Evaluating Temporal and Spatial Light Exposure Profiles for Typical Building Occupants

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ABSTRACT
Many of the daylight metrics that we use today rely on grid-based illuminance data to evaluate the spatial distribution of daylight at a building scale, but we lack methods to evaluate how an occupant's temporal and spatial behavior impacts our assessment of performance. This is particularly problematic when we consider the effects of light on human health. Light-exposure at eye-level drives responses in both the visual and non-visual (circadian) systems. This paper adapts a simulation workflow to evaluate the non-visual effects of light using existing models like Equivalent Melanopic Lux (EML) and non-visual Direct-Response (nvRD) at an occupant scale, accounting for typical user profiles, sky condition, and time of year. Our paper considers four typical user profiles within a side-lit office environment to query location and view directions from a multi-point, multi view-direction, multi time-step simulation of eye-level illuminance and return individual light-exposure profiles. This approach allows us to compare each profile as a product of the occupant’s spatial and temporal behavior and begin to consider the lighting performance of our case study building through the performance of its users.

Author Keywords
Daylight performance; health; non-visual; circadian; lighting simulation; human-centric lighting; occupant behavior; visualization

ACM Classification Keywords
•Applied computing--Arts and humanities--Architecture (buildings)•Computing methodologies--Modeling and simulation

1 INTRODUCTION
As we continue to learn more about the circadian and direct effects of light on human health, new models and tools have emerged to quantify the effect of light exposure on the health potential of building occupants [2, 16, 18, 19, 22]. While organizations like the International WELL Building Institute have recommended a standard to support circadian health by setting a minimum threshold, we lack any grounded methods to simulate the eye-level illuminance that a user receives over space and time [24]. As daylight is most often analyzed from a horizontal task-plane, a shift towards the consideration of eye-level light exposure from a dynamic user perspective would create a radical shift in our understanding of lighting performance at the building scale. Rather than quantifying illuminance levels over time across the floor area of a building, we would need to consider the spatial and temporal behavior of building occupants and compute the aggregated performance of a building’s users.

As building occupants move throughout a space over the course of any given day, they are exposed to variations in brightness and spectrum. Changes in sky condition, time of year, time of day, user location, and view-direction creates a vast matrix of possible light exposure profiles for any given user in a space. Depending on where a building occupant spends time, their accumulated light exposure profile will change throughout the day, week, month, or year, impacting alertness, sleep quality, and overall health. To provide a more robust assessment at the occupant level, we must account for both spatial and temporal human behavior within a given building.

This paper proposes a novel method to evaluate and compare dynamic user light-exposure profiles over time and throughout space. To exemplify this method, we’ve created four typical user profiles for hypothetical building occupants in a side-lit office space in Portland, OR, USA. We queried illuminance values for the exact location and view direction of each user profile and used it as input for both the WELL Building Standard and the non-visual Direct-Response (nvRD) model [2, 24]. By doing this, we are able to illustrate the impact of occupant behavior on daylight performance and compare the performance prediction of existing metrics, which offer divergent performance narratives through the way they ‘count’ light towards a daily dose. While these four user profiles cannot give a holistic overview of daylight performance for the entire occupied building, this method could be used to evaluate the performance of all building users and begin to create an aggregated narrative about healthy light exposure from a dynamic occupant perspective. Using this approach, we are able to determine if and when various building
occupants would reach a recommended daily light dose and discuss the different outcomes of WELL Building Standard and nvRD models in influencing building design decisions.

2 BACKGROUND

In order to begin evaluating the effects of eye-level exposure on human health, a handful of studies have suggested new evaluation methods to transition from a horizontal task-plane (i.e. illuminance measurements across a 2D surface) to a vertical view-based approach.

Using circadian equivalent threshold values, Pechacek et al. (2008) evaluated vertical illuminance at the eye-level [17], which was later extended to a multi-point, multi-view direction approach by randomly sampling point values for two locations and eight view directions from a uniform distribution [6].

A 2017 study by Amundadottir et al. proposed a method to simulate eye-level daylight performance from an occupant’s perspective using rendered 360-degree images that could be unrolled and analyzed across multiple view directions [2]. From these unrolled view-directions, the nvRD model was applied to predict direct non-visual responses in addition to other view-based performance models. While that method used a single point in space, later publications by Rockcastle et al. (2018,2019) applied the same method to an array of view directions, resulting in the OCUVIS web-based visualizer that illustrates the frequency of views that exceed a given threshold for both visual (glare, task brightness, and visual interest) and non-visual light responses (nvRD) [19, 20].

Analyzing light exposure patterns from a fixed sensor point might, however, be too reductive as we move our eyes and head continually by gaze direction and position in space. As a preliminary attempt to test this concept, four different strategies were applied to generate light exposure patterns based on occupants’ spatial behavior [5]. These light exposure patterns where used as an input for a preliminary version of the nvRD model [4]. The results confirmed that the use of a space is an important factor, which strongly relates to the temporal pattern property of light.

Additional models have been developed to simulate non-visual or “circadian” responses to light exposure. These models, like Circadian Stimulus (CS) [18] and Equivalent Melanopic Lux (EML) [16, 24] have been integrated into international standards/reports [8, 22] and simulation tools like Adaptive Lighting for Alertness (ALFA) [22].

A 2019 study by Saiedlue et al. used ALFA to quantify how various light sources and glazing types affect non visual light exposure within a space [21]. Acosta et al. considered the effect of view direction by simulating both horizontal and vertical illuminance to represent a healthcare patient either lying down or sitting up [1]. In this study, 3D models were simulated in two latitudes to test high and low room reflectance values and window to wall ratios (10%-80%). A 2017 study by Konis used a grid of view positions and view directions to map the strength and frequency of the minimum acceptable stimulus frequency threshold on a daily basis within a space [14].

While multi view-direction simulations have become more common, so to have methods of multi-spectral computation using HDR images. Inanici et al. (2015) calculated circadian values with both Rea et al. (2005) circadian spectral sensitivity curve [18] and Lucas et al. (2014) melanopsin spectral sensitivity curve [16]. A north-facing conference room in Seattle, WA was used to test how red and blue partition walls would impact instantaneous photopic and melanopic illuminance using a false color analysis of the space under clear, intermediate, and overcast skies [13].

Despite the uptick in simulation workflows that include non-visual/circadian models, there is still a lack of methods for applying those models to a dynamic user profile rather than to a fixed position in space. Both Amundadottir et al. and Figueiro discuss the importance of considering light exposure history to determine an occupant’s total light dose [2, 12]. History implies the knowledge of what a user has been exposed to over time.

A 2018 field study by Konis used similar methods to his simulation-based workflow [14, 15], but collected physical light exposure data in a variety of existing dementia care facilities. The results from this experiment emphasize the importance of location and view direction in receiving an effective circadian light exposure.

Figueiro et al. (2019) conducted an experiment using tunable luminaires at a user’s desk to provide an optimal light spectrum throughout the day. Participants wore Daysimeters [7] to calculate their non-visual light exposure and smart watches that logged the user’s activity levels. While they should have received sufficient light from the luminaires, the time not spent at their desk and the movement of data loggers throughout the study were both found to impact the participant’s circadian light exposure [10, 11].

Of the field and simulation studies mentioned here, none have integrated exposure history, timing, user location, view direction and spatial behavior in a single study. Being able to account for the spatial and temporal behavior of building occupants in a simulation workflow would allow us to predict the circadian performance of each user and compare factors that impact that performance. From the architectural design of the building to the choice of seating location and scheduled activities, we could offer a more holistic assessment of daylight performance on human health.

3 METHODOLOGY

In this paper, the authors adapted a simulation-based framework developed by Amundadottir et al. (2013) to investigate a dynamic occupants’ daily light exposure to daylight and its impact on their health and well-being in an
office space [5]. An array of sensor points was simulated across a side-lit building to reproduce all possible locations that an occupant may sit or stand for more than 15 minutes at a time. Each sensor point produced an array of 8 vertical view-directions. Four occupant profiles were then used to query illuminance data for each position, view direction, date, sky, and time-step to evaluate the occupant’s light exposure profile across the day. Two sets of performance criteria were used to compare the different light exposure profiles and testing visual representation.

3.1 Daylighting Simulation
Our selected case study consists of a two-story side-lit office building with double-height glazing along the South-West facing facade. This building is located in Portland, OR at 45.5 N, 122.67 W (Figure 1). The building was recently remodeled by SRG Partnership and houses their Portland design offices.

Three variables were simulated in this study: sky condition (clear and overcast), date (March 20th, June 21st and December 21st), and time (9am-6pm in 15-minute intervals. Gensky was used to create CIE clear and overcast sky conditions for these three annual instances.

Illuminance levels are computed vertically at eye-level to simulate the light entering the eye. Photosensors were placed at a height of 1.14m above the floor for standard chairs, and 1.5m above the floor for high stools at workstations and at other locations. Eight view directions were simulated at each position and were aligned to building geometry and desk orientation to account for the slight west-facing angle of the south facade.

Default rtrace RADIANCE v5.2 parameters were used except for the following adjustments to: -dt 0.05, -de 0.5, -ds 0.15, -dr 3, -ab 3, -aa 0.15, -ar 32, -ms 0.066, -lr 8, -lw 0.002.

No blind controls or devices were used for consideration within this study to minimize variables, but further research should address the use of dynamic facade controls and breaks (Figure 2). Because the time-step used in this study is 15-minutes, none of the circulation zones were simulated as people would typically only spend a second in each as they pass through.

Figure 2a shows schedules for four typical office workers and Figure 2b shows their path in the office space. These profiles were created manually based on typical functions that each user may be expected to perform.

- Occupant 1: The Senior Manager profile consisted of desk work and intermittent meetings, with a majority of time spent receiving phone calls and answering emails at their desk. Their position was located directly adjacent to the windows, with optimal views.
- Occupant 2: The Junior Manager profile was scheduled for more intermittent desk work, with meetings and trips to the material lab that regularly interrupted desk time. Their desk was located farther from the window on the ground-level where they could easily manage their team.
- Occupant 3: As an entry-level position, the Intern profile spent most of their time between their desk and the material lab, with their desk located on the mezzanine, farther from the window in a less desired zone of the space.
- Occupant 4: The fourth employee profile is represented as the IT Manager. Their desk was located in the back of the space adjacent to the company servers. They were scheduled to make frequent visits into the common space on the first level to assist other employees with computational issues.

3.3 Non-visual light-response evaluation
In order to evaluate the effects of light on the non-visual system, RGB values obtained from RADIANCE simulations were weighted and summed into melanopic illuminance, which is based on the spectral sensitivity of the ipRGCs. The weights are obtained from [13]. The melanopic illuminance values are used as inputs to both the WELL Building Standard criteria for circadian lighting and the nvRD model [3, 24]. The nvRD model was then translated into a dose measure (i.e. cumulative response). Unlike the implementation of WELL Building Standard, the nvRD model is influenced by continuous light exposure throughout the day (not only 9am – 1pm) and also considers variations in light intensity, wavelength, duration, pattern, and history. This makes it more sensitive to intermittent light exposure or short periods of bright light exposure.

3.4 Performance criteria for visual representation
The WELL Building Standard requires a certain threshold of melanopic illuminance which is usually converted into photopic illuminance based on the spectral distribution of individual light sources using the term Equivalent Melanopic Lux (EML).

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Figure 1 A photo of the selected case-study in Portland, OR. Image courtesy of SRG Partnership.
The WELL Q4 2019 version Feature 54: Circadian Lighting Design [24], implements a minimum threshold of 200 lx of equal-energy light source which is equivalent to 182 lx of daylight illuminant D65. This threshold applies to work areas measured at the vertical plane, which must be achieved (between 9am to 1pm) for every day of the year. While the authors acknowledge that WELL Building Standard assumes the use of electric lighting to supplement daylight during occupied hours, this paper attempts to provide a means of comparing occupant profiles in relative terms.
For the nvRD model, the non-visual response results are accumulated over the day to predict the daily light dose. The threshold value of 4.2 was established in [2] as a reasonable criterion for achieving beneficial effects of light. For the purpose of this paper it is lowered to 4, so it is comparable to the period length applied in WELL Building Standard criteria. These tentative thresholds correspond to the number of “vital” hours in a day, when adequate daylighting is desired.

4 RESULTS

The results of this study represent a substantial shift in the way we quantify and visualize lighting performance at a building scale. While existing annual daylight performance metrics account for time and space, which already requires a significant abstraction of information to achieve a compact number, our approach adds yet another dimension with the consideration of occupant activity. To adequately cover the impact this has on our daylight performance narrative, we have organized the results into three sections.

4.1 Daily Performance Overview

This section presents a compact overview of results for our four hypothetical building occupants on June 21st and December 21st. Table 1 shows the daily average of vertical illuminance (Ev), WELL Building Standard criteria (percentage of time when Ev ≥ 182 lx), and daily nvRD cumulative response. Yellow cells represent when Ev ≥ 182 lx is achieved between 9am and 1pm. Green cells indicate when a recommended nvRD dose of 4 is achieved.

<table>
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<th>Occ. id</th>
<th>Ev</th>
<th>WELL</th>
<th>nvRD</th>
<th>Ev</th>
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<th>nvRD</th>
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<td>8%</td>
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</tr>
<tr>
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<td>714</td>
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<td>186</td>
<td>19%</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 1. Daily performance overview comparing results for a) June 21st and b) December 21st for all occupants.

This table can be used to provide a high-level comparison between our four building occupants, revealing the impact of day (June 21st vs. December 21st) and sky condition (clear vs. overcast) on the percentage of time when Ev exceeds the WELL threshold as well as the cumulative response nvRD achieved during occupied hours. Based on the performance criteria, the light exposure for Occupants 3 and 4 is the same between the two days, where Occupants 1 and 2 show minor variations.

While this table is helpful in comparing multiple users, it does not reveal the temporal granularity of light exposure that underlies either the WELL Building Standard or the nvRD model and is not super useful in revealing which activities and locations may be preventing the occupants from receiving the recommended light exposure.

4.2 Understanding Temporal Light Exposure

This section explains two different visual representations of the temporal light exposure for a single user across two days (June 21st and December 21st) and two sky conditions (clear and overcast). Figure 3 shows the daily profile for Occupant 2: Junior Manager with the time and activity they were performing indicated along the x-axis. Clear sky results are indicated in grey, overcast in black, and the Ev ≥ 182 lx threshold is shown as a dotted line.

If we refer to Figure 2b (which shows the occupant paths in axonometric), this occupant’s desk position was located several seats from the window, with a head position facing East. As shown in Figure 3 for both days and sky conditions, the occupant received the highest light exposure levels while at lunch and secondarily while at their desk. As they periodically got up from this position to attend meetings and visit other locations within the office, this profile varies as a result of the occupant’s shifting position in space and the shifting position of the sun.

Assuming the same exact schedule as on June 21st, Figure 3b shows the exposure profile for the same occupant on December 21st. While the impact of day (June 21st vs. December 21st) and sky condition (clear vs. overcast) may seem obvious, the impact on eye-level exposure may be less intuitive when shifting solar altitude angles change the depth of sun penetration through a building envelope. As a result, some occupants may be exposed to brighter pulses of light during the winter months.

Figure 3 clearly illustrates the dynamic nature of light exposure for a typical building occupant, where scheduled activities determine the available light received at eye-level. The impact of sky condition is clearly shown when comparing the line graph in Figure 3a and 3b, however this type of graph is not well suited for viewing multiple days. Thus, this information can be translated into a heatmap as shown below the line graph. The heatmap maps the Ev,ipRGC values on a logscale to four colors, ranging from dark red to bright yellow. The Ev,ipRGC values that exceed 200 EML or 182 lx are labeled with the number 1 to indicate those time periods that would meet the recommended light exposure under the WELL Building Standard. Representing the results in a more compact way, will allow us to view the results on a temporal map for the full year.

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Figure 3 The effective ipRGC illuminance $E_{v,ipRGC}$ (also called melanopic illuminance) as a function of time-of-day for the Junior Manager on a) June 21st and b) December 21st. The upper graph shows the $E_{v,ipRGC}$ on a log-scale for clear and overcast skies. The dashed line shows the threshold of 200 EML. The lower graph shows the same data as the upper graph. The color represents the log-scale $E_{v,ipRGC}$ divided into 4 bins by the gridlines in the graph above ranging from low illuminance (dark red) to higher illuminance (bright yellow). 0 and 1 indicate whether the value is below or above the 200 EML threshold, respectively.

4.3 Comparing Occupants & Metrics Over Time
To better understand the impacts of time and schedule on the performance of our four building occupants, Figure 4 shows a) the light exposure between 9am and 6pm on March 20th in a plain line graph, b) the derived analysis by highlighting periods (or timesteps) when the $E_v$ that exceeds the 182 lx threshold between 9am-1pm as outlined in the WELL Building Standard criteria, and (c) the cumulative nvRD received during occupied hours from 9am - 6pm. This compact comparison reveals the disconnect in performance narrative between the WELL Building Standard criteria and the nvRD model. As WELL only takes into consideration the light exposure that is received between 9am - 1pm, some occupants will never achieve WELL using daylight alone.

The nvRD model is more sensitive to periodic light exposure profiles, like the one experienced by Occupant 4 (the IT Manager). While the WELL Building Standard criteria would not award credit to this type of light exposure profile due to the lack of continuous exposure over the $E_v \geq 182$ lx threshold, the nvRD model shows that this occupant was able to achieve the recommended dose by the late afternoon.
In architectural spaces where light exposure may be continuous, but occupation is intermittent and/or more dynamic, continuous threshold-driven methods like the WELL Building Standard may provide an incomplete narrative about healthy light exposure. The nvRD model accounts for a wider set of variables that influence the non-visual system. As such, nvRD may offer a more robust way to evaluate the impact of intermittent light exposure, which is a reality experienced by occupants who move throughout an office over the course of a day. Accounting for this dynamic behavior may encourage us to think about the impact of programming as well as seating location. A well-lit break room or coffee station frequented by many occupants could help enhance the intermittent exposure of those who are more deprived in their current seating location.

The comparison between occupant profiles underlines the importance of considering spatial and temporal behavior when predicting the health potential of a space for its occupants. The comparison between the WELL Building Standard and nvRD model reveals the need for rigorous discussion about how these models are implemented in an architectural context and how they may be integrated into predictive simulation-based workflows.

5 CONCLUSION

This paper introduced a method for evaluating the circadian performance of daylight for four building occupants based on their spatial and temporal behavior in a side-lit case study. With an increased understanding of dynamic lighting environments, human behavior, and the effects of light on health and well-being, we can produce better predictions regarding the benefits of daylight and eventually, their integration within the design process. As a next step for this research, we would like to extend our evaluation to include the full population of building occupants and develop an aggregated metric that relies on a percentage of people that achieve performance rather than a percentage of space.

By shifting the narrative of daylight performance from the space of the building to the performance of its occupants, we can place more emphasis on the impact of architecture on health in the built environment. In order to do this, we need robust methods of predicting occupant behavior through space and over time. Future work in this area could consider agent-based modelling to generate user profiles in the absence of recorded field data or in the design-phase before occupant profiles have emerged. Building on work by Breslav et al., 2014 and Schaumann et al., 2015, this research could use behavioral narratives to predict granular narratives that account for a fine-grain temporal resolution [8, 23]. To provide a holistic evaluation of health in our buildings, the future of predictive daylight modeling must consider human behavior or we may continue to miss a large part of the performance narrative.

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