

A simulation workflow for exposure characterisation of daylit spaces based on occupant gaze orientation

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Abstract

Characterization of spectral lighting depending on occupants' position and gaze is explored through a simulation-based framework and an experimental pilot study. Our knowledge on the spectral effectiveness of light by regulating our biological rhythms is advancing. Hence, defining the actual exposure to spectral lighting as a result of the building design from the occupants' line of gaze is an important step forward. A simulation framework was developed to account for occupants' gaze behavior and to compute circadian lighting for customised solutions at individual level. Computed spectral exposure's relation to occupants' performance were explored in a pilot study, where dwell and track data and attention levels of participants were gathered. Indications of higher attention levels when exposed to higher computed spectral lighting thresholds were found.

Key Innovations

- A pre-validated simulation workflow was developed.
- The developed workflow coupled with occupancy sensors can give real-time information to the occupants regarding their light environment and achievable productivity levels towards building digitalization.
- Such solutions will allow for customised lighting solutions at individual's level.
- We are set out to investigate the possibilities of relating spectral light exposure levels to human performance and productivity.

Practical Implications

The developed framework is used at this stage to illustrate exposure to spectral lighting as well as illumination levels at the eye level at any given position in space and thus allow for exposure characterization of the space at any given point. Acquiring such information could help making or suggesting better decisions and towards healthier indoors environment customised for each individual where higher performance rate could be expected. Moreover, in a more practical level, the developed workflow coupled with occupancy sensors can give real-time information to the occupants regarding their light environment and achievable productivity levels. The effect of such framework for the building occupant and owner are beyond the immediate needs of the society and towards continuous performing results.

Introduction

Located in eyes, Photosensitive Retinal Ganglion Cells (ipRGCs), serve as input in effectively synchronizing the human circadian rhythms to the daily 24h light and dark cycle when exposed to light. Timing, intensity, duration, wavelength, and prior history of exposure to light (Lockley, 2009) affect the resulting effects of this process. Despite different existing wavelength-dependent models to predict spectral-effectiveness of light (M. L. Amundadottir, Lockley, & Andersen, 2017; M. S. Rea, Bierman, Figueiro, & Bullough, 2008), these methods predict the circadian light exposure and its health potentials with assumption of static building occupants on fixed pre-defined points (Maria L Amundadottir, Rockcastle, Khanie, & Andersen, 2017).

With great benefits on our well-being (Birchler-Pedross et al., 2009; Lockley, 2009), a spectral characterization of space based on dynamic occupant behaviour, is a step forward where a realistic input of at least four of the affecting factors, i.e., timing, intensity, duration and wavelength can be derived. Such approach allows for better understanding of occupant well-being based on actual occupant light-exposure and in support of customised health solutions at the individual level.

In this study using Grasshopper3D (GH), a new framework was developed based on a previously developed gaze prediction GH tool (M. S. Sarey Khanie et al., 2018) to account for occupants' gaze as well as gaze behaviour and Lark (Inanici & ZGF Architects LLP, 2015). The latter is a Radiance-

based (Ward-Larson & Shakespeare, 1998) multi-spectral and physically accurate spectral lighting simulation tool to account for photopic, Rea (M. Rea, 2015) and Lucas (Lucas et al., 2014) circadian illuminance computation methods. The developed simulation framework can hence identify light exposure related to actual human position and orientation (*gd* and gaze behaviour) in space to identify healthier solutions for each individual. The simulation framework, in addition, uses an existing gaze movement database and gaze behaviour model (Maria L Amundadottir et al., 2017) obtained and developed obtained at a daylight lab in Freiburg, Germany, in a user-assessment study where eye-tracking systems were used to record visual responses to the luminous environment (M Sarey Khanie, Stoll, Einhäuser, Wienold, & Andersen, 2017).

The developed framework, based on the aforementioned existing methods, takes as input dynamic gaze direction

coordinates and delivers as output the computed light and spectral light levels using multi-spectral lighting simulations. As the final step, in order to explore the relation between computed exposure ranges to human performance and productivity in conceptual pilot study, dwell and track data as well as attention levels of participants were gathered.

Background

Dynamic gaze behaviour

Addressing dynamic occupant gaze behaviour, could be done either by using predictive models in early design phases or by using occupancy sensor that could provide dwell and track data in post-occupancy stages. Gaze reflexes are relatively well-understood eye movements (Krauzlis, 2008), that coexist with head and body movements ('t Hart & Einhäuser, 2012; Hayhoe & Ballard, 2005). Understanding the natural behaviour of gaze, which has a strong impact on the amount of light received in the field of view (FOV), in relation to the real- world conditions, e.g. illumination, requires accounting for all these coexisting movements in order to provide information about the actual gaze control during a real- life behaviour ('t Hart & Einhäuser, 2012; Fairchild, Johnson, Babcock, & Pelz, 2001; Hayhoe & Ballard, 2005).

Computational models that aim at predicting gaze orientation typically focus on the control of large eye movements by low-level stimulus features, such as luminance contrast, colour, orientation or motion (Itti, Koch, & Niebur, 1998; Navalpakkam & Itti, 2005). Experimentally, however, gaze is long since known to be influenced by task (Maria L Amundadottir et al., 2017; Buswell Thomas, 1935) or context (Rothkopf, Ballard, & Hayhoe, 2007; Torralba, Oliva, Castelhana, & Henderson, 2006). In relation to light as stimulus, the focus on gaze behaviour has largely been on urban street lighting (Heynderickx, Ciocoiu, & Zhu, 2013; Winter, Fotios, & Völker, 2019) or pedestrian lighting (Fotios, Gado, & Fotios Gado, 2005; Fotios, Uttley, Cheal, & Hara, 2014). In similar context, when viewing static images of natural scenes (streets lit with lamppost at night) observers tend to avoid bright and dark stimulus regions and to direct gaze to regions of medium luminance instead (Nuthmann & Einhäuser, 2015). The studies that have investigated the relationship between gaze shifts and building-induced visual context such as the presence of window (Mandana Sarey Khanie, 2015; Sury, Hubalek, & Schierz, 2010; Yamín Garretón, Rodriguez, & Pattini, 2016) or light (Kokoschka & Haubner, 1985; Y. Lin et al., 2015; Vincent, Baddeley, Correani, Troscianko, & Leonards, 2009). These studies deny the fixed assumption of gaze direction (*gd*) (Hubalek & Schierz, 2004) and recommend balance luminance distribution in FOV to avoid transient adaptation when working on different tasks (Kokoschka and Haubner 1985). Dependencies on visual context such as task or view outside have also been shown in several studies (Hamedani et al., 2019).

Dynamic gaze-behaviour as result of light exposure towards prediction models has been addressed in fewer studies. In these studies, photometric measurements and eye-tracking methods have been coupled for observations of gaze or eye responses to light (Doughty, 2014; Mandana Sarey Khanie, Stoll, Einhäuser, Wienold, & Andersen, 2016; Yamín Garretón et al., 2016). These studies, among others, have shown the perceived incidence angle of light which varies with the passage of the sun across the sky, also varies with dynamic gaze changes.

The dynamic gaze direction behaviour has been modelled in a preliminary prediction model as function of light behaviour (Maria L Amundadottir et al., 2017). Figure 1, illustrates a light-driven

gaze model where avoidance to a directional source gg^{\rightarrow} , e.g., glare, and attraction to the directional source aa^{\rightarrow} , e.g., view, is predicted by the model. This iterative model predicts the responsive behaviour, i.e., an angular shift, over the space for all possible directions. The visual scene inputs are identified using the high dynamic range (HDR) input data.

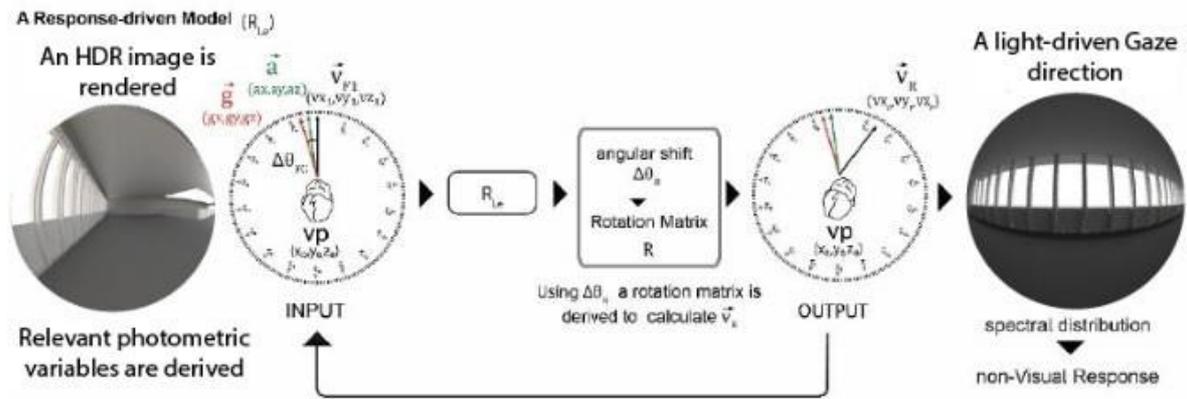


Figure 1. Illustrates a light-driven gaze model where gaze behaviour is predicted using HDR renderings.

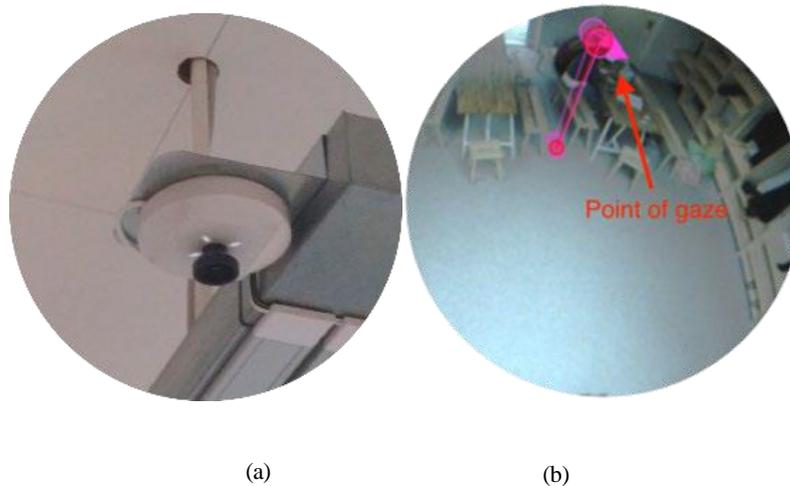


Figure 2. (a) A camera with wide angle lens for occupancy video analysis, (b) an example of gd recognition.

Another novel way of addressing gaze behaviour in building segments is cross-camera tracking methods, with applications ranging from surveillance (Wang & Zhang, 2010) or behaviour recognition (H. Lin et al., 2014) to building digitalisation. Fewer of these methods are using image-based occupancy sensors coupled with video analytics while having specific algorithms to ensure privacy Figure 2.a. Such methods are mainly used to provide real-time data on occupants such as occupancy rate and gender, but more importantly they provide the possibility of extracting spatio-temporal dwell and track data. Another possibility of data extraction explored briefly in this study using such sensors, is the occupant's orientation in the space Figure 2.b. Here the occupant orientation is recognised in the image and the room- references

coordinates are extracted.

Multi-spectral Lighting simulation

Radiance (Ward-Larson & Shakespeare, 1998) is a physically based light rendering open-source tool which works based on High Dynamic Range image-rendering in RGB colour space. The HDR rendered images are then converted to photometric values using a CIE-XYZ to RGB conversion formula.

$$L = 179.(0.265R + 0.67G + 0.065B) \quad (1)$$

The possibility of changing the existing 3 channel approximation of the spectral signal to larger waveband bin was shown by (Ruppertsberg & Bloj, 2006, 2008) where the N-stepping (N consecutive wavebands) method for approximation waveband average of the original signal is used and implemented. Multi-spectral lighting simulation methods in field of architecture and building (Balakrishnan & J.Jakubiec, 2020) have adopted the aforementioned method for circadian lighting calculations. Two of the well-known and available tools are the open-source Lark (Inanici, Brennan, & Clark, 2015; Inanici & ZGF Architects LLP, 2015) and a more commercialised variation known as Appropriate lighting for alertness (ALFA) (Solemma, 2018) which are both user-friendly interfaces to adopt the N-stepping method for circadian lighting computation. In these tools the visible light spectrum is divided into larger number of channels and the computations are performed in different intervals that span the entire visible light spectrum for each visual scene to derive per-pixel photopic luminance (or illuminance) values and by circadian spectral sensitivity curve $C(\lambda)$ to derive per-pixel circadian luminance (or illuminance) with necessary adjustments to equation (1). In this study we have only adopted Lark spectral lighting for spectral lighting simulations.

Methods

The methodologies regarding the simulation framework and the follow up pilot case study are explained in the following sections. The simulation framework is a Grasshopper3D tool that was designed to integrate dynamic gaze and spectral simulation in order to derive gaze dependent exposure characterisation of space. The obtained computed data is then processed to explore health potentials

in buildings and further on relate to human productivity levels through a pilot case study.

Characterization of spectral exposure

Several embedded components of the Grasshopper3D plug-in and its related tools including Ladybug and Honeybee were used in development of the framework. Several components were scripted in Python ranging from *gd* and grid setup, andsetup and setting the Rhino view based on *gd* using a modification of “SetTheView” from Honeybee, to gaze shifts and counts which are implemented to be used in any form of architectural space by using correct intersections to the surrounding geometry. And finally, a set of components were scripted for Lark in order to read and process the data in relation to the specified *gds*.from *gd*.

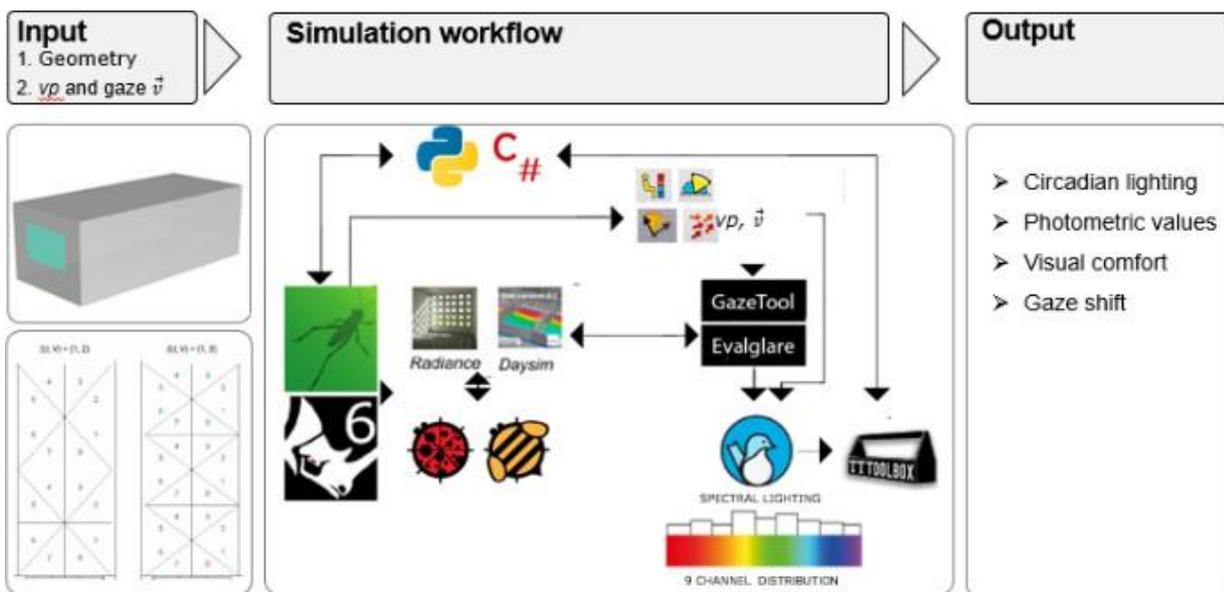


Figure 3. A schematic of implement dynamic gaze changes and non-visual effects in relation to daylight in Grasshopper 3D; the daylight simulations run through Radiance and DAYSIM using Honeybee and Ladybug components. Finally, a C# script is used together with TT toolbox for arranging obtained data.

The developed framework, as shown in Figure 3, takes the 3D geometry and photometric information of the surfaces as input. Then material properties are added to the respective surfaces through Honeybee components. Dynamic gaze changes are computed through Python- written components

from GazeTool (M. S. Sarey Khanie et al., 2018), which can predict a gaze avoidance from glare detected using the Radiance-based tool, Evalglare (Wienold, 2009). The basis of the analysis is a grid of viewpoints (vp), and a set of gds in 360° visual span. As default the number of gds is set to 8 in 45° intervals. For final gaze counts when using GazeTool and in order to depict a dominant gaze zone or direction, the gaze shifts are binned into 8 zones of 360° visual span divisions as shown in Figure 4. Otherwise, the spectral lighting is calculated for any given or input gd . In case the gaze position and direction are coming from the real-world conditions, i.e., occupancy sensor or eye tracking device, this data can be inputted directly to the workflow. HDR images are generated for each vp and gd in order to derive the relevant photometric values and enabling characterization of space-level exposure at any given position. Adopting a circadian rhythm metric which is a tool for characterizing light that acts as a stimulus for the human circadian rhythm system, e.g., or Equivalent Melanopic Lux (EML), the obtained images are processed into meaningful results. The threshold value CS explained the optimal stimulus throughout the working day, where specific values are given for each hour, while the threshold value EML gives a fixed value over all hours. In this paper EML is used and shown in the results as an example. In order to obtain a higher precision for circadian rhythm metrics, the 9-channel methodology is applied, which divides each of the three bins (RGB) into three channels. The division of the bins means that there will be three materials for both the sky and the 3D model surface materials, separated in red, green, and blue bins. The image-based and grid-based simulations are performed each with the three material bins, which eventually results in 2×3 simulations for a single vp and gd specific situation. The output is given in Photopic, Rea, and Lucas lux by combining both HDR images and illuminance values for the viewpoint into a single value or image. Furthermore, to get the EML, the conversion $(179/149) * \text{Lucas}$ is used. Figure 5. shows an example of two viewpoints with nine gds over 360° visual span. This example illustrates whether along each gd shown as vectors, the threshold for EML – in this case the threshold is 200 lux based on WELL protocol – with green being above and red being below the threshold.

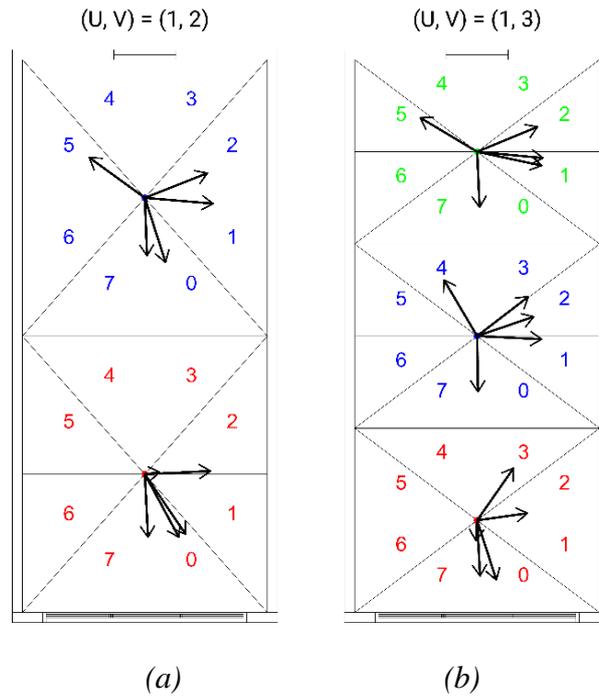


Figure 4. The binning of the shifted gds in visual span zones are shown in an example using the MIT reference office (Reinhart, Jakubiec, & Ibarra, 2013). Creation of eight gaze zones (numbered 0 to 7) centered around: (a) two vps ((U,V)=(1,2)), (b) three vps ((U,V)=(1,3)).

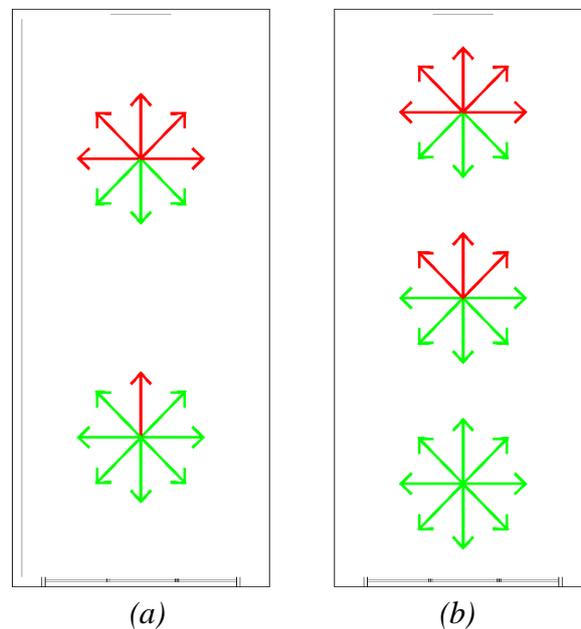


Figure 5. MIT reference office (Reinhart et al., 2013), an example of two vp and eight gd is shown. The green arrows for the computed period meet the EML threshold in this case: (a) two vps ((U,V)=(1,2)), (b) three vps ((U,V)=(1,3)).

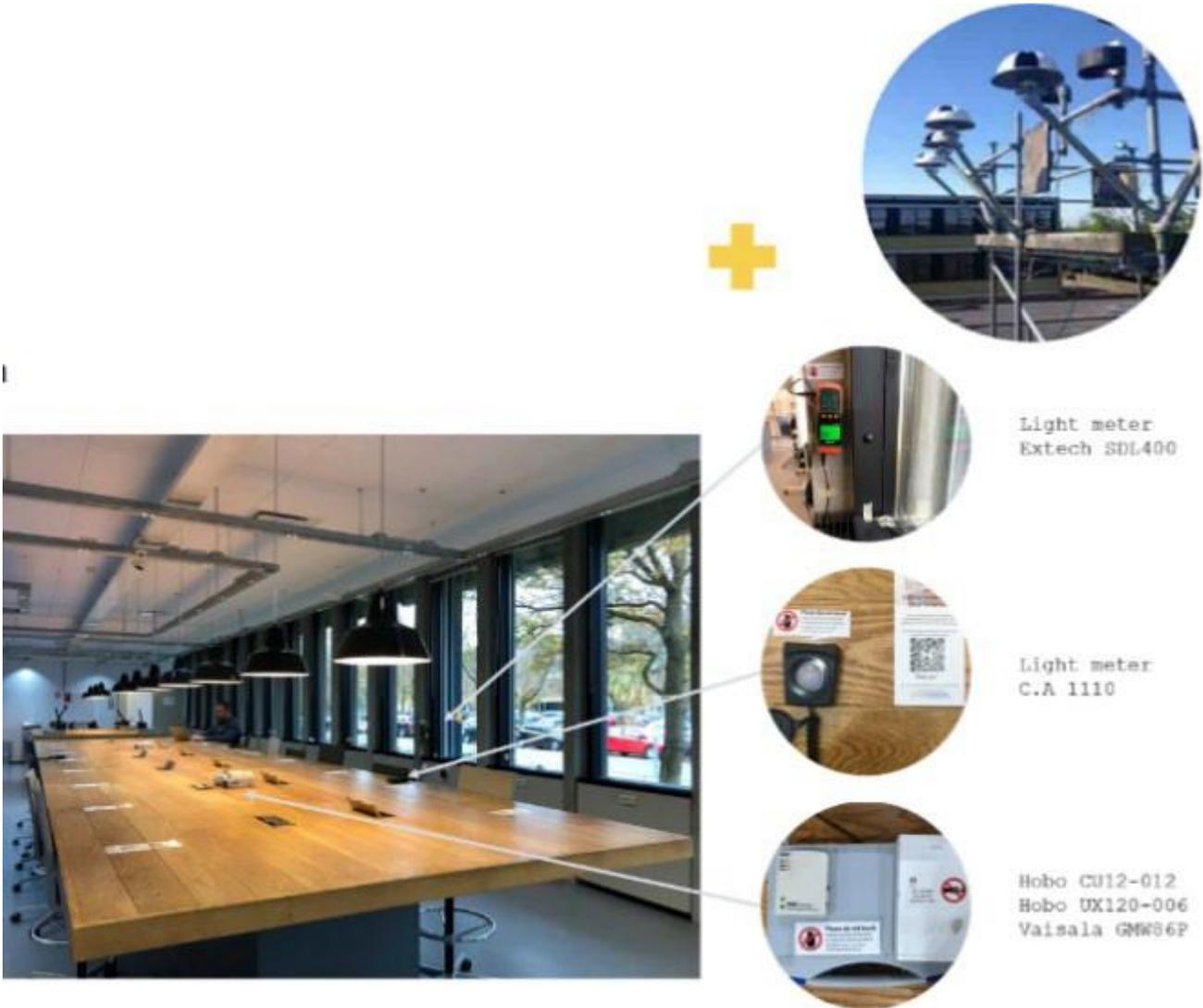


Figure 6. The measurement devices used in the study as used in one of the zones.

The pilot case study

The pilot study was done at the SMART Library at Technical University of Denmark (DTU) between 31st of October until 13th of November with the aim of collecting occupants' gaze, satisfaction, and performance data. The study was performed in two selected areas, in first and third floor of the library, respectively facing west and north/east. Several physical indoor environmental measurements were made including temperature and humidity using Hobo, and CO₂, using calibrated Vaisalas as well as illuminance light levels using two different types of luxmeters. Outdoor light levels were extracted from the global horizontal irradiance measured at the campus weather station (Andersen et al., 2017). A questionnaire was developed and used, collecting demographic data, mood, task purpose, satisfaction, and performance (Bille, 2019). To examine performance, we adopted D2 test, which is a neuropsychological measure of selective and sustained attention. Occupants' gaze orientations were tracked using an image-based sensor as well as through self-reported logging in the questionnaire.

Simulation and case study setup

A detailed 3D model was made to ensure that the same scene that the test participants' face is reflected in the digital format. Through the programs WINDOW and Optics6, a spectral distribution was calculated for a window pane type similar to that seen at DTU library. A 2-layer window pane with 4 mm clear glass, 12 mm air layer, and 6 mm energy glass has been used. Pilkington windowpanes were chosen, with 4 mm Optifloat™ Clear and their 6mm Suncool™ Brilliant 50/25 which has a transmission of 0.5 and a direct transmission of 0.24. Furthermore, window parameters are shown in Table 1. Table 2 shows the materials used in the simulation study. Finally, Table 3 shows the rendering parameters used in the simulations. Movable furniture and partitioning was not included, as there is great uncertainty about their position at each instant of time. Using the mentioned tools, the workflow goes through 6 main steps.

Table 1: Window properties.

Window parameters	Value
Thickness	22 mm
Solar factor	0.49
Daylight transmittance	50%
Direct transmittance	25%
Reflectance	39%
Absorbance	37%

Table 2: Surface materials reflectance.

Materials	Description
Generic Interior Wall	Diffuse reflectance of 50%
Generic Ceiling	Diffuse reflectance of 70%
Generic Floor	Diffuse reflectance of 20%
Generic Exterior Wall	Diffuse reflectance of 35%
Exterior Ground	Diffuse reflectance of 10%

Table 3: Radiance rendering parameters.

dt	dj	ds	ab	aa	ar	ad	as	lr	lw	pl	ps	pt
0.05	0	0.15	3	0.1	512	4096	2048	8	0.005	2	1	0

In the 1st step, the location of each occupant vp , in the space is set. At these defined vps , eight initial gds are assumed over 360° visual span. Next, the global horizontal illuminance is calculated for a specified sky. In step 3, the spectral sky is calculated through 9-channels based on the horizontal illuminance and the spectral power distribution. In this simulation, a D65 spectral power distribution has been used, which describes the average noon light for Northern/Western Europe. In step 4, the spectral distribution of the glass is calculated, which is calculated through Optics6. In step 5, the 9-channel simulation is started, after which the simulated results can be collected in step 6. Step 6 combines the simulated results from the 3 respective grid-based and image-based simulations. The results consist of a series of 9-channel simulations from which the EML is derived for each gd .

Results

The pilot case study

30 data points were obtained after cleaning the data based on fully responded questionnaires. The data was gathered in indoor environmental conditions with the minimum effect of the temperature, CO₂ levels and humidity as these parameters were kept in close to constant limits (Bille, 2019). Among the participants, there were 69% male and 31% female with 51% under 24 years old. The participants had Danish nationals 60% or an international background of 40%. The occupancy rate and accumulated *gds* in each zone are shown in **Error! Reference source not found.**

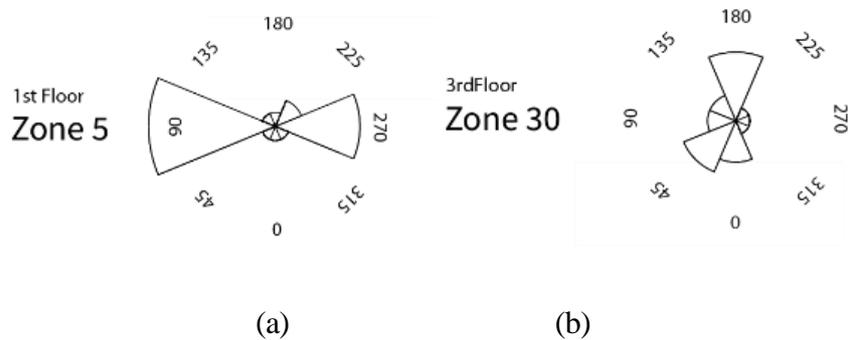


Figure 7. Participants accumulated gaze in the two selected areas where 180 is directed towards the North.

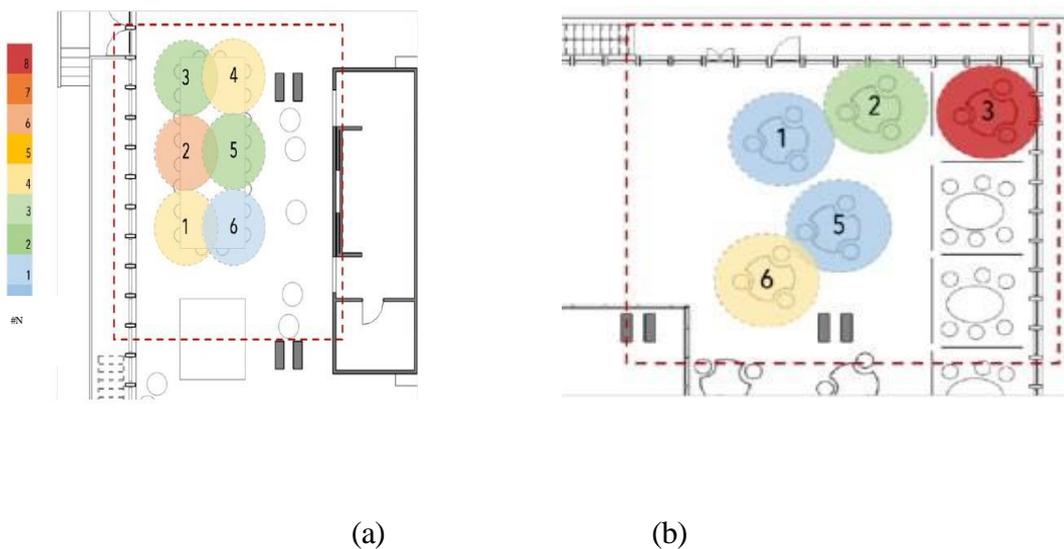


Figure 8. The occupancy rate of the participants in the selected respective zones, with North at the top.

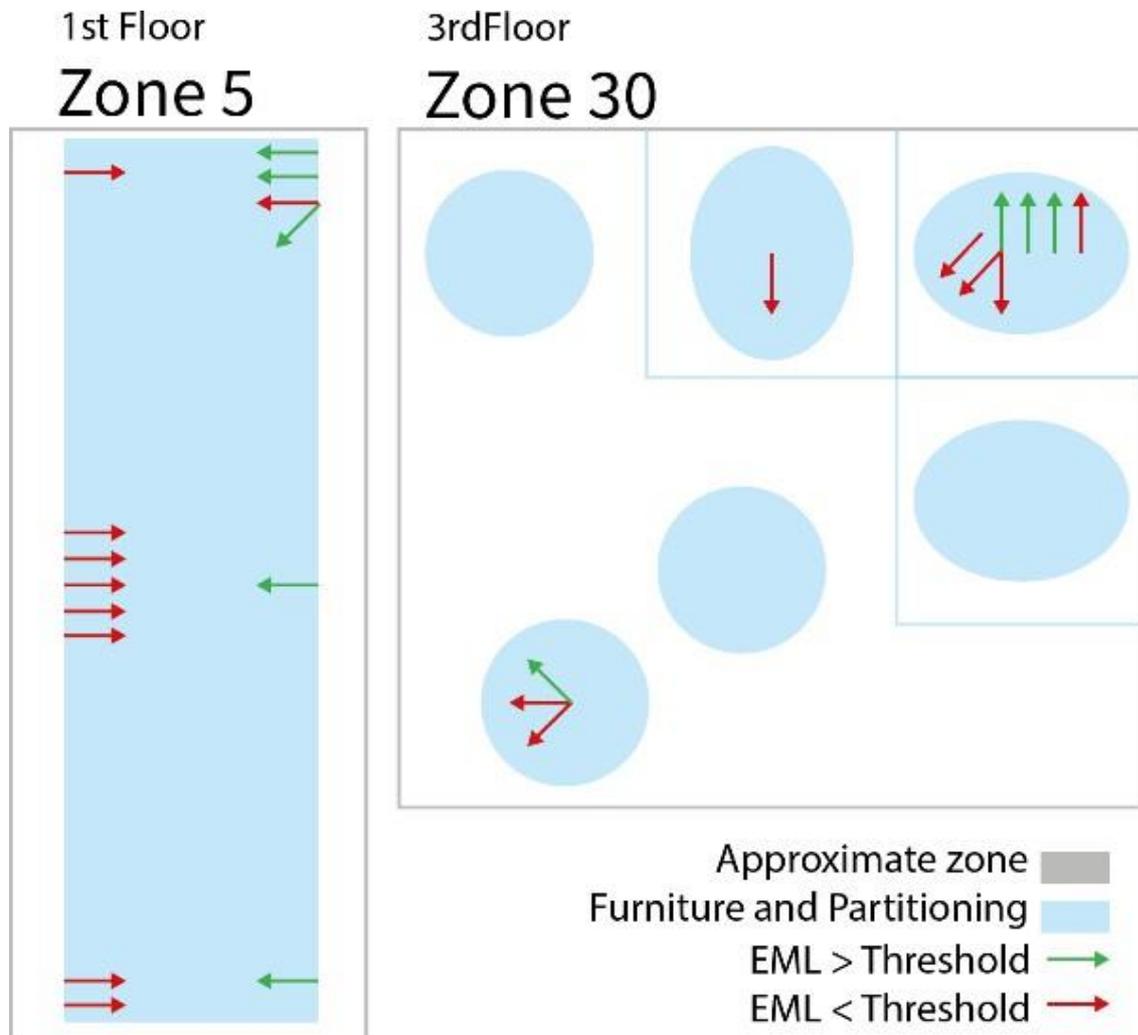


Figure 9. The achieved EML threshold at each *vp* and *gd* in the two zones are shown in green, otherwise in red.

Exposure at participants' position

The time of the day, occupant *gd*, and date are all predetermined based on the pilot study. The health potential was computed for each participant dominant gaze orientations. These calculations were done without electric lighting. The thresholds are at 500 lux for photopic results and 200 for EML. Figure 9. illustrates EML at each *vp* and *gd* with the green arrows meeting the criteria. We can see that required daylight exposure is not met on most of positions and *gds* depending on time of the day in this period of the year. Only a few situations achieved the threshold values. On the north façade, minimal visual discomfort was found, allowing orientations towards the window, which resulted in a higher health potential. Figure 10 and **Error! Reference source not found.** Figure 11. illustrates percentage of

photopic and EML results meeting the respective thresholds for each individual at zone 5 and 30 where the results were not zero due to lack of daylight. The graphs are sorted from minimum to maximum exposure which also corresponds to the minimum and maximum access to view depending on the participants' dominant orientation in the space shown on top of each individual graph. In both zones, the only sunny day is shown. The rest of tests were done under overcast sky. At the time of study and under overcast conditions, the recommended thresholds cannot be met in most points. The gaze orientation towards window and view ensures a higher exposure at the eye level in both zones.

Exposure and Performance

While we could see some effects of gender or concentration on the D2 responses, these observations was not significant or could be explained due to confounding variables. The attention rates were averaged 50% in cases where exposure thresholds were not met and improved to above 56% only in higher levels of exposure in zone 5. In zone 30 we could see the same trend with an increase from average 48% concentration to 50%. While a small agreement with a coefficient of determination of 14% could be seen in zone 5 between the exposure levels and attention rates, this agreement drops dramatically in zone 30 due to presence of glare in some cases.

Discussion

The developed simulation workflow, creates an easy platform to connect occupants gaze orientation to their light exposure. The information provided using this framework can be valuable to each individual in terms of how they place themselves in the building. The developed framework works with any input data on gaze orientation. The pilot study allowed for further assessment and development of the project concept. However, due to small sample size and limited experimentation period, the relation between spectral exposure and productivity cannot be conclusive. Time dependencies of the obtained health potentials can be addressed when occupancy sensors are available. Using dwell data, this information can be derived to enhance the results beyond the threshold-based representations.

1st Floor Zone 5

Exposure at individual level

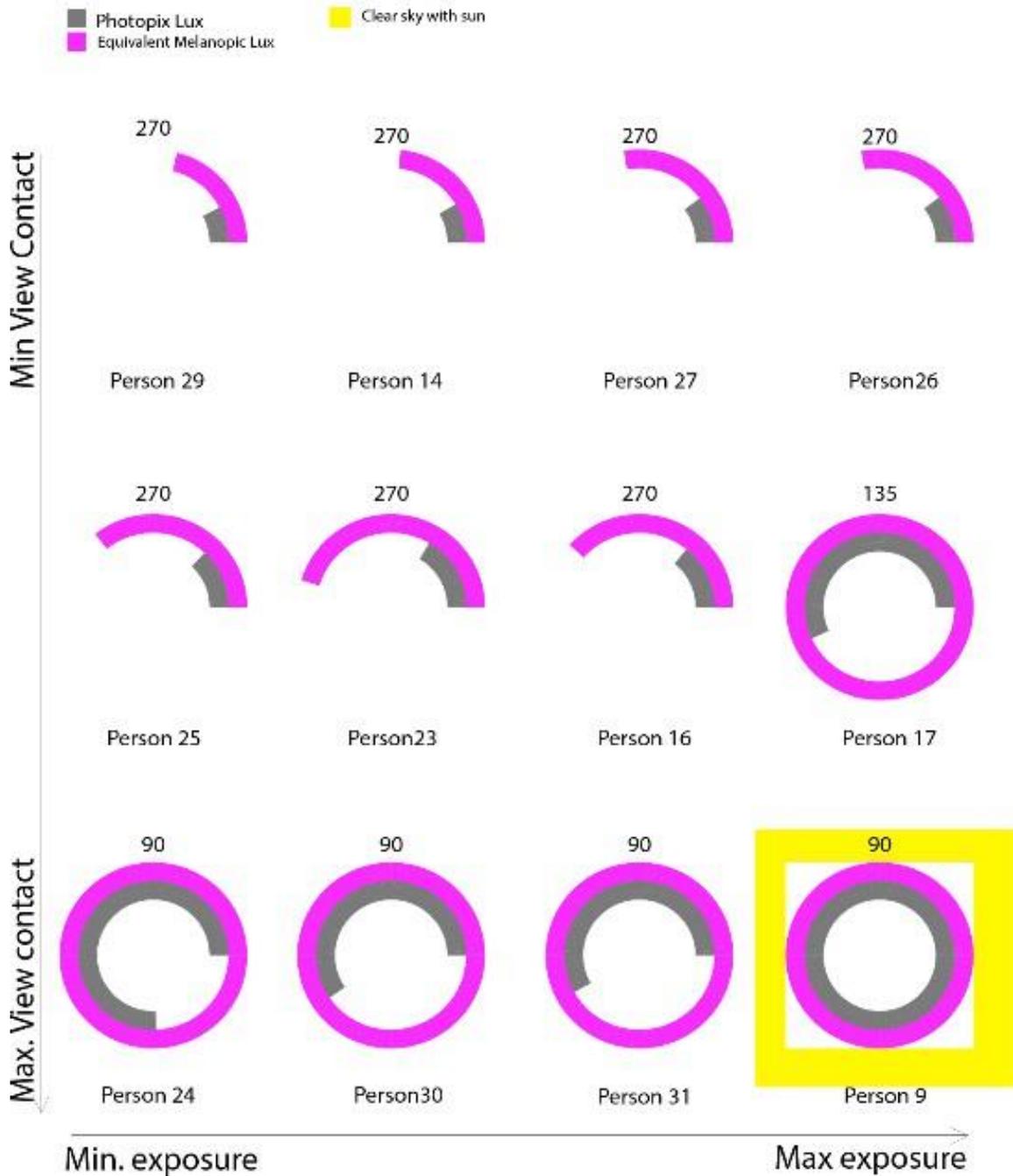


Figure 10. Percentage of photopic and EML relative to thresholds at zone 5.

3rdFloor Zone 30

Exposure at individual level

Photopic Lux
 Equivalent Melanopic Lux
 Clear sky with sun

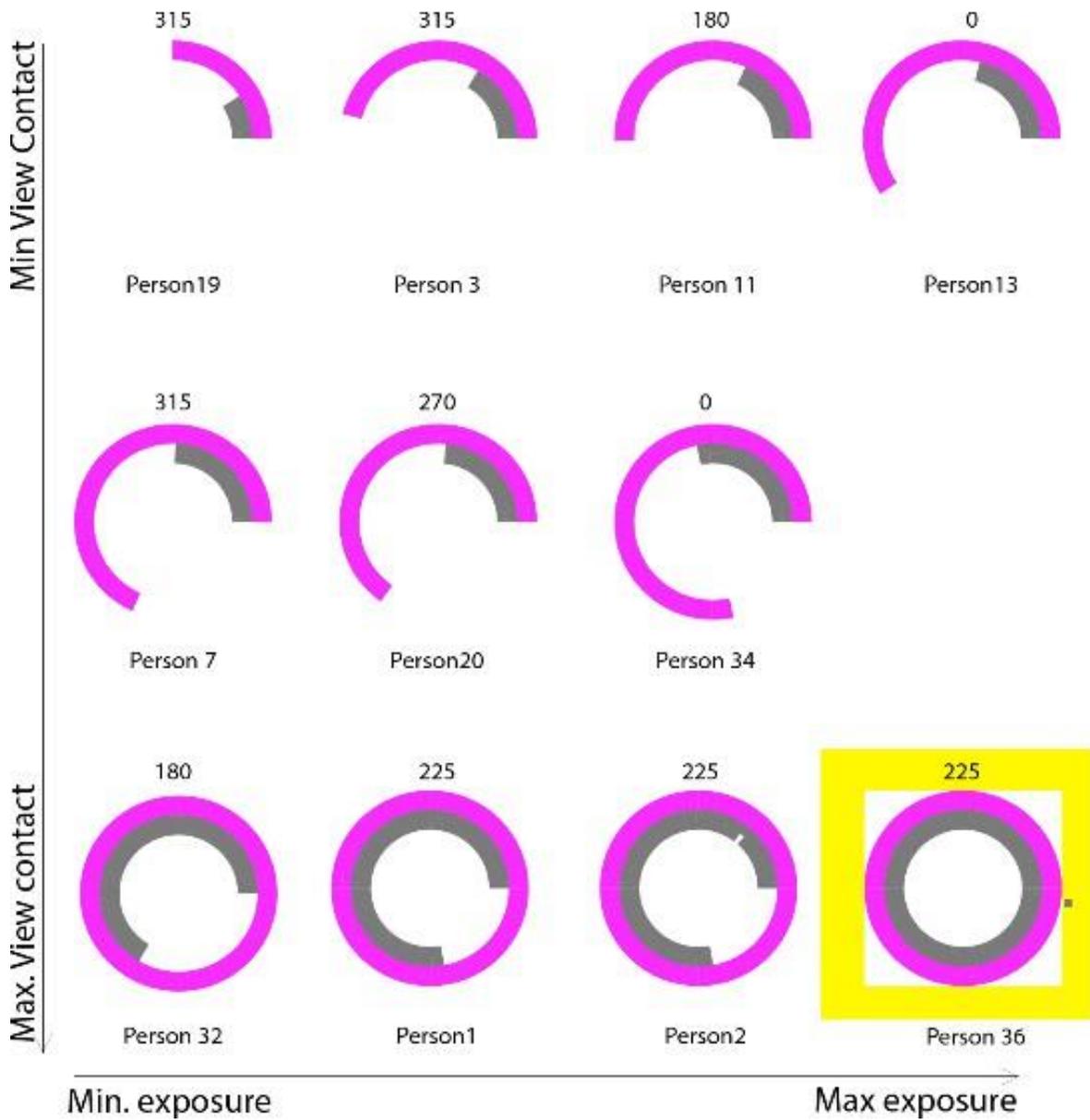


Figure 11. Percentage of photopic and EML relative to thresholds at zone 30.

Conclusion

The presented simulation framework provides a demonstration of gaze and light exposure patterns at different points in space based on a dynamic occupant gaze behaviour. A threshold-based health potential of the participants in a pilot study is processed using the developed method and related to

their attentions levels. It can be seen that only fewer positions would reach the thresholds under overcasts skies and only when higher levels of light available. In absence of visual discomfort, higher health potentials can be achieved when participants are oriented towards the window. It can therefore be concluded that the orientation in space is crucial for exposure at the eye level, but it is still important that the visual comfort is maintained. Considering the high variation of results at different points in time and position for each individual in an open spaces such as library or similar, indoor climatic regions are crucial for optimized compliance with health potentials. Using the developed method which allow for acquiring gaze-dependent information, identifying such regions in the space, or advising the occupants at individual level will be possible. Several aspect of the study can be enhanced or further investigation is needed. Addressing time-dependency of health and performance potentials in space is a crucial aspect of the study. Retrieving a “time dependent” health potential instead of merely a threshold-based using dwell and track data is an advantage in the developed method. Such data is retrievable in case of a real-time occupancy monitoring. In a situations where only a simulation-based approach is used, the time-dependency of the health potentials at each point cannot be addressed directly in the current version of the simulation framework. The pilot study allowed for further relations to occupant .productivity and performance. However, more studies in controlled conditions are needed to achieve this goal.

Several algorithms are used which can be updated as the research in each area advances. Finally, full-annual studies are not supported in the current version. The simulation workflow and a tutorial can be seen using the links below.

<https://zenodo.org/deposit/4436380> <https://youtu.be/JhkCtallEZA>

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References

- 't Hart, M., & Einhäuser, W. (2012). Mind the step: complementary effects of an implicit task on eye and head movements in real-life gaze allocation. *Experimental Brain Research*, 223(2), 233–249.
- Amundadóttir, M. L., Lockley, S. W., & Andersen, M. (2017). Unified framework to evaluate non-visual spectral effectiveness of light for human health. *Lighting Research and Technology*, 49(6), 673–696. <https://doi.org/10.1177/1477153516655844>
- Amundadóttir, Maria L, Rockcastle, S., Khanie, M. S., & Andersen, M. (2017). A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior. *Building and Environment*, 113, 5–21.
http://dx.doi.org/10.1016/j.buildenv.2016.09.033
- Andersen, E., Johansen, J. B., Furbo, S., Perers, B., Andersen, L. K., Dragsted, J., & Dannemand, M. (2017). *Availability of high quality weather data measurements. DTU Civil Engineering ReportsNo. R-379.*
- Balakrishnan, P., & J.Jakubiec, A. (2020). Spectral Rendering with Daylight: A Comparison of Two Spectral Daylight Simulation Platforms. *Proceedings of Building Simulation 2019: 16th Conference of IBPSA*, 16, 1191–1198. <https://doi.org/10.26868/25222708.2019.211158>
- Bille, A. S. W. (2019). *Lighting Environment for better Performance, Bachelor Thesis, Department of Civil Engineering, Technical University of Denmark* <https://findit.dtu.dk/en/catalog/2484247969>
- Birchler-Pedross, A., Schröder, C. M., Münch, M., Knoblauch, V., Blatter, K., Schnitzler-Sack, C., Cajochen, C. (2009). Subjective Well-Being Is Modulated by Circadian Phase, Sleep Pressure,

- Age, and Gender. *Journal of Biological Rhythms*, 24(3), 232–242.
<https://doi.org/10.1177/0748730409335546>
- Buswell Thomas, G. (1935). *How people look at pictures: A study of the psychology of perception in art*. Univ. Chicago Press
- Doughty, M. J. (2014). Spontaneous eyeblink activity under different conditions of gaze (eye position) and visual glare. *Graefe's Archive for Clinical and Experimental Ophthalmology*, 252(7), 1147–1153. <https://doi.org/10.1007/s00417-014-2673-8>
- Fotios, S., Gado, T., & Fotios Gado, T. (2005). A comparison of visual objectives used in side-by-side matching tests. *Lighting Res. Technol.*, 37(2), 117–131.
- Fotios, S., Uttley, J., Cheal, C., & Hara, N. (2014). Using eye-tracking to identify pedestrians' critical visual tasks. Part 1. Dual task approach. *Lighting Research and Technology*, 1477153514522472.
<https://doi.org/10.1177/1477153514522472>
- Hamedani, Z., Solgi, E., Skates, H., Hine, T., Fernando, R., Lyons, J., & Dupre, K. (2019). Visual discomfort and glare assessment in office environments: A review of light-induced physiological and perceptual responses. *Building and Environment*, 153, 267–280.
<https://doi.org/10.1016/j.buildenv.2019.02.035>
- Hayhoe, M., & Ballard, D. (2005). Eye movements in natural behavior. *Trends in Cognitive Sciences*, 9(4), 188–194. <https://doi.org/10.1016/j.tics.2005.02.009>
- Heynderickx, I., Ciocoiu, J., & Zhu, X. (2013). Estimating eye adaptation for typical luminance values in the field of view while driving in urban streets. *Light & Engineering*, 21(4).
- Hubalek, S., & Schierz, C. (2004). LichtBlick– photometrical situation and eye movements at VDU work places. *CIE Symposium*, 4, 322–324.
- Inanici, M., Brennan, M., & Clark, E. (2015). Spectral daylighting simulations: Computing circadian light. *14th International Conference of IBPSA - Building Simulation 2015, BS 2015, Conference*

Proceedings, 1245–1252.

- Inanici, M., & ZGF Architects LLP. (2015). Lark Spectral Lighting. Retrieved January 31, 2021, from Webpage website: https://faculty.washington.edu/inanici/Lark/Lark_home_page.html
- Itti, L., Koch, C., & Niebur, E. (1998). A Model of saliency-based visual attention for rapid scene analysis. *20(11)*, 1254–1259.
- Kokoschka, S., & Haubner, P. (1985). Luminance ratios at visual display workstations and visual performance. *Lighting Research and Technology*, *17(3)*, 138–144. <https://doi.org/10.1177/14771535850170030101>
- Krauzlis, R. J. (2008). Eye movements. *Fundamental Neuroscience*, 775–792.
- Lin, H., Chaisorn, L., Wong, Y., Liu, A. A., Su, Y. T., & Kankanhalli, M. S. (2014). View-invariant feature discovering for multi-camera human action recognition. *2014 IEEE International Workshop on Multimedia Signal Processing, MMSP 2014*. <https://doi.org/10.1109/MMSP.2014.6958807>
- Lin, Y., Fotios, S., Wei, M., Liu, Y., Guo, W., & Sun, Y. (2015). Eye movement and pupil size constriction under discomfort glare. *Investigative Ophthalmology & Visual Science*, *56(3)*, 1649–1656.
- Lockley, S. W. (2009). Circadian Rhythms: Influence of Light in Humans. *Encyclopedia of Neuroscience*, *2*, 971–988. <https://doi.org/10.1016/B978-008045046-9.01619-3>
- Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., ... Brainard, G. C. (2014). Measuring and using light in the melanopsin age. *Trends in Neurosciences*, Vol. 37. <https://doi.org/10.1016/j.tins.2013.10.004>
- Navalpakkam, V., & Itti, L. (2005). Modeling the influence of task on attention. *Vision Research*, *45(2)*, 205–231. <https://doi.org/10.1016/j.visres.2004.07.042>
- Nuthmann, A., & Einhäuser, W. (2015). A new approach to modeling the influence of image features on fixation selection in scenes. *Annals of the New York Academy of Sciences*, *1339(1)*, 82–96.

<https://doi.org/10.1111/nyas.12705>

Rea, M. (2015). The lumen seen in a new light: Making distinctions between light, lighting and neuroscience. *Lighting Research & Technology*, 47(3), 259–280.

<https://doi.org/10.1177/1477153514527599>

Rea, M. S., Bierman, A., Figueiro, M. G., & Bullough, J.

D. (2008). A new approach to understanding the impact of circadian disruption on human health. *J Circadian Rhythms*, 6, 7. <https://doi.org/10.1186/1740-3391-6-7>

Reinhart, C. F., Jakubiec, J. A., & Ibarra, D. (2013). Definition of a reference office for standardized evaluations of dynamic façade and lighting technologies. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, 3645–3652.

Rothkopf, C. A., Ballard, D. H., & Hayhoe, M. M. (2007). Task and context determine where you look. *Journal of Vision*, 7(14), 16. <https://doi.org/10.1167/7.14.16>

Ruppertsberg, A. I., & Bloj, M. (2006). Rendering complex scenes for psychophysics using RADIANCE: How accurate can you get? *JOSA A*, 23(4), 759–768.

<http://www.opticsinfobase.org/abstract.cfm?id=89036>

Ruppertsberg, A. I., & Bloj, M. (2008). Creating physically accurate visual stimuli for free: Spectral rendering with RADIANCE. *Behavior Research Methods*, 40(1), 304–308.

<https://doi.org/10.3758/brm.40.1.304>

Sarey Khanie, M. S., Kjærgaard, S. V., Johnsen, M. H. K., Negendahl, K., Wienold, J., & Andersen, M. (2018). A Gaze Visualizer tool implementation of gaze data into lighting rendering tools using radiance and honeybee for Grasshopper3d. *Building Performance Analysis Conference and SimBuild*. Chicago, United States.

Sarey Khanie, M., Stoll, J., Einhäuser, W., Wienold, J., & Andersen, M. (2017). Gaze and discomfort glare, Part 1: Development of a gaze-driven photometry. *Lighting Research and Technology*, 49(7), 845–865. <https://doi.org/10.1177/1477153516649016>

Sarey Khanie, Mandana. (2015). *Human responsive daylighting in offices*. EPFL.

- Sarey Khanie, Mandana, Stoll, J., Einhäuser, W., Wienold, J., & Andersen, M. (2016). Gaze and discomfort glare, Part 1: Development of a gaze-driven photometry. *Lighting Research & Technology*. <https://doi.org/10.1177/1477153516649016>
- Solemma. (2018). Solemma LLC | ALFA. Retrieved April 29, 2020, from Alfa – adaptive lighting for alert-ness website: <https://solemma.com/Alfa.html>
- Sury, P. M., Hubalek, S., & Schierz, C. (2010). *A first step on eye movements in office settings: Eine explorative Studie zu Augenbewegungen im Büroalltag* (Vol. 51). GRIN Verlag.
- Torralba, A., Oliva, A., Castelhana, M. S., & Henderson, J. M. (2006). Contextual guidance of eye movements and attention in real-world scenes: the role of global features in object search. *Psychological Review*, *113*(4), 766. Retrieved from <http://psycnet.apa.org/journals/rev/113/4/766/>
- Vincent, B. T., Baddeley, R., Correani, A., Troscianko, T., & Leonards, U. (2009). Do we look at lights? Using mixture modelling to distinguish between low-and high-level factors in natural image viewing. *Visual Cognition*, *17*(6–7), 856–879.
- Wang, T., & Zhang, R. (2010). Study of moving object detecting and tracking algorithm for video surveillance system. *5th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Smart Structures and Materials in Manufacturing and Testing*, 7659, 76590N. <https://doi.org/10.1117/12.865457>
- Ward-Larson, G., & Shakespeare, R. (1998). *Rendering with radiance: the art and science of lighting visualization*. Morgan Kaufmann Publishers.
<http://portal.acm.org/citation.cfm?id=286090>
- Wienold, J. (2009). Dynamic daylight glare evaluation. *Eleventh International IBPSA Conference: Building Simulation*, 944–951. <https://doi.org/citeulike-article-id:11069372>
- Winter, J., Fotios, S., & Völker, S. (2019). The effect of assuming static or dynamic gaze behaviour on the estimated background luminance of drivers. *Lighting Research & Technology*, *51*(3), 384–401. <https://doi.org/10.1177/1477153518757594>

Yamín Garretón, J. A., Rodríguez, R. G., & Pattini, A. E. (2016). Glare indicators: An analysis of ocular behaviour in an office equipped with venetian blinds. *Indoor and Built Environment*, 25(1), 69–80. <https://doi.org/10.1177/1420326X14538082>