Colour and Colorimetry
Multidisciplinary Contributions

Vol. XIII B

Edited by Veronica Marchiafava and Francesca Valan

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Index

Circadian lighting design: analysis of the properties of natural lighting in a home environment

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1. Introduction

Light is so important to human beings that its main definition from the Commission International de l'Eclairage [CIE] is linked to the human capabilities. The photometric quantities are based on the human visual responses to a specific portion of the electromagnetic spectrum (380-780nm) weighted to the visibility curve $V(\lambda)$. Furthermore, it has been scientifically established that light is useful for tuning the principal biological clock of humans to the cycles of night and day. By influencing non image forming (NIF) processes, lighting (quantity, duration and time, distribution and direction, spectral power distribution SPD) has a fundamental role in physical, mental and behavioural regulation. In sync with the circadian rhythm, many physiological and neuropsychological phenomena are regulated: heart rate, body temperature, hormonal secretion, brain wave activities and blood pressure. Those can consequently affect cognitive performances, subjective alertness, short term memory, appetite and wakefulness/sleep. The NIF effects of light have been extensively studied and experienced in different field of application such as workplaces, education and healthcare. Conversely, the research about circadian lighting has not yet disruptively entered the lighting design in domestic environment. Despite of this, laboratory experiments have shown that light can reduce insomnia by helping the wake up in the morning with diminished sleep latency; it can increase mood and induce positive humoral conditions by preventing depression and dementia; it can support relaxation and turn health in general [1].

1.1 Lighting Disruption and dysfunctions with the modern lifestyles

The introduction of electrical lighting in the XIX century and, more recently, the intensive use of screen technologies (television, notebook, smart phones and tablets), has changed completely the relationship between humans and lighting. Human beings live under artificial conditions, with limited time passed in open air and poor chances to get good natural light. During daytime, we rely more and more on artificial lighting which has also provided the extension of life activities during the night, with the negative impact on sleep habits without complete darkness.

If the human activities are no longer tied to the sunrise and sunset, the human biology is still linked to the astronomical cycle and, as a consequence, circadian disruption and dysfunctions may occur. In this paper, we focus on older adults which show problems of insomnia and depression. These can be related to the age degenerations of the visual and cognitive system [2].

1.2 Elderly people visual system

The human eyes' lens become thicker and more yellow with age (60 years and above) [3], this resulting in the reduction of the amount and the transformation of the spectral quality of lighting reaching the retina. The lens of older adults filters out prominently UV and short wavelengths of the spectrum [4]. After cataract surgery operations, older adults might use Yellow Intraocular Lenses (Yellow IOL) which mimics the spectral transmission of the human lens, protecting the macula from potentially damaging UV short wavelengths [5].The spectral transmission curve of the Yellow IOL has been used to calculate the quantity and quality of light (average) reaching the cornea of elderly people.

Along with the decreased visual acuity, changed colour perception and limited contrast sensitivity, older adults experience also cognitive changes derived from the reduction of the number of neurons in the retina and in the suprachiasmatic nucleus (SCN). In addition to this, the reduction of mobility abilities determines more sedentary lifestyle, with the consequence of receiving less qualitative natural light. All these transformations influence the capacity of the light for entraining the endogenous circadian rhythm of elderly people which can cause insomnia (e.g. frequent nocturnal awakenings followed by frequent diurnal naps) and can be associated with the reduction of physical health (e.g. cardiovascular problems, irregularities of the endocrine system operation, decline in immune functions).

1.3 Active Aging and Aging in place phenomena

The share of elderly people will grow dramatically in 2030: it is expected an increase of 37% of the age group 65-79 years old and of 54% of people over 80 [6]. Since this growth has considerable social, health and wellbeing consequences, Europe promotes the "Active aging" defined by WHO as the process of optimizing opportunities for health, participation and security in order to improve the quality of life when getting older [7]. The definition therefore includes the notion of extending the activities of older people through the participation in the social, economic, civil and cultural activities with quality of life being both physical and psychological. According to the Journal of Housing for the Elderly [8], aging in place responds to these issues, preventing the transfer from home and having the necessary supportive services to the changing needs, which enhance comfort, independence and safety.

2. Research scope

In order to understand the contribution of lighting for the wellbeing of elderly people in their domestic environment, the natural lighting conditions experienced in a real environment by elderly people (compared with young people) have been investigated throughout a case study of a real domestic application. The study’s objective was to provide insights about the available amount of natural lighting for human well-being in interiors, regardless the age of users. Is natural lighting enough for activating NIF effects in residential interiors? Which conditions and features are limiting or enhancing its efficacy in circadian terms? What is the difference between elderly and young people?

3. Method

The simulation of the natural light has been performed by modelling the 3D of the apartment with the software Dialux Evo. The space is an Italian vernacular two-rooms apartment of about 60 square meters configured to accommodate from one to four people, located at the third floor of a residential building. It presents a double exposure (east E- west W) with no occlusions of other buildings since it overlooks a large courtyard (W) and a park (E). It is located in Milan (Lat. 45.504044 Long. 9.177164).

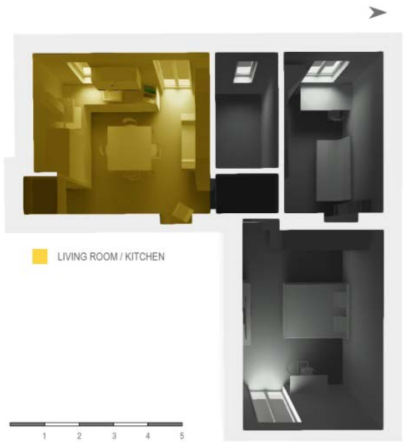

Figure 1 – Evaluated areas for the natural lighting simulation in order to access the non-visual effects of lighting on young and elderly people

The virtual model was simulated with achromatic grey materials with reflection factors defined by the norm [9](walls 0.5, ceiling 0.7, floor 0.2 and furniture 0.5-0.7) as a convenient simplification to achieve general results (independent from specific textures and colours of different situations) with a good approximation [10].
The daylight simulation was performed over the course of one year, calculating every hour from sunrise to sunset of the astronomical beginning of the seasons: spring equinox on March 20th, the summer solstice on June 21st, autumnal equinox on September 22nd, solstice winter December 21st(2017). Simulations were performed in different conditions of sky (clear, overcast, intermediate), in different rooms and considering the different tasks performed by the users. The photopic vertical illuminance on the eyes (E_{eye}) was calculated and the appropriate equivalence circadian-lux was derived based on the model of Rea [11]: the minimum and maximum threshold for circadian stimulation of elderly and young people has been defined. Those values has been compared to the ones obtained through simulation to gather a general understanding of the circadian activation available with solely natural lighting in a domestic interior.

4. Defining natural lighting in digital simulations

The correlated color temperature (CCT) of the sky depends on the weather conditions and timing: at sunset, in the sun nearby locations, the value of the CCT may be less than 3000K; a partially covered sky can have a CCT of 5000K or higher, while a clear sky can reach values higher than 20000K. In the research of Chain et al. [12], a model that relates the CCT and the distribution of luminance of the sky has been proposed based on a series of measurements of the spectral radiance of the sky dome: high luminance values corresponds to a moderate value of the CCT and vice versa. In overcast conditions, the CCT is almost uniformly distributed across the sky.
In the present study, overcast, intermediate and clear sky along with the condition of the direct sun's radiation filtered by a diffusing curtain has been simulated. The presence of the curtain has been considered only for clear and intermediate sky

along the four seasons at specific hours of the day. The simulation of the curtain into the program was defined through the "method of replacement source"[13]: the relative luminance distribution of the windows (determined by the spatial distribution of luminance of the sky and depending on the geographic location, time and geometrical characteristics of installation) was replaced with a lighting system of equal dimensions of the window with a suitable diffuse light distribution.

5. Space and activity evaluation

Figure 2 – Living room /kitchen with eye position and orientation of the gaze (code)

Table 1 - Defining the functions, tasks, time, duration, position of the observer with relative height of the eye and the gaze orientation related to the living room

Function	Activity	Time (h)	Duration (minutes)	Position	Eyes height	Gaze orientation	Eyes Position Code Refer to Figure 2
Food preparation	Cooking	7:00 a.m. 12.00 a.m 7.00 p.m.	10 min. 20 min. 20 min.	Standing	1.70 m	30°	7
	Manipulating	7:00 a.m. 12.00 a.m 7.00 p.m.	10 min. 20 min. 20 min.	Standing	1.70 m	30°	18-12
	Washing	7:00 a.m. 12.00 a.m 7.00 p.m.	10 min. 10 min. 10 min.	Standing	1.70 m	30°	12
Food Consumption	Eating	7:00 a.m. 12.00 a.m 7.00 p.m.	20 min. 30 min. 30 min.	Sitting	1.20 m	← + 30°	1-2-3-4-11-13-14-15
Concentration	Manipulating	9:00 a.m. 2.00 p.m	180 min. 360 min.	Sitting	1.20 m	30°	1-2-3-4-11-13-14-15
	Working	9:00 a.m. 2.00 p.m	180 min. 360 min.	Sitting	1.20 m	30°	1-2-3-4-11-13-14-15
	Crafting	9:00 a.m. 2.00 p.m	180 min. 360 min.	Sitting	1.20 m	30°	1-2-3-4-11-13-14-15
Relaxing	Reading	9:00 a.m. 1.00 p.m	180 min. 360 min.	Sitting	1.20 m	30°	9-10-16
	Chatting	9:00 a.m. 1.00 p.m	180 min. 360 min.	Sitting	1.20 m	←	5-6-7

Simulations were performed in the whole apartment except the bathroom and circulation area because of their modest use in time duration. In this paper, we would present the evaluated area of the living room / kitchen, considered as the most important room were older adults spend most of their daily time. The space has been also provided with the main furniture in order to properly position the observer's viewpoints (orientation of the head, height of the eyes, direction of the gaze) in relation to the different activities surveyed in the domestic environment.(Figure 2 and Table 1).

6. Circadian lighting: quantity, quality, time and duration of exposition

6.1 Lighting Quantity and Quality

Several studies show that the circadian response (for example the suppression of nocturnal melatonin secretion) approaches maximum levels after a period of exposure between 0.5 to 1.5 hours [14] to white light at 300lux. A longer period of exposure to light (6.5 hours) determine the saturation of the circadian response with only 200lux measured at the cornea [15]. The above values are based on photopic values expressed in lux generated by a particular SPD. For the simulations of this study, the circadian model of light's sensitivity proposed by Rea [16,17] has been used, between others [18,19]. It was possible to establish the appropriate equivalence circadian-lux considering different SPDs. Starting with the levels of illumination corresponding to the minimum and maximum thresholds referred to the D55 illuminant [20], the minimum and maximum thresholds relative to the other SPDs (D65 and D75) has been calculated.

Taking into account the uncertainties in the modeling of NIF effects of light on human beings, a simple ramp function has been used as a reasonable model for representing the probability that the vertical illuminance at a point (E_{eye}), maintained for a sufficient time and according to a given direction of observation, is enough to affect the circadian system: low probability (0%) below the minimum threshold limit, and high probability (100%) above the upper limit and linear interpolation between these values.

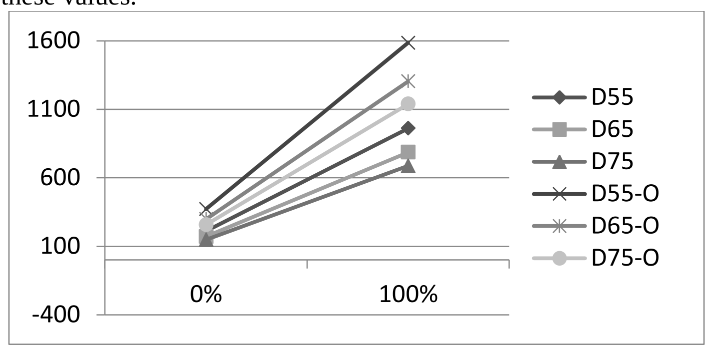

Figure 3 - Comparison between values of relative illuminance threshold eye useful for the circadian activation for a normal user under different lighting conditions (D55, D65, D75) and a senior member (D55-O, D65-0, D75 -O)

In this research, applying some model's simplifications and according to the literature review [21,22,23], the following correspondences were determined: intermediate sky to an illuminant D55 (5500K), an overcast sky with scattered radiation to an illuminant D65 (6500K), a clear sky to an illuminant D75 (7500K). As a consequence, the threshold values used in this study for the elderly observer are: 372lux and 1584lux with intermediate sky conditions at 5500K (Figure 3: D55-O); 298lux and 1303lux with overcast sky at 6500K (Figure 3: D65-O); 257lux and 1138lux with a clear sky condition at 7500K (Figure 3: D75-O).

6.2 Moment and duration of lighting exposure

Since the light exposure history plays an important role for evaluating the NIF effects of lighting, the simulated days were divided in three distinct periods:

• **Morning** (6am - 10am): lighting should synchronize the circadian clock and enable concentration and productivity;

• **Mid-morning and afternoon** (10am - 6pm): high lighting levels increase alert, focus and concentration;

• **Late afternoon and night** (6pm - 6am): light exposure should be avoided as it may trigger the secretion of cortisol and decrease the secretion of melatonin and thus determine an alteration of the circadian system with respect to the solar day.

These periods are correlated to different rooms depending on the performed activities of an older adult with reduced activity outdoors and high sedentary lifestyle at home (Figure 4).

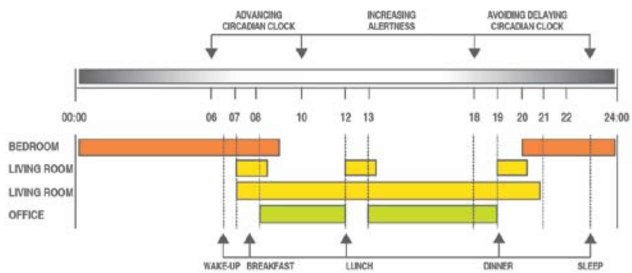

Figure 4 – Diagram readapted [24] of the relation between light exposure, day timing, activities and domestic room.

In addition to this, for the NIF effect to happen, it is required a more prolonged exposure to light compared to that for the vision: the circadian system in fact operates at a much slower pace, especially because it is based on the secretion of hormones in the blood. Several studies [25,26] show that the greater the amount of E_{eye}, the faster the blood melatonin suppression: the 25% of the melatonin suppression can be achieved in 20 minutes with an E_{eye} of 1000 lux; in 60 minutes with an E_{eye} of 500 lux. Below 200 lux, the suppression of melatonin would never be superior to 25%. Although a lot of research is needed to determine the actual duration of the light treatment to suppress the secretion of hormones, Rea [27] has proposed an approximation to achieve effects on the circadian system: lighting with 1000 lux at the eye with a SPD peak of around 420-480 nm and an exposure period of about 1-2 hours.

7. Results

The overcast sky condition occur for the 21% of the year at the considered latitude [28], mainly in autumn and winter. In this sky conditions, the results of the simulations show that the E_{eye} of every point of observation and also the average values are always below the minimum threshold: natural lighting from 10am to 6pm is not sufficient to activate the circadian system both for young and elderly people. The circadian activation is achieved only during the summer season (11:30am and 5pm) when the observer is facing directly the window (Observer 18, referring to Table 1, Figure 2, Figure 5). The available natural lighting is not optimal to stimulate the awakening in the early morning and to increase alertness and concentration, which can result in delaying the falling asleep phase in the early afternoon.

The clear sky conditions occur for the 52% of the year, for the selected latitude for an approximate duration of about 191 days [29]. During the morning (8am - 1pm), the natural lighting is generally not effective in circadian terms for elderly observers, for all seasons. The level of E_{eye} is optimal in activating the circadian system during the year (with winter as an exception) at the observation position in front of the windows (Observer 18, referring to Table 1, Figure 3, Figure 7), where short terms activities (less than 30 minutes) can be performed, this resulting in a limited exposure period which is not enough to activate the circadian system. In addition to this, the position of the observer sitting at the table (Observer 3, referring to Table 1, Figure 3, Figure 7) results activated for a period of time of about 60 minutes in the morning (except from winter) with E_{eye} values higher than 257lx. According to the literature [30], these values are enough for suppressing the melatonin secretion of about the 25%. Young observer results not to achieve circadian activation during the whole year in the morning if their head/gaze is not oriented toward the windows and when they are positioned far from the windows.

Given the specific orientation of the windows of the room (W), the lighting conditions increasingly improve in the afternoon (2pm–6pm) when the levels of E_{eye} are higher than the minimum threshold for the circadian activation (higher for younger observers, lower for older ones) with the winter exception, when no activation occurs. Spring and summer result optimal for achieving circadian activation for longer exposure periods (about 240 minutes) from the majority of the positions of the observers which are frontal and nearest to the windows (Observer 5-1-14-6-15-9-4-10, referring to Table 1, Figure 3, Figure 7). Nevertheless, in the same timeframe, observers positioned in the more distant part of the room from the windows and with the gaze not oriented toward the windows result not activated (Observer 17-16-13-12-11, referring to Table 1, Figure 3, Figure 7). As evident from the Figure 6, the simulations at certain hour of the day has been done with a diffusive curtain in front of the windows to reduce glare from the direct natural lighting entering the room that could be detrimental for the visual comfort and capabilities of elderly people.

The intermediate sky conditions occur, for the latitude selected, the 27% of the year [31] when the levels of E_{eye} are not sufficient to activate the circadian system of elderly people during the morning (8am-1pm), especially in winter (exception is the

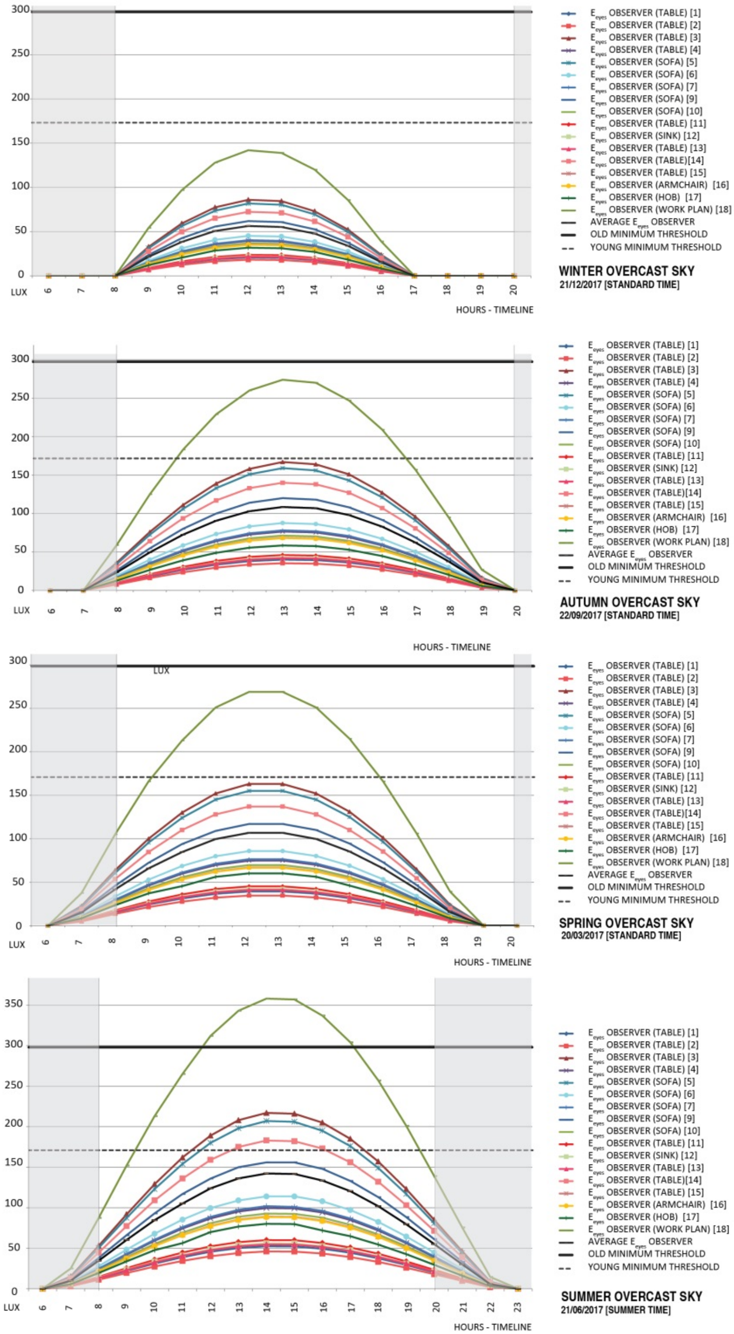

Figure 5 - Simulation results of the E_{eye} in overcast sky conditions in the living room for different observers

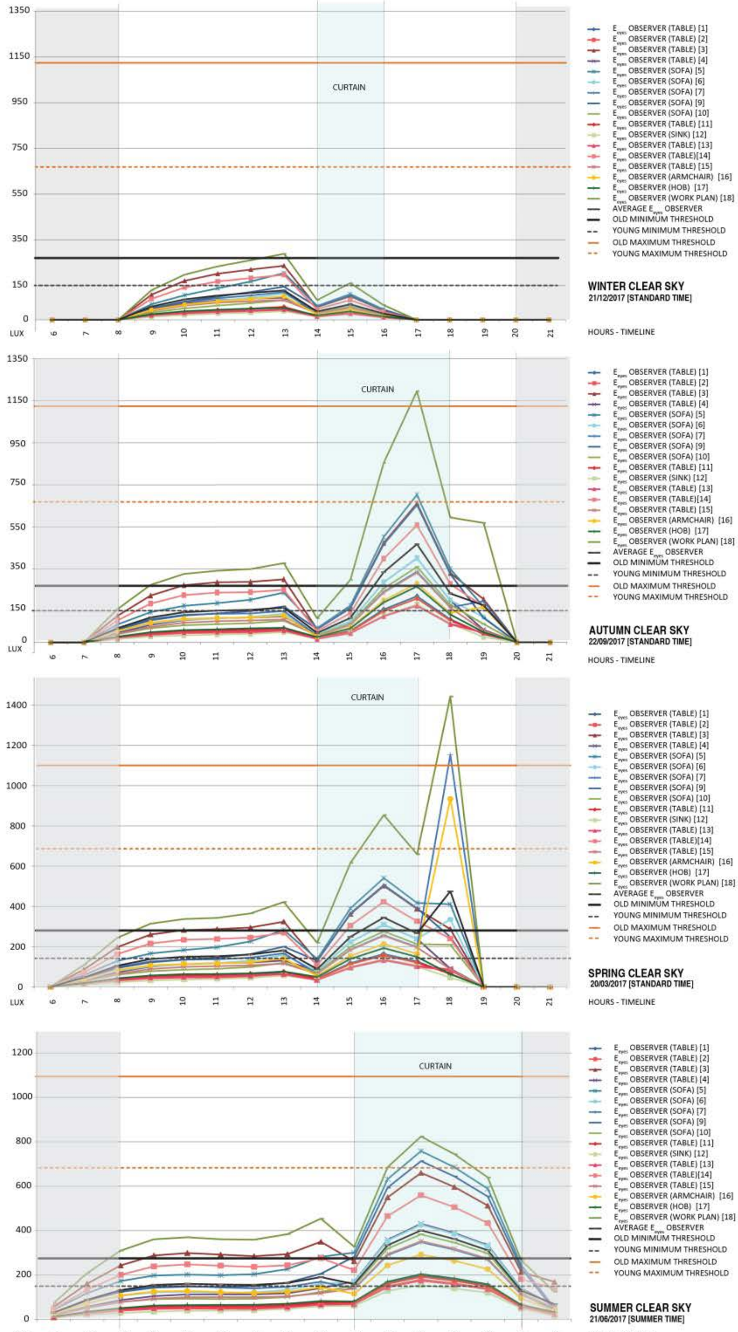

Figure 6 - Simulation results of the E_{eye} in clear sky conditions in the living room for different observers

Observer 18, referring to Table 1, Figure 3). During the afternoon, the lighting levels are higher but not sufficient to determine a circadian activation of the elderly people which occurs only in the summer season for a duration of exposure of about 120 minutes with E_{eye} values comprised between 400-600lx (for Observer 18-5-9-3, referring to Table 1, Figure 3). According to the literature [32], these values are more than enough to suppress the melatonin secretion more than the 25%.

8. Conclusions

Bearing in mind that this study has some limitations because it is just focused on a single case study (a sample living environment located in Milan-Italy), it should be also evidenced that several conditions which were simulated such as the orientation of windows (W-E) and location (no-obstruction and Lat. Long.) might represent optimal conditions if compared to more pessimistic situations (e.g. northern latitudes, presence of obstruction and single exposure of windows). Despite of this, the results of simulation achieved for the living room/kitchen reveal that, at particular times of the year and with specific sky conditions, the amount and quality of light to which elderly individuals are exposed is limited and not sufficient to enable NIF effects of lighting. In specific periods of the year (winter and autumn, particularly with overcast and intermediate sky), the simulated E_{eye} levels are below the minimum threshold level for circadian activation also for young people.

The circadian activation at the beginning of the day (8am – 1pm) is not guaranteed in the living room in overcast and intermediate sky condition (48% of the year for the selected latitude). In clear sky conditions, in the morning, the internal lighting situation appears not to activate effectively the circadian system because of the orientation and the depth of the room, particularly in winter season, regardless the age of users. These results suggest that it would be useful to increase the lighting levels inside of the room in the morning during the entire course of the year, in all sky conditions and thus increase the exposure of older adults to a light of higher quantity and better quality in terms of SPD for achieving NIF effects.

If alternatively it would be possible to promote the exposure to natural light in outdoors on a regular basis for the elderly which do not have mobility limitations, it has to be also considered that, with bad weather conditions and during cold seasons (autumn and winter), the active older adults are generally reluctant to leave their house, conducting a more sedentary lifestyle.

The results also demonstrate that the observers can be effectively activated by natural lighting during the afternoon (1pm – 6pm) for the entire year with the solely exception of winter and overcast sky conditions (21% of the full year). It might be also stated that, in the majority of the cases in which circadian activation occurs via the natural lighting, even with clear sky, the observers’ gaze results perpendicularly oriented toward the windows, at very close range. In contrast, from other observation points and positions which occur in the more internal part of the room, the NIF effects are not achieved via natural lighting both in overcast and clear sky conditions. This means that with diffuse and indirect lighting conditions, in the more distant areas of the premises, the effectiveness of natural light for the circadian system decreases for both elderly and young observers. More light of a better and continuous SPD is needed in those conditions and situations.

9. Further steps

The study presents preliminary contributions for advancing the knowledge about the NIF effects of natural lighting in older adults in domestic applications which are seldom forgotten by circadian studies. In order to get a wider understanding about the influence of circadian natural lighting in a domestic living environment, the present study could be further developed by simulating daylight in other locations and orientations [33], by taking into account the presence of other buildings which obstruct the view and the light entry along, by considering the different design, shape and materials used for the windows around the world [34]. Further studies would include compared simulations performed with other dedicated software along with a comparison of the simulations with measurements taken in the real space.

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