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SIMULATION–BASED EVALUATION OF NON–VISUAL RESPONSES TO DAYLIGHT: PROOF–OF–CONCEPT STUDY OF HEALTHCARE RE–DESIGN

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ABSTRACT

The discovery of a novel non-rod, non-cone photoreceptor in the human eye that mediates a number of effects on the brain has sparked a growing interest in incorporating these non-visual effects of light into the design process of buildings. Appropriately–timed light exposure has the potential to stabilize and improve circadian rhythms, including sleep, and has direct stimulating effects on alertness and performance. The novel photoreceptors are more sensitive to blue light than the rods and cones used for vision, and respond differently to light intensity, duration, history and timing of a light exposure. The dynamic behavior of the non–visual system provides new challenges in evaluating lighting performance of buildings. In this proof–of–concept study, a novel model that predicts the non–visual responses to light is introduced. The model is used as a part of simulation–based framework for the evaluation of daylighting performance. The evaluation includes four different light pattern generation methods used to investigate the influence of occupants' movements and activities on simulation results. The framework is applied to the re–design of a healthcare facility. The results lead to new ideas and suggestions for future re–design.

INTRODUCTION

The common objective of sustainable lighting design is to reduce the impact of the built environment by efficiently using energy, protecting human health and improving occupant productivity. Good lighting design has important beneficial effects both visually and biologically. Light is the main environmental cue influencing circadian rhythms, such as sleep–wake cycles and hormone production. In addition to improving sleep, there is evidence that light exposure can directly improve alertness and performance, reduce depression, ease pain, decrease length of stay in hospitals and even improve some cognitive symptoms of dementia in elderly residents (Alessi et al., 2005; Choi et al., 2012; Riemersma-van der Lek et al., 2008). These biological or non-visual (n–v) effects of light are mediated primarily via a novel, non-rod, non-cone photoreceptor. The novel photoreceptor contains the photopigment melanopsin and is more sensitive to blue (short wavelength) light than the rods and cones. In addition to exhibiting a different sensitivity to light spectrum, the human n–v system responds differently to light intensity, duration, history and timing than the visual system (Lockley, 2009).

The discovery of the novel photoreceptor has led to the consideration of the n–v effects of light as an important element of good lighting design in addition to visual effects (Webb, 2006). Using conventional methods of evaluating time series of light intensities based on horizontal illuminance values might be too simple–minded to evaluate the n–v effects of light. Both the head and the eye are in constant motion relative to light sources and the light spectrum reaching the retina depends on the age of the lens and other ocular structures (Pokorny et al., 1987). Therefore it is a challenging task to specify the quantity of light that is received at the retina of the eye. Moreover, a spectral sensitivity function for the human n–v system has not been standardized yet. One of the reasons is that the maximum sensitivity for n–v responses to light is not definitive.

Exposure to daylight has long been linked with human health and wellbeing. Daylight is rich in the spectral region of short wavelength radiation and might therefore play a large role in new lighting recommendations for health. The spectral distribution of daylight varies with the season and the weather conditions. The unpredictability of natural light is more complex than electric light, especially in terms of computer simulation. Many current daylighting simulation tools remain limited to time–independent calculations such as the daylight factor, while recent advances in dynamic daylight simulation (DDS) offer the capability to carry out climate–based, annual calculations of daylight (Reinhart et al., 2006). Several studies have demonstrated that the dynamic, RADIANCE–based daylight simulation method DAYSIM is able to reliably and effectively calculate time series of illuminance and luminance in buildings (Mardaljevic, 2000; Reinhart and Walkenhorst, 2001).

The concept of designing buildings with regards to the benefits of n–v effects of light is in its early stages of development. Pechacek et al. (2008) developed a method to study the impact of architectural decisions on achieving predefined illuminance threshold values for a given design. This research was the first to incorporate these new discoveries into a preliminary lighting simulation framework assuming that the n–v effects of light were described with the circadian sensitivity curve $C(\lambda)$ proposed by Gall and Bieske (2004) using the effects on melatonin suppression as the indicator of spectral sensitivity based on measured data from Brainard et al. (2001) and Thapan et al. (2001). Further, it was assumed that all surfaces and window glazings were spectrally neutral, and the illuminance thresholds and the circadian spectral sensitivity curve were history– and time–independent. This study was extended and modified by Andersen et al. (2012), where the 24-hour day was divided into three periods to distinguish between the effects of exposure time.

The aim of this study is to evaluate daylighting performance using a simulation–based framework. The framework consists of four steps, including a preliminary mathematical model that accounts for light exposure duration in addition to intensity, spectrum and timing. A case study is presented as an example to explore how such a model can provide meaningful decision support for the re–design of a healthcare facility, ultimately improving health and sleep outcomes of occupants. The effects of occupants' actions, movements and activities on daylighting performance are evaluated to assess requirements for design to drive at solutions that are more robust to the influence of occupants' dynamic behavior.

METHODOLOGY

In order to investigate the influence of the case study building on the n–v responses to light, a simulation–based framework was developed that consists of four steps. The four steps were conducted in a consecutive order as illustrated in Fig. 1.

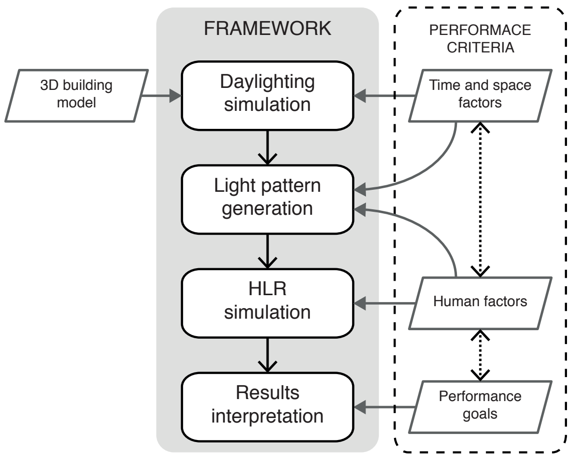

Figure 1: A schematic of the simulation–based framework for the evaluation of daylighting performance.

Lighting simulation

In the first step, DAYSIM 3.1e was used to carry out detailed daylighting simulations to obtain time series of illuminance values over a year at selected sensor point locations and view directions (Reinhart, 2006). The necessary input for a daylighting simulation is a 3D building model, a climate data file of the building site, and a sensor point file. The RADIANCE simulation parameters were set to default scene complexity 2 and the DDS daylight coefficient file format combined with shadow testing was used in all simulations.

It is known that occupant's blind control actions to avoid visual discomfort will affect the distribution of daylight in a space. To account for this, a simple passive blind control algorithm was applied. The dynamic shading device model (simple) was selected in DAYSIM to consider the effect of a generic venetian blind system on the annual daylight availability. This model returns an additional illuminance output file assuming that the lowered blinds block all direct sunlight and transmit 25% of all diffuse daylight. The passive blind control algorithm uses the two different blind settings to create one annual illuminance profile. The blind control strategy assumes that a user closes the blinds to avoid direct sunlight and leaves them down for the remainder of the day. Fig. 2 shows a temporal map of annual daylight illuminances for someone looking towards a window after applying the passive blind control algorithm. The fluctuations in the light intensity are due to a stochastic autocorrelation model that DAYSIM uses to convert the climate data from a time series of 1 hour steps to a series with 5 minute steps of daylight illuminances for all sky conditions of the year.

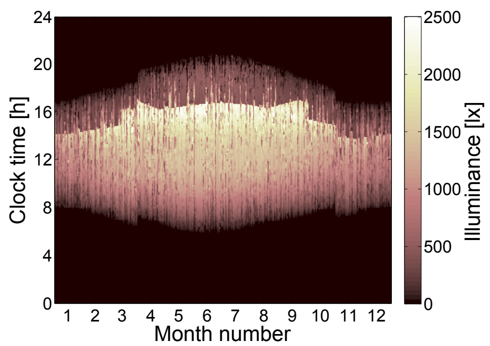

Figure 2: An example of an illuminance map for one sensor point location and view direction after applying the passive blind control algorithm.

Light pattern generation

Occupant's movements and activities in buildings influence the light exposure received at the occupant's eye. Healthy humans move their body, head and eyes constantly. Movements of occupants may introduce uncertainty in predictions of n–v responses to light, since those responses depend on duration, timing and history of a light exposure. Fig. 3 summarizes the four different evaluation methods used in this study to generate light patterns. Evaluating light exposure patterns at fixed sensor point locations and view directions may not be realistic (zone–based, fixed). In order to evaluate temporal and spatial effects of a lighting scenario, the sensor point locations and view directions were thus sampled randomly over the course of the day from a uniform distribution to account for occupant's movements within a defined space, called zone hereafter (zone–based, random). The same random pattern was used for each day and the sample size was $N_s = 100$.

To investigate the weight of the occupants' daily activity on the n–v response to light in a building, new activity–based light patterns were created by rearranging zone–based light patterns based on a daily activity schedule of occupants. This type of analysis was performed both for fixed (activity–based, fixed) and random (activity–based, random) sensor point locations and view directions.

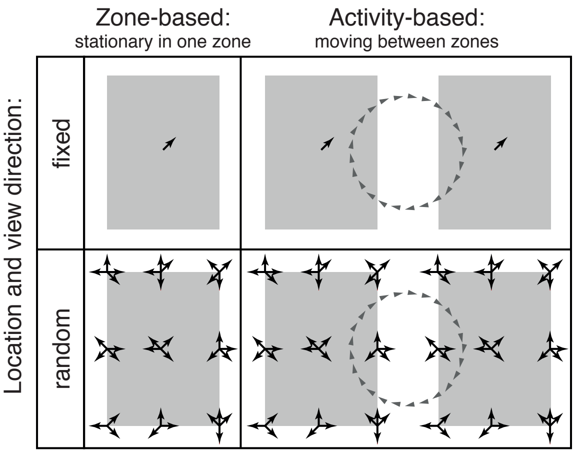

Figure 3: An overview of the four light pattern generation methods used in this study.

Human light–response simulation

It is known that the n–v system exhibits a nonlinear mechanism that controls responsiveness, as a function of light intensity (Cajochen et al., 2000; Zeitzer et al., 2000). A typical intensity–response curve is shown in Fig. 4 (a). In addition to the intensity–response curves, it has been shown that the system shows a nonlinear duration–response relationship (Chang et al., 2012) and light exposure patterns do not need to be continuous to affect the system (Gronfier et al., 2004; Rimmer et al., 2000). We applied a preliminary mathematical model, the human light–response (HLR) model, which predicts the relative n–v human responsiveness to light using a functional approach recently developed by the authors (Amundadottir et al., 2013). The HLR model is composed of linear filters and a nonlinear function to account for the nonlinear intensity– and duration–response relationship.

The HLR model is dependent on current light exposure and past light exposure duration, where brief exposures to light are more effective than longer exposures (Chang et al., 2012) and intermittent light patterns are more effective than constant light patterns (Gronfier et al., 2004; Rimmer et al., 2000). The main component of the HLR model is the nonlinear function that transforms light intensity into n–v relative response, as in Fig. 4 (a). This transformation is not only dependent on light intensity but also on light spectrum, timing, prior light history and subject's age.

It has been shown that high lighting condition (∼1000 lx) compared to lower lighting condition (∼200 lx) during daytime has positive effects on subjective alertness and performance (Münch et al., 2012; Smolders et al., 2012). Based on these two recent studies, we cannot say that subjects exposed to lower lighting condition (∼200 lx) were at 100% of their peak level of alertness as demonstrated by Cajochen et al. (2000) during nighttime study. Since this study focuses on evaluation of daylighting performance, we assume that 22 years old subjects observe 95% of n–v response under 1000 lx of fluorescent tubes of 4100 K. The spectrum of CIE standard illuminant F11 is used as a reference spectrum, shown in Fig. 4 (b).

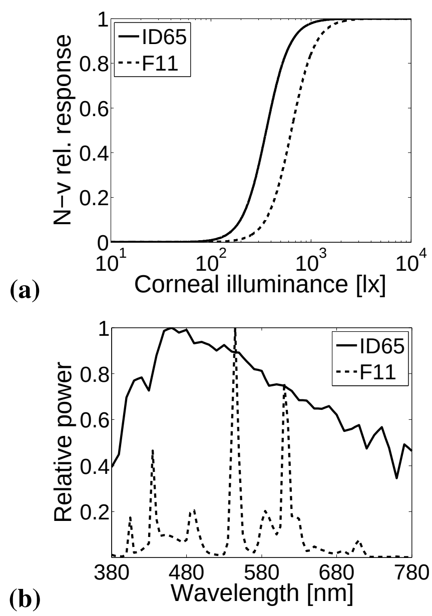

Figure 4: (a) The n–v relative response as a function of corneal illuminance for CIE standard illuminants ID65 (noon daylight) and F11 (fluorescent lamps of 4000 K). (b) The relative spectral power distribution of illuminants ID65 and F11.

The yellowing of the human lens with age reduces the transmission of blue light at the retina. By using an algorithm to convert to lens density functions (Pokorny et al., 1987) the upper threshold value of 1000 lx is recalculated for different age groups. For example 1415 lx of F11 is needed for 60 year old people to induce the same response as 1000 lx for 22 years old people. Fig. 5 shows the difference between lens transmittance of 20, 60 and 80 years old individuals. We use cubic spline interpolation for the range 400-650 nm to obtain values at every 5 nm (instead of 10 nm intervals) and cubic spline extrapolation for out of range values (380-400 nm).

The human retina has two types of visual photoreceptors that have a very different relative spectral sensitivity. The photopic efficiency function, $V(\lambda)$, corresponds to the spectral sensitivity of cones that operate when light is plentiful, whereas the scotopic efficiency function, $V'(\lambda)$, describes the spectral sensitivity of rods operating when light is very limited. For daylighting conditions, the $V(\lambda)$ function best approximate the response of the visual system. Since a spectral sensitivity function for the n–v system has not been standardized; Lamb's photopigment nomogram (Lamb, 1995) is used to construct a spectral sensitivity function, $S(\lambda)$, with peak sensitivity at $\lambda_{\max} = 480$ nm. Fig. 5 shows the $S(\lambda)$ function together with the $V(\lambda)$ and $V'(\lambda)$ functions. The $S(\lambda)$ function is used to determine n–v equivalent upper threshold values for different light sources. Fig. 4 (a) shows two intensity–response functions comparing daylight and fluorescent light spectrum.

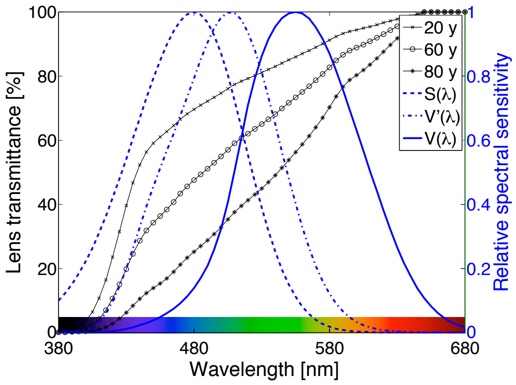

Figure 5: Left y–axis: Lens transmittance as a function of wavelength for 20, 60 and 80 years old individuals. Right y–axis: Relative spectral sensitivity as a function of wavelength for n–v responses $S(\lambda)$, dim light vision $V'(\lambda)$, and colour vision $V(\lambda)$.

Results interpretation

The results should be easy to interpret and inform the designer about the n–v potential of a space or a building thus the results are presented graphically using temporal maps, as shown in Fig. 2. Temporal maps are plotted to visualize the average n–v relative response of occupants. To achieve this we take the average of the simulated n–v relative responses, R, over the number of time steps in one hour and the number of days in one month. The resulting temporal map has the resolution of one month along the x-axis and one hour along the y-axis.

The average n–v relative response, $\bar{R}$, is useful to compare how the n–v effects of light accumulate over the course of the day. A temporal map can present performance over time referring to a single or several points in a space. For fixed light patterns, the $\bar{R}$ is averaged over the number of sensor point locations for each view direction. Thus we have eight temporal maps, one for each view direction per zone or activity schedule. For random light patterns, we average the $\bar{R}$ over the number of samples N_s. Thus we have one temporal map per zone or activity schedule.

In addition to temporal maps of $\bar{R}$, we are interested in the maximum n–v relative response, $R_{\max}$, reached per day. A directional plot (octagon), Fig. 6, illustrates the performance over the year for 8 view directions at a single point location. The plot shows the frequency of $R_{\max}$ occurrences above or equal to a specified threshold value T during a specific time period to the length of the time period. Directional plots or octagons can only be used for fixed light pattern performance evaluation. For random light pattern performance evaluation, we use traditional histograms.

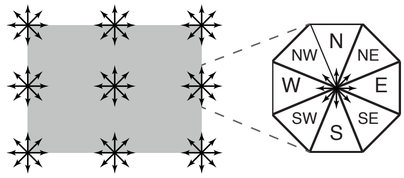

Figure 6: Each zone is populated with 72 sensor points. For static evaluation, the percentage frequency of $R_{\max} \geq T$ is shown for each view direction at every location using a directional plot or an octagon.

SIMULATION SETUP AND PARAMETERS

Case study building

An adult daycare center was selected for this study. The daylit spaces of the case study building are divided into 5 zones based on building configuration and function as illustrated in Fig. 7. The windows are located on the West and North facing side of the building, all outfitted with venetian blinds. Table 1 shows material properties assigned for the case study. The interiors are assumed to be spectrally neutral or gray.

Each zone is populated with 72 vertical sensor points at 9 locations. At each sensor point location, 8 view directions are analyzed at height 1.3 m to approximate the position of the human eye, illustrated in Fig. 6.

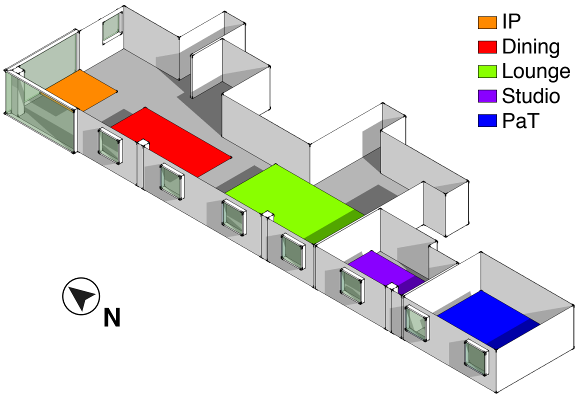

Figure 7: The case study building and locations of the 5 daylighting zones.

Table 1: Modelled material properties (incl. light reflectance value (LRV) and visual transmittance (VT)).

Materials	Properties
Ceiling	80% LRV
Floor	20% LRV
Wall	50% LRV
Typical window	78% VT, 2.25 m^2 (1.5 m $\times$ 1.5 m)
Corner window	70% VT, 13.5 m^2 (5 m $\times$ 2.7 m)

Time and space factors

The investigated building is located at 40.92 degrees North (latitude). Daylight savings time is assumed to last from April 1st to October 31st.

The daycare is assumed to be occupied from 10:00 to 15:00. During the stay in the daycare center, occupants take part in different activities customized for every individual. To analyze the use of the 5 daylit zones, we use the activity schedules listed in Table 2 to generate activity–based light patterns. The dining area and the lounge are used for large group events. Smaller group events take place in the indoor patio (IP) and the studio for activities such as gardening or arts and crafts. The pied-à-terre (PaT) space is a day apartment for individuals with high functioning.

The CIE standard illuminant D65 (i.e. typical noon daylight spectrum) is used to represent average daylight throughout the year. More specifically, we use recommended indoor daylight illuminant ID65 (CIE 184:, 2009) that corresponds to 6500 K correlated color temperature and accounts for transmission of window glass, shown in Fig. 4 (b).

Table 2: Daily activity schedules.

	10:00-12:00	12:00-13:00	13:00-15:00
A	IP	Dining	Studio
B	Studio	Dining	IP
C	Lounge	Dining	Dining
D	Lounge	Dining	Lounge
E	PaT	PaT	PaT

Human factors

Occupants are assumed to be 60 years old and older. The HLR model takes into account the yellowing of the lens as the only age–related factor that could explain why n–v responses to blue light are impaired in older people. It is common that eldery persons have reduced functional mobility. The four different methods of generating light patterns, Fig. 3, consider the very extremes of functional mobility, where occupants' movements and behavior can vary between individuals.

Performance goals

Aging is associated with increased disturbances in the timing, duration and quality of sleep; this can have a substantial impact on older people's quality of life and daytime functioning. One method of improving sleep/activity may be to boost the amplitude of the circadian clock by strengthening the light–dark cycle. The efficacy of light exposure strongly depends on the light intensity, spectrum, duration, timing and history. Making sure that the daily light exposure is sufficient to have a non–visual impact, the goal in this study analysis is set to $T = 0.75$. Taking into account the length of the period 10:00-15:00, which can only induce a 90% response due to the HLR model assumptions.

RESULTS

The cumulative n–v effects of light on health and well-being are evaluated using four different light pattern generation strategies derived from Fig. 3.

Zone–based, fixed evaluation

The first evaluation strategy assumes that occupants maintain a fixed location and view direction within a zone. We compare the five zones that have access to daylight in the case study building. The difference between summer and winter time is significant. The octagons or directional plots in Fig. 8 (a, b) show the percentage frequency of R_{max} reaching a threshold value of T during summer Fig. 8 (a) and winter period Fig. 8 (b). In enclosed spaces, the selection of sensor point location and view direction is more sensitive than in open spaces where daylight can reach a wider area. For example the PaT space, which has two windows on the West facing side, shows lower performance than the dining area, which is located in an open space and has more access to daylight.

Although, the directional plots in Fig. 8 (a, b) are useful to visualize the n–v response of stationary occupants, they overlook parts of the day. Fig. 8 (c) shows the maximum n–v visual response per day, $R_{\max}$, over the time of year for two view directions in the mid-

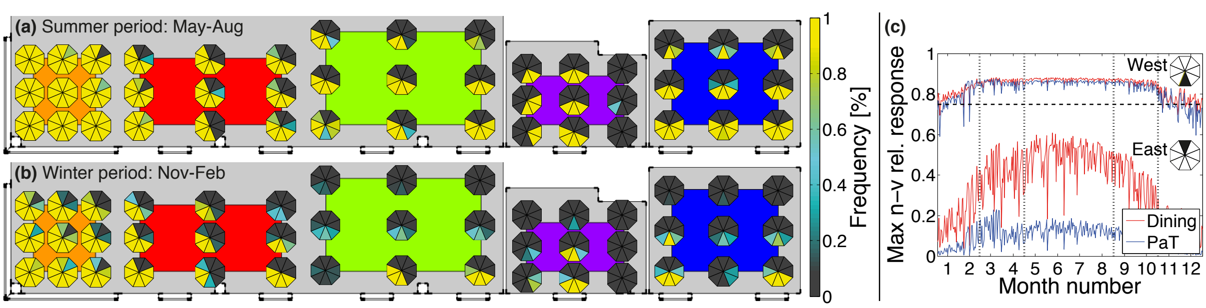

Figure 8: Percentage frequency of $R_{\max} \geq T$ per (a) summer period and (b) winter period. Health outcomes will depend on whether the occupant tends to look towards or away from windows. (c) The maximum n–v relative response, $R_{\max}$, as a function of time of year for the PaT space (blue) and the dining area (red). The dashed horizontal line marks the threshold value of $T = 0.75$. The dotted vertical lines mark the grouping of seasonal periods.

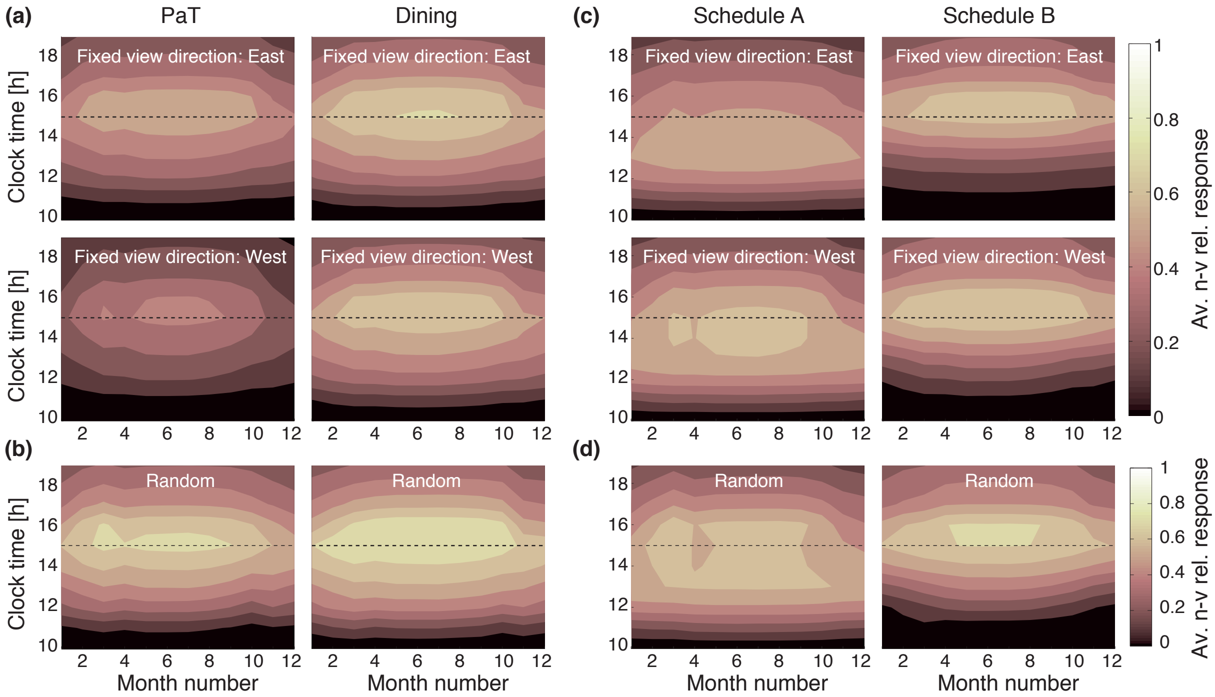

Figure 9: The average n–v relative response ($\bar{R}$) as a function of time of year and time of day. (a) Zone–based, fixed evaluation. (b) Zone–based, random evaluation. (c) Activity–based, fixed evaluation. (d) Activity–based, random evaluation. The dashed line shows the time when occupants typically leave the daycare center.

dle of the PaT space and the dining area. All $R_{\max}$ values that fall below the threshold value, $T = 0.75$, are counted as 'misses' in Fig. 8 (a, b), although the results for the two zones facing East (away from the windows) vary from ~0.1 for the PaT space and ~0.5 for the dining area. This variation is apparent in Fig. 9 (a), which shows the average n–v relative response, $\bar{R}$, for view directions pointing towards the window (West) and away from the window (East). Due to the averaging of the n–v relative response, the maximum values are not visible in Fig. 9 (a).

Zone–based, random evaluation

Instead of having eight temporal maps for each view direction, we have only one per zone, illustrated in Fig. 9 (b) for the PaT space and the dining area. By randomizing locations and view directions, the overall performance improves compared to the zone–based, fixed evaluation. The $\bar{R}$ gained over the day during summer time after randomizing is 0.7 for the PaT space (Fig. 9 (b)) compared to 0.6 after averaging over 9 sensor point locations facing the windows (East) (Fig. 9 (a)). Moreover, the $\bar{R} = 0.7$ for the dining area is distributed over a greater area of time for the random evaluation compared to the fixed evaluation. This is due to the temporal integration property of our HLR model, where intermittent light patterns are more effective than continuous light patterns.

Fig. 10 shows the frequency of $R_{\max}$ above or equal to the threshold T for months of the year. Comparing the frequency per month for all zones, see Figure 10, the dining area and the indoor patio (IP) perform the best having the highest frequency of $R_{\max} \geq T$. The lounge area and the PaT space show similar medium performance. The performance of the studio almost never passes the threshold value of T. The general trend is that performance for months of summer are reduced by half for winter months.

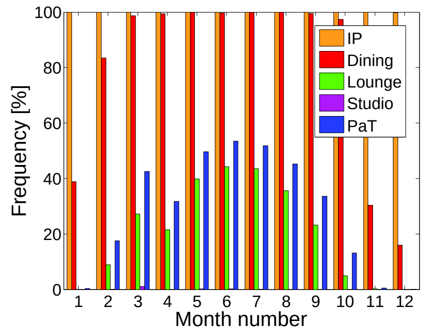

Figure 10: Percentage frequency per month for all five zones.

Activity–based, fixed evaluation

Occupants normally move around frequently, both within a space or between spaces. In the daycare center, the PaT space is the only zone where some occupants spend their entire day. To account for occupants' activity, four different daily activity schedules shown in Table 2 are analyzed. If we compare schedule A and B, where equal amount time is spent in each zone but in a different order, the resulting directional plots show a better performance for schedule B, as seen in Fig. 11, where schedule B shows higher percentage frequency than schedule A. However, the annual temporal maps show that the $\bar{R}$ peaks earlier following schedule A compared to schedule B (Fig. 9 (c)).

Light patterns based on daily activity schedules for fixed sensor point locations and view directions may not represent a typical behavior of occupants in the daycare center. However, it is useful for simulating occupants' behavior with impaired functional mobility, which is often the case in healthcare facilities.

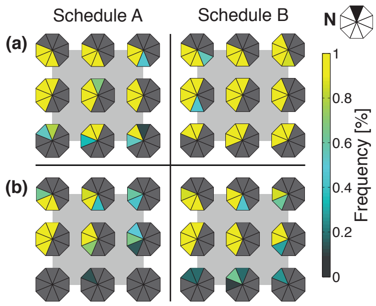

Figure 11: Comparing frequency of $R_{\max} \geq T$ for two different daily activity schedules: (a) schedule A and (b) schedule B.

Activity–based, random evaluation

Fig. 9 (d) shows the average n–v response for an occupant following activity schedules A and B, respectively. The figures show that although an equal amount of time is spent in each zone the order in which the zones are occupied influences the distribution of $\bar{R}$ throughout the day. Occupants following schedule A, Fig. 9 (d), have an early rise in n–v response and maintain a level higher than 0.5 from noon throughout the afternoon. Occupants following schedule B do not reach a n–v response higher than 0.5 until around 14:00 in the afternoon. Fig. 12 shows a histogram with the frequency of $R_{\max}$ values larger than the threshold T. The figure shows that occupants following schedule B and C have a n–v response surpassing the threshold value more frequently than occupants following schedule A and D.

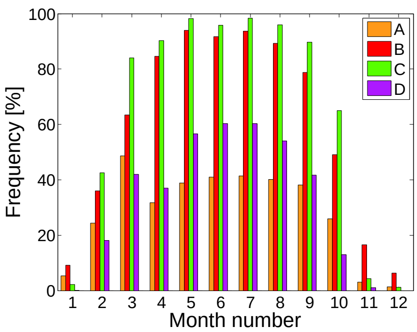

Figure 12: Percentage frequency per month for four different daily activity schedules A, B, C and D.

DISCUSSION

The dynamic behavior of the n–v system provides new challenges in evaluating lighting performance of buildings. One of the challenges is that our n–v system is affected by light exposure duration and history over much longer time period than the visual system. The performance evaluation strategy aims to evaluate whether occupants receive enough light to stabilize their circadian clock and to maintain relative high daytime alertness/activity level.

Although spending time outdoors would likely provide an adequate light dose, it may not be possible for the occupants at the daycare center under study. Therefore, it is important to make sure that the adequate light dose can be obtained by spending time in brightly lit spaces. As shown by the case study this can be achieved by properly adjusting the daily activity schedule, where higher light intensities all day are not necessary to achieve a predefined threshold value. The period 10:00-15:00 may be too short to influence the sleep–wake cycle, since the circadian system is relative insensitive to light during daytime. However, it may influence sleep quality indirectly by increasing daytime activity and reducing daytime napping.

Appropriate light exposure in healthcare facilities is critical for the health and wellbeing of patients and staff. An improved daylighting design of buildings may lead to significant health improvements. Making the most of the available daylight, which is naturally rich in the blue part of the spectrum, and supplementing this with appropriate electric light, is a promising approach and might play a large role in new lighting recommendations for health. Especially early design decision will contribute to daylight penetration in buildings. The evaluation of the simulation results show that view direction and distance from window are important factors. The easiest change is to make windows more accessible and more attractive to look at. If brighter areas are more frequently viewed, it may be enough to provide n–v 'active' light, instead of increasing the light intensity throughout the interiors. In enclosed and poorly lit zones, as for example the PaT space, where occupants spent their entire day. It might be feasible to install light pipes, since the space has direct roof access, and/or increase daylight penetration using reflective panels.

CONCLUSION

This study applies recent findings in photobiology into lighting design. More specifically, it uses simulation–based framework to evaluate daylighting performance in an actual healthcare facility. For a proof–of–concept, we evaluated different light patterns to assess occupants' movements and activities in a building to support design decisions. The light pattern generation is important and gives information on the light exposure variability experienced by an occupant. The advantage of using our HLR model is that it can predict the relative effectiveness of different light patterns, both continuous and intermittent, which is useful when evaluating daylighting performance. There is, however, no agreement about the optimal daily light dose yet. Despite this limitation, using predefined threshold values to evaluate the simulation results, it is possible to develope new methods for simulating and evaluating the n–v responses to light and compare different design solutions.

With increasing complexity of building designs and higher performance requirements on sustainability, use of building simulation will become more important. The concept of healthy lighting is still relative new in the lighting community and the link between lighting design and health outcomes is only starting to be established. The body of experimental evidence supporting the development of modelling the n–v responses to light is growing. However, challenges associated with measuring occupants' dynamic behavior and biological response in realistic lighting environments continue to be a barrier for developing design tools supporting the evaluation of n–v responses to light in architectural settings.

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