

Lighting for circadian well-being: a simulation-based workflow for the visual and non-visual lighting design of a nursing home

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Abstract

This paper presents a methodological framework and workflow for the simulation of the visual and non-visual lighting performance of a nursing home. A recently-developed software tool, ALFA (Adaptive Lighting for Alertness), was used to estimate the adequacy of the lighting strategy to provide proper luminous conditions and circadian stimulation to the residents. Where required thresholds could not be met, improvement strategies were proposed and tested. This study provides evidence that robust methodologies and tools can support the design of spaces to comprehensively respond to the needs of visual comfort, task performance, and luminous satisfaction, while enhancing the circadian well-being of occupants.

Key Innovations

- Use of a recently-developed software, ALFA, within a case study to simulate visual and non-visual conditions via combined metrics.
- Consideration of age-related changes in visual and non-visual needs.
- Proposal of design and activity-based strategies (lighting, occupancy, and furniture arrangement) to address luminous and circadian requirements.

Practical Implications

The simulation-based approach described in this paper, featuring recently-developed software tools and metrics, is particularly relevant to the comprehensive (visual and non-visual) lighting design of buildings, especially at early stages of the design process and when considering a population of users with specific and variable needs.

Introduction

For almost a century, the luminous efficiency function $V(\lambda)$ has been the sole means to characterise human responses to light based on its ability to excite the visual system (CIE, 1926). Recent research, however, provides evidence that light exposure, other than enabling *visual* comfort, offers a cue to entrain *non-visual* physiological, endocrine, and behavioural processes conducive to the *circadian* well-being of observers (Altomonte, 2008). The following paragraphs provide a synthetic overview of the current state of research in this area, even if knowledge is still under constant development.

The *circadian* (from the Latin *circa*, about, and *dies*, day; that is: *approximately a day*) rhythm is a mechanism that orchestrates several human biological functions on an

approximate 24-hour schedule (Gibson et al., 2009). The duration of the circadian rhythm for humans varies between 23.5 and 24.7 hours, with an average of 24.2 hours among healthy adults (Czeisler et al., 1999). This means that, naturally, there is a phase shift between the intrinsic timing of the circadian clock and the 24-hour average duration of a day. This implies that the body needs a day-to-day reset to a 24h cycle, which is made possible by exposure to stimuli (*zeitgebers*) that allow the synchronisation between the external environment and internal bodily events. One of the main *zeitgebers* of the circadian system is light (Turner and Mainster, 2008).

Luminous signals serve two principal purposes: one is the *image forming*, or *visual*, process that enables us to see the world around us. The other process is termed, by opposition, *non-image forming* (NIF, or *non-visual*), which contributes to regulate many of our metabolic functions. These two processes are linked to different photoreceptors in the eye, each sensitive to diverse wavelength ranges of the luminous spectrum. In general, the photoreceptors responsible for circadian entrainment show higher sensitivity to *melanopic* light, that is light characterised by a blue-shifted wavelength content (around 480nm). Green-yellow and red-shifted light is more effective in stimulating visual, *photopic*, processes.

Daylight encompasses all visible wavelengths, and it is characterised by a continuous spectrum. It represents an abundant, free, light resource that can provide for both visual and non-visual processes. This resource is, however, still poorly exploited in our built spaces. In fact, although adults today spend around 90% of their lives indoors (Klepeis et al., 2001), lighting in buildings is still mostly considered for addressing the needs of the visual system and rarely includes consideration of circadian requirements. For example, electric lighting in buildings has mostly its peak emission at longer wavelengths (red-shifted) in order to primarily respond to visual tasks demands. Since circadian *zeitgebers* are essential to the entrainment of biological functions, a decreased sensitivity, or reduced access, to lighting cues could have serious health effects (Hood and Amir, 2017). This has been noticed within older subjects: in fact, the amplitude of circadian rhythms (linked to melatonin and cortisol secretion, sleeping cycles, body temperature, etc.) seems to decrease with age. This can be due to two phenomena:

- Elderly often spend most of their time indoors in poorly lit environments (Shochat et al., 2000).

- The lens in the retina thickens, expands, and yellows with age, decreasing light transmission, mainly toward the blue end (Kessel et al., 2010).

These two phenomena can lead to a weak or absent input of (day)light to the retina and might contribute to alter circadian rhythms (e.g., the quality and quantity of sleep), with negative consequences on health and well-being.

For this reason, it is important that our buildings are designed and operated in ways that are conducive to visual comfort, but also to support the rhythmic cycles of human needs. Unfortunately, there is yet no national or international regulation that mandates adequate lighting measures to respond, at once, to visual and non-visual functions. Some research organisms, such as the International WELL Building Institute (IWBI) and the Lighting Research Center (LRC), offer recommendations to quantify thresholds for regulating non-visual responses. However, none of these yet fully considers the age-related physical and physiological changes that can largely affect the requirements in terms of light exposure for the elderly.

On these bases, this study sought to investigate the lighting strategies necessary, in the design and operation of buildings, to respond simultaneously to the requirements for visual comfort and the needs of non-visual well-being and circadian entrainment for an elderly population (e.g., individuals of 65+ years of age). To this aim, a nursing home was selected as a case study. The Stephenson Garden is a 6-storey warehouse located in the northern part of Brussels (Belgium) that, in 2015, was refurbished into a residence for the elderly (Figure 1).



Figure 1: The Stephenson Garden nursing home

The renovation focused on conceiving spaces that could provide luminous continuity throughout residents' daily activities and increase the penetration of light, particularly at the lowest floors. Within this study, three dining rooms and three bedrooms were selected to evaluate their potential to offer to the residents a proper lighting environment for visual comfort and circadian well-being.

Methods

The original program for this study included conducting a measurement campaign to collect real data on existing lighting conditions, calibrate a simulation model, and administer surveys to the personnel. This would have provided a baseline scenario to evaluate the effectiveness of the current lighting, and benchmark the results of any proposed strategy. However, the SARS-CoV2 lockdown of Spring 2020 hindered access to the building, therefore the study had to solely rely on simulation methods, based on the initial observations made at a preliminary visit.

Several simulation tools are available to support designers in estimating the daylighting performance of a building. However, the development of software tools to robustly model the non-visual stimulation characterising a naturally or electrically lit space are still at their infancy. This is due to uncertainties in the metrics and thresholds to be utilised, but also to the difficult definition of the effective needs, and their variation over time, of building users, especially when they belong to different and fragile age groups. In response, this study utilises a recently-developed software tool, ALFA (Adaptive Lighting for Alertness), to estimate the lighting performance of a nursing home, computing the levels of visual comfort and non-visual stimulation received at various times by a population of elderly residents, and proposing strategies for their improvement. The software ALFA was firstly launched in 2018 (Balakrishnan and Jakubiec, 2019) and is integrated within Rhinoceros 3D (Solemma, 2020).

Simulation Workflow and Personas

The simulation workflow used to evaluate and improve the visual and circadian lighting potential of the nursing home is summarised in Figure 2 and described below.

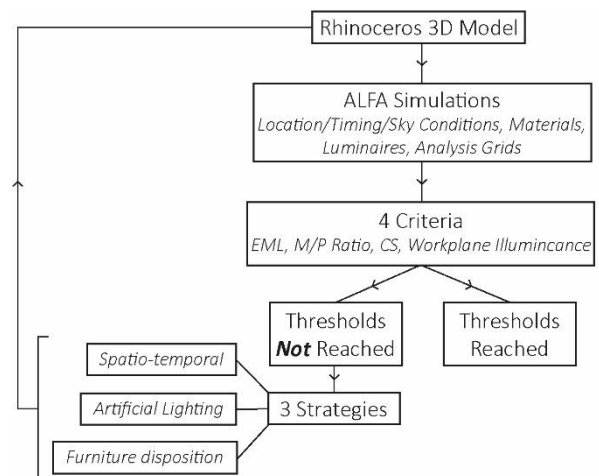


Figure 2 : Schematic of the simulation workflow

First, a 3D model of the building was built in Rhinoceros with different layers, each representing a specific material (e.g., walls, ceilings, windows). Once the geometry was exported to ALFA, different parameters had to be defined, including the location and timing of the simulations, materials and luminaires, analysis grid, and orientations. The results obtained were evaluated based on four criteria focusing on visual and non-visual requirements. If the set thresholds were reached, then it was considered that the baseline scenario responded to the visual and circadian needs of residents. Otherwise, three types of proposed strategies were tested to improve the current situation:

- Complementing luminaires in living rooms and bedrooms with red- or blue-shifted LED lamps.
- Adjustments of daily schedules and space occupancy plans based on sun path exposure.
- Modification of furniture arrangement.

Strategies were implemented in the model and tested, in isolation or combined, to measure performance outcomes. The sections below describe these steps in greater detail,

together with the specific selections made for the setup of the simulation model. This is done to facilitate the replicability of the proposed workflow within the practice of design, and possibly at an early stage of the process.

Before entering in such detail, however, it must be considered that the simulation workflow was set up in a way to reduce the number of simulations that needed to be run and analysed, yet without risking to oversimplify the computation and missing effects of significant magnitude. This is one of the most recurrent challenges in building performance simulation, where a parsimonious approach is often required to avoid untreatable amounts of data. Among the methods that can be used to facilitate this process, substantial interest is being given to the use of *personas*, that is personal representations of occupants' activities that can exemplify the different lighting conditions experienced in a given situation by following them throughout a typical day. For these reasons, three fictional personas have been created for this study, each one testing a radically different condition concerning the lighting in the building. This was made to consistently analyse, for each simulation scenario, the best- and worst-case condition and an intermediate or alternative situation.

ALFA Model Setting

The model settings were based on the literature (Konis, 2018; Reinhart et al., 2013) and organised as follows:

Location. The location allows to choose a city or to insert geographic coordinates. Based on the available data, the coordinates of the nursing home were input in the tool. The orientation of the building must be fixed in the XY plane of the model, the Y direction indicating North.

Timing. In order to simulate lighting conditions under two extreme seasonal situations, it was chosen to run the computations at the two solstices, 21st December and 21st June. For these 2 days, simulations were run every 3 hours from 7am to 7pm in different rooms according to the personas' daily schedule of activities provided.

Sky condition. ALFA proposes the following sky conditions: Clear, Hazy, Overcast, or Heavy rain cloudy. The tool utilises the radiative transfer library *libRadtran* (Emde et al., 2016) to define physically-accurate spectral characteristics of these sky types based on the chosen location. For each timing of simulation, the model was analysed under a Clear and an Overcast sky condition to capture lighting exposures under extreme conditions.

Materials. Opaque and transparent materials were selected for each layer based on their reflectance and transmission properties (photopic and melanopic) and specularity. Using ALFA's library, for all walls and ceilings, the 'White Painted Room Walls' and the 'White Painted Room Ceilings' were chosen (Figures 3 and 4).

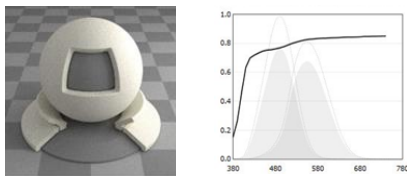


Figure 3: White Painted Room Walls (ALFA)

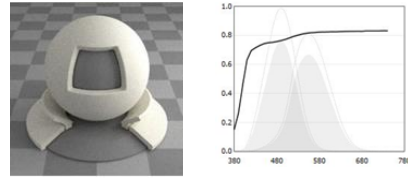


Figure 4: White Painted Room Ceiling (ALFA)

Coherently with the observations made, the 'Dark Grey Floor Tiles Nonslip' was chosen for all floors (Figure 5).

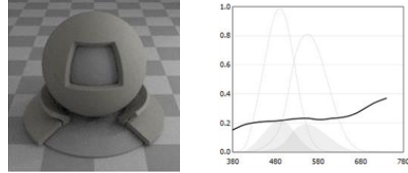


Figure 5: Dark Grey Floor Tiles Nonslip (ALFA)

Some of the simulations required consideration of the light reflected from external walls, particularly due to the presence of an internal patio. Since the patio walls of the Stephenson Garden are relatively clear, and based on literature studies (e.g., Reinhart et al., 2013), the chosen material for external walls was 'Rock 13' (Figure 6).

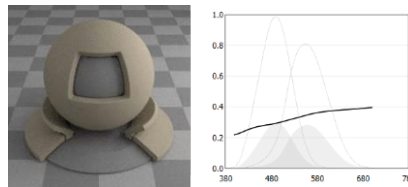


Figure 6: Rock 13 (ALFA)

For the glazing, a double-glazed unit with low-emissivity coating and a visible transmittance of $\tau_{vis} = 65\%$ was chosen, coherently with initial observations and previous literature studies (Reinhart et al., 2013) (Figure 7).

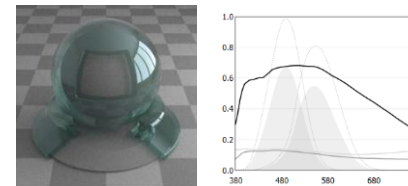


Figure 7: Double IGU Blue Green, $\tau_{vis} = 65\%$ (ALFA)

Luminaires. Pre-set luminaires could be selected based on their shape (e.g., circular, bulb, linear suspended, etc.) and type (e.g., LEDs) as provided within the nursing home's technical information sheets of the lighting system. The available data, however, did not include description of the spectral properties of the lamps installed. Since the baseline scenario intended to represent lighting conditions that are likely to be found in typical healthcare buildings, lamps with a M/P ratio of 0.87 were chosen (Figure 8).

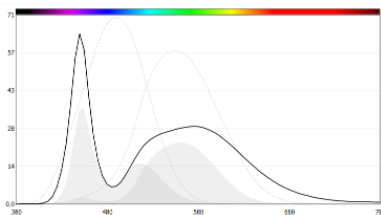


Figure 8: Spectral distribution, LED 0.87 (ALFA)

The bedrooms were equipped with a LED spotlight in the entrance, emitting a luminous flux of 340lm, and a ceiling lamp in the middle of the room, with an output of 1770lm. These ceiling luminaires were also used in dining rooms.

Analysis Grids. In each room, two reference planes had to be positioned to calculate viewplane and workplace illuminance, these measured by sensor points spaced on two analysis grids. Viewplane photopic illuminance was measured vertically in the direction of the view. This was used also to estimate the circadian potential of the spaces, including consideration of physical movements and changes of view direction. Workplace illuminance was, conversely, measured on the horizontal plane.

Workplane and viewplane have adjustable heights, these being by default 0.76 and 1.2m, respectively. In this study, however, the viewplane sensor was set a height of 1.07m, coherent with a previous study from the literature (Konis, 2018). To reduce the number of data points to be analysed, it was decided that for each given location, only one view orientation was considered based on the direction that the occupant would more likely be looking at (e.g., out of the window, towards the TV, etc.). For all view directions, the horizontal view angle was set at 155°. The workplane sensors were situated by default at 0.76m above the ground, because this is commonly considered to be the height of a workplane or a dining table.

Table 1 summarises all settings of the ALFA simulations.

Table 1: Summary of ALFA simulations settings

Component	Material Proprieties
Glazing	Double IGU BlueGreen, $\tau_{vis}= 65\%$
Interior walls	White Painted Room Walls
Exterior walls	Rock 13
Ceiling	White Painted Room Ceilings
Floor	Dark Grey Floor Tiles Nonslip
Luminaires	Bedrooms: LED B13 Bulb, 40W, 340lm; LED Circular Downlight 6-inch, 1770lm Dining Rooms: LED Circular Downlight 6-inch 1770lm

Evaluation Criteria

In order to adequately combine conventional lighting measures (e.g., horizontal and vertical photopic illuminance) with novel metrics that have been recently proposed in the scientific literature to quantify and qualify the capacity of a light source of stimulating the circadian system, four different evaluation criteria were used as key performance indicators to benchmark the results obtained. The sections below present these evaluation criteria in detail and illustrate how they can be obtained from ALFA.

Equivalent Melanopic Lux. The circadian effects of light on humans can be measured in *Equivalent Melanopic Lux* (EML), a metric that is adjusted to the sensitivity of the melanopic photoreceptors in the human retina and that can be obtained by multiplying the value of vertical photopic illuminance for a weighting factor that depends on the specific spectral composition of the incident light (Lucas et al., 2014). At the moment, the only regulatory or certification body proposing a threshold of EML needed for circadian resetting is the International WELL

Building Institute (IWBI), which since 2014 has been developing an international certification system called the WELL Building Standard. Two versions, v1 and v2, of the WELL standard have been released to date. Values up to 200 EML and 240 EML are recommended respectively in the WELL v1 and v2 systems (IWBI, 2014 and 2018). WELL v2 also specifies the timing between 9am and 1pm during which the proposed EML threshold has to be achieved. Since 9am was likely chosen in the WELL standard because it corresponds to the opening hour of offices, for this study the hour of 7am was selected, this being the waking up time of the residents. One of the recommendations of WELL v1 also addresses the evening hours, proposing a maximum threshold of 50 EML. This recommendation was implemented in this study to benchmark melanopic light exposure starting from 7pm.

The values proposed by IWBI, however, do not consider the age-related changes in the light transmission within the retina for an elderly population. In response to this, a previous study (Konis, 2018) suggested using a tool developed by the LIPID group at EPFL (Switzerland), called SpeKtro, to set the required lighting level for a person of a given age. SpeKtro provides an interactive dashboard for exploring non-visual responses to light, with the possibility to set the age of the observer between 0 and 100 years (EPFL, 2015). The tool allows to select a specific light source, or to import spectral power distribution values, and establish the desired effect of the light stimulus on circadian resetting from 0 to 100%.

Since the WELL standard does not propose lighting requirements specifically for the elderly, based on the outputs of the SpeKtro tool, a threshold of 250 EML was set for an acceptable circadian resetting of an individual of 85 years of age. This was the age established for the three personas in our simulation workflow. Similar to the value set within the literature (Konis, 2018), this EML value can produce an expected 2-hour phase-shift and fulfils the minimum requirements of both v1 (200 EML) and v2 (240 EML) of the WELL certification scheme.

M/P Ratio. This metric represents the *ratio between the melanopic and photopic illuminance* produced by light sources of a given spectral power distribution. The methods to calculate the M/P Ratio, and the values to attribute to different thresholds, are still debated within the scientific community (Miller and Irvin, 2019). Studies indicate that, the higher the ratio, the more stimulating the light source is toward circadian resetting (Eyrise, 2019). Two thresholds have been proposed: a M/P Ratio greater than 0.9 corresponds to blue-enriched light conducive to alertness (during the day) and melatonin suppression (at night); a value under 0.35 characterises a blue-depleted light, fostering melatonin secretion and resulting in drowsiness. When the ratio lays between the two values, there is no direct impact on circadian processes.

Circadian Stimulus. A second way to assess the circadian efficiency of a light source is the *Circadian Stimulus*, a metric proposed by the Lighting Research Center (USA). This coefficient indicates the extent to which a light source of given intensity and spectrum elicits circadian

responses, such as the suppression of melatonin secretion. The coefficient ranges from 0 to 0.7, varying from no circadian effect (0) to maximal melatonin suppression (0.7) (Figueiro et al., 2016). Accordingly, two thresholds have been adopted in this study: a CS of 0.3 or greater at the eye for at least 1 hour between 7am and 11am, and a CS not exceeding 0.1 starting from 7pm (LRC, 2018).

Workplane Illuminance. The criterion used to measure lighting to support visual comfort and task performance was the workplane illuminance level. Belgian regulations indicate, for nursing homes, a workplane illuminance of at least 300 lux measured on the horizontal plane in bedrooms and in living rooms (BBRI, 2011).

The results provided by ALFA are presented in Figure 9: A) the spectral power distribution of the light source; B) an interactive rendering, allowing to select and browse every sensor point in the scene and obtain detailed spectral power distribution curves for every set position and view direction within the space; C) a list of numerical results, organised in three categories: alertness, visual comfort, and workplane illuminance. The menu D) allows exporting the results to obtain numerical data that can help verify compliance with the set evaluation benchmarks.

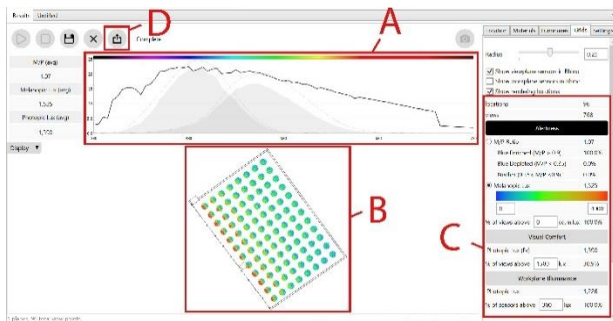


Figure 9: Display of Results (ALFA)

The Alertness data is directly linked to the efficiency of the lighting conditions to entrain the circadian system and features information related to the Equivalent Melanopic Lux (Figure 10) and the M/P Ratio (Figure 11).

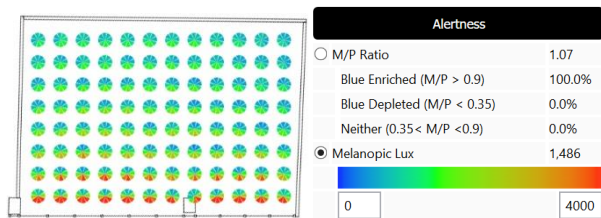


Figure 10: Equivalent Melanopic Lux (ALFA)

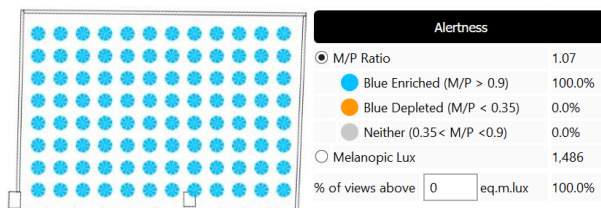


Figure 11: M/P Ratio (ALFA)

The Visual Comfort category provides the Photopic Lux (Ev) measured vertically at the chosen height, and in the set directions and view angles, perpendicular to the vertical plane (Figure 12).

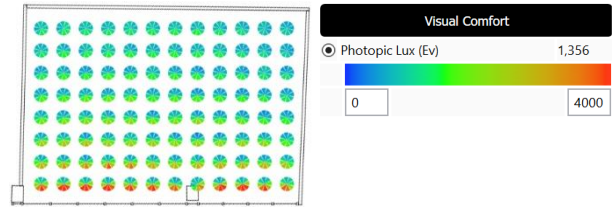


Figure 12: Photopic Lux (Vertical) (ALFA)

The Workplane Illuminance is expressed with the same unit of measure (Photopic Lux) as the previous category, but it is measured on the horizontal plane (Figure 13).

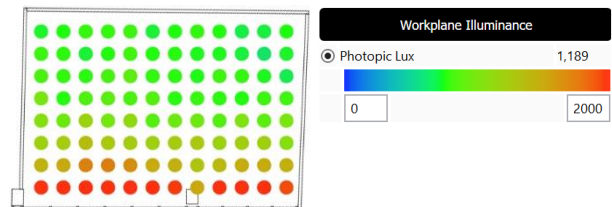


Figure 13: Photopic Lux (Horizontal) (ALFA)

The complete set of data can be exported to a .csv file providing – for workplane and viewplane sensors, and for each location and view direction – the relative spectral power value at 5nm wavelength intervals, ranging from 380 to 780nm, the photopic lux, the equivalent melanopic lux, and the M/P Ratio. The relative spectral power data can be used to calculate the Circadian Stimulus of the lighting sources via an online CS Calculator (LRC, 2018).

Improvement Strategies

For all lighting scenarios where benchmarks could not be met, thus potentially leading to a reduction of visual comfort or to circadian misalignments for the residents, three types of improvement strategies were proposed.

Electric Lighting. The selection of a suitable electric lighting strategy can highly contribute to stimulate the occupant's visual and non-visual systems. Since daylight is a dynamic source, changing over the day and seasons, its luminous input cannot be constant across different spaces. Moreover, daylight can enter spaces until a certain depth but might not always provide sufficient illumination for an entire room. For these reasons, it is essential to provide a complementary solution ensuring an adequate light supply, at all times, inside the spaces. Several parameters can qualify an electric lighting system: its spectrum, intensity, adaptability, control (e.g., manual, automatic), etc. In the context of this study, the proposed strategies mainly consisted in the addition of luminaires or in the variation of the characteristics of the lamps (e.g., their spectral power distribution) for existing luminaires.

Space Occupancy. Depending on the season and time of day, different rooms of a same building can experience diverse qualities and quantities of daylight exposure. While at some moment, a space may offer conditions that properly stimulate visual performance and circadian rhythmicity, the same space may present sources of visual discomfort (e.g., glare, contrast) or inadequate non-visual stimulation at a different time. A similar consideration can be made with respect to the change of seasons, whereas winter presents lower sun altitudes, and with times and angles of illumination that differ radically from summer.

Accordingly, where required, the schedule of occupation of spaces was adapted to the variability of the sun path.

Furniture Arrangement. Depending on one's position in a space, visual and non-visual responses might vary. Being near a window and with direct access to an external view does not entail the same effects than being at the back of a room, facing the opposite direction. For this reason, where necessary, the furniture arrangement was modified to maximise spaces' potential to offer proper quantity and quality of light. In so doing, consideration was also given to the awareness that views to the outside, particularly in the presence of naturalistic elements (Ulrich, 1984), can entail restorative effects that are strongly beneficial to the mental well-being of building users (Batool et al., 2021).

Results

The results are presented below at 3-hour intervals from 7am to 7pm, following the daily activities of the three personas, on the 21st of June and the 21st of December.

7am. The results of the simulations highlighted that, in general, residents do not have access to sufficient melanopic and photopic lighting when they wake up in the morning, either due to poor lighting (i.e., in winter, the sun has not yet risen and electric lighting is the only light source available) or to an inadequate room orientation (i.e., some rooms face the internal patio or the North-West direction). To respond to these needs, blue-shifted desk lamps (Figure 14), to be switched on in the morning, were proposed to be implemented in each bedroom. This allowed to reach values of EML, CS, and Workplane Illuminance meeting the set thresholds for all personas.

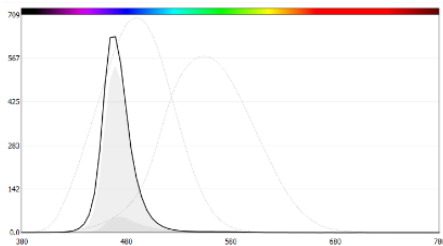


Figure 14: Blue LED 7.79 M/P (ALFA)

10am. At this time, residents engage with morning activities in a South-West oriented room. This provides to the occupants sufficient lighting for both their visual and non-visual needs in June. However, on an overcast day on the 21st of December, a lack of light exposure can be noticed, especially for the residents sitting at the back of the room. A simple change in the spectrum of the lamps, shifting the spectral content of the resulting lighting, is generally sufficient to address this situation (i.e., by using LEDs with a 1.00 M/P ratio instead of 0.87) (Figure 15).

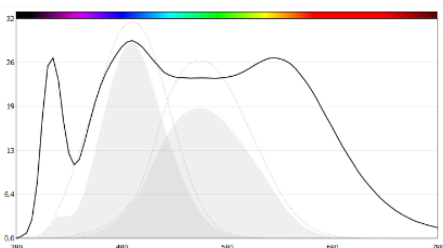


Figure 15: LED 1.00 M/P (ALFA)

1pm. At lunchtime, the dining rooms occupied by the three personas are all South-West oriented, this ensuring adequate light exposure for visual and non-visual needs. However, on an overcast day on 21st December, residents turning their back at the window might experience a lack of workplane illuminance. This issue can be addressed by changing the arrangement of the furniture, placing every table in a position perpendicular to external openings.

4pm. The dining room used for the afternoon activities is located at ground floor and oriented towards the North-West, facing the patio. Its position in the building does not allow abundant light to enter the room. Although in June all required thresholds are met, in December even the residents that are sitting closer to the windows experience excessively low workplane illuminance. To reach the required thresholds, a complementary electric lighting system was proposed (using LEDs with 1.00 M/P Ratio).

7pm. Residents can generally choose to have supper in their bedroom or in one of the South-West oriented dining rooms. In the latter case, given the characteristics of solar geometry in June, the intensity of light can be so high that the residents' melanopic exposure might largely exceed the recommended maximum value of 50 EML at this time of day. This means that the desirable increase in melatonin secretion triggered in the early part of the evening might be inhibited by an excessive amount of light reaching their retina. In response, a strategy was suggested for residents to they have supper in the North-West oriented dining room (i.e., the same used for the 4pm activity). However, the simulations highlighted that, on clear sky days on the 21st June, the light exposure might still go beyond the maximum recommendations. A solution was proposed to add curtains to be used in the evening and to include a second system of electric lighting, characterised by a red-shifted spectrum (i.e., with a 0.01 M/P ratio). With the implementation of this strategy, the residents could still enjoy abundant light during their afternoon activity and then transit to a more dimmed ambiance at dinner, characterised by closed curtains and an electric lighting veered toward the red. In this case, exposure to a dynamic luminous environment, marking the transition between afternoon and evening, could also help to stimulate the visual system of the residents. On these grounds, this solution was also recommended for the winter period.

For the residents having dinner in their bedroom, mainly for the rooms oriented to the South-West, a strategy based on the same principles was proposed. Curtains may need to be drawn in June, and a red-shifted light must be added to complement the ceiling luminaire and ensure sufficient workplane illuminance while reducing melanopic stimulation. This could be integrated within the desk lamp already suggested for the morning, although – at dinner time – the light emitted would be red-shifted. One could imagine a 'morning' and a 'evening' switch that would trigger, manually or automatically, the required blue- or red-shifted light based on specific temporal needs.

Discussion

After implementing the proposed strategies, all thresholds could be reached, meaning that an adequate combination

of electric light and daylight could effectively be achieved throughout the day and the year. This would enable the creation of lighting conditions that are beneficial to the circadian rhythms of the residents, fostering their health and well-being, while providing for their visual comfort.

As an example, Table 2 below summarises the results for a bedroom and a dining room, at specific times of day, on the 21st December under an overcast sky, comparing the baseline (before) with the improved scenarios (after).

Table 2: Selected exempla of ALFA simulations results

	Before				After			
	M/P	EML	CS	Plane lx	M/P	EML	CS	Plane lx
Bedroom								
07:00	0.75	12	0.02	12	1.00	772	0.51	357
19:00	0.71	5	0.01	11	0.02	8	0.02	307
Dining Room								
16:00	0.95			306	0.68			975
	0.82			232	0.23			768
19:00	0.85	120	0.23	247	0.01	2	0.01	456
	0.79	39	0.08	224	0.01	4	0.01	459

Blue-enriched Neutral Blue-depleted Meet threshold Not meet threshold

Across all the rooms and times tested, the value of 250 EML was consistently exceeded from the wake-up time of the residents at 7am to their lunch at 1pm, coherent with the requirements suggested in the literature (Konis, 2018). In the evenings, values lower than 50 EML were attained, as recommended in current standards (IWBI, 2016). The Circadian Stimulus (CS) values obtained were all above 0.3 for the entire morning until at least 1pm, hence largely exceeding the recommendations by the LRC. The CS was also below the limit of 0.1 starting from 7pm (LRC, 2018). The workplane illuminance was consistently above 300 lux, as requested by international standards (e.g., EN 12464-1), allowing an appropriate distribution of illuminance at work plane height. It can finally be noted that the M/P Ratios at 7pm were all characterised by blue-depleted light, which corresponds to the type of lighting necessary to support circadian functioning, promoting melatonin secretion, while guaranteeing the required luminous levels for visual comfort and task performance.

Following the completion of the simulations, the results of all the strategies proposed were discussed with the health care personnel (n= 7) and with the nursing home director to gather their views and opinions. The responses received were generally supportive of the solutions suggested. It was, in fact, emphasised that most residents spend a relevant amount of time in their bedroom, making it essential to provide them with suitable lighting conditions by ensuring an efficient workplane illuminance along with appropriate EML and CS values throughout the day. The proposition of dynamic lighting settings via the use of blue-shifted lighting in the morning, and red-shifted lighting in the evening, could provide substantial benefits, especially since residents often tend to keep their curtains closed. However, the director stressed that it would be challenging for the health care personnel to implement the required lighting strategy at the appropriate timing, thus recommending the use of an automated system that could provide the residents with the proper light exposure based on season and time of day. Before the findings of this work can be generalised and transferred to other contexts, some limitations need to be

acknowledged. It must be considered, in fact, that the sun is a powerful dynamic energy source, but its contribution continuously changes over a day and throughout the seasons. This entails that the selection of only five time slots for two different days cannot be fully representative of the lighting conditions encountered within a year. However, the times and days of simulation were selected to offer a visualisation of ‘extreme’ lighting situations.

Also, only two sky types were included in the simulations, with spectral characteristics derived from libraries of radiative transfer calculations. Substantial work is still required to define the forecast accuracy of existing spectral sky models based on available datasets of measurements and integrate such models within the prediction of non-visual effects of daylight (Diakite-Kortlever and Knoop, 2021). The influence of spectral sky models on lighting simulation for non-visual effects was, however, beyond the direct scopes of this paper, although it is part of ongoing research from the authors.

The choice of creating three personas having consistent habits and behaviours throughout days and seasons might not correspond to the human nature of the residents. Each of the occupants (more than a hundred) of the nursing home have their different needs, move through the spaces freely, can elect to spend their time in different ways, etc. The age of the three personas has also been fixed to 85 years, corresponding to the reference age that was chosen in a previous study from the literature to establish the melanopic threshold of 250 EML (Konis, 2018). Of course, not all the residents are 85 years old. If some residents were older, it is possible that the modifications proposed might not be sufficient to correctly activate their circadian responses. For this reason, nonetheless, attention was paid for all the EML, CS, and Workplane Illuminance results to largely exceed proposed thresholds.

Finally, in the current scientific literature, there is still significant debate on the metrics to be used to express the capacity of a light source to entrain the circadian system. In fact, more complex processes might be in place to drive circadian responses other than the stimulus received by the photoreceptors activated by melanopic light (ipRGC, *intrinsically photosensitive Retinal Ganglion Cells*). This makes it theoretically incorrect to solely use EML values as thresholds to assess non-visual effects. This is also the reason why the LRC has suggested using the Circadian Stimulus instead of the Equivalent Melanopic Lux as the appropriate metric to quantify circadian responses (LRC, 2018). This metric, in fact, is based on observed effects of different light sources rather than on their lighting output. Since substantial research is still necessary in this domain, both metrics (EML and CS) have been used in this study.

Conclusion

Other than by the relevance of its findings, the original contribution of this study has consisted in presenting a methodological framework to concurrently simulate the visual and non-visual effects of light applied to the case study of a nursing home. This has allowed to describe, in great detail, a simulation workflow based on a recently-developed software tool, ALFA, and featuring a series of

combined metrics (EML, M/P Ratio, Circadian Stimulus) that have been proposed in the literature to complement conventional lighting measures (Workplane illuminance). Transfer of this framework to design research and practice can contribute substantially to improve the quality of our built spaces, particularly if implemented at early stages of the process to address the needs of fragile populations of users. Through proposing different design and operation strategies, in fact, and following the results of a simulation workflow, this study has shown that an existing nursing home can adequately respond to the visual and non-visual demands of its elderly residents with relatively simple solutions, a review of its daily schedule, and a proper arrangement of its furniture and lighting systems.

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