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 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 behaviour and to compute circadian lighting for customised solutions at individual’s 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 digitalisation.
- 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.

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, Castelhano, & 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; Yamin Garretón, Rodriguez, & Pattini, 2016) or light (Kokoschka & Haubner, 1985; Y. Lin et al., 2015; Vincent, Baddley, Correani, Troschianko, & 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; Yamin 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 $\hat{g}$, e.g., glare, and attraction to the directional source $\hat{a}$ , 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.

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 2a. 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 2b. 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.

\[ L = 179 \times (0.265R + 0.67G + 0.065B) \]  

The possibility of changing the existing 3 channel approximation of the spectral signal to larger waveband can be switched to by using either RGB or any other waveband, e.g., Red, Green, and Blue channels (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 (Iranici, Brennan, & Clark, 2015; Iannici & 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 computations. 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 \( gd \).

\[ L = \text{Photopic} + \text{Rea} + \text{Melano} \]

where the N-stepping (N consecutive wavebands) method for approximation waveband average of the original signal is used and implemented. 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 2x3 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
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 vps and eight gds 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 \((U,V)=(1,3)\). single value or image. Furthermore, to get the EML, the conversion \((179/149)\times\text{Lucas}\) 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 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 window panes 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.

<table>
<thead>
<tr>
<th>Window parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>22 mm</td>
</tr>
<tr>
<td>Solar factor</td>
<td>0.49</td>
</tr>
<tr>
<td>Daylight transmittance</td>
<td>50%</td>
</tr>
<tr>
<td>Direct transmittance</td>
<td>25%</td>
</tr>
<tr>
<td>Reflectance</td>
<td>39%</td>
</tr>
<tr>
<td>Absorbance</td>
<td>37%</td>
</tr>
</tbody>
</table>

Table 2: Surface materials reflectance.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic Interior Wall</td>
<td>Diffuse reflectance of 50%</td>
</tr>
<tr>
<td>Generic Ceiling</td>
<td>Diffuse reflectance of 70%</td>
</tr>
<tr>
<td>Generic Floor</td>
<td>Diffuse reflectance of 20%</td>
</tr>
<tr>
<td>Generic Exterior Wall</td>
<td>Diffuse reflectance of 35%</td>
</tr>
<tr>
<td>Exterior Ground</td>
<td>Diffuse reflectance of 10%</td>
</tr>
</tbody>
</table>

Table 3: Radiance rendering parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dt</td>
<td>0.05</td>
</tr>
<tr>
<td>dj</td>
<td>0.15</td>
</tr>
<tr>
<td>db</td>
<td>2</td>
</tr>
<tr>
<td>da</td>
<td>0.01</td>
</tr>
<tr>
<td>ar</td>
<td>0.85</td>
</tr>
<tr>
<td>ad</td>
<td>0.5</td>
</tr>
<tr>
<td>as</td>
<td>0.005</td>
</tr>
<tr>
<td>lr</td>
<td>2</td>
</tr>
<tr>
<td>pl</td>
<td>1</td>
</tr>
<tr>
<td>pl</td>
<td>0</td>
</tr>
</tbody>
</table>

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 an indoor environmental conditions with minimum effect of the temperature, \( CO_2 \) levels and humidity as these parameters were kept in a 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 international background 40%. The occupancy rate and accumulated \( gds \) in each zone are shown in Error! Reference source not found.

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

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.

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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