The Impact of Behavior on Healthy Circadian Light Exposure Under Daylight and Electric Lighting Scenarios

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ABSTRACT

This paper presents a novel approach to simulating the impact of dynamic spatial and temporal occupant behavior on healthy circadian light exposure under daylight and electric lighting scenarios. To understand the impact of each scenario on the health of typical building occupants, a side-lit office space was used to simulate light under clear and overcast sky conditions across a series of daily and hourly instances. To collect occupancy data from building occupants on their spatial and temporal activity within the building, a web survey was used to generate profiles for 38 building occupants. Each occupant profile was then run through the simulated light data to produce daily exposure profiles that were used to compute occupant health potential using the Non-Visual Direct Response (nvRD) and Equivalent Melanopic Lux (EML) via the WELL Q1 2020 version Feature L03 (Circadian Lighting Design). A comparison of daylight only and daylight + electric light reveals the impact of each source on occupant health which varied depending on sky condition and location within the building. In addition to providing a novel workflow for simulating occupant-driven health performance assessments, this paper motivates further exploration into the impacts of electric lighting systems and their control strategies that can optimize health outcomes alongside task and energy considerations.

Introduction

Over the last decade, research into the human non-visual system has revealed the impact of light intensity, timing, and duration on the circadian rhythms that drive our alertness and sleep-wake cycle. With this knowledge, new measures, metrics, and tools have been developed in an attempt to quantify the impact of lighting performance on occupant health in buildings. These metrics include Circadian Stimulus (CS), Equivalent Melanopic Lux (EML), Melanopic/Photopic ratios (M/P), and Non-Visual Direct Response (nvRD) (Rea & Figueiro, 2018; Lucas et al., 2014; WELL, 2020; Amundadottir, 2017). While EML provides a measure of lux weighted towards the melanopic rather than the photopic sensitivity curve, M/P provides a ratio of melanopic to photopic lux and CS calculates the effectiveness of spectrally-weighted irradiance. These instantaneous metrics can help designers evaluate whether a lighting scheme provides adequate source intensity/spectrum for entrainment at eye-level, but they do not integrate the duration or timing of exposure needed to achieve a healthy cumulative response. Metrics like EML have been used as a basis for recommended light exposure levels in the WELL Q1 2020 version Feature L03 standard by assuming a threshold value (200 EML) over some designated period of time (between 9am and 1pm). Similarly, the nvRD model integrates instantaneous eye-level exposure levels over the course of the day to provide a cumulative daily dose.

Traditional lighting simulation workflows have relied on 2D analyses to provide spatial and temporal data about whether daylight and electric lighting sources provide sufficient task illumination. While beneficial to the design process by providing a relative comparison of horizontal illumination values throughout a space, this approach does not take into consideration the dynamics of occupant behavior or how this behavior can define the light an occupant experiences at eye level across space and time. Shifting from a 2D analysis to an analysis of eye-level illumination could reveal the dynamics of lighting performance at an occupant scale. When aggregated across occupants, this would result in a radically different understanding of lighting performance at the building scale. By considering the dynamic behavior of individual building occupants as they move throughout a building, we can begin to see differences in the health potential of inhabitants based on seating location, furniture layout, and schedule.

A number of variables can impact the composition of light received at eye-level and the effectiveness of that light in circadian entrainment. Environmental characteristics such as sky condition, time of day, and time of year, as well as the wavelength, intensity, and directionality of electric sources can impact eye-level exposure (Rockcastle, Amundadottir, Andersen, 2017). The timing and duration of an occupant's exposure to these sources can also alter the effectiveness of light to entrain an occupant's circadian clock (Figueiro, 2017). Behavioral characteristics such as light history, gaze direction, location, and movement throughout a space will ultimately determine how individual occupants perform relative to one another. This paper will introduce a method that integrates these variables into a simulation workflow that allow us to compare the effect of lighting source (daylight vs. electric) and human behavior on the relative circadian health of building occupants within a side-lit case study.

Shifting our analysis approach from a spatially-centric to an occupant-centric narrative disrupts the way we typically describe lighting performance. While there has been increased interest in the effects of behavior on lighting performance in recent years (Rockcastle, Amundadottir, Andersen, 2018; Read et al, 2018; Figueiro et al, 2019a; Danell, Amundadottir, Rockcastle, 2020), there are several practical challenges associated with the complexity of developing a simulation-based workflow that integrates all the necessary variables. Such a workflow requires the simulation of a large matrix of daylight conditions, including sky condition, time of day, and time of year, as well as electric lighting conditions from supplemental sources. We then need to develop occupant profiles based on schedule, location, and view direction for individual building occupants and run them through the matrix of conditions listed above to generate daily dose profiles. Based on where an occupant is located within a space at any given time, we are then able to calculate that occupant's light exposure profile by integrating all those instances over time. The accumulation of this light exposure profile over a day, week, month, or year can influence sleep quality, alertness, and overall health. While a building may appear to provide energy-efficient illumination for task purposes using conventional horizontal illuminance metrics, the eye-level exposure of occupants within that building may vary dramatically depending on when and where those occupants spend time.

This paper proposes a simulation-based method to evaluate the circadian potential of daylight and electric lighting sources in a building through the dynamic performance of its occupants. To achieve this, the authors have built upon a preliminary method for comparing dynamic user light-exposure profiles across space and over time. The work presented by Danell, Amundadottir, Rockcastle, 2020 compared the daylight performance of 4 hypothetical occupant profiles in an office building in Portland. This paper advances that workflow by integrating electric light sources and user profiles collected via survey for 38 building occupants. Using a web survey developed by our research team, occupants from our case study responded to questions about their seating location and typical daily schedule. Behavior profiles were then generated and run through a matrix of simulated light data for March 21, June 20, and December 20, during clear and overcast sky conditions. Simulations were run with and without electric light sources to compare the impact of daylight and artificial light on the non-visual health potential of each occupant as well as their aggregated performance under different sky conditions and time of year. This paper uses nvRD and EML via the WELL Q1 2020 criteria to calculate the daily exposure of light at eye-level as users move throughout the space. These metrics provide a stte-of-the-art assessment of light's potential to stimulate the circadian system, although at this time, nvRD does not negatively penalize high levels of exposure at night and WELL Q1 2020 only penalizes this exposure when applied to living areas, not work places. The results reveal a range of potential health scenarios for different occupants within the same space, highlighting the importance of behavior on health outcomes and a potential variance in health equity.

Background

While a range of metrics have emerged in the last decade to quantify the stimulating effects of light on the circadian system, research into the *application* of non-visual health metrics in building-scale lighting analysis is still relatively new. In 2017, Amundadottir et al. proposed a method to analyze non-visual daylight performance from an occupant's simulated eye-level view position. A time series of 360-degree renderings were generated and then evaluated across a series of 180-degree view directions using the nvRD model, which computes a cumulative light dose, taking into account a user's history of light exposure and the duration, timing, and composition of light received at eye level over time (Amundadottir, 2016). Although this work began with a single view position, Rockcastle, Amundadottir, and Andersen, 2018 later applied the same method to an arrayed grid of points to provide a spatial analysis across the floorplan of a building. This hybrid spatial and temporal method, similar in scope to the one proposed by Konis, 2017, could quantify the frequency that a given threshold of eye-level exposure achieved a recommended dose. While the work of Rockcastle, Amundadottir, and Andersen, 2018 relied on nvRD to calculate the *cumulative* light exposure over a day for a series of annual instances, the work of Konis, 2017 relied on a measurement called Circadian Effective Stimulus (CE stimulus) that determined whether view directions exceeded a 250 EML threshold between 7am – 10am.

In addition to evaluating view directions over time, EML has also been used to compare the effect of architectural variables like glazing type and source type on the health potential of light in buildings. A study by Saiedlue et al, 2019 used the Adaptive Lighting for Alertness (ALFA) software (https://solemma.com/Alfa.html) to evaluate the impact of various glazing types and lighting sources on EML. ALFA can also compute the M/P ratio for a given scene, taking into account spectral light and reflectance values. Using CS, Acosta, Leslie, Figueiro, 2017 analyzed the impact of window to wall ratios, reflectance values, latitudes, sky conditions, and position (laying down or sitting up) of a patient's instantaneous light dose in a healthcare setting.

In addition to the simulation-based studies described above, research into occupant-based light exposure has developed simultaneously through experimental field studies. A study by Konis, 2018 relied on physical light measurements captured from a series of view positions in existing dementia care facilities. Results from this experiment reinforce the importance of view direction and view position with respect to daylight exposure. Temporal light exposure has also been explored using field study methods. In 2018, Read et al. collected light exposure data This study sought to find a potential correlation between the duration of daylight exposure and myopia or *nearsightedness*. A comparable study collected light exposure data in winter and summer seasons to connect data between young adults and emmetropes and myopes (Ulaganathan et al, 2019). Both of these studies collected data for the purpose of understanding the relationship between temporal behavior and light exposure but did not consider spatial position as a variable in these studies. Two recent field studies by Figueiro et al, 2019a & 2019b implemented individual electric lighting interventions into office buildings to determine the impact of spectral lighting interventions on eye-level CS. Both CS *and* location in space were logged throughout the duration of each study, with the results showing that both lighting intervention and behavior (time spent away from desk) had an impact on eye-level exposure.

As the health potential of light becomes more pervasive in our conversation about lighting performance, there is a growing demand to consider the energy efficiency of this exposure through a parallel analysis of both daylight and electric sources. Balancing health and energy considerations would allow us to fine tune interior lighting applications for circadian exposure while minimizing negative environmental impacts associated with excessive energy consumption. The study of energy use and occupant behavior is nothing new in the field of electric lighting. Yun et al, 2012a and 2012b conducted a series of case studies using similar office spaces occupied by graduate students and administrative staff. Horizontal and vertical illuminance measurements were collected from February through June while recording occupancy patterns, lighting patterns, and energy consumption. Their results found that electric lighting use was not found to be significantly impacted by exterior sky condition between the offices, but it was significantly impacted by occupancy factors. Not surprisingly, the offices with higher occupancy rates over longer periods of time resulted in the highest energy consumption. Based on the collected data, there was an untapped energy savings potential of up to 30% if occupants had turned off lights in response to available daylight or if photosensors had been deployed.

While applications of non-visual light response models have developed over the past few years to integrate spatial and temporal factors, limited attention has been paid to the impact of dynamic occupant behavior on healthy light exposure predictions. Both Amundadottir, 2016 and Figueiro, 2017 discuss the importance of considering light exposure history in determining an occupant's daily health dose, and yet we lack simulation-based approaches to compute an occupant's dynamic eye-level light exposure through a building over time. This paper introduces such a method to simulate eye-level light exposure for dynamic user profiles in an attempt to understand the impact of a building's electric and daylight systems on human health across a population of occupants.

Methods

The following section describes our selected case study building, the survey used to determine dynamic occupant profiles, the lighting conditions and simulation assumptions we used in our analysis, and the methods we used to determine light exposure profiles and apply performance criteria.

Case Study Building

As a base for our analysis, we selected an existing 2-story office space (primarily side-lit from the southeast) renovated for and occupied by SRG Partnership in Portland. The building is located at 45.5 N, 122.67 W and contains double-height desk space on the ground floor with additional desk space on the mezzanine. Meeting rooms are located beneath the mezzanine along the northwest-facing and east-facing walls. The main kitchen and cafeteria spaces are located under the mezzanine along the southwest-facing windows. Additional spaces for physical modelling and material research are located on the mezzanine, also along the northwest-facing wall. Figure 1 shows the layout of this office space along with the behavior pattern for two of our surveyed occupants (occupant 10 and occupant 24). Based on our survey (introduced in the next section), occupant 10 primarily occupies the perimeter of the building in well daylit zones while occupant 24. Orange is used to identify locations or time spent working, blue indicates meetings, green indicates breaks, and grey indicates outdoor activities. These activities are coded spatially in the axonometric diagram and temporally via the activity bars used to illustrate each occupant's daily routine.

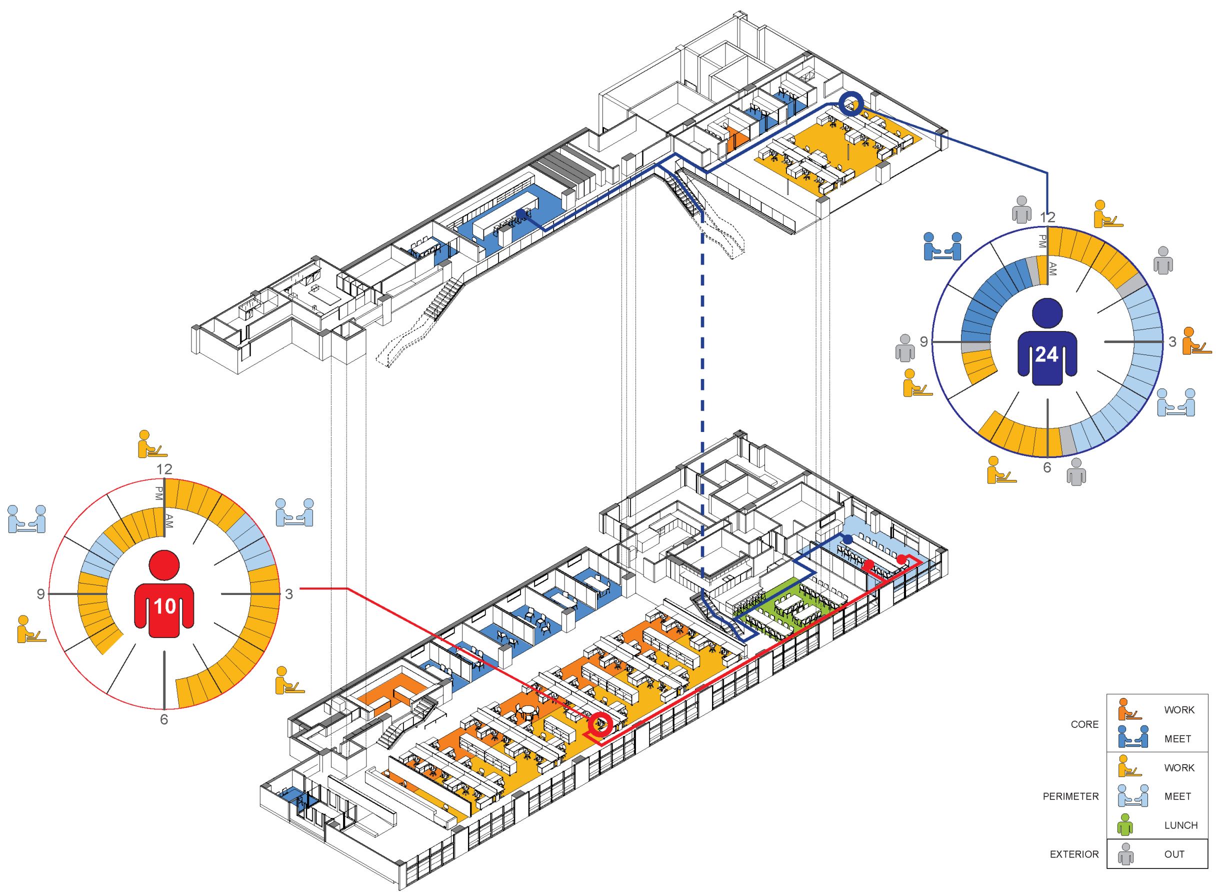

Figure 1. SRG's side lit office space in Portland, Oregon with occupant profiles for occupant 10 and occupant 24 based on surveyed information. While occupant 10 occupies the perimeter of the building in well daylit zones, occupant 24 spends a majority of time on the mezzanine in the core of the building. Orange identifies locations or time spent working, blue indicates meetings, green indicates breaks, and grey indicates outdoor activities. Core spaces are designated using dark orange and dark blue, while perimeter spaces are shown in light orange and light blue.

Web Survey

To collect data from building occupants and develop typical user profiles across our occupant population, a web survey was developed and sent out to office employees. Google Forms was used to construct a survey of 14 questions requesting information that would impact occupant behavior such as time of arrival and departure, desk location, time spent at desk throughout the day, typical time of meetings, duration spent in meetings, location of meetings, time and location of lunch break, and percentage of time spent outside the office. Respondents received this survey through a link embedded in an email distributed by a firm principal in February of 2020. This survey was anonymous and voluntary, resulting in 38 responses.

Based on employee responses from this survey, a 'typical' schedule for each occupant was manually created with 15-min time intervals tracking both location and dominant view direction. Where adequate information was not apparently clear, the research team made an informed guess based on likely seating orientation for a given task. Locations of longer-term occupation included desk seating, break areas (cafeteria), and meeting tables. Activities were categorized into four main activities: 'work,' 'meet,' and 'lunch.' Time spent 'out' of the office was accounted for by using an exterior illuminance sensor. An overview of these schedules is provided in Figure 2, broken up by activity and duration of time spent doing that activity. Occupancy hours are not fixed but rather adapted based on the survey responses of each employee. Typical arrival times ranged from 6:00am to 8:45am with total duration of occupation ranging from 9.25 hours to 11.25 hours/day (including lunch). Of the 38 respondents, 19 left the office building at some time during the day. The time spent outside varied from 15 min to 2.5 hours. Due to simulation time-steps being broken down into 15-minute increments, no simulation data was collected in spaces of circulation and continuous movement.

Simulation Inputs

The digital model of our case study was converted to Rhino from a Revit model shared by the architect. A grid of sensor points was placed in this model based on occupant seating locations, indicated by furniture. Each sensor was location at eye level; 1.14 m above the floor for standard and 1.5 m above the floor for bar-height seating. Occupants were assumed to be predominately facing the Northeast or the Southwest given desk orientation and furniture cues.

Simulating Daylight & Electric Lighting Sources

We simulated this model under four lighting conditions: clear sky daylight, overcast sky daylight, clear sky daylight + electric light, and overcast sky + electric light. Default rtrace (RADIANCE v5.2) parameters were used except for the following adjustments to: -dt 0.05, -dc 0.5, -ds 0.15, -dr 3, -ab 3, -aa 0.15, -ar 32, -ms 0.066, -lr 8, and -lw 0.002. Surface reflectance and transmittance values were determined based on informed assumptions for floor (0.20), wall (0.70), furniture (0.50), fixture (0.70), mullion (0.50), and glass (0.70 VLT).

In addition to sky condition, time of year (March 21st, June 20st, and December 20st) and time of day (6:00 am - 7:30 pm) were simulated with 15-minute time-steps. CIE clear and overcast sky conditions were created using gensky for all three annual instances. To simulate electric lighting sources, LED IES files were converted to a .rad format and placed according to the existing light fixtures in the digital model of the office space. Figure 3 shows the range of electric luminaires present within our case study.

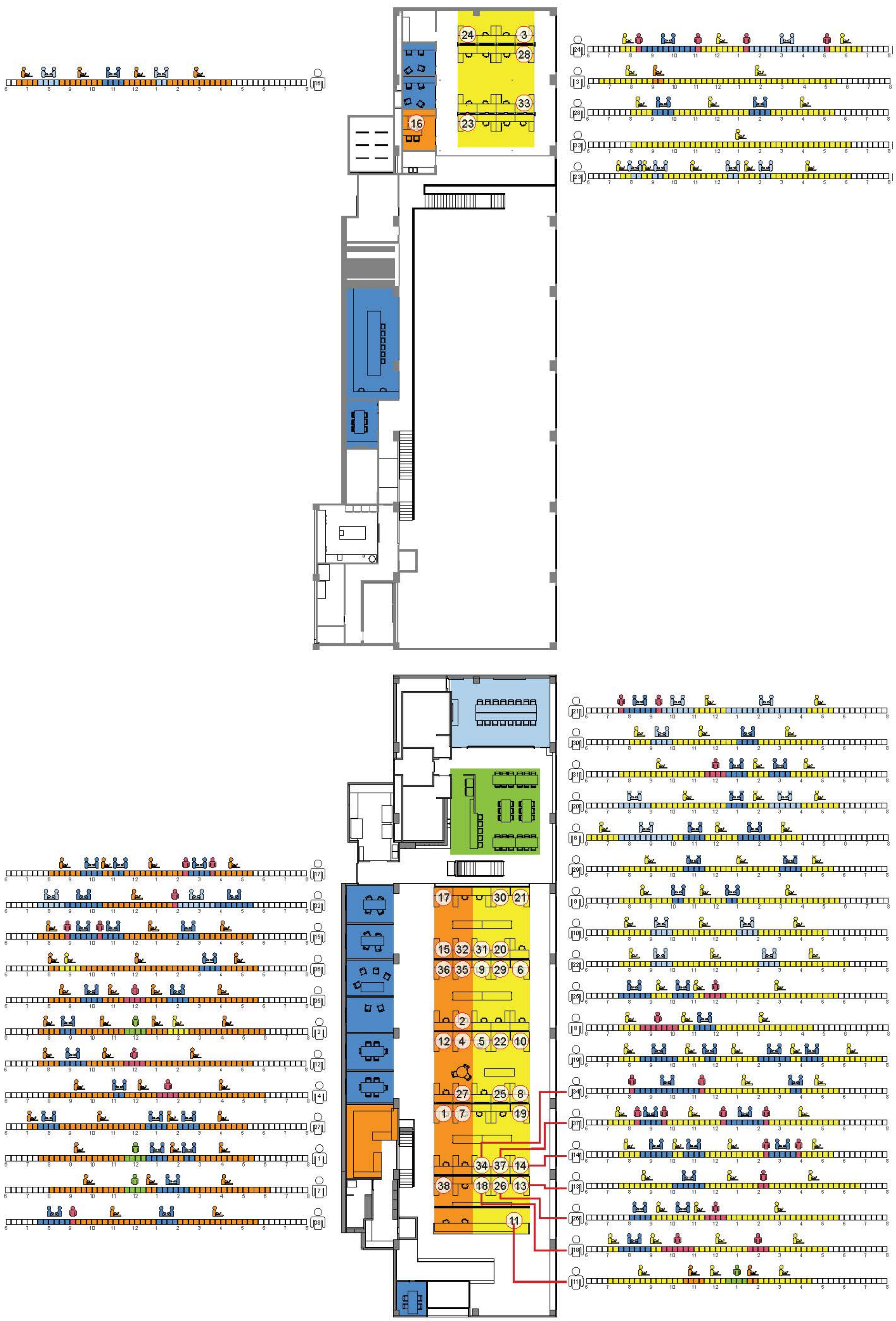

Figure 2. Activities were categorized into ‘work,’ ‘meet,’ and ‘lunch’ and ‘out’. These activities are coded (by color and icon) the same way as in Figure 1 but are represented via a linear rather than radial graphic.

To represent similar lighting specifications to those used in the case study, we used a combination of 'System 50' (suspended linear) and 'Luxient150 Surface' (cylindrical recessed) by Efficient Lighting Systems (http://elslighting.com.au/downloads/ies-files/). The 'System 50' module produces 106 lumens/Watts (2560 lumens/meter with 24 system Watts/meter) with a CCT of 4000K and a CRI of 80. The 'Luxient 150 Surface' module produces 102 lumens/Watts (28 Watts, 2865 lumens) at a beam angle of 85 degrees with a CCT of 3000K and a minimum CRI of 95.

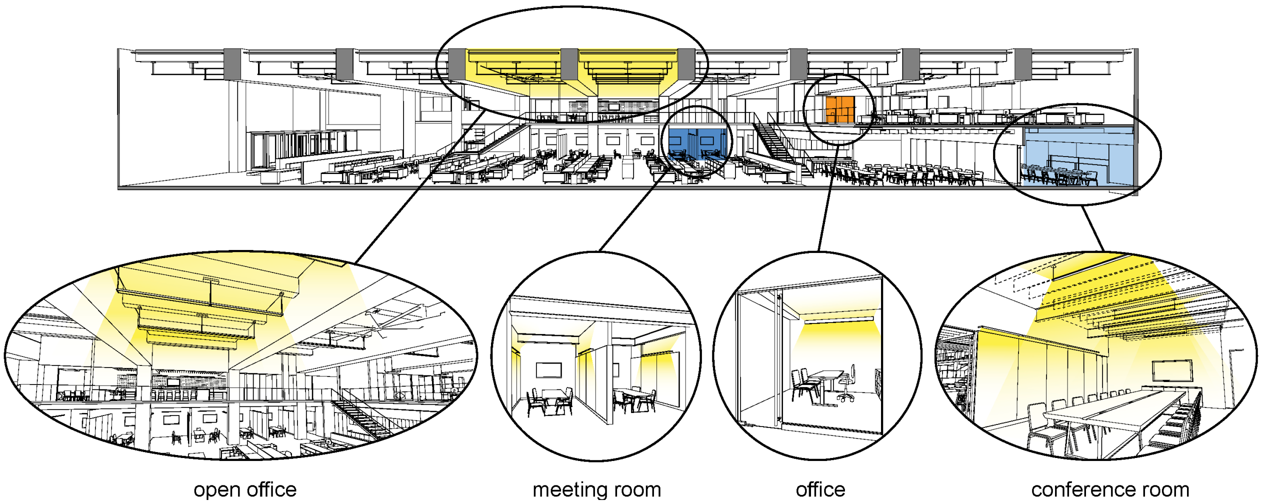

Figure 3. The electric lighting conditions present within our side-lit office space include suspended and wall-mounted indirect lighting and suspended direct lighting.

Evaluation of Occupant Light Exposure Profiles

Based on the behavior profiles developed for each survey respondent, a light profile was constructed by compiling data from view positions, view directions, date, time-step, duration of occupation, and sky condition to evaluate that occupant's light exposure throughout the day. Each occupant profile was evaluated based on the vertical illuminance weighted towards the sensitivity of the melanopsin-containing photoreceptors in the eye or the so-called ipRGCs. Melanopic illuminance is used in both the WELL building standard and nvRD (non-visual direct response) (Amundadottir, 2016; WELL, 2020). Where the WELL building standard criteria only considers EML light exposure between 9am - 1 pm, nvRD considers light exposure throughout the day and is capable of extending beyond the current scope of this paper to consider weeks, months, and even years. The nvRD model integrates light intensity, wavelength, duration, pattern, and light history, allowing it to be more sensitive to short durations or intermittent periods of light exposure.

Performance Criteria for Visual Representation

The WELL Building Standard uses threshold EML values, which are computed by taking the melanopic illuminance and converting them to photopic illuminance according to the spectral distribution of the light source. The current WELL Q1 2020 version Feature L03 (Circadian Lighting Design) identifies two performance thresholds: 150 lx and 240 lx. WELL points are awarded if these thresholds are met or exceeded between 9 am - 1 pm.

For the nvRD model, the accumulation of non-visual light exposure is used to predict a daily light dose (Amundadottir, 2016). In order to compare nvRd to the WELL building standard, two thresholds have been considered: 4 and 8. These thresholds correspond to the number of "vital" hours in a day, when adequate lighting is desired for alertness. An nvRD threshold of 4 is comparable to the WELL Building Standard (which credits light exposure between 9am – 1pm). An nvRD threshold of 8 assumes that circadian health could be achieved across a broader range of daylit hours, but this threshold is only mentioned in one of the results sections below. As mentioned briefly in the introduction, neither nvRD or WELL (for work areas) penalize excessive light exposure or light exposure received at the wrong time of day. As both of these metrics are being applied in an office setting that is vacated by 8pm, we assume no upper limit to the nvRD response. Both the WELL Building Standard and the nvRD model are used to provide a relative comparison of threshold-driven and cumulative daily dose metrics.

RESULTS

The results from this study reveal the importance of occupant behavior over space time as well as the impact of electric light as a supplement to daylighting, especially under overcast sky conditions. The following section explores the impact of occupant behavior under daylight and electric lighting scenarios to determine the non-visual light exposure performance by population, by behavior, by light exposure type (source and sky), and by occupancy location. Figure 4 shows an overview of results for all 38 occupants on March 21st. Figure 4a shows results under overcast skies *without* electric lighting and figure 4b shows results under overcast skies *with* electric lighting. Yellow squares indicate time periods when eye-level exposure of $EV\_ipRGC \geq 200$ and grey squares indicate time periods when eye-level exposure $EV\_ipRGC < 200$. This comparison reveals the impact of electric lighting sources on the eye-level exposure of building occupants, but it also shows that even with electric lights turned out, many occupants experience periods of time when eye-level exposure drops below the threshold recommended by WELL's Q4 2019 version Feature 54: Circadian Lighting Design. This may be due to dynamic daylight conditions or view positions that do not achieve high levels of vertical eye-level illuminance. In this version of WELL, occupants should receive 200 lux of equal-energy light source (which is equivalent to 182 lx of daylight illuminant D65) maintained at eye-level between the hours of 9am-1pm.

Light Dose by Population

One way to evaluate the lighting performance of our side-lit case study is through the aggregated health performance of all 38 occupants. If we look at the percentage of occupants who achieve a recommended eye-level exposure under each sky and lighting condition, we can compare the relative impact of electric lighting and the overall health performance of our lighting design. Figure 5 compares results for March 21st, June 20th, and December 20th under clear and overcast sky conditions with and without electric lighting. The (*) marks instances when electric light is added to the occupant's daily exposure. The bar graphs show the number of occupants that achieve performance measures for (a) non-visual direct response (nvRD thresholds 4 and 8) and (b) WELL Building Standard Q1 2020 for circadian lighting (thresholds EV_ipRGC 150 and 240). During each of the three simulated days, a higher percentage of occupants achieved a recommended light dose under overcast sky conditions when electric light sources were turned on.

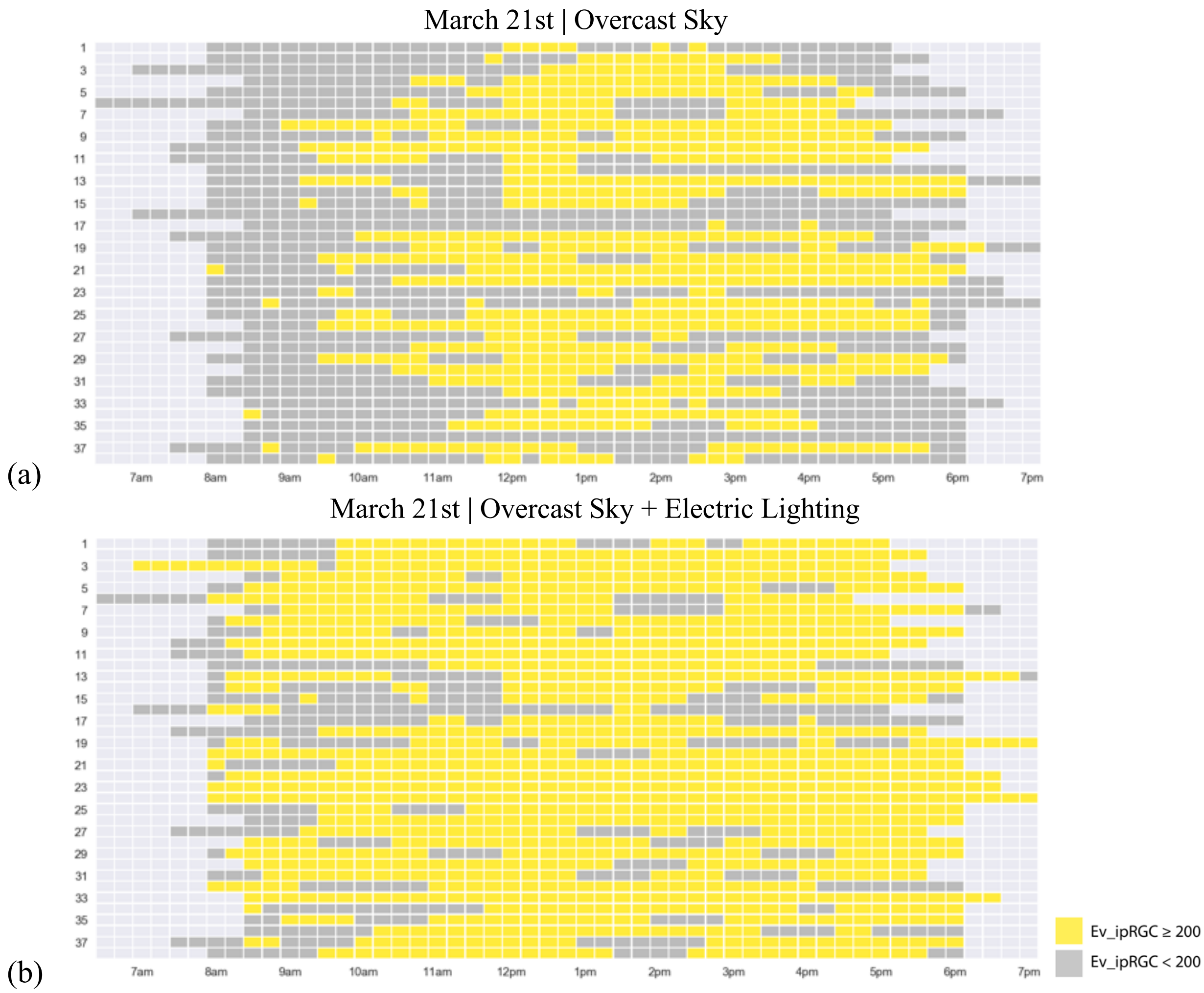

Figure 4. Results showing the eye-level light exposure for all 38 occupants from the time of their arrival in the office to their departure on March 21st under a) overcast sky conditions and b) overcast sky conditions with electric light. Each square represents a 15-minute interval. Yellow squares indicate time periods when eye-level exposure = EV_ipRGC ≥ 200 and grey squares indicate time periods when eye-level exposure = EV_ipRGC < 200.

That being said, clear sky conditions substantially outperformed overcast sky conditions, even when electric fixtures were enabled. Figure 5(a) shows that a majority of occupants achieved a daily nvRD dose of 4 with daylight only (no electric lights turned on), except on December 20th under overcast sky conditions. Figure 5(a) Under overcast sky conditions, only a handful of occupants achieved a daily nvRD ≥ 8, even with the electric lights turned on, although this is not surprising given the diminish illumination capacity under overcast skies.

Figure 5b shows the percentage of occupants that achieved the WELL Building Standard Q1 2020 for circadian lighting. While a majority of occupants did not achieve WELL under overcast sky conditions, even with electric lights turned on, the addition of electric lighting to the clear sky condition pushed the population across the 50% threshold.

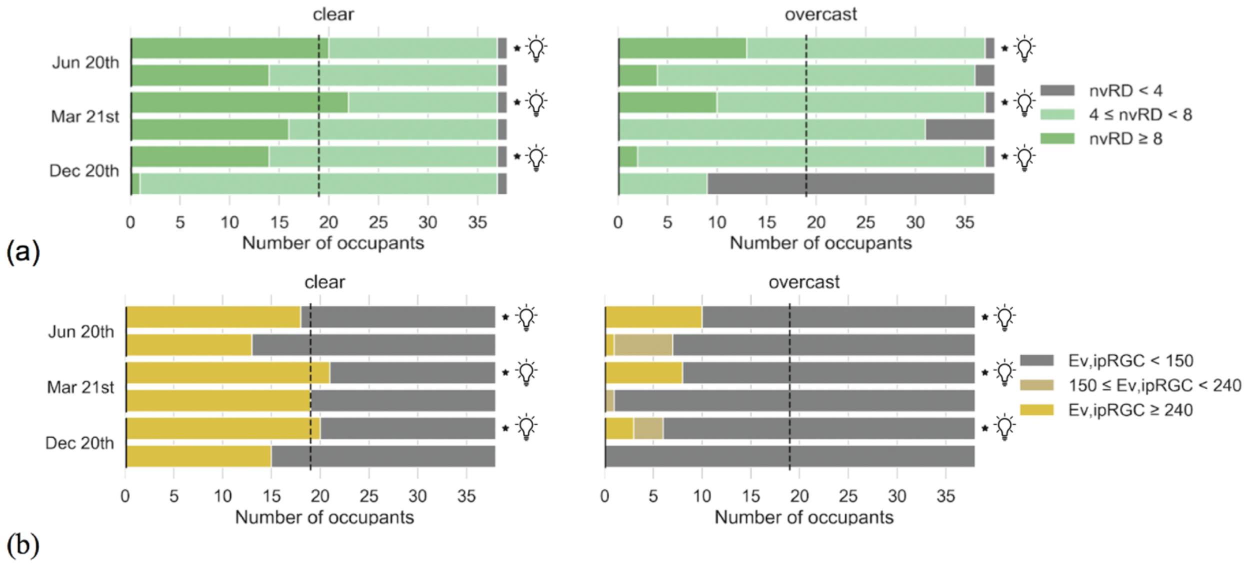

Figure 5. Percentage of occupants that achieve a recommended light dose under clear and overcast sky conditions under daylight only or *with daylight and electric light for a) nvRD and b) WELL Building Standard.

The difference between the two non-visual health metrics is that WELL Building Standard Q1 2020 (Figure 5b) only considers the time period between 9am and 1pm, where nvRD (Figure 5a) evaluates the entire day from arrival and departure and reports a cumulative response for each occupant. For those occupants not achieving the recommended WELL light dose between 9am and 1pm, many went on to achieve that dose when the full day was taken into consideration. When we refer to Figure 2 and observe the variability in occupant behavior during these hours, it is no surprise that a more flexible metric shows improved circadian performance. Occupants who arrive early in the morning would be more likely to have a shifted circadian schedule and these hours should be taken into consideration when determining their daily light dose. nvRD allows for a broader and more flexible computation of light dose based on individual behavior.

Occupant Behavior and the Impact of Electric Light

Complementary to the previous section on population, this section looks at the impact of electric lighting when it is considered in addition to daylighting for each individual occupant. Figure 6 illustrates results for all 38 occupants, taking into consideration their varying schedules, locations, and view directions over time. Each bar includes the results from all three annual instances (March 21st, June 20th, and December 20th) and sky conditions (clear and overcast) so that we can clearly see the effect of electric lighting as compared to daylight only. The size of the dark grey bar indicates the relative impact of electric lighting for each occupant based on their behavior. While occupant 10 is capable of achieving almost twice the recommended nvRD with daylight only, electric lighting makes up a big portion of the nvRD dose for occupants 23 and 24. Electric lighting improves the cumulative light dose of most occupants over the day, but there are still some individuals, like occupant 16 who would benefit from an increase in supplemental lighting merely to achieve the minimum recommended dose. While horizontal illuminance levels met recommended task targets throughout the space (with electric lights turned on), we may need to rethink these targets when considering adequate eye-level exposure for circadian health. Future research should explore the impact of light distribution on eye-level light exposure to balance the benefits of energy efficiency and human health.

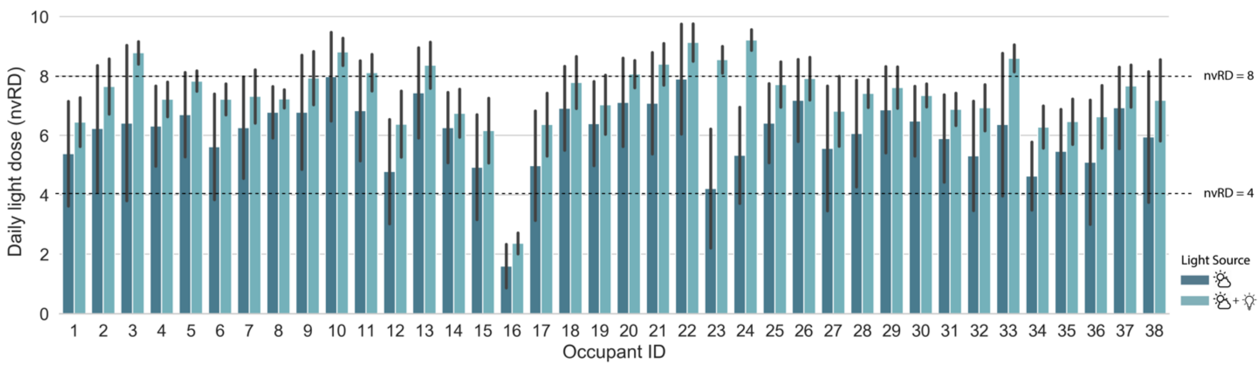

Figure 6. Average cumulative nvRd per occupant under daylight conditions (dark blue) and daylight + electric light (light blue). The daylight condition includes results for both overcast and clear sky conditions.

Threshold Light Exposure vs. Daily Light Exposure

Results in this section compare the impact of daylight and electric lighting sources on the distribution of occupant light exposure under each sky condition. Figure 7a shows the impact of each light source and sky condition on the nvRD for each occupant. This plot combines data from June 20th, March 21st, and December 20th instances to focus on the impact of light source independently from the time of year. To compare nvRD to WELL for the same time steps, this analysis highlights nvRD levels that surpassed a threshold of 4 before 1pm in light green. While a majority of points exceed the nvRD threshold of 4, only a handful do this before 1pm, challenging the notion of a strict time period of enforcement.

Figure 7b shows the impact of each light source and sky condition on the daily average EV_ipRGC for each occupant. Only instances that achieve the WELL criteria between 9am-1pm are highlighted in yellow. The results for both nvRD and WELL criteria reveal that many occupants achieve a sufficient daily dose over the day, but they are not considered sufficient for healthy entrainment under a strict threshold approach, such as the one implemented in the WELL standard. This raises the question about whether the WELL standards should to be adapted to accommodate a more flexible timeframe and account for variations in individual sleep/wake cycles and arrival times within the workplace.

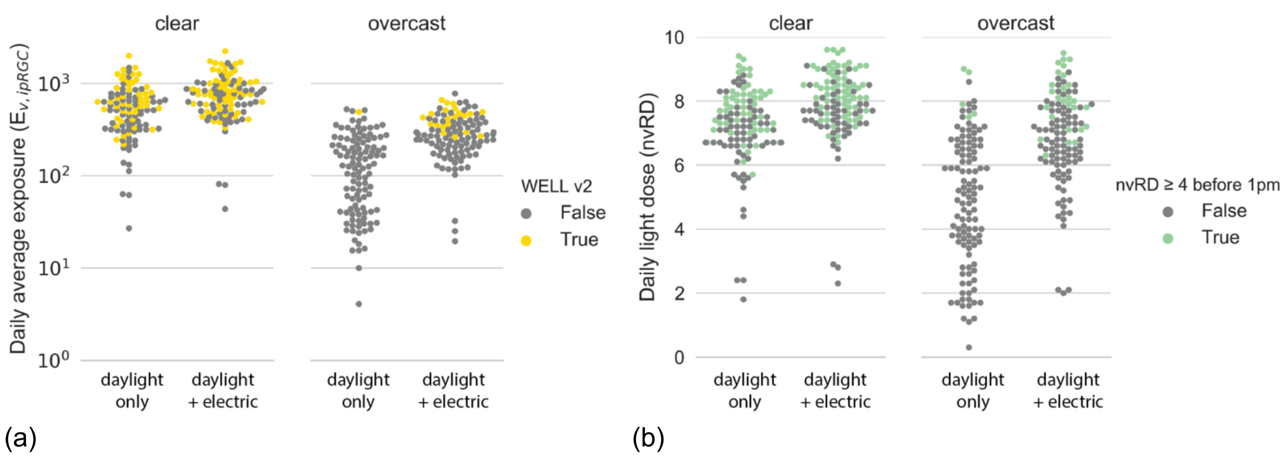

Figure 7. The distribution of daily average light exposures between clear and overcast lighting conditions for both daylight only and daylight + electric lighting sources. Figure a) shows daily average exposures in yellow that have achieved WELL between 9am-1pm and b) shows daily nvRD values of 4 or higher that are reached by 1pm in green.

Performance by Location within the Building

In addition to activity classification (work, meet, lunch), each seating location in our study was also tagged based on proximity to the façade: perimeter (near the windows) or core (more than half the distance from the windows to the back wall). For this analysis, all 38 profiles were placed into two groups based on the amount of time they spent in the core versus the perimeter. This grouping resulted in 13 occupants in the core and 25 in the perimeter. According to Figure 8, health potential is impacted by *where* the occupant spends a majority of their time. Occupants who spent more time in the perimeter of the building resulted in a higher nvRD for both clear and overcast sky conditions. These results also reveal that adding electric lighting to the core can allow occupants to achieve a similar exposure profile to those on the perimeter, although the relative impact of adding electric light is greater under overcast sky conditions. As the distance from windows increases, electric lighting becomes more important to meet individual light exposure recommendations.

Under clear sky conditions, electric lighting accounts for only 9% of the total average exposure compared to 35% under overcast sky conditions. The impact of electric lighting is much higher under overcast sky conditions, where the median nvRD dose increases from 4 to 6.1 (53%) in the core and from 5.7 to 7.5 (29%) in the perimeter zone.

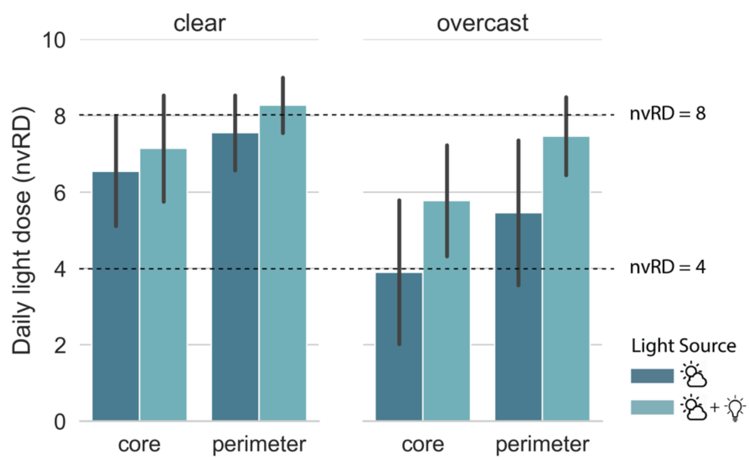

Figure 8. The average daily light dose (nvRD) between clear and overcast lighting conditions (with daylight only shown in dark blue and daylight + electric lighting in light blue) for the building core and perimeter zones.

Rather intuitively, this means that the impact of electric lighting reduces proportionally to the intensity of daylight present within the space, but it is less clear how we may implement photosensors that control the supplementation of electric lighting for vertical eye-level illuminance. Lighting distribution is an important design consideration to achieve a visual environment that is both comfortable, pleasing, and energy efficient. Designing a lighting scheme that integrates health would require us to consider a fixture and/or control scheme that optimizes when and where we distribute light for eye-level exposure. While the wall-mounted indirect luminaires used in the small meeting spaces within the current case study likely do not offer the most efficient distribution strategy eye-level exposure, they create a desired distribution for task-related purposes. Future work may consider a lighting control scheme that can shift between task and 'ambient health' modes. This very premise leads the authors to question our broader understanding of light distribution is it pertains to recommended illumination levels for health applications.

DISCUSSION

When considering the design of an electric lighting scheme and its integration with daylight for non-visual light exposure, it's important to balance occupant health with other considerations like energy consumption, comfort, and task performance. While there is generally consensus supporting the use of daylight for energy-efficient task-based illumination, we should also maximize the use of daylight, when and where its available, to achieve healthy light exposure. That being said, there are many instances and building types that require primary or supplemental electric lighting to achieve occupant needs. Minimizing energy consumption while maximizing comfort, task performance, and health can be achieved in a number of different ways. Lighting and shading controls could be designed to prioritize distribution on vertical, rather than horizontal surfaces when task and comfort needs are otherwise being met. Many of our current lighting control schemes already use photosensors to modulate electric lighting systems, but these sensors are often ceiling or wall mounted and do not account for the individual dynamics of occupant exposure at eye level.

WELL recommends the use of individual task lighting located at the desk to meet non visual light requirements, but there is a lack of research that validates whether these task solutions (in combination with ambient and daylight solutions) provide adequate light exposure for dynamic building occupants. To achieve an energy efficient *and* healthy solution, lighting and control systems could be programmed to coordinate vertical and horizontal illumination between task, wall, and ceiling mounted fixtures. Wearable or desk-mounted sensors could then communicate personal light exposure data across components within a lighting system. With the use of a wearable photosensor, electric lighting systems could be tuned to provide sufficient illumination for the spatial and temporal behavior of individual occupants. If we refer to Figures 6 & 8, a majority of occupants receive an adequate *daily* nvRD light dose with daylighting alone. This begs the question as to where supplemental lighting should be located, how it should be distributed, and when it should be switched on. While we would need to consider task and comfort considerations at the same time, an occupant-centric control strategy could help could improve health equity between occupants while optimizing energy use. From our results, electric lighting appears to have the greatest impact on non-visual health under overcast conditions when occupants are located in the core, away from windows. Wearable or desk-mounted sensors that can compute a cumulative light dose for individual seating locations could inform a zoned lighting control strategy that engages core and perimeter lighting systems.

Finally, it should be noted that more light exposure does not always result in improved health outcomes. After a particular threshold of light exposure, the benefits plateau and excessive exposure in the evening before bedtime can begin to have detrimental effects that disrupt a healthy sleep/wake cycle. So far, WELL guidelines for workspace have yet to address the potential for excessive artificial light exposure at night as they assume that people vacate their offices well before bedtime. This does not account for the risk to night-shift workers and those employees who engage in additional screen time when working from home after hours. As such, we need to think about increasing electric lighting in zones that are inadequate for healthy eye-level exposure, and reducing it in areas where the distribution does not improve occupant health, task performance, or comfort. Being able to simulate eye-level exposure for building occupants and accounting for their dynamic spatial and temporal behavior allows us to evaluate a building's lighting systems more holistically and opens the door for improved energy, task, and health outcomes.

CONCLUSION

In this paper, lighting performance was evaluated through the dynamic eye-level exposure of individual occupants over space and time. In order to compare the health potential of interior lighting applications in achieving occupant health, we must shift from a 2D task analysis to an analysis of eye-level lighting exposure over time. By considering the dynamic temporal and spatial behavior of individual occupants, the authors have presented a method to compare the impact of electric and daylight sources on healthy light exposure. The results of our study show the relative impact of electric lighting on individual and collective light exposure profiles for health-based metrics like the WELL Building Standard and nvRD. That being said, we have yet to explore the optimal integration of electric lighting as a supplement to daylight for eye-level light exposure. As health-based metrics continue to offer a new narrative about lighting performance, we have the opportunity to reconsider electric lighting applications (systems and controls) to provide high-quality and energy efficient eye-level illumination in addition to horizontal task performance.

Future research will seek to explore the impacts of lighting distribution on healthy light exposure, taking into consideration the energy consumption required to activate non-visual light responses. Additional work is also needed to strengthen our understanding of dynamic human behavior and move beyond the rough granularity of 15-minute time steps. In addition to energy efficiency, the authors would like to consider the relationship between non visual light exposure and visual comfort, as any future control strategy that optimizes for health must also consider visual comfort and glare avoidance.

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