. Besides, the variable area light-reflecting assembly (VALRA) with tracking ability of light extended the power of reflecting light [32]. Moreover, the maintenance and cost of movable light shelves are generally more than fixed ones. Both types demand regular cleaning from dust, snow, and nests of birds or insects, negatively affecting their reflective properties [32].

2.3. Nonvisual effects of daylight

Light has a significant influence on whole organisms, including human beings. A considerable number of studies on daylight have been conducted regarding nonvisual effects on humans. The initial studies mainly investigated the effect of color temperature concerning human physiology, sleep architecture, and parameters like blood pressure, body temperature, and heart rate variability [85–89]. The circadian rhythm is an extensively investigated nonvisual response to light [90,91]. Figueiro et al. (2018) explained that light incident on the retina profoundly affects the timing of the biological clock and enhances entrainment to the local time on Earth [92]. Hence, daylight serves as the primary environmental time cue for synchronizing the internal circadian clock. Many facets of human physiology and behavior are controlled by 24-hour circadian rhythm. Failure to receive an inadequate amount of daylight would result in health and well-being difficulties such as the sleep-wake cycle, alertness and performance patterns, and many daily hormone profiles [93–96].

In 1980, Lewy et al.'s (1980) study connected light exposure to acute human melatonin suppressions [97]. Melatonin is a hormone produced in the pineal gland at night-time by diurnal and nocturnal animals, often referred to as the "darkness hormone" [98]. Melatonin production is regulated by the brain's suprachiasmatic nucleus (SCN). The SCN is connected via the retinohypothalamic tract (RHT) to the retina of the eye, a pathway used in many mammals to transmit light-dark signals for entrainment (or photoentrainment). Light information is captured by the eyes using specialized retinal photoreceptors located in the ganglion cell layer. These Intrinsically Photoreceptive Retinal Ganglion Cells (ipRGCs) contain a novel photopigment called Melanopsin and project directly to the SCN via a dedicated neural pathway, the retinohypothalamic tract [10–12]. It should be noted that the connection between the ipRGCs and the brain is not limited to the SCN and not limited to the function of circadian entrainment [99]. There are ongoing researches on the interaction between ipRGCs and other photoreceptors; recent research has shown that one subtype of ipRGC has an inhibitory, dampening effect on circadian phase-shifting mammals [100]. Figure 2 briefly represents the literature review process.

2.4. Lighting simulation platform for the nonvisual effect of daylight

Since light exposure/intensity is affected by the built environment [95], architects should determine daylighting possibilities in the preliminary design phase of buildings [101]. The integration of building performance and design processes has received significant attention in the last two decades. A wide range of metrics and advanced tools are available to assess indoor daylight and energy consumption. However, building design must move beyond energy-centric approaches and focus on psychological and physiological human well-being [102–104]. This approach involves the human need to be in a living environment conducive to health and psychological light exposure needs, in conjunction with dynamic nature through windows and views [105]. Since the health of the visual and nonvisual system is a crucial concern, precise tools and guidelines were demanded to evaluate eye-level photopic (daylight availability) and health performance to determine how the illuminance can be advanced in various situations [106].

Climate Based Daylight Modeling (CBDM) is known as daylighting guidance. Konis (2017) asserted that the current objective of LEED Daylight Environmental Quality is to improve circadian rhythms. However, he mentioned that relying on metrics like Spatial Daylight Autonomy (sDA) is problematic. Eventually, circadian lighting design demands developed a circadian daylight metric based on scientific knowledge related to the timing, intensity, duration, wavelength, and history of light exposures [27]. Circadian Stimulus (CS), a recent metric developed by the Lighting Research Center (LRC), was introduced by Rea (2012). This metric measures the effectiveness of a light source ranging from 0 (no stimulus) to 0.7 (full saturation). The LRC suggests exposure of CS greater than 0.3 (=180 Lx from daylight) for at least one hour in the early morning [107,108]. Lucas et al. (2014) have studied metrics to measure the biological effect of light to quantify it. Accordingly, the Equivalent Melanopic Lx (EML) was proposed to measure light's impact on the circadian systems. They provided a toolbox that analyzes the EML for every five photoreceptors in the eye (Cyanopic, Melanopic, Rhodopic, Chloropic, and Erthyropic) for specific spectrums [109]. The EML metrics measure the impact of light on human circadian rhythms in the absence of rods and cones. As a result, its spectral range differs from empirical melatonin suppression responses in normal humans [21–27]. Moreover, as a novel metric measure of circadian effectiveness, The WELL Building Standard v1.0 adopted EML in 2015[110].

Most daylight simulation platforms depend on three-dimensional color spaces for predictive renderings. Computations in RGB color space do not meet the requirements for predicting color shifts and color-dependent lighting metrics, such as circadian light [111]. Andersen et al. (2012) [95] and Mardaljevic et al. (2013) [24] collaboratively proposed a photobiology-based lighting model to predict the circadian effect based on various parameters, including intensifying of vertical illuminance, light source spectrum, and timing. Radiance was validated for color and luminance accuracy using an N-step method by Ruppertsberg and Bloj (2006) [107] to perform multispectral simulations. This method was developed by Inanici et al. (2015) to determine circadian lighting. Consequently, a Grasshopper plug-in, LARK, was released to provide a more available N-step method for architects and designers [112]. Similarly, Adaptive Lighting for Alertness (ALFA) is a radiance-based multispectral simulation platform to evaluate circadian lighting [113].

LARK and ALFA are the two most recent programs to perform multispectral daylight simulation. Despite having specifications in common, there are differences between the platforms. At the same time, ALFA performs simulations on 81-color channels, while LARK runs a maximum of 9-channel simulations. Additionally, the outputs of spectral irradiance measured by LARK are nine values, one for each of the discrete nine-channel bins between 380-780 nm. ALFA offers the spectral irradiance outputs at every 5nm interval from 380-780 nm. Moreover, Lark can measure global spectral sky as an input, while a lack of an atmospheric

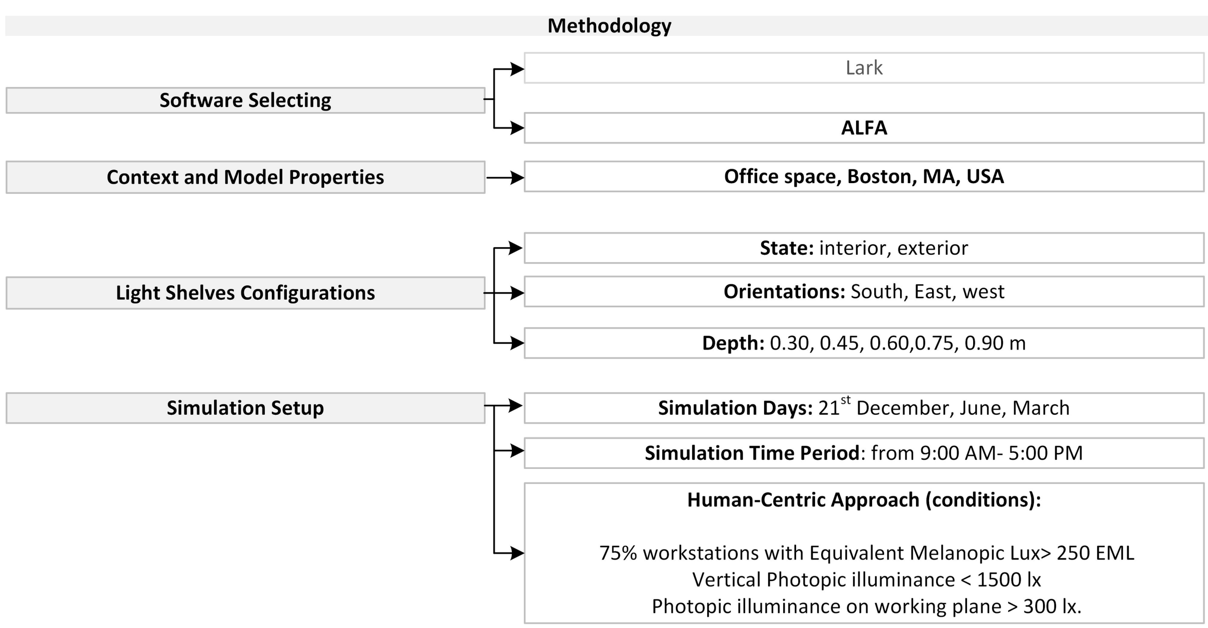


Fig. 3. The methodology abstract - by authors.

profile can be found within ALFA. Color renditions of the low-angle sun of the sky cannot be shown without an atmospheric profile [112–114].

3. Methodology

The current study adopts ALFA as a simulation tool to evaluate the effect of natural light redirected by light shelves to an interior space. Moreover, ALFA can predict EML through physically accurate, high spectral resolution simulations. Spectral raytracing allows ALFA to indicate the amount of light absorbed by nonvisual photoreceptors of an observer, given the location and direction of view [113]. The room geometry and light shelves are primarily modeled in the Rhinoceros 3-D modeling software [115] and imported into ALFA [113]. The following sections describe the procedures developed to quantify the effects of a light shelf as a representative of redirecting the daylight system. Figure 3 briefly represents the methodology.

3.1. Context and model properties

The reference room is a side-lit office located in Boston, MA, the USA, with no neighboring buildings. The room dimensions are 3.60 m wide, 8.20 m deep, and 2.80 m high. The room depth is large enough to demonstrate the effect of daylighting and its reflection for all variants. It is assumed the interior wall thickness is 0.15 m and floor to floor distance is 3.10 m, the window-to-wall ratios are 45% (interior WWR) and 39% (exterior WWR) (Fig. 4) [116]. The optical properties of surface materials are listed below, and the proposed property of materials is based on spectrophotometric measurements provided in ALFA software (Table 2). Clear sky conditions with a uniform ground spectrum with an albedo of 0.15 are set as context parameters in this study. Also, no luminaire for interior space is considered, so the only light source is natural daylight.

Since the depth of light shelves is the most effective parameter in their performance [79], this parameter is taken into consideration which varies between 0.30m to 0.90m with the step

Table 2. Optical properties of material surfaces.

Opaque Materials							
Surface	**Properties**	**Specularity (%)**		**Photopic Reflectance (%)**		**Melanopic Reflectance (%)**	
Interior Wall	White Painted	0.4		81.2		76.8	
Ceiling	White Painted	0.4		82.2		77.4	
Floor	Dark Grey Tile	1.2		20.1		19.1	
Light Shelf	Metal Reflector	44.8		57.2		58.0	
Mullion	Window Mullion	3.4		19.8		19.9	
Monitor Body	Dupont Midnight Black	0.0		0.3		0.3	
Door	Wooden Door	0.8		4.9		4.3	
Table	Wooden Table	0.6		22.7		12.4	
Ceiling Reflector	Metal Reflector	44.8		57.2		58.0	
External Ground floor	Asphalt	0.0		8.6		7.4	
Exterior Wall	Grey Aluminum Cladding	2.1		20.0		18.9	
Roof	Concrete	0.0		15.3		13.3	
Glazing Materials							
Surface	**Properties**	**Front Reflectance (%)**		**Back Reflectance (%)**		**Transmittance (%)**	
		Photopic	**Melanopic**	**Photopic**	**Melanopic**	**Photopic**	**Melanopic**
Window	Double IGU Clear	11.1	11.0	11.7	11.9	70.1	70.1
Monitor Screen	Single Plane Clear 6mm	8.0	8.2	8.0	8.2	88.3	89.0

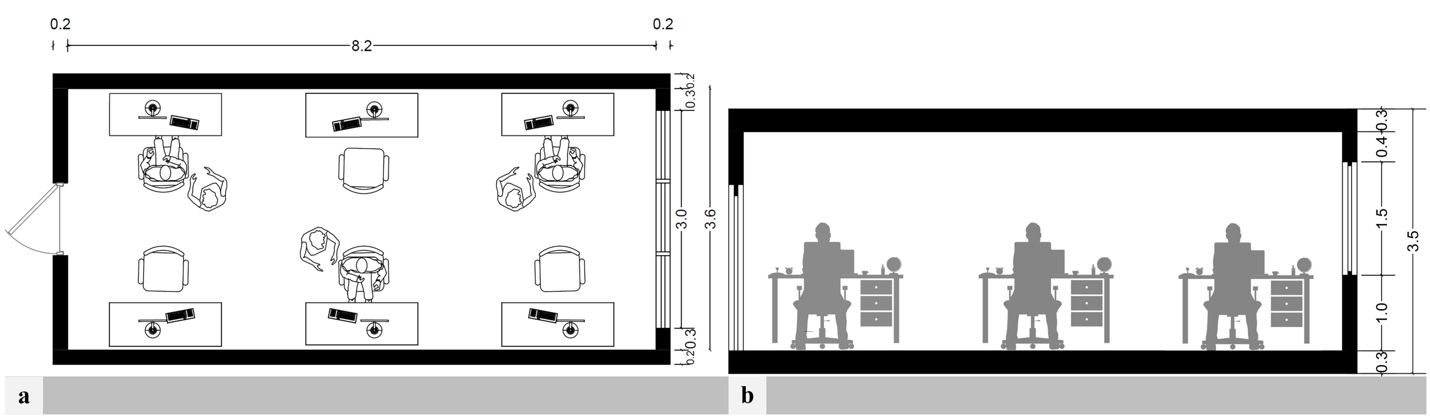


Fig. 4. Reference room: (**a**) plan and (**b**) section.

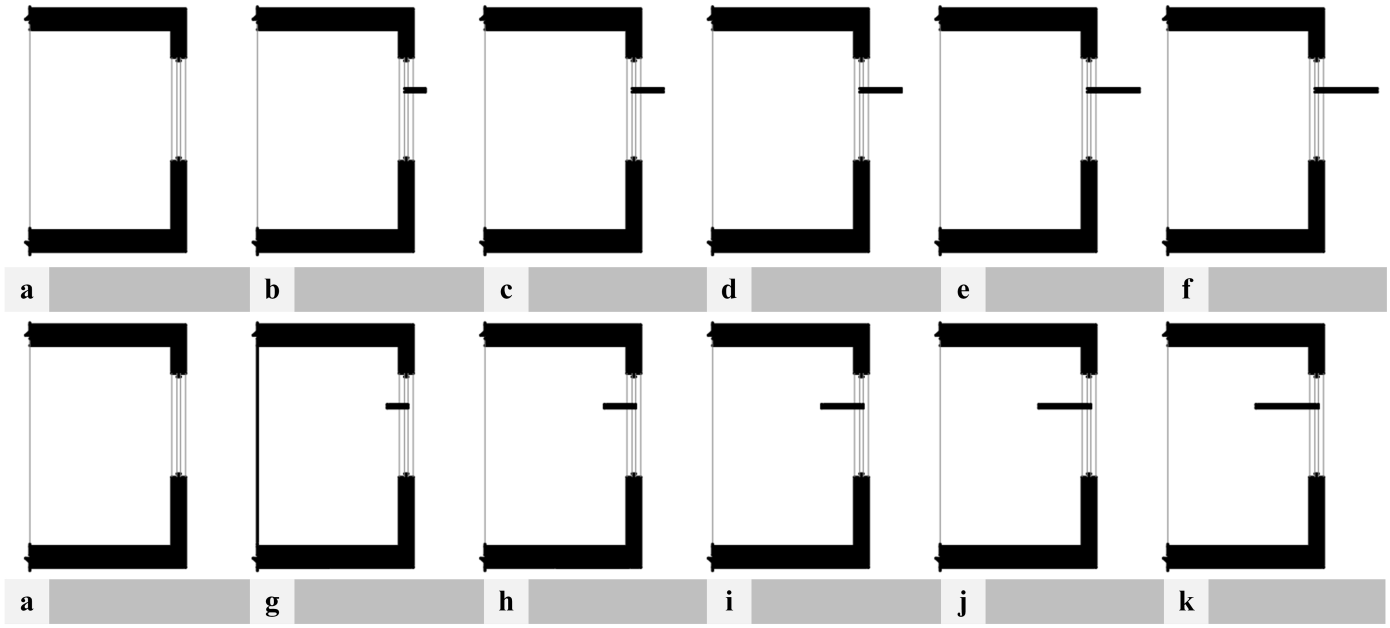


Fig. 5. Light shelves' configurations: exterior (a-f): a: base case, b: 0.30 m, c: 0.45m, d: 0.60m, e: 0.75m, f: 0.90m / Interior (a-k): a: base model, g: 0.30m, h: 0.45m, i: 0.60m, j: 0.75m, k: 0.90m.

of 0.15m). The light shelves are located interior or exterior to evaluate their performance thoroughly. Light shelves thickness is considered 0.05m and positioned at the height of 2.00m from the floor. Eventually, the room orientation in the three directions has been studied to simulate the effects of light shelves inclusively.

3.2. Simulation setup

Andersen et al. (2012) asserted that the nonvisual impacts of light depending on the time of the day and time exposure duration; the authors proposed a three-time period division for a day, including 6:00-10:00 (circadian resetting), 10:00-18:00 (alerting effects of daylight), and 18:00- 6:00 (bright light avoidance, dim light) [95]. Since a typical office schedule starts at 9:00 to 17:00, the current study only considers the first two time periods (6:00-10:00, 10:00-18:00). Therefore, the workspace is occupied from 9:00 to 17:00 by six occupants, and the time-step set in the current study is 1 hour. 21st March, 21st June and 21st December have been simulated as equinox and solstice.

Further, the sensors were located at the occupant working positions, and Illuminance levels were computed vertically at eye level to simulate the light entering the eye. Photosensors representing the number of workstations were placed at the height of 1.20 m above the floor for occupants sitting on the standard chair and at the height of 0.76 m to calculate photopic illuminance on the working stations. View directions to monitors were simulated at each position and aligned to building geometry and desk. Moreover, the ambient bounce (-ab) and limit weight (-lw) in the radiance setting are set to 8 and 0.01 to represent the reflection of light shelves better. The number of passes for ALFA is set to 100 for more accurate results.

3.3. Human-centric approach

As stated in the introduction, the WELL Building Standard introduces the circadian stimulus potential when at least 250 EML is presented at more than 75% of workstations [28]. Moreover, the vertical photopic illuminance below 1500 lx represents comfortable subjective evaluations, while above 1500 lx is increasingly uncomfortable [117,118]. Accordingly, the vertical direct illuminance in a view should be considered under 1500 lx to reduce glare risk. Besides, illuminance on the work plane is applied to check daylight quality as an indicator of daylight. The acceptable minimum illuminance on the work plane is 300 lx for offices based on Chartered Institution of Building Services Engineers (CIBSE) [119]. This amount is desirable illuminance for both paper and computer work [120,121].

Therefore, these three conditional situations should be satisfied to have a comfortable workplace environment for occupants. A reference room in Boston (Fig. 4) is simulated to evaluate the daylight performance of ten light shelves (Fig. 5) and a base model in different orientations, in terms of Equivalent Melonopic Lux (EML), visual comfort (vertical Photopic illuminance), and task performance (Photopic illuminance on working planes). Results of each occupant have been compared to the criteria mentioned above. As a final result, the number of occupants having a comfortable work environment each hour is suggested to represent an occupant-centric metric for evaluations.

3.4. Context and model properties

As mentioned before, the WELL Building Standard introduces the circadian stimulus potential when at least 250 equivalent melanopic lx is presented at more than 75% of workstations [110].

As an indicator of daylight, Work Plane Illuminance is applied to check daylight quality. Based on the Chartered Institution of Building Services Engineers (CIBSE), the minimum acceptable range for work plane illuminance is 300 lx for offices [119], which is a desirable illuminance for both paper and computer work [122].

Based on the vertical photopic illuminance, more light reaching the eye causes a higher level of discomfort. A vertical photopic illuminance below 1000 lx represents comfortable subjective

Table 3. Specification of models.

State	Depth	Orientation	Days	Time
Interior	0.30 m, 0.45 m, 0.60 m, 0.75 m, 0.90 m	South, East, West	21st June, March, and December	9-17
Exterior	0.30 m, 0.45 m, 0.60 m, 0.75 m, 0.90 m	South, East, West	21st June, March, and December	9-17
Base Model	Simple window	South, East, West	21st June, March, and December	9-17

Table 4. Equivalent Melanopic Lx (>250), Vertical Photopic illuminance (< 1500 lx), photopic illuminance (Lx) on work planes (>300 lx), the percentage of each indoor that met the conditions, Orientation: South.

South	**S**	**D (cm)**	**Equivalent Melanopic Lux (EML)**						**Vertical Photopic Illuminance (lx)**						**Photopic Illuminance on Work Planes (lx)**					
			21st June		**21st March**		**21st December**		**21st June**		**21st March**		**21st December**		**21st June**		**21st March**		**21st December**	
			Ave.	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**	**Ave.**	**Min.**
	B		649	66	2008	10	963	49	618	69	2436	12	1204	118	1125	174	5117	19	7196	103
	E	**30**	598	81	1906	8	834	47	566	82	2318	9	1008	115	1035	147	4982	18	6990	104
		45	586	88	1707	7	796	43	554	89	2086	8	961	128	1017	151	4912	19	6922	91
		60	575	84	1251	7	766	45	546	86	1547	8	913	125	989	177	4876	18	6865	97
		75	580	75	1219	9	741	53	552	78	1508	10	870	104	986	159	4826	19	6812	96
		90	569	90	1209	6	721	52	542	92	1491	7	846	123	985	174	4769	16	6775	119
	I	**30**	603	98	1906	7	828	49	575	99	2311	8	1013	136	1029	148	4988	18	1440	111
		45	589	74	1877	7	804	51	563	77	2276	8	987	116	1027	145	4976	16	1441	104
		60	602	81	1834	7	818	43	575	83	2217	8	993	107	1022	164	4921	16	1428	107
		75	587	90	1807	7	805	45	559	89	2176	8	985	125	996	149	4654	15	1389	93
		90	581	79	1775	7	784	36	552	82	2132	8	955	116	967	131	4311	19	1364	97

S: State, D: Depth, E: Exterior, I: Interior, B: Base case

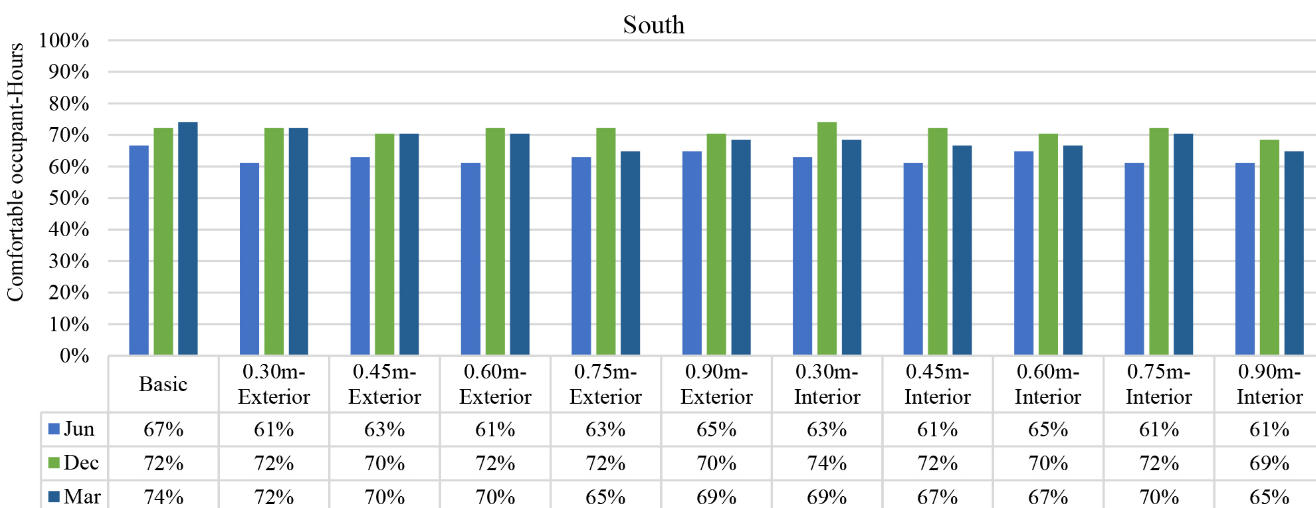


Fig. 6. The percentage of workstations with more than 250 EML.

evaluations, while values above 1500 lx grow increasingly uncomfortable. Accordingly, the vertical direct illuminance at eye level should be considered under 1500 lx to reduce glare risk [120,121].

4. Results and findings

The simulations are performed in a typical room for six occupants in Boston, the United States (Figs. 3 and 4, Table 3). The analyses evaluate the daylight performance of ten light shelves and a base model in terms of circadian stimulus potential (Equivalent Melanopic Lux), visual comfort (vertical Photopic illuminance), and task performance (Photopic illuminance on working planes).

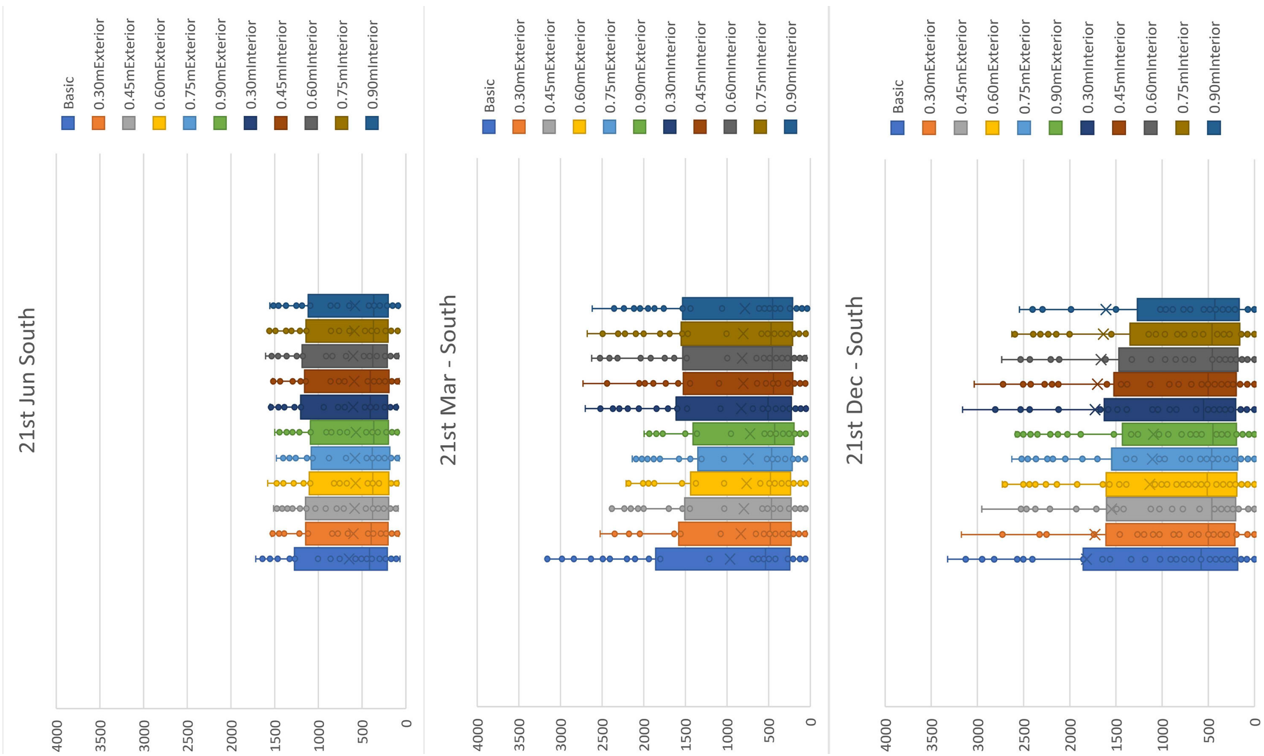
4.1. Performance evaluation results

Given the significance of orientation in daylight and the variation of the color index of sky and atmosphere, especially in sunset and sunrise directly related to Melanopic lux (nonvisual effect), orientation was considered critical in result representation. In the result section, the EML (nonvisual effects of daylight) was first evaluated. The visual effects and photopic illuminance were explained thoroughly in the next step. Regarding the described information, Tables and Figures are provided.

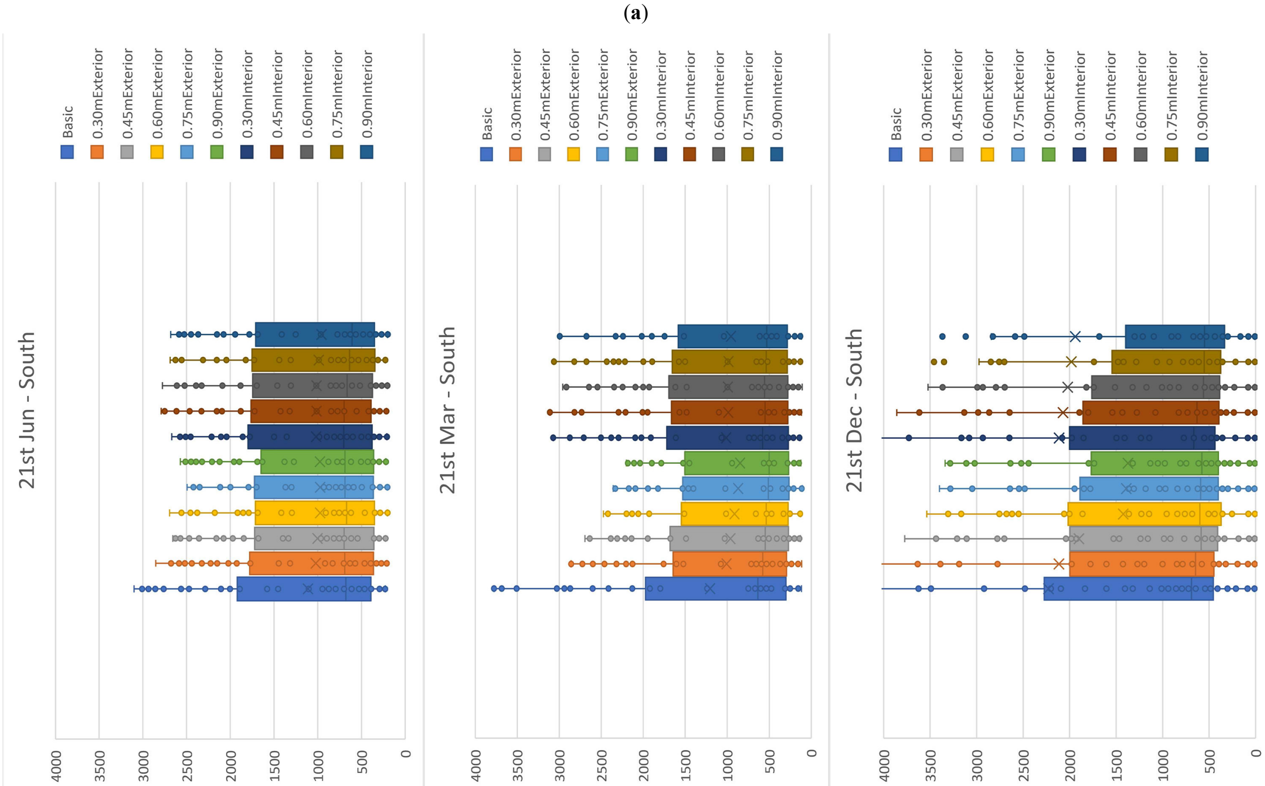
4.1.1. Performance of light shelves, orientation: South

Table 4 and Figs. 5 and 6 summarizes the performance of cases in terms of daylight metrics on the South orientation.

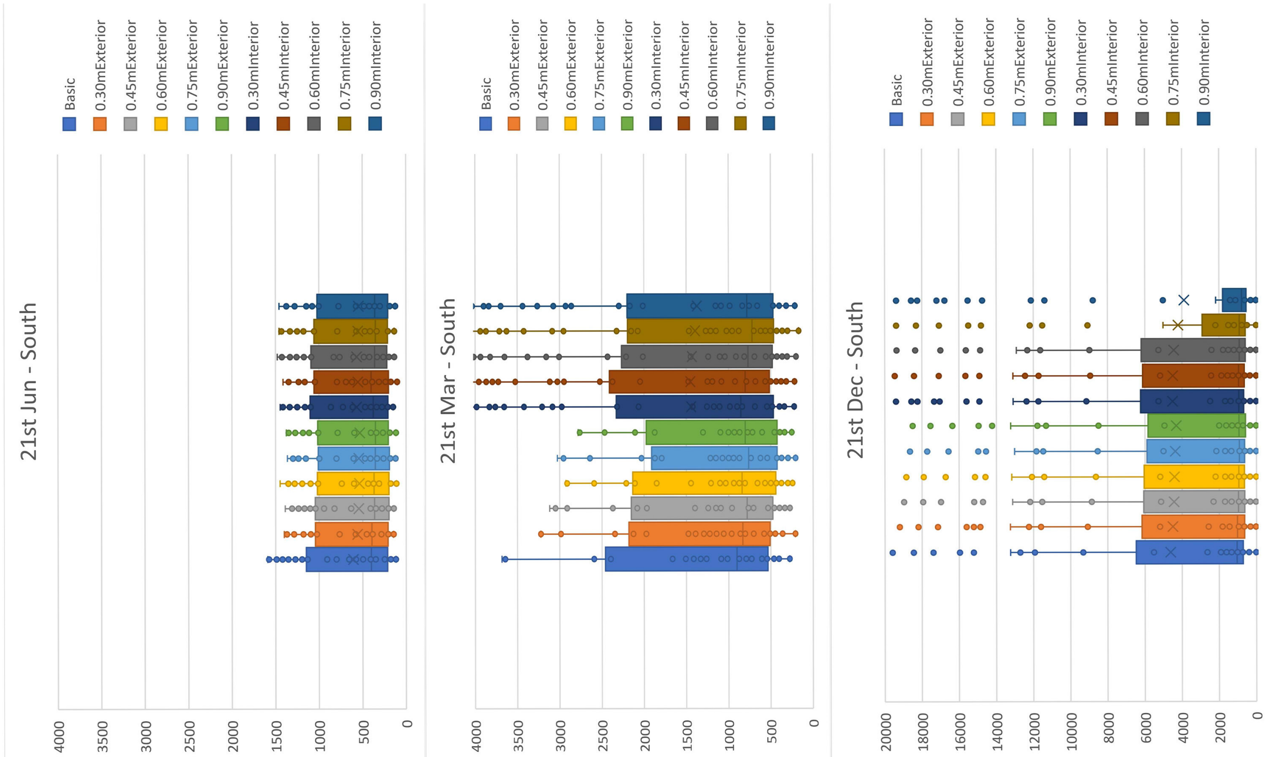
The best performance in EML was with the base model on the simulation days by providing the highest average of EML in the simulated space. Comparing the performance of light shelves reveals that their effects on EML did not significantly differ from each other. Additionally, compared with the base case, medium reductions have been reported. For instance:



(a)



(b)



(b)

Fig. 7. (**a**) Equivalent Melanopic Lx, (**b**) Vertical Photopic illuminance, (**c**) photopic illuminance (Lx) on work planes.

Table 5. The average Equivalent Melanopic Lx (>250), Vertical Photopic illuminance (< 1500 lx), Photopic illuminance (lx) on working plane (>300 lx), the percentage of each indoor that met the conditions, Orientation: East.

East	S	D (cm)	Equivalent Melanopic Lux (EML)						Vertical Photopic Illuminance (lx)						Photopic Illuminance on Work Planes (lx)					
			21st June		21st March		21st December		21st June		21st March		21st December		21st June		21st March		21st December	
			Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.
	B		610	102	445	7	596	53	591	97	480	7	596	52	1048	163	764	14	1395	78
	E	30	577	107	415	7	548	48	553	108	447	7	539	49	965	152	705	14	871	81
		45	563	93	396	6	530	49	537	92	423	6	519	49	925	156	683	12	842	90
		60	566	99	389	5	523	46	541	96	416	5	509	45	916	159	671	13	826	76
		75	550	93	379	9	510	46	525	88	406	8	497	47	902	148	652	13	802	84
		90	546	80	377	5	515	46	523	80	403	5	501	45	884	143	642	13	784	83
	I	30	546	82	371	7	518	43	520	81	393	7	512	43	907	136	666	12	1262	83
		45	554	93	381	8	525	43	530	91	405	8	518	42	929	150	673	13	1285	74
		60	556	78	393	6	536	32	530	79	419	6	530	32	957	126	695	13	1307	79
		75	565	81	398	7	535	45	541	81	426	7	530	44	973	151	699	13	1312	85
		90	567	96	413	8	563	45	543	97	444	8	559	45	962	140	711	16	1315	82

S: State, D: Depth, E: Exterior, I: Interior, B: Base case

- On 21st March, it was found with the highest average of 2008 lx by the base model followed by 1906 EML by the interior and exterior light shelves with 0.30 m depth, which is an ample reduction.
- The lowest minimum is reported under 20 EML on the same day, indicating simulated models' relatively analogous performances.

According to the WELL building standard, more than 75% of workstations should be offered by an EML of at least 250 EML. Figs. 5 and 6 indicates that none of the simulation models could supply an appropriate amount of daylight to provide nonvisual comfort for occupants.

In the case of vertical photopic illuminance, although the application of light shelves reduces it, the changes are minor. For example:

- On 21st March, the highest illuminance is observed (2436 lx by base model). The light shelves decrease to 1491 lux (exterior light shelf with 0.90 depth).

- On the same day, the lowest minimum vertical photopic illuminance, under 20 lx, is reported by most light shelves.

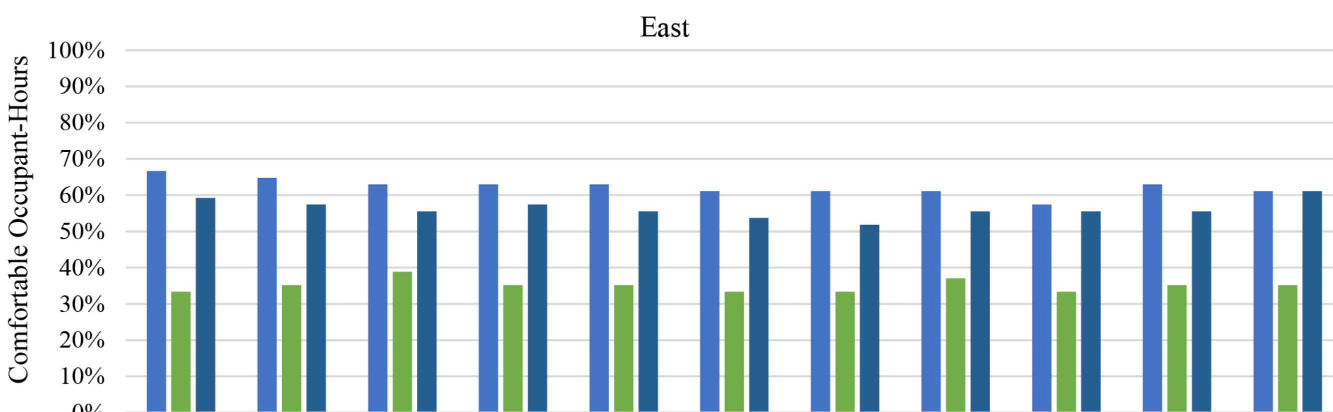
Furthermore, applying light shelves altered the amount of photopic illuminance (lx) on work planes. Based on Table 4 and Figs. 6 and 7, the changes are variable in the simulation days. For instance:

- On 21st December, the highest illuminance is achieved by the base model (7196 lx), which encounters the highest reduction to 1364 by the interior light shelf of 0.90 depth compared to other days.
- On June and 21st March, the changes were minor from 1125 to 913 lx and 5117 to 4311 lx, respectively.

4.1.2. Performance of light shelves, Orientation: East

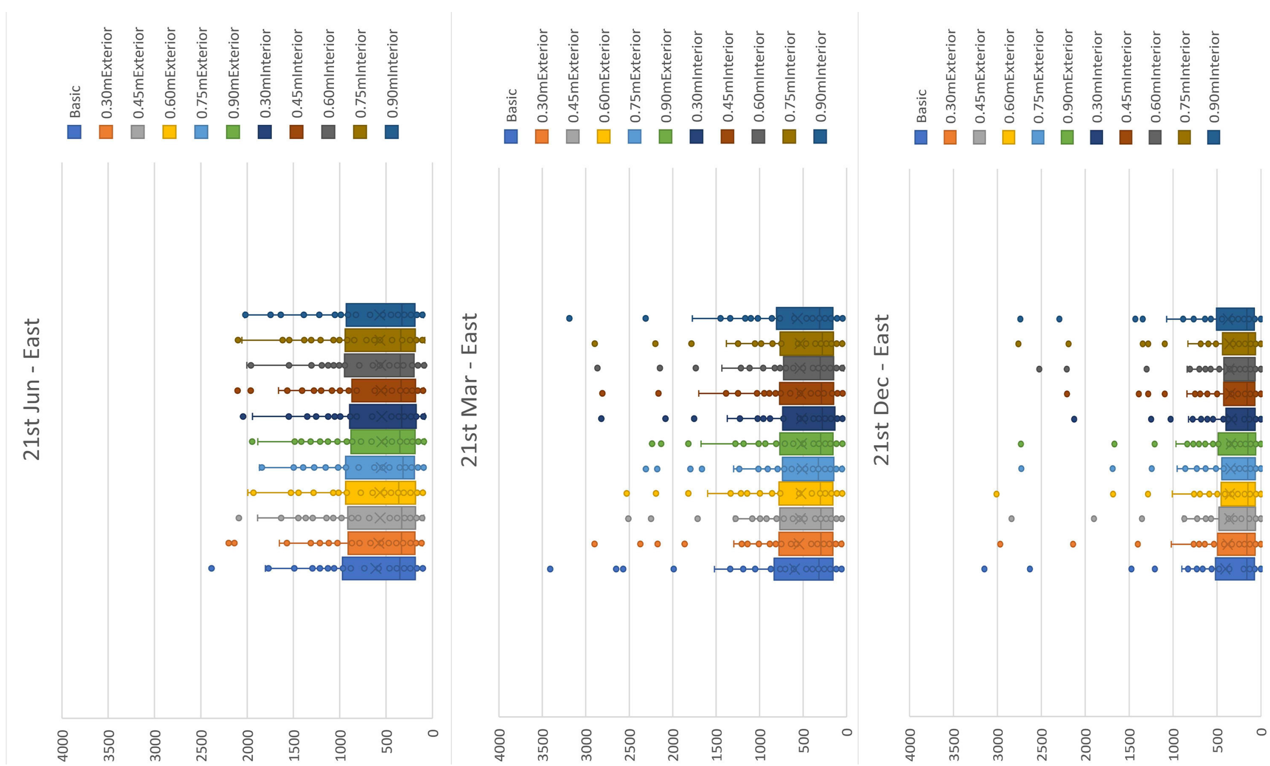
Table 5 and Figs. 8 and 9 report the daylight performance of the light shelves on the East orientation. In the case of EML, results indicate a minor discrepancy between the simulated models. For instance:

- On 21st March, EML was found with the highest average of 610 lx by the base model, while the lowest average is 546

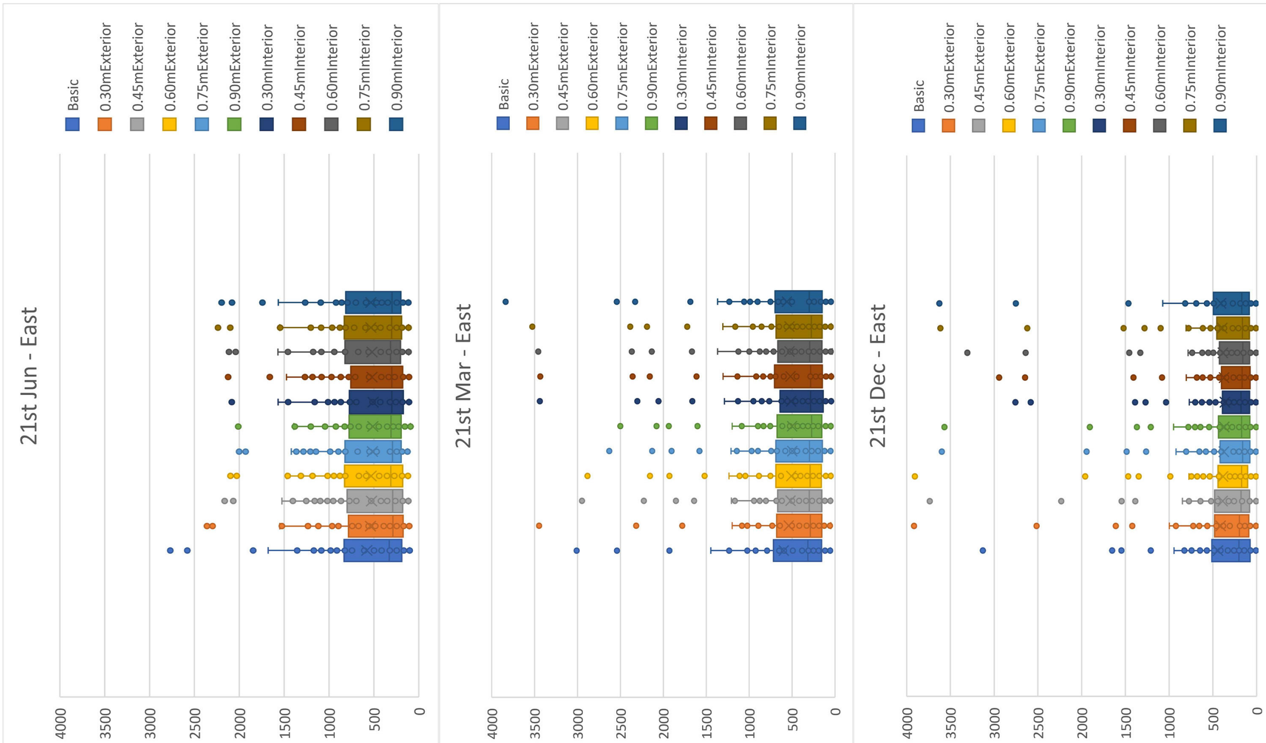


	Basic	0.30m-Exterior	0.45m-Exterior	0.60m-Exterior	0.75m-Exterior	0.90m-Exterior	0.30m-Interior	0.45m-Interior	0.60m-Interior	0.75m-Interior	0.90m-Interior
Jun	67%	65%	63%	63%	63%	61%	61%	61%	57%	63%	61%
Dec	33%	35%	39%	35%	35%	33%	33%	37%	33%	35%	35%
Mar	59%	57%	56%	57%	56%	54%	52%	56%	56%	56%	61%

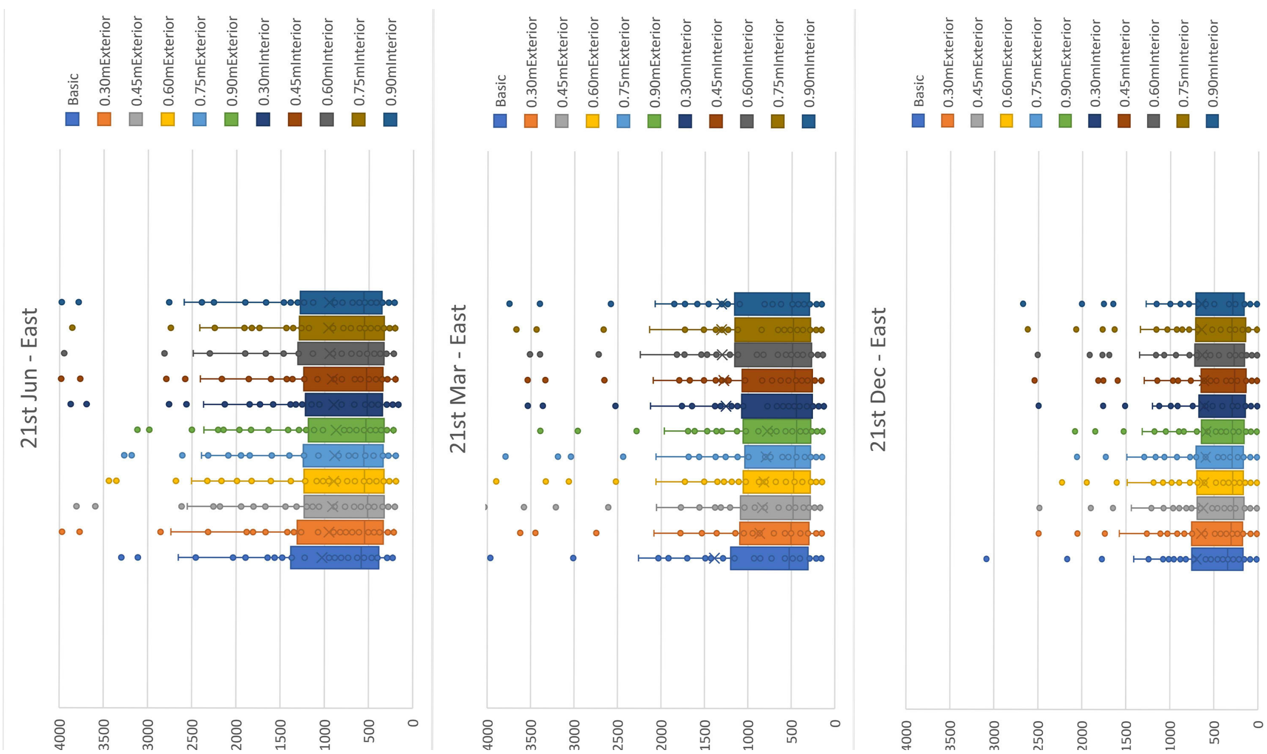
Fig. 8. The percentage of workstations with more than 250 EML.



(a)



(b)



(c)

Fig. 9. (**a**) Equivalent Melanopic Lux, (**b**) Vertical Photopic illuminance, (**c**) photopic illuminance on work planes.

EML by the interior and exterior light shelves with 0.30 and 0.90 m depth. These unimportant variations can be observed on other days.

Based on the WELL building standard, more than 75% of workstations should have at least 250 EML. Figures 8 and 9 indicates that none of the simulation models could fulfill the expectation to provide nonvisual comfort for occupants.

Additionally, Table 5 indicates minor changes in vertical photopic illuminance simulation days. Light shelves could not

Table 6. The average Equivalent Melanopic Lx (>250), Vertical Photopic Illuminance (< 1500 lx), Photopic lx on working plane (>300 lx), the percentage of each indoor that met the conditions, Orientation: West.

West	S	D (cm)	Equivalent Melanopic Lux (EML)						Vertical Photopic Illuminance (lx)						Photopic Illuminance on Work Planes (lx)					
			21st June		21st March		21st December		21st June		21st March		21st December		21st June		21st March		21st December	
			Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.	Ave.	Min.
	B		1005	120	496	10	1399	119	1075	122	557	13	1564	118	4473	256	774	25	3500	176
	E	**30**	926	135	454	9	1335	97	983	137	512	11	1492	100	4328	291	711	27	3394	178
		45	809	127	442	11	1314	100	842	131	498	14	1464	100	3301	258	699	24	3358	172
		60	775	116	430	10	1271	92	805	122	483	13	1408	94	3265	267	675	25	2859	184
		75	758	137	414	11	1070	122	784	144	464	14	1175	122	3218	233	656	21	2831	177
		90	760	139	411	10	1067	97	781	145	460	12	1166	101	3197	280	644	24	2812	212
	I	**30**	872	120	422	9	939	112	923	123	471	12	1048	111	2904	237	661	26	2555	162
		45	881	126	413	9	951	83	933	129	461	13	1062	85	2934	236	675	23	2597	159
		60	898	128	436	10	966	100	953	131	488	14	1082	101	2976	242	691	27	2626	189
		75	903	124	449	9	974	106	960	129	504	12	1092	106	2994	263	703	25	2860	191
		90	916	138	448	10	994	84	975	141	506	13	1118	86	3003	271	726	23	2876	185

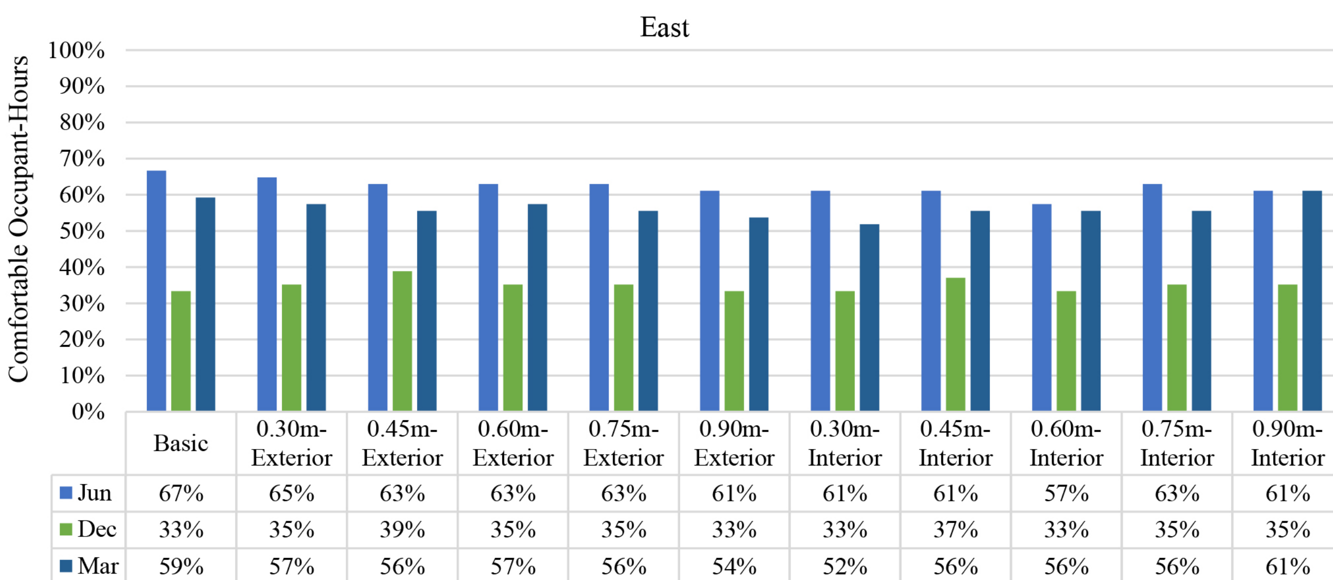


Fig. 10. The percentage of workstations with more than 250 EML.

significantly regulate the amount of photopic illuminance at the eye level. For example:

On simulation days, the highest observed averages are 591, 480, 596 lx provided by the base model. When they are compared to the averages after applying light shelves, insignificant variations can be recognized.

Furthermore, according to Table 5 and Figs. 8 and 9, employing light shelves insignificantly alters photopic illuminance (lx) on work planes. For instance:

- On 21st March, the difference between the highest and lowest averages is 122 lx. It confirmed that the maximum average amount of natural light for task performance does not experience noticeable changes.

4.1.3. Performance of light shelves, Orientation: West

Table 6 and Figs. 10 and 11 describe the results of simulation about daylight performance of models. Accordingly, employing light shelves do not noticeably change EML achieved by a simple window (the base model):

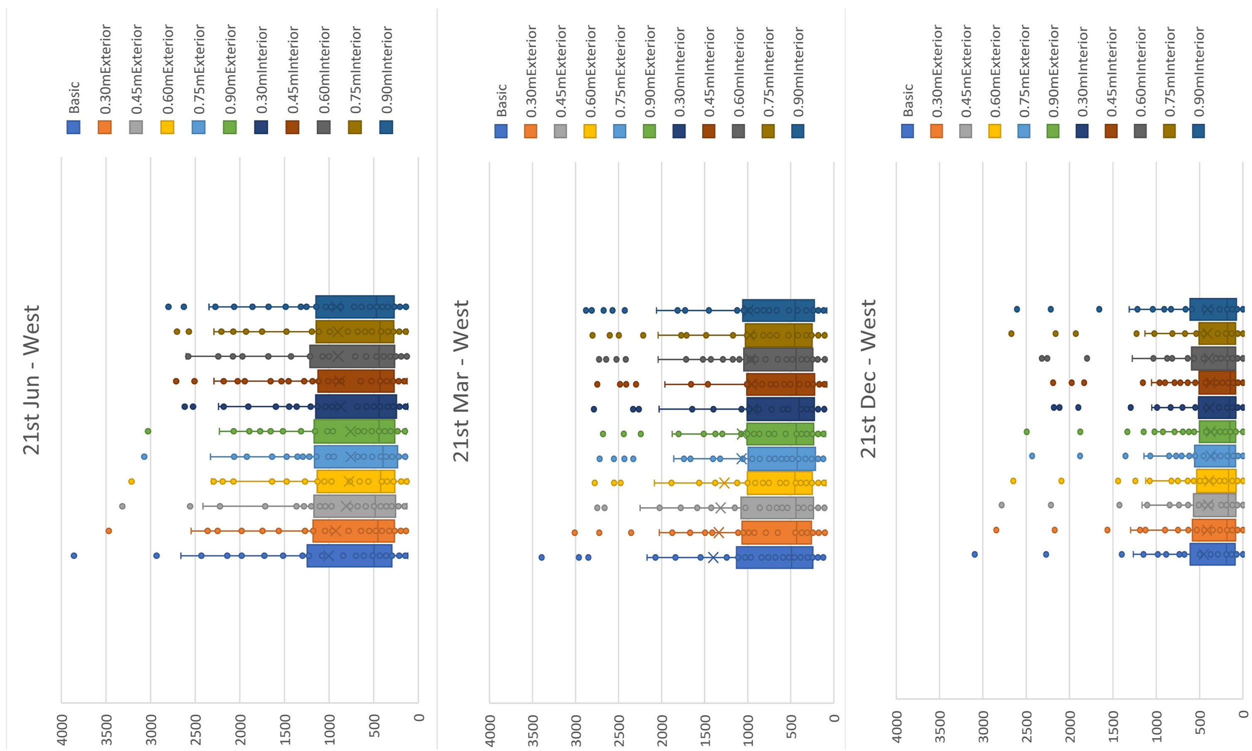
- On 21st December, the average EML with no light shelf was 1399 EML. While light shelves reduce the average EML on the simulation days, the changes are not noticeable. For example, applying light shelves reduced equivalent melanopic to 939 (interior light shelf with a depth of 0.30).

Additionally, the average vertical photopic illuminance (Lx) experienced a decrease on all three days. Overall, the base model provided the maximum amount of natural light at eye level on the simulation days.

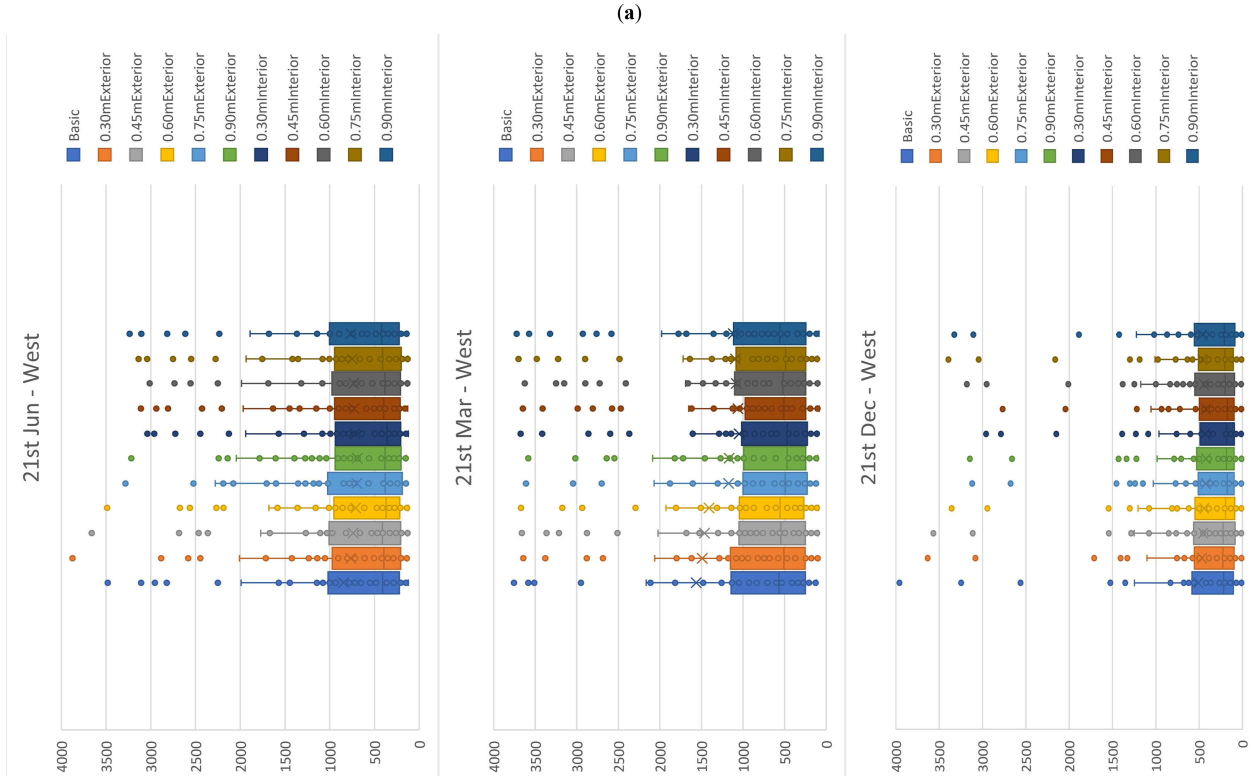
Moreover, applying light shelves reduces the photopic values on working planes. Overall, the best performance in providing adequate natural light for task performance is with the base model on the simulation days 4473, 774, 3500 lx.

5. Discussion

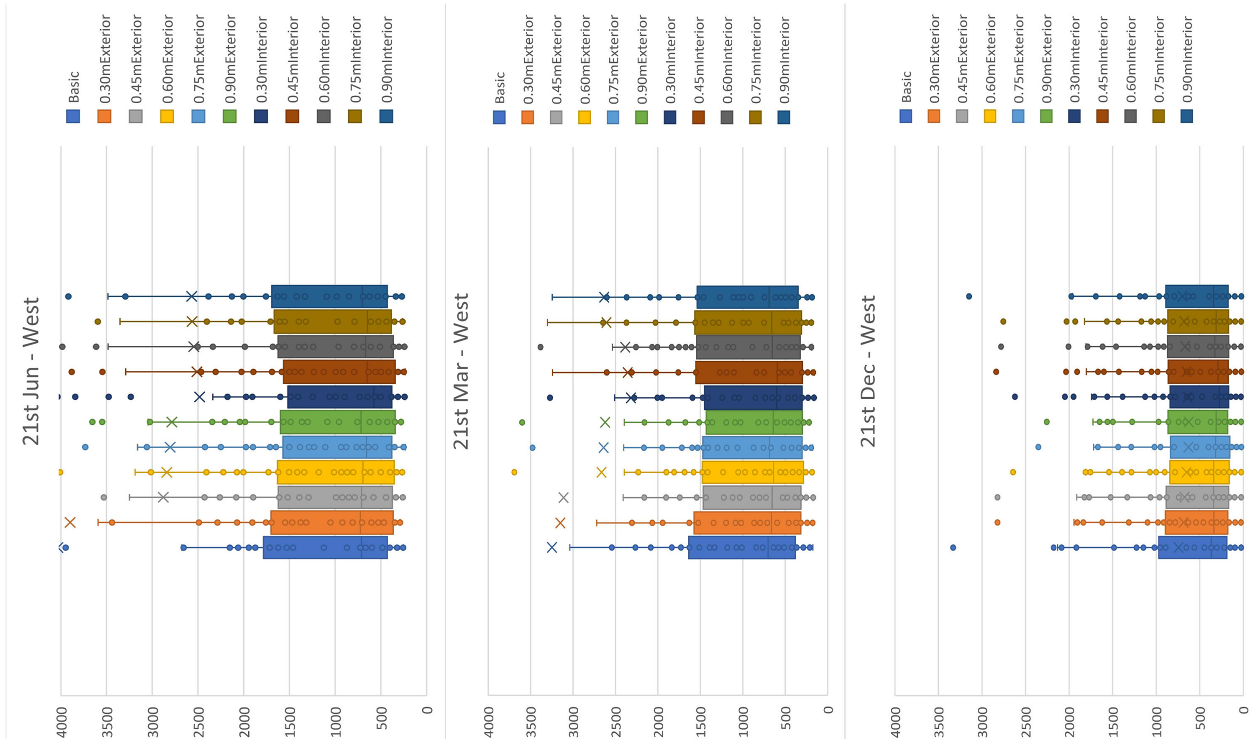
The paper aims to investigate the daylight performance of light shelves and their visual and nonvisual effects on occupants in an office space. To this end, the authors simulated ten light shelves with different configurations through a human-centric simulation-based approach. In detail, visual comfort, task performance, and circadian stimulus indicators were selected. Accordingly, three following conditions were set that if a model could provide simultaneously, the occupants would be in a comfortable space both visually and non-visually: 75% workstations with Equivalent Melanopic Lux> 250 EML concurrently with Vertical Photopic illuminance < 1500 lx, and Photopic illuminance on working plane > 300 lx.



(a)



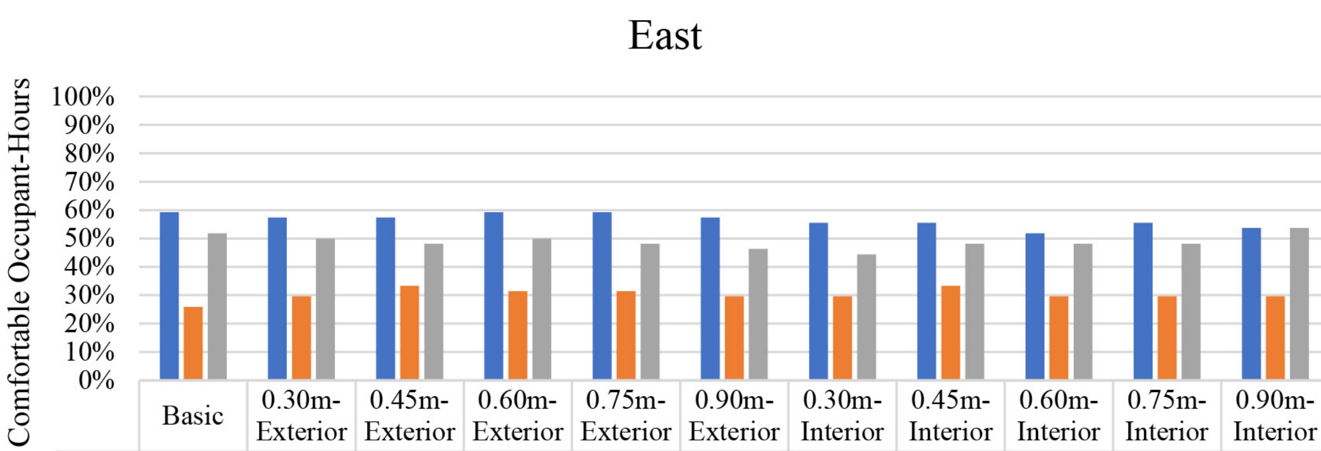
(b)



(c)

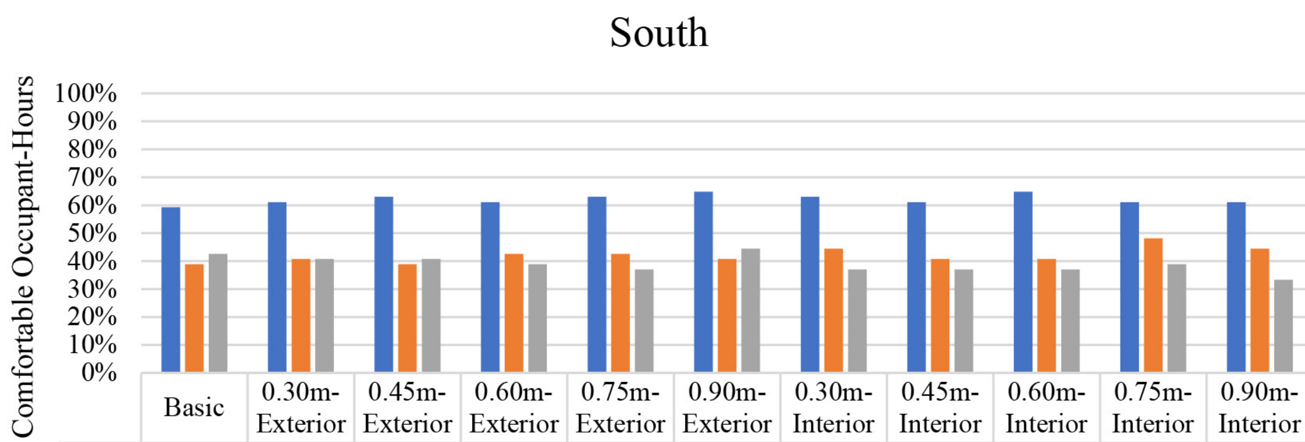
Fig. 11. (**a**) Equivalent Melanopic Lx, (**b**) Vertical Photopic illuminance, (**c**) photopic illuminance on work planes.

The overall comparison of simulated models indicated insignificant differences in Eastward and Westward orientations as expected. In detail, Figs. 4-11 and Tables 4-6 revealed that light shelves could not fulfill expectations about the requirement of the appropriate amount of daylight to provide occupants with both visual and nonvisual comfort. Although in the literature review, section 2, most of the studies mentioned the efficiency of light shelves, the discussed performance was solely limited to work plane illuminance considering task performance instead of occupants' comfort at eye level. This study encountered vertical photopic and Equivalent melanopic lux beside task performance, resulting in decreased efficiency in light shelves' performance compared to the discussed literature. The decreased efficiency is due to the height difference between photosensors on the working plane (0.76 m) and at eye level (1.20 m), owning to the height of light shelves (2.00 m).



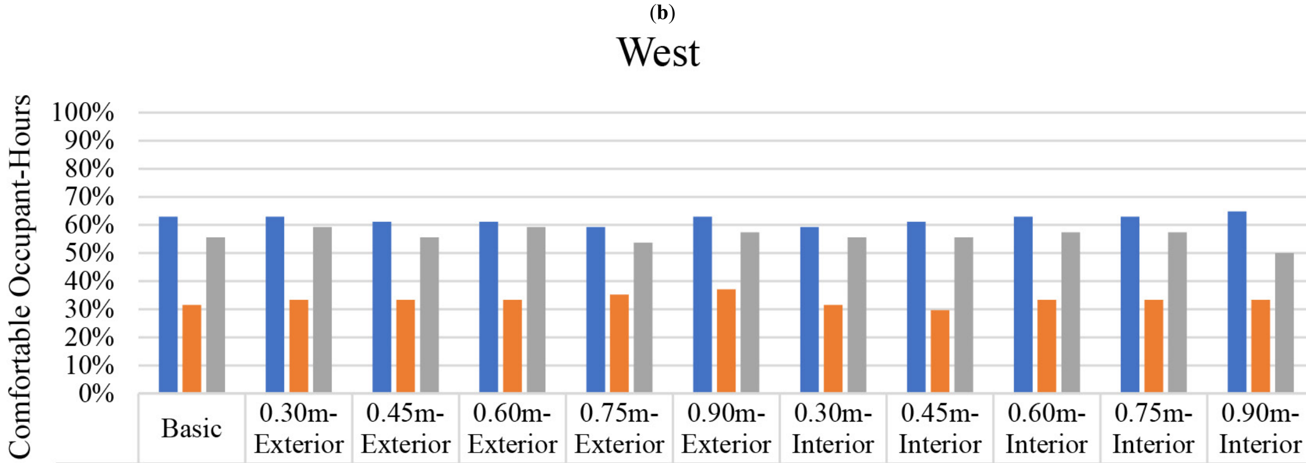
	Basic	0.30m-Exterior	0.45m-Exterior	0.60m-Exterior	0.75m-Exterior	0.90m-Exterior	0.30m-Interior	0.45m-Interior	0.60m-Interior	0.75m-Interior	0.90m-Interior
Jun	59%	57%	57%	59%	59%	57%	56%	56%	52%	56%	54%
Dec	26%	30%	33%	31%	31%	30%	30%	33%	30%	30%	30%
Mar	52%	50%	48%	50%	48%	46%	44%	48%	48%	48%	54%

(a)



	Basic	0.30m-Exterior	0.45m-Exterior	0.60m-Exterior	0.75m-Exterior	0.90m-Exterior	0.30m-Interior	0.45m-Interior	0.60m-Interior	0.75m-Interior	0.90m-Interior
Jun	59%	61%	63%	61%	63%	65%	63%	61%	65%	61%	61%
Dec	39%	41%	39%	43%	43%	41%	44%	41%	41%	48%	44%
Mar	43%	41%	41%	39%	37%	44%	37%	37%	37%	39%	33%

(**b**)



	Basic	0.30m-Exterior	0.45m-Exterior	0.60m-Exterior	0.75m-Exterior	0.90m-Exterior	0.30m-Interior	0.45m-Interior	0.60m-Interior	0.75m-Interior	0.90m-Interior
Jun	63%	63%	61%	61%	59%	63%	59%	61%	63%	63%	65%
Dec	31%	33%	33%	33%	35%	37%	31%	30%	33%	33%	33%
Mar	56%	59%	56%	59%	54%	57%	56%	56%	57%	57%	50%

(**c**)

Fig. 12. The percentage of workstations simultaneously meet the three conditions of (**a**) 75.00% workstations with more than 250 EML, (**b**) Vertical Photopic Illuminance < 1500 lx, (**c**) Photopic Illuminance on working plane > 300 lx.

Figure 12 gives a comprehensive overview of the percentage of workstations that simultaneously met the abovementioned conditions.

In the East, for instance, the base model kept 26% of work stations meeting the conditions on 21st December. Although this percentage is increased up to 33% by applying light shelves, the changes indicate the necessity of applying artificial light or other daylight systems. On two other days, light shelves mostly underperformed compared to the base model. They decreased the percentage of occupants with visual and nonvisual comfort at the same time.

In the South, subtle fluctuations in the percentage of working stations meeting the objectives are reported. In detail, an increase of 6% and 9% are achieved by the light shelves on June and 21st December, respectively. Figure 7 also depicts a minor decrease from 43% to 33% by the base model and the interior light shelf with 0.90 depth.

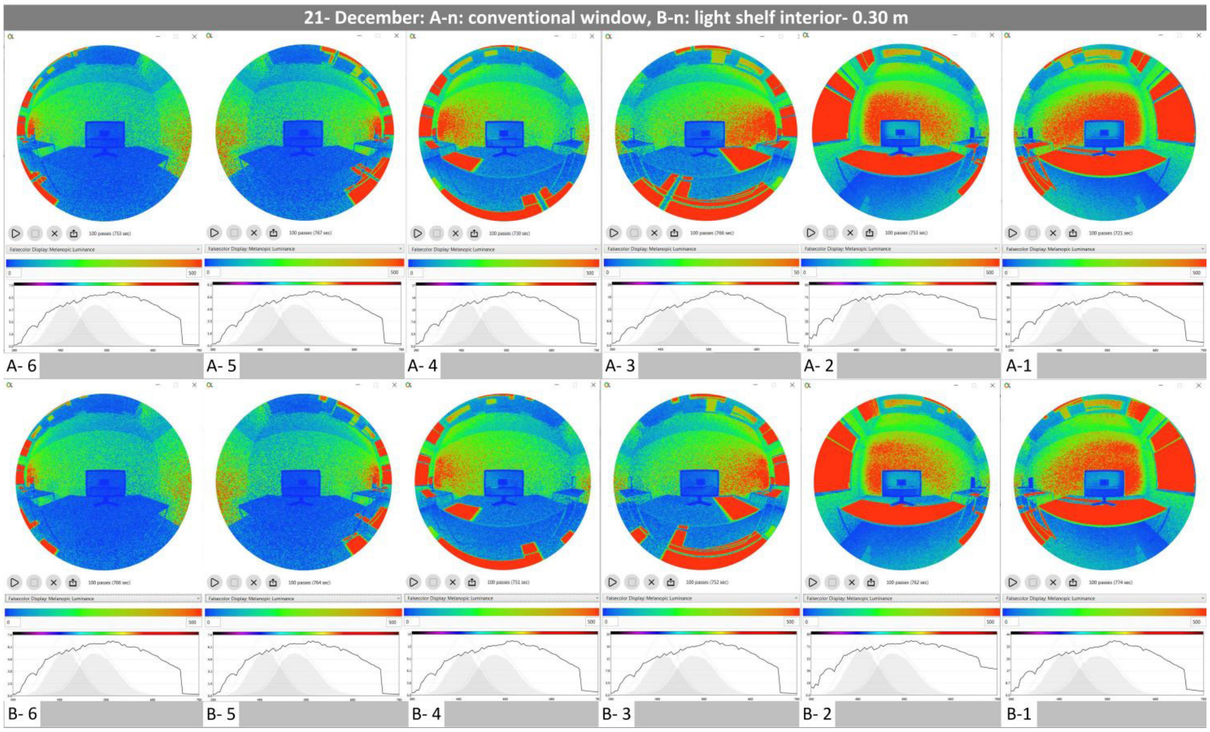
In the West, similarly insignificant alteration in the percentages of working stations can be noted.

Overall, extracted information from Figs. 4-11 and Tables 4-6 gave an in-depth understanding that the percentages of space that satisfied the three conditions concurrently were roughly law. They disclosed critical issues about the performance of light shelves to provide a comfortable space for occupants during working hours.

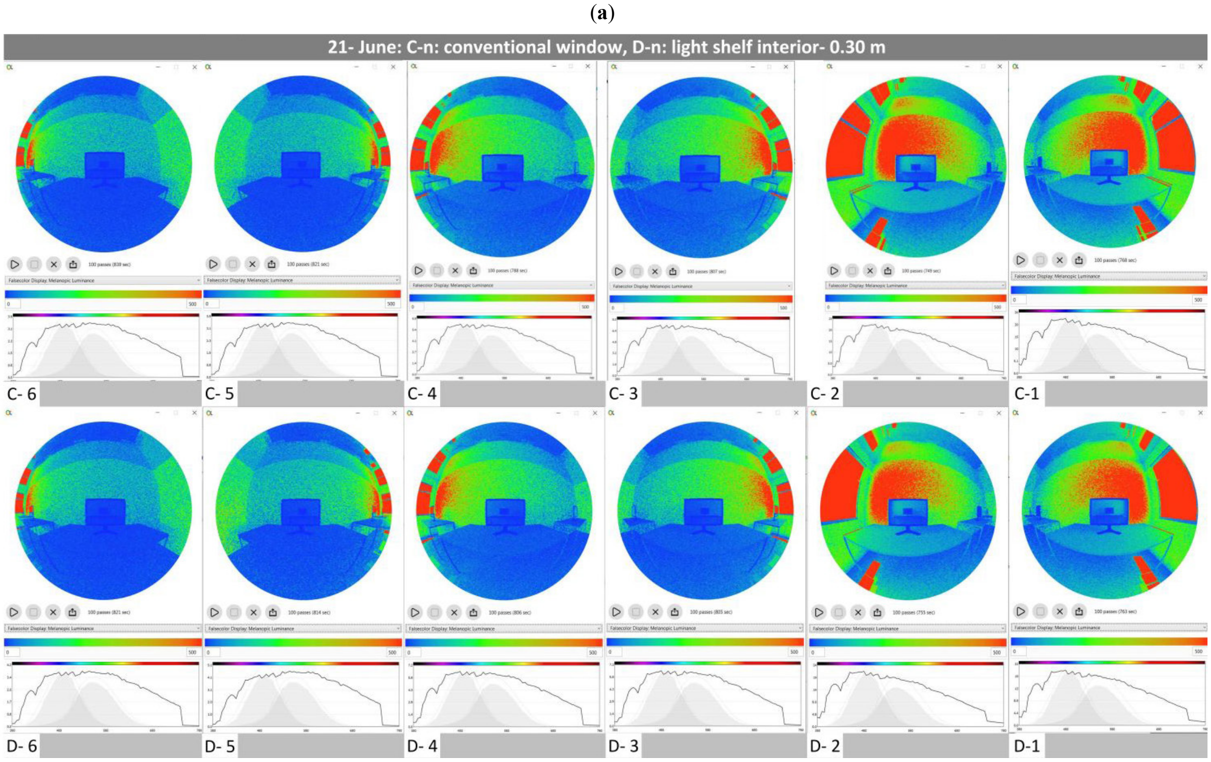
6. Conclusion

The contribution of daylight to a comfortable environment for humans has been the subject of research for years. Daylight performance evaluations often rely on metrics mainly related to task performance that is evaluated mainly by the grid distributed in space that does not represent humans in space; instead, assess the potential of space in that metric. Recently, a new approach has been developed that discusses the nonvisual effects of light, such as circadian rhythm; subsequently, new metrics and simulation tools are introduced to analyze this aspect.

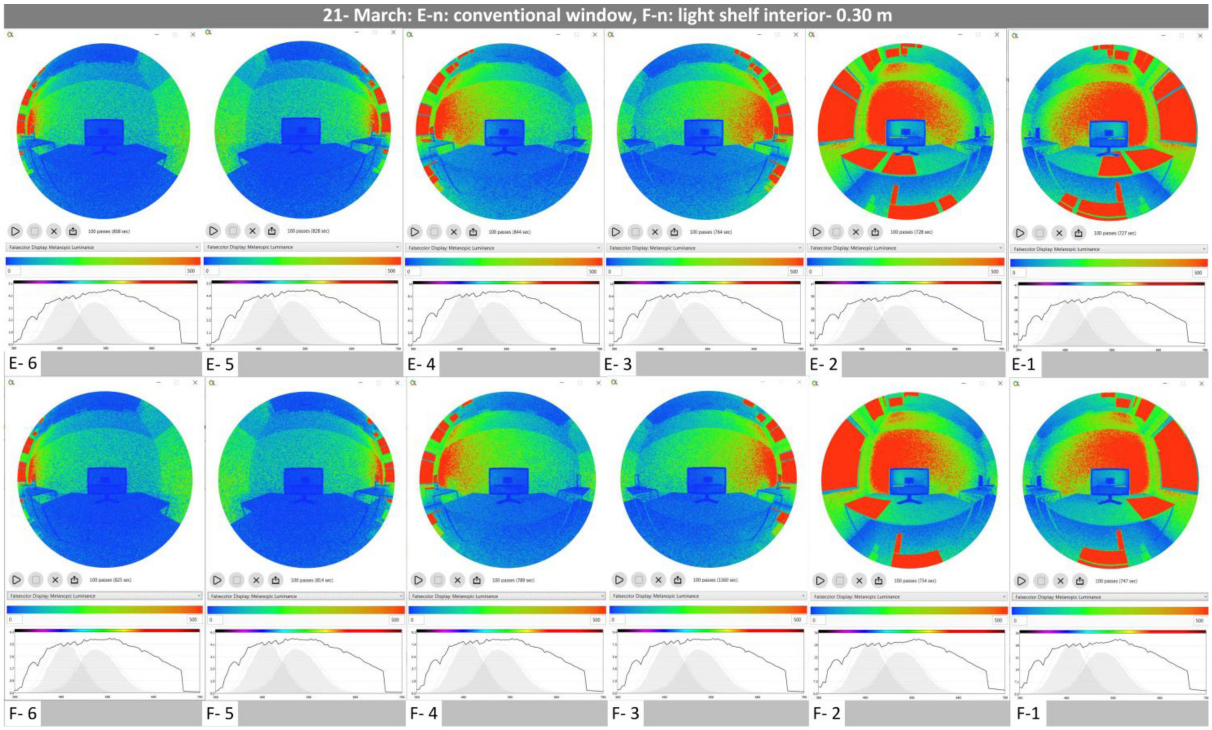
This paper evaluated the performance of light shelves via a human-centric simulation-based approach. Therefore, indicators including circadian stimulus, visual comfort, and task performance were selected to assess the effectiveness of light shelves based on three following conditions: (1) 75.00% workstations with more than 250 Equivalent Melanopic Lux, (2) Vertical Photopic illuminance < 1500 lx, (3) Photopic illuminance on working plane > 300 lx. Meeting the three conditions altogether would offer occupants a satisfying working space. All metric in this approach has been evaluated based on occupant position and field vision. The simulation outcomes are reported in Tables 4-6 and Figs. 4-11.



(**a**)



(**b**)



(c)

Fig. 13. (**a**)-(**c**) Performance of the light shelf with a depth of 0.30 m and the base case on the South orientation.

Findings indicated that although applying light shelves impacts the metrics, minor changes in a given orientation. Notably, they were ineffective in offering occupants' nonvisual comfort within the office space over working hours. According to Tables 4-6 and Figs. 4-11 the chief problem was with the equivalent melanopic lux. Since two out of six occupants are at the corner of space and we have a human-centric assessment approach, inadequate EML levels were observed in all orientations on the simulation days. Besides, changes in the photopic illuminance at the eye and workstations levels were not substantial (Fig. 13). Compared to previous literature studying light shelves, the minor enhancement of results is because of the height level of photosensors applied in this research. Generally, these sensors are located at 0.76 m, representing the work plane, while the vertical photopic illuminance and Equivalent Melanopic Lux require the photosensors to be positioned at the eye level of a sitting occupant (1.20 m).

Several reasons were identified affecting light shelves' performance that can be the subject of future studies:

- The correlation of geometrical properties of the reference room with the performance of light shelves.
- The focus of the current study is on daylight. Future research can evaluate light shelves using daylight performance and artificial lighting design.
- Standard structural materials are considered in this work. Changing them would affect the indoor environment by considering occupants' preferences and the optical properties of materials.

Contributions

All the authors contributed equally.

Declaration of competing interest

Authors report no conflicts of interest.

References

[1] R. A. Rizi and A. Eltaweel, A user detective adaptive facade towards improving visual and thermal comfort, Journal of Building Engineering 33 (2021).

[2] M. L. Amundadottir, S. Rockcastle, M. Sarey Khanie, and M. Andersen, A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior, Building and Environment 113 (2017) 5-21.

[3] K. M. Beauchemin and P. Hays, Dying in the dark: Sunshine, gender and outcomes in myocardial infarction, Journal of the Royal Society of Medicine 91 (1998) 352-354.

[4] S. M. Hosseini, M. Mohammadi, T. Schröder, and O. Guerra-Santin, Integrating interactive kinetic façade design with colored glass to improve daylight performance based on occupants' position, Journal of Building Engineering 31 (2020).

[5] B. Ransley, An Overview of Recent Findings on the Effect of Light on Circulation Rhythms, Journal of Sustainable Design & Applied Research 8 (2020).

[6] C. L. Ruby, Adenosine and Glutamate in Neuroglial Interaction, in Modulation of Sleep by Obesity, Diabetes, Age, and Diet, Elsevier (2015) 321-327.

[7] S. W. Lockley, G. C. Brainard, and C. A. Czeisler, High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light, Journal of Clinical Endocrinology and Metabolism 88 (2003).

[8] J. A. Veitch, G. van den Beld, G. C. Brainard, and J. E. Roberts, Ocular Lighting Effects on Human Physiology, Mood and Behavior (2004).

[9] S. W. Lockley, Circadian Rhythms: Influence of Light in Humans, Encyclopedia of Neuroscience, Elsevier Ltd (2009) 971-988.

[10] I. Provencio, I. R. Rodriguez, G. Jiang, W. P. Hayes, E. F. Moreira, and M. D. Rollag, A novel human opsin in the inner retina, Journal of Neuroscience 20 (2000) 600-605.

[11] J. J. Gooley, J. Lu, T. C. Chou, T. E. Scammell, and C. B. Saper, Melanopsin in cells of origin of the retinohypothalamic tract, Nature Neuroscience 4 (2001).

[12] S. Hattar, H. W. Liao, M. Takao, D. M. Berson, and K. W. Yau, Melanopsin-containing retinal ganglion cells: Architecture, projections, and intrinsic photosensitivity, Science 295 (2002) 1065-1070.

[13] G. C. Brainard, J. R. Hanifin, J. Greeson, M. B. Byrne, Glickman, E. Gerner, and M. Rollag, Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor, Journal of Neuroscience 21 (2001) 6405-6412.

[14] K. Thapan, J. Arendt, and D. J. Skene, An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans, Journal of Physiology 535 (2001) 261-267.

[15] C. Cajochen, W.S. Lockley, G. C. Brainard, and A. C. Czeisler, High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light, Journal of Clinical Endocrinology and Metabolism 90 (2005) 1311-1316.

[16] S. L. Chellappa, R. Steiner, P. Blattner, P. Oelhafen, T. Götz, and C. Cajochen, Non-visual effects of light on melatonin, alertness and cognitive performance: Can blue-enriched light keep us alert?, PLoS ONE 6 (2011).

[17] J. J. Gooley, S. M. W. Rajaratnam, G. C. Brainard, R. E. Kronauer, C. A. Czeisler, and S. W. Lockley, Spectral responses of the human circadian system depend on the irradiance and duration of exposure to light, Science Translational Medicine 2 (2010).

[18] USGBC, LEED v4 CREDITS for Building Design and Construction, LEED Publications (2019) 147.

[19] M. L. Amundadottir, S. W. Lockley, and M. Andersen, Unified framework to evaluate non-visual spectral effectiveness of light for human health, Lighting Research and Technology 49 (2017) pp. 673-696.

[20] CIE System for Metrology of Optical Radiation For Iprgc-Influenced Responses To Light (2018), Vienna, Austria.

[21] W. Krzysztof, Calculation of the Circadian Illuminance Distribution With Radiance, Radiance-Online.Org, 1-10.

[22] G. J. Ward, The RADIANCE lighting simulation and rendering system, Proceedings of the 21st Annual Conference on Computer Graphics and Interactive Techniques (1994) 459-472.

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

[24] C. S. Pechacek, M. Andersen, and S. W. Lockley, Preliminary Method for Prospective Analysis of the Circadian Efficacy of (Day)Light with Applications to Healthcare Architecture, LEUKOS - Journal of Illuminating Engineering Society of North America 5 (2008) 1-26.

[25] J. Mardaljevic, M. Andersen, N. Roy, and J. Christoffersen, A framework for predicting the non-visual effects of daylight - Part II: The simulation model, Lighting Research and Technology 46 (2014) 388-406.

[26] I. Acosta, R. P. Leslie, and M. G. Figueiro, Analysis of circadian stimulus allowed by daylighting in hospital rooms, Lighting Research and Technology 49 (2017) 49–61.

[27] M. T. Brennan, A. R. Collins, and Z. G. F. A. Llp, Outcome-Based Design for Circadian Lighting : An Integrated Approach to Simulation & Metrics, Building Performance Analysis Conference and Simulation Buildings, Chicago (2018) 141-148.

[28] Standard | WELL V2. (2021).

[29] P. J. Littlefair, Light shelves: Computer assessment of daylighting performance, Lighting Research & Technology 27 (1995) 79-91.

[30] M. E. Aiziewood, Innovative daylighting systems: An experimental evaluation, Lighting Research and Technology 25 (1993) 141-152.

[31] A. Kontadakis, A. Tsangrassoulis, L. Doulos, and S. Zerefos, A Review of Light Shelf Designs for Daylit Environments, Sustainability 10 (2017).

[32] IEA SHC, Daylight in Buildings - a source book on daylighting systems and components, IEA SHC Task 21 - ECBCS Anexo 29 (2000) 262- 268.

[33] J. Wienold and J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy and Buildings 38 (2006),743–757.

[34] S. Rockcastle, M. L. Amundadottir, and M. Andersen, Contrast measures for predicting perceptual effects of daylight in architectural renderings, Lighting Research and Technology 49 (2017), 882–903.

[35] M. Sarey Khanie, Human responsive daylighting in offices: a gaze-driven approach for dynamic discomfort glare assessment (2015), EPFL, Switzerland.

[36] S. Saljoughinejad and S. Rashidi Sharifabad, Classification of climatic strategies, used in Iranian vernacular residences based on spatial constituent elements, Building and Environment 92 (2015) 475–493.

[37] J. Scherer, Light and libraries, Library HiTech 17 (1999) 358-372.

[38] S. N. Hosseini, S. M. Hosseini, and M. HeiraniPour, The Role of Orosi's Islamic Geometric Patterns in the Building Façade Design for Improving Occupants' Daylight Performance, Journal of Daylighting 7 (2020) 201-221.

[39] S. M. Hosseini, M. Mohammadi, A. Rosemann, and T. Schröder, Quantitative Investigation Through Climate-based Daylight Metrics of Visual Comfort Due to Colorful Glass and Orosi Windows in Iranian Architecture, Journal of Daylighting 5 (2018).

[40] R. Hyde, Climate responsive design: a study of buildings in moderate and hot humid climates. Taylor & Francis (2013).

[41] A. Jovanović, P. Pejić, S. Djorić-Veljković, J. Karamarković, and M. Djelić, Importance of building orientation in determining daylighting quality in student dorm rooms: Physical and simulated daylighting parameters' values compared to subjective survey results, Energy and Buildings 77 (2014) 158-170.

[42] C. Munoz, P. Esquivias, D. Moreno, I. Acosta, and J. Navarro, Climate-based daylighting analysis for the effects of location, orientation and obstruction, Lighting Research & Technology 46 (2014) 268-280.

[43] C. Brebbia, Environmental Health Risk IV. WIT Press (2007).

[44] I. L. Wong, A review of daylighting design and implementation in buildings, Renewable and Sustainable Energy Reviews 74 (2017) 959-968.

[45] M. Boubekri, Daylighting, Architecture and Health: Building Design Strategies. Architectural Press (2008).

[46] M. Aries, M. Aarts, and J. van Hoof, Daylight and health: A review of the evidence and consequences for the built environment, Lighting Research & Technology 47 (2015) 6-27.

[47] S. M. Hosseini, M. Mohammadi, A. Rosemann, T. Schröder, J. Lichtenberg, and P. Woods, A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review, Building and Environment 153 (2019) 186-204.

[48] S. M. Hosseini, M. Mohammadi, and O. Guerra-Santin, Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes, Building and Environment 165 (2019).

[49] A. Tabadkani, M. Valinejad Shoubi, F. Soflaei, and S. Banihashemi, Integrated parametric design of adaptive facades for user's visual comfort, Automation in Construction 106 (2019).

[50] P. Littlefair, Designing with innovative daylighting. United Kingdom: Watford: Building Research Establishment (1996).

[51] A. Tsangrassoulis, A Review of Innovative Daylighting Systems, Advances in Building Energy Research 2 (2008) 33-56.

[52] A. De Herde and A. Nihoul, Overheating and daylighting in commercial buildings, Renewable Energy 5 (1994) 917-919.

[53] J. T. Kim and G. Kim, Overview and new developments in optical daylighting systems for building a healthy indoor environment, Building and Environment 45 (2010) 256-269.

[54] H. D. Cheung and T. M. Chung, Calculation of the Vertical Daylight Factor on Window Façades in a Dense Urban Environment, Architectural Science Review 48 (2005) 81-91.

[55] A. Meresi, Evaluating daylight performance of light shelves combined with external blinds in south-facing classrooms in Athens, Greece, Energy and Buildings 116 (2016) 190-205.

[56] M. Moazzeni and Z. Ghiabaklou, Investigating the Influence of Light Shelf Geometry Parameters on Daylight Performance and Visual Comfort, a Case Study of Educational Space in Tehran, Iran, Buildings 6 (2016).

[57] R. A. Mangkuto, F. Feradi, R. E. Putra, R. T. Atmodipoero, and F. Favero, Optimisation of daylight admission based on modifications of light shelf design parameters, Journal of Building Engineering 18 (2018) 195-209.

[58] H. Lee, H.-I. Jang, and J. Seo, A preliminary study on the performance of an awning system with a built-in light shelf, Building and Environment 131 (2018) 255-263.

[59] Y.-W. Lim and C. Y. S. Heng, Dynamic internal light shelf for tropical daylighting in high-rise office buildings, Building and Environment 106 (2016) 155-166.

[60] T. Dogan and P. Stec, Prototyping a façade-mounted, dynamic, dual-axis daylight redirection system, Lighting Research & Technology 50 (2018) 583-595.

[61] B. J. Al-Khatatbeh and S. N. Ma'bdeh, Improving visual comfort and energy efficiency in existing classrooms using passive daylighting techniques, Energy Procedia 136 (2017) 102-108.

[62] A. Motamed, L. Deschamps, and J.-L. Scartezzini, On-site monitoring and subjective comfort assessment of a sun shadings and electric lighting controller based on novel High Dynamic Range vision sensors, Energy and Buildings 149 (2017) 58-72.

[63] M. Roshan and A. S. Barau, Assessing Anidolic Daylighting System for efficient daylight in open plan office in the tropics, Journal of Building Engineering 8 (2016) 58-69.

[64] M. V. Collados, D. Chemisana, and J. Atencia, Holographic solar energy systems: The role of optical elements, Renewable and Sustainable Energy Review 59 (2016) 130-140.

[65] J. Song, G. Luo, L. Li, K. Tong, Y. Yang, and J. Zhao, Application of heliostat in interior sunlight illumination for large buildings, Renewable Energy 121 (2018) 19-27.

[66] M. M. Marmoush, H. Rezk, N. Shehata, J. Henry, and M. R. Gomaa, A novel merging Tubular Daylight Device with Solar Water Heater - Experimental study, Renewable Energy 125 (2018) 947-961.

[67] B. Malet-Damour, S. Guichard, D. Bigot, and H. Boyer, Study of tubular daylight guide systems in buildings: Experimentation, modelling and validation, Energy and Buildings 129 (2016) 308-321.

[68] L. Sharma, S. F. Ali, and D. Rakshit, Performance evaluation of a top lighting light-pipe in buildings and estimating energy saving potential, Energy and Buildings 179 (2018) 57-72.

[69] L. Sedki and M. Maaroufi, Design of parabolic solar daylighting systems based on fiber optic wires: A new heat filtering device, Energy and Buildings 152 (2017) 434-441.

[70] A. Barbón, J. A. Sánchez-Rodríguez, L. Bayón, and N. Barbón, Development of a fiber daylighting system based on a small scale linear Fresnel reflector: Theoretical elements, Applied Energy 212 (2018) 733-745.

[71] I. Ullah, H. Lv, A. J.-W. Whang, and Y. Su, Analysis of a novel design of uniformly illumination for Fresnel lens-based optical fiber daylighting system, Energy and Buildings 154 (2017) 19-29.

[72] Y. Kim, H. J. Jeong, W. Kim, W. Chun, H. J. Han, and S. H. Lim, A comparative performance analysis on daylighting for two different types of solar concentrators: Dish vs. Fresnel lens, Energy 137 (2017) 449-456.

[73] L. Santos, A. Leitão, and L. Caldas, A comparison of two light-redirecting fenestration systems using a modified modeling technique for Radiance 3-phase method simulations, Solar Energy 161 (2018) 47-63.

[74] IEA, Daylight in Buildings, Energy Conservation in Buildings and Community Systems Program. (2010).

[75] A. Soler and P. Oteiza, Light shelf performance in Madrid, Spain, Building and Environment 32 (1997) 87-93.

[76] C. Aghemo, A. Pellegrino, and V. R. M. LoVerso, The approach to daylighting by scale models and sun and sky simulators: A case study for different shading systems, Building and Environment 43 (2008) 917-927.

[77] S.-T. Claros and A. Soler, Indoor daylight climate-comparison between light shelves and overhang performances in Madrid for hours with unit sunshine fraction and realistic values of model reflectance, Solar Energy 71 (2001) 233-239.

[78] S.-T. Claros and A. Soler, Indoor daylight climate-influence of light shelf and model reflectance on light shelf performance in Madrid for hours with unit sunshine fraction, Building and Environment 37 (2002) 587-598.

[79] G. A. Warrier and B. Raphael, Performance evaluation of light shelves, Energy and Buildings 140 (2017) 19-27.

[80] H. Lee, K. Kim, J. Seo, and Y. Kim, Effectiveness of a perforated light shelf for energy saving, Energy and Buildings 144 (2017) 144-151.

[81] U. Berardi and H. K. Anaraki, The benefits of light shelves over the daylight illuminance in office buildings in Toronto, Indoor and Built Environment 27 (2018) 244-262.

[82] A. Soler and P. Oteiza, Dependence on solar elevation of the performance of a light shelf as a potential daylighting device, Renewable Energy 8 (1996) 198-201.

[83] L. O. Beltrán, E. S. Lee, and S. E. Selkowitz, Advanced optical daylighting systems: Light shelves and light pipes, Journal of the Illuminating Engineering Society 26 (1997) 91-106.

[84] H. Lee and J. Seo, Performance Evaluation of External Light Shelves by Applying a Prism Sheet, Energies 13 (2020).

[85] T. Deguchi And M. Sato, The Effect of Color Temperature of Lighting Sources on Mental Activity Level, The Annals of physiological anthropology 11 (1992) 37-43.

[86] H. Kobayashi And M. Sato, Physiological Responses to Illuminance and Color Temperature of Lighting, The Annals of physiological anthropology 11 (1992) 45-49.

[87] T. Kozaki, S. Kitamura, Y. Higashihara, K. Ishibashi, H. Noguchi, and A. Yasukouchi, Effect of Color Temperature of Light Sources on Slow-wave Sleep, Journal of Physiological Anthropology and Applied Human Science 24 (2005) 183-186.

[88] A. Kruithof, Tubular luminescence lamps for general illumination, Philips Technical Review 6 (1941) 65-96.

[89] H. Mukae And M. Sato, The Effect of Color Temperature of Lighting Sources on the Autonomic Nervous Functions, The Annals of physiological anthropology 11 (1992) 533-538.

[90] A.-M. Chang, D. Aeschbach, J. F. Duffy, and C. A. Czeisler, Evening use of light-emitting eReaders negatively affects sleep, circadian timing, and next-morning alertness," Proceedings of the National Academy of Sciences 112 (2015) 1232-1237.

[91] A. S. Fisk, S. K. E. Tam, L. A. Brown, V. V. Vyazovskiy, D. M. Bannerman, and S. N. Peirson, Light and Cognition: Roles for Circadian Rhythms, Sleep, and Arousal, Frontiers in Neurology 9 (2018).

[92] M. Figueiro, R. Nagare, and L. Price, Non-visual effects of light: How to use light to promote circadian entrainment and elicit alertness, Lighting Research & Technology 50 (2018) 38-62.

[93] M. Andersen, J. Mardaljevic, and S. Lockley, A framework for predicting the non-visual effects of daylight – Part I: photobiology- based model, Lighting Research & Technology 44 (2012), 37–53.

[94] C. S. Pittendrigh, Circadian rhythms and the circadian organization of living systems, Cold Spring Harbor symposia on quantitative biology 25 (1960) 159-184.

[95] S. Lockley, J. Arendt, and D. J. Skene, Visual impairment and circadian rhythm disorders, Dialogues Clin Neurosci 9 (2007).

[96] T. Katsuura and S. Lee, A review of the studies on nonvisual lighting effects in the field of physiological anthropology, Journal of Physiological Anthropology 38 (2019).

[97] A. Lewy, T. Wehr, F. Goodwin, D. Newsome, and S. Markey, Light suppresses melatonin secretion in humans, Science 210 (1980) 1267-1269.

[98] J. Arendt, Melatonin and the pineal gland: Influence on mammalian seasonal and circadian physiology, Reviews of Reproduction 3 (1998) 13-22.

[99] T. M. Schmidt, A.M. Chang, D. Aeschbach, J. F. Duffy, and C. A. Czeisler, A Role for Melanopsin in Alpha Retinal Ganglion Cells and Contrast Detection 82 (2014) 781-788.

[100] T. Sonoda, J. Y. Li, N. W. Hayes, J. C., Chan, Y. Okabe, S. Belin, H. Nawabi, and T. M. Schmidt, A noncanonical inhibitory circuit dampens behavioral sensitivity to light, Science 368 (2020) 527-531.

[101] P. Khademagha, M. B. C. Aries, A. L. P. Rosemann, and E. J. van Loenen, Implementing non- image-forming effects of light in the built environment: A review on what we need, Building and Environment 108 (2016), 263–272.

[102] M. J. Witte, R. H. Henninger, G. Jason, and C. D. B, Testing and Validation of a New Building Energy Simulation Program, Conference: Building Simulation (2001) 353–360.

[103] C. F. Reinhart and J. Wienold, The daylighting dashboard - A simulation-based design analysis for daylit spaces, Building and Environment 46 (2011) 386-396.

[104] M. Andersen, Unweaving the human response in daylighting design, Building and Environment 91 (2015) 101-117.

[105] L. Heschong, Day lighting and student performance, ASHRAE J 44 (2002) 65-67.

[106] A. Sánchez-Cano and J. Aporta, Optimization of Lighting Projects Including Photopic and Circadian Criteria: A Simplified Action Protocol, Applied Sciences 10 (2020).

[107] M. G. Figueiro, K. Gonzales, and D. Pedler, Designing with Circadian Stimulus. Lighting Design and Applications (LD+A), The magazine of the Illuminating Engineering Society of North America (IESNA).

[108] M. Rea, M. Figueiro, A. Bierman, and R. Hamner, Modelling the spectral sensitivity of the human circadian system, Lighting Research & Technology 44 (2012) 386-396.

[109] R. J. Lucas, T. Sonoda, J. Y. Li, N. W. Hayes, J. C. Chan, Y. Okabe, S. Belin, H. Nawabi, and T.M. Schmidt, Measuring and using light in the melanopsin age, Trends in Neurosciences 37 (2014) pp. 1-9.

[110] International Well Building Institute, The WELL Building Standard. V1 (2021).

[111] K. Devlin, A. Chalmers, A. Wilkie, and W. Purgathofer, Tone Reproduction and Physically Based Spectral Rendering (2002).

[112] M. Inanici, M. Brennan, and E. Clark, SPECTRAL DAYLIGHTING SIMULATIONS : COMPUTING CIRCADIAN LIGHT University of Washington , Department of Architecture (2015) 1245-1252.

[113] Solemma LLC | ALFA.

[114] P. Balakrishnan and J. A. Jakubiec, Spectral Rendering with Daylight: A Comparison of Two Spectral Daylight Simulation Platforms (2020).

[115] Rhino - Rhinoceros 3D .
[116] C. F. Reinhart, J. A. Jakubiec, and D. Ibarra, Definition of a reference office for standardized evaluations of dynamic façade and lighting technologies, Proceedings of BS: 13th Conference of the International Building Performance Simulation Association (2013) 3645-3652.
[117] J. A. Jakubiec, C. F. Reinhart, and K. Van Den Wymelenber, Towards an integrated framework for predicting visual comfort conditions from luminance-based metrics in perimeter daylight spaces, Conference of International Building Performance Simulation Association (2015) 1189-1196.
[118] K. Van Den Wymelenberg and M. Inanici, A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight, LEUKOS 10 (2014) 145-164.
[119] CIBSE, Code for Interior Lighting. London, UK: Chartered Institution of Building Services Engineers (CIBSE) (1994).
[120] C. Reinhart, Daylighting Handbook II. Building Technology Press (2018).
[121] C. Reinhart, Daylight performance predictions, Building performance simulation for design and operation, First Edit. (2011).
[122] M.C. Dubois, Impact of Shading Devices on Daylight Quality in Offices - Simulations with Radiance, Research Report (2001). [Online]. Available: http://www.byggark.lth.se/shade/bok-3062.pdf.