The Impact of Light Distribution and Furniture Layout on Meeting Light Exposure Objectives in an Office – A Simulation Case Study

Megan Danell [1], Steffen Hartmeyer[1], Lisa Petterson[2], Robert Davis[3], Marilyne Andersen[1], Siobhan Rockcastle[4]

[1]Laboratory of Light and Perception in Design, Lausanne, Switzerland

[2]SRG Partnership, Portland, OR United States

[3]Pacific Northwest National Lab, Portland, OR United States

[4]Baker Lighting Lab, Eugene, OR United States

Abstract

The present simulation case study compares the impact of electric lighting distributions in relation to work-desk location and orientation on work-plane and eye-level illumination within a small private office. The aim of this study is to better understand the implications of lighting and furniture design decisions on ocular light exposure with consideration of work-plane illuminance based on current recommendations by the IES and the International WELL Building Institute. Five electric lighting configurations, 3 occupant seating locations, and 3 view directions were simulated and compared. No conditions met work-plane and eye-level illumination targets at the same time. Only by adjusting the spectrum and output intensity were both illumination targets achieved. Overall, vertical wall illumination when seated close to the illuminated wall resulted in the highest eye-level light exposure. These results indicate that vertical plane illumination can act as an effective lighting design for *both* horizontal and vertical illuminance when furniture configurations are selected accordingly.

Key Innovations

- Impact of electric light distribution and furniture layout on work-plane and eye-level illumination with respect to non-visual effects of light
- Impact of occupant location and view direction in relation to a given light distribution
- Combination of horizontal and vertical illuminance levels to evaluate lighting design

Practical Implications

Under the conditions presented in this study, 5000 lumens at 3500K was insufficient to meet task-based (300 lux) and health-based (150 lux or 240 lux) illumination targets. Wall-mounted light distributions perpendicular to the occupant's view direction consistently performed better in terms of ocular EML levels than the ceiling-mounted distributions, indicating that vertical plane illumination can act as an effective lighting design for *both* horizontal and vertical illuminance when furniture configurations are selected accordingly. Ceiling mounted luminaires require increased output intensity and spectrum alteration while wall mounted luminaires require increased output intensity but limits effective furniture configurations.

Introduction

Lighting design has traditionally focused on meeting recommended illumination targets for visual tasks on a horizontal work plane (Reinhart et al., 2006; IES, 2012). However, recently we have come to understand that light is not only important for vision but also affects human physiology and behaviour and may thereby be linked to human well-being and health (Price et al, 2019). Given that nowadays humans spend about 90% of their time indoors, responsible and holistic day- and electric-lighting design is necessary. As such, the horizontal plane should no longer be the only consideration for meeting lighting requirements and recommendations, but vertical illumination at the eye must also be taken into account (Lucas et al. 2014; Boyce, 2010). The intensity, spectrum, direction, timing, and duration of light, as well as prior light exposure all affect the circadian system and the physiological responses of an occupant (for a review, see Prayag et al., 2019). Additionally, light has been found to elicit acute non-visual effects, such as on alertness, cognitive performance or mood (Cajochen et al., 2019; Chelappa et al., 2011). The non-visual system's sensitivity to light is different to that of the visual system and, new metrics were developed in order to quantify light exposure needs with respect to the former. While different metrics exist, the only one endorsed by the CIE is based on the concept of photometric equivalence, weighing the light stimulus by the action spectrum of individual photoreceptor types in the human retina, and relating it to an equal alpha-opic irradiance of daylight (alpha-opic EDI; CIE, 2018) or an equal energy spectrum (equivalent alpha-opic lux; Lucas et al., 2014; Amundadottir et al., 2017). Because the sensitivity of the non-visual system is largely defined by the photopigment melanopsin (Brown, 2020), *melanopic EDI* measured vertically at eye-level has been recommended to be considered in lighting design (CIE, 2019). The similar metric *equivalent melanopic lux* (EML), which is linearly related to melanopic EDI, has been adopted by many lighting designers and is included in the WELL Building Standard (IWBI, 2021).

Given how important it is to consider the amount and quality of light reaching the eye, lighting design standards such as WELL have incorporated recommendations regarding EML at the workplace. Although research on the non-visual effects of light has not yet developed enough to provide concrete guidelines, these recommendations provide a first step towards integrative lighting design and help raise awareness to physiological considerations when it comes to lighting environments.

Digital modeling and simulation is frequently resorted to when prospectively evaluating the impact of lighting and/or architectural design strategies, and office and health care environments are of particular interest here due to the amount of time occupants spend in these spaces during waking hours (Boyce, 2010; Figueiro & Rea 2016;). Studies pertaining to such environments (and which use daylight and/or electric light) have investigated the impact of a range of lighting design decisions and features of a space. These include, but are not limited to, window-to-wall ratio (Acosta et al., 2017; Campano et al., 2019), view directions (Inanici et al., 2015), wall reflectivity (Campano et al., 2019, Dai et al., 2018, Jarboe et al., 2020), luminaire types (Jarboe et al., 2020, Dai et al., 2018), and occupant seating location and behaviour over time (Danell et al., 2020). Note that most of these (and other) simulation-based studies have focused on either daylight (e.g., Campano et al., 2019, Rockcastle et al., 2019, Rockcastle et al., 2020, Ewing et al., 2017) *or* electric light (e.g., Jarboe et al., 2020, Dai et al., 2018) with very few having studied the interaction of both sources, due in part to the complexity associated with their combination (Rockcastle et al., 2020).

In a recent simulation study, Jarboe et al. (2020) investigated the impact of different electric lighting strategies specifically on circadian stimulus (Rea et al., 2005), which is defined as the phototransduction by the human circadian rhythm predicting nocturnal suppression. In their study, six luminaire types, two luminous intensity distributions, six spectral power distributions, and two horizontal work-plane illuminance values were evaluated in resulting vertical eye-level illumination and energy efficiency. The impact of a supplemental desktop luminaire which delivered light directly to the occupant's eye was also studied. They found that supplementing overhead luminaires with desktop luminaires was the most impactful and energy efficient lighting strategy, resulting in the highest circadian stimulus levels. These results confirm the obvious: that supplying light from the vertical plane results in higher illumination levels at the eye. Using a human factors pilot study, subjects indicated the use of a desk luminaire while completing tasks was not found to be glaring or uncomfortable. As IES does not recommended illumination levels over 500lux on the work plane (IES, 2013), the use of a vertical luminance plane could mitigate visual discomfort while meeting adequate horizontal and vertical illumination targets. While this effect has been simulated for direct vertical light sources (i.e. desktop luminaires), to our knowledge, no study has yet investigated the relative effect of illuminating a vertical plane (e.g. a wall or half-height partition) through indirect illumination. Providing designers with the recommended distribution, intensity, and color of wall-washing luminaires could help integrate circadian performance alongside task and visual ambiance into a holistic lighting design strategy.

With the present study, we aim to investigate the impact of indirect vertical illumination on an occupant's eye-level and work-plane light levels in a small private office, here used as a case study. This work is a follow-up to a series of previously performed simulations investigating daily temporal and spatial light exposure profiles within a large office building (Danell et al., 2020), that the private office space considered here is part of. Specifically, a first analysis investigated how hypothetical spatial and temporal occupant behaviour may affect individual light exposure profiles. A follow-up study looked at real behavior profiles based on a survey amongst the building employees and simulated their light exposure profiles for electric light and daylight conditions (Rockcastle et al., 2020). The results revealed that for one of the simulated employees who happened to be working in a private office space, the received daily light dose was much lower compared to all other employees, due to a singular dependency on electric lighting. These results motivated further research into how lighting and architectural design decisions within the employee's office space might affect the occupants' light exposure profile under electric lighting conditions. Together with the lack of research into indirect vertical illumination strategies as outlined previously, in the present study we aimed to address the following research questions:

- *Does indirect vertical illumination via wall-mounted luminaires result in higher levels of equivalent melanopic lux at the eye compared to ceiling-mounted luminaires?*
- *What combination of luminaires can be used to achieve IES and WELL illumination targets for both the work-plane and eye-level exposure?*
- *How do desk location and view orientation impact the effect of different light distributions on vertical and horizontal illumination targets?*

These questions were selected with the intention to better understand how indirect vertical illumination performs in comparison to ceiling mounted luminaires, what lamp source characteristics are required to achieve both horizontal and vertical illumination targets, and what role furniture configurations play in effecting ocular light exposure levels within the context of this individual office space. By analyzing these three factors, the outcomes of various spatial electric lighting distributions and the relationship the occupant should have to that electric light source to better achieve health *and* performance-based lighting standards can continue to develop. This work provides a continued analysis of benefits and consequences of various spatial lighting design scenarios, in particular consideration of vertical illumination, and furniture configurations that could improve health-based lighting conditions within an individual office.

Methods

Taking the private office space mentioned above as spatial context, we want to study the variations in resulting work-plane illuminance and eye-level EML when simulating and comparing five light distributions achieved by three luminaire types (one wall-mounted, two ceiling-mounted) in relation to work-desk location and orientation. It was hypothesized that the wall-mounted light distributions eye-level illumination would be higher than for the ceiling-mounted light distributions, due to it being a vertical light source. Moreover, it was expected that the effect of the wall-mounted distributions would be more strongly dependent on work-desk location and orientation (which determine typical occupant location and view direction) than ceiling mounted distributions might be.

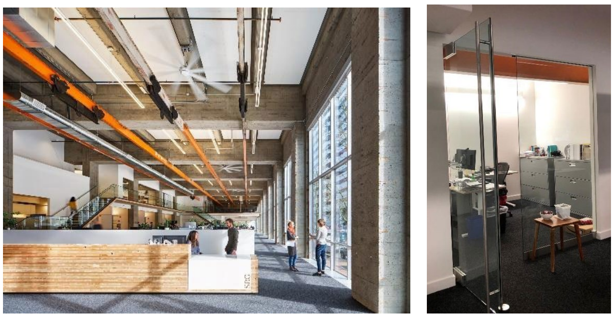


Figure 1: Left) SRG Partnership office, Right) individual office simulated in the present study

Simulation Environment

Simulations were conducted using ALFA (Version 0.5.4.4, Solemma LCC) in Rhino 3D (Version 5.0 SR14, Robert McNeil & Associates, Seattle, WA, USA) for a small private office within the SRG Partnership architecture firm in Portland, OR, USA (see Figure 1 for pictures of the space). The 3D model used in this study was provided by the architects and converted from Autodesk Revit to Rhino in order to allow simulations using ALFA.

The interior dimensions of the office space are 9’ 7” W x 12’ 4” L x 12’ 4” H with a dropped ceiling. Materiality of the space remained constant throughout all simulations except for the reporting on wall reflectivity. The materials were selected in correspondence to existing conditions in the space with consideration of photopic reflectivity, melanopic reflectivity, and M/P ratio. The photopic reflectivity values of the selected materials follow as: ceiling 81%, floor 22%, concrete 28%, and furnished elements ranging from 23% for chairs and 87% for the whiteboard, all used respectively for each furnished element. A structural concrete beam cuts through the width of the room (see Figure 3). Furthermore, glazing spanned over half of the entrance office wall (see Figure 1 and 4). To limit the conditions under consideration, simulations were conducted using electric lighting only. In order to avoid the inclusion of daylight, point-in-time simulations were associated to midnight (12am).

Three luminaire types (suspended direct/indirect, recessed, wall-mounted direct/indirect) were used (see Figure 3), each of which corresponds to a different light distribution. IES files from Focal Point Lights (Focal Point LCC, Chicago, IL, USA) were used for each luminaire type, to match the selection of light fixtures that were considered during the design of SRG’s current office space. The IES files were selected in coordination with the lighting designer responsible for this space and were based on typical design recommendations resulting in 8 linear ft (2.44 m) of fixture at about 5000 lumens. To achieve 5000 lumens at 8 linear feet of fixture, each luminaire had an output as follows: recessed at 625 lm/ft, suspended direct/indirect 375 lm/ft up and 275 lm/ft down, and wall mounted washers 375 lm/ft up and 250 lm/ft down.

The light spectrum used for all luminaires is depicted in Figure 2A. The CCT of the light source was 3500K with a CRI of 90, and the melanopic to photopic (M/P) ratio was calculated to be 0.693 (IWBE, 2014).

Simulations

Equivalent melanopic lux (EML) at eye-level (vertical) and horizontal work-plane illuminance (E_{WP}) were simulated. Target illumination values were based on the WELL Building Standard for “Circadian Lighting Design” for the former (IWBI, 2021), and on the IES LM-83 standard for the latter (IES, 2012). The WELL standard focuses on translating knowledge to practice for the health and well-being of occupants in the built environment, and sets minimum and recommended targets for EML at 150lux and 240lux, respectively (WELL v2, Q1 2021). The LM-83 standard focuses on spatial daylight autonomy metrics for common workplace environments and sets 300lux as the recommended threshold for work-plane illuminance.

Vertical illumination at eye-level was simulated at a height of about44” (3’8”) and work-plane illumination at a height of 2’ 6” (see Figure 3). Although in ALFA it is possible to simulate multiple viewing directions, we only used a single view direction as indicated by the selected furniture configurations shown in Figure 4A. This simulation method provided consistency by using a single furniture configuration at a time with no overlapping or extra surfaces in the space.

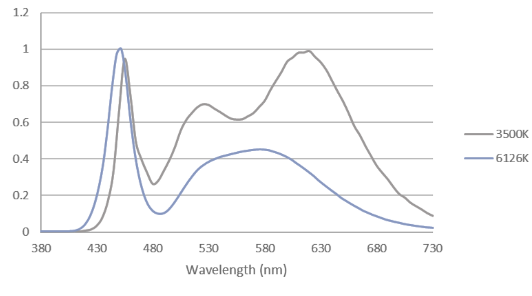


Figure 2: 3500K and 6126K spectrums

Study Design

Simulations were conducted for all combinations of the following factors: Light *Distribution* (recessed, suspended, left wall, center wall, right wall), occupant seating *Location* (left, center, right), and work-desk *Orientation* (0°, 90°, 270°). In the first part of simulations, *Wall Reflectivity* (46.2%, 60.2%, 74.7%) was also included as an additional factor. With the exception of wall reflectivity, all material finishes remained constant throughout this study.

Distribution

Five light distributions were explored: ceiling recessed, ceiling suspended, wall-mounted left, wall-mounted center, and wall-mounted right. For both the recessed and suspended conditions, two parallel fixtures of 4 linear feet (1.23 m) were located in the center of the office space at 1.23 m apart. The recessed fixtures were flush with the ceiling plane, while the suspended fixtures were located 0.91 m (3 ft) below the ceiling plane. In the wall-mounted conditions the fixtures were placed next to each other to obtain a continuous fixture of 8 linear feet, centered on either the left, center, or right wall (see Figure 3 and 4B), 1.5 m (5 ft) below the ceiling plane.

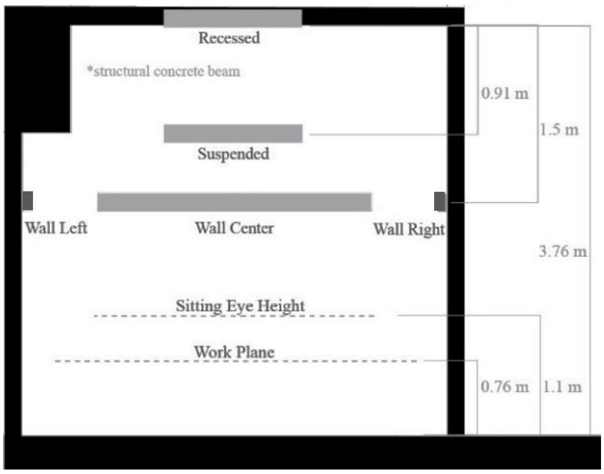


Figure 3: Longitudinal section of office space with location of luminaires.

Location

Three occupant seating locations were explored: left, center, and right (see Figure 4B). All three locations were located on the same axis, 0.91 m parallel to the back wall of the room and were selected to allow realistic desk arrangements, either close to the side walls or in the center of the room.

Orientation

Three desk orientations were explored: 0°, 90°, 270° (see Figure 4A), which determines the typical view direction of the occupant at work. Because a desk arrangement placing the occupant with their back to the entrance of the room is unlikely, a desk orientation of 180° was not included in the simulations.

Note that the existing office layout is represented by the center wall-mounted direct/indirect light distribution, and a center seating location with a desk orientation of 270°.

Simulation Procedure

The simulations were conducted in three steps. In the first step, *Wall Reflectivity* was included as a factor in order to test whether wall reflectivity affected EML in a linear fashion as would be expected. This step was included in the simulation procedure to ensure the results of the present study could be generalizable to different materials with different reflectivity values. In total, 135 simulations were conducted in the first step (5 lighting distributions x 3 locations x 3 view directions x 3 wall reflectivities).

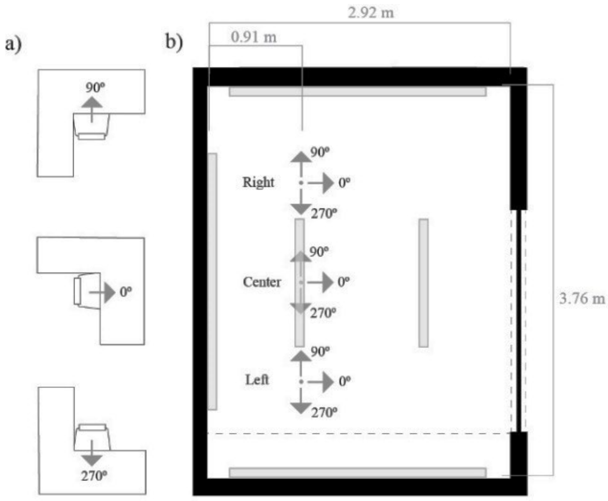


Figure 4: A) work-desk orientations, B) luminaire position, occupant seating location, and desk orientation/occupant viewing direction.

In the second step, the influence of light distribution, occupant location, and desk orientation on vertical and horizontal illumination were explored. Given a linear impact of wall reflectivity, simulations were conducted for 74.7% reflectivity, which yielded the highest illumination values. In total, 45 simulations were conducted (5 lighting distributions x 3 locations x 3 view directions x 1 wall reflectivity).

In the third and final step, simulations were conducted for a different light spectrum and a higher output intensity since the illumination outcomes in the second step did not meet both recommended work-plane *and* eye-level illumination targets. The light spectrum used in this part of simulations is shown in Figure 2B. The spectrum is available as a default in ALFA and has a CCT of 6126K at 80 CRI and a M/P ratio of 0.87. This spectrum was selected due to its higher CCT and its appropriateness within the given office setting. Additionally, new IES files were selected to achieve an output intensity of 8000 lm. The resulting output per luminaire type was 1000 lm/ft for the recessed luminaire and 500 lm/ft up and 500 lm/ft down for both the suspended and wall-mounted luminaires.

Results

The following section presents the results from our simulation-based analysis for each step of the study: 1) the impact of wall reflectance on EML, 2) the impacts of light distribution (fixture type and location), occupant seating location, and desk orientation on EML and work-plane illuminance (E_{WP}), and 3) impacts of increased light intensity and adjusted spectrum.

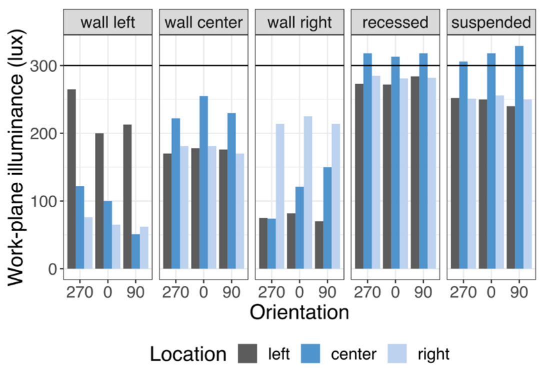
Step 1: Linear relation between EML and wall reflectivity

In order to check whether wall reflectivity affected EML in a linear fashion, EML was averaged for each reflectivity and their collinearity was calculated by comparing the slopes between the two adjacent pairs of reflectivities (46.2% and 60.2%, 60.2% and 74.7%). As expected, wall reflectivity and EML were almost linearly related (0.96 vs. 1.04). This small discrepancy may be due to remaining noise in the simulations, as part of a randomization factor integrated within this simulation method, since simulations were only run once per condition. To test whether wall reflectivity affected EML differently for ceiling-mounted and wall-mounted distributions, EML was averaged for the two distribution types and each ratio between EML for 46.2% and 74.7% reflectivity was computed. Both distributions produced a very similar ratio, with only a slightly higher value for the wall distribution (1.41 vs. 1.45). Note, however, that the increase in EML was not proportional to the increase in wall reflectivity, which had a ratio of 1.62 (74.7%/46.2%). Due to the linear relationship, it is justifiable to use the reflectance value of 74.7% in further simulations with the ability to estimate EML values at lower reflectivity values.

Step 2: Effects of light distribution, location, and direction

Figure 5 shows EML and E_{WP} for all conditions. Overall EML was highest for the recessed (mean = 118lux) and suspended (mean = 109lux) distributions, followed by the right wall (mean = 78.3lux), center wall (mean = 77.2lux) and left wall (mean = 71.4lux).

A)



B)

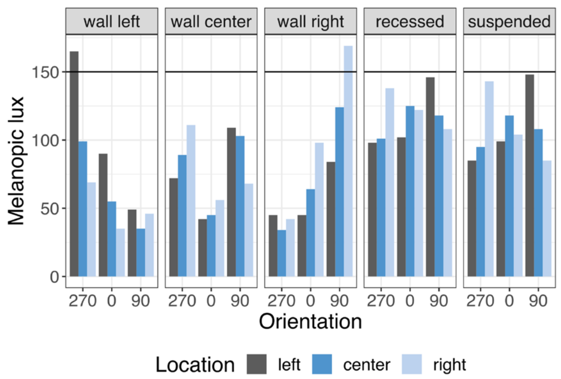


Figure 5: A) Melanopic lux, and B) work-plane illuminance, for all conditions. Horizontal lines indicate minimum eye-level EML (150lux) and recommended work-plane illuminance (300lux).

However, EML substantially varied between desk orientations and locations, especially for the wall-mounted light distributions. For all conditions, desk orientation resulted in higher EML when the desk was oriented towards the light source. At the same time, EML decreased for locations further away from the illuminated wall for the wall-mounted distributions. For the ceiling-mounted distributions (suspended and recessed), EML was lowest for the location in the center of the room directly underneath the light fixtures, while the highest EML was measured in the right and left location when the desk was oriented towards the light source (i.e. 270° and 90°, respectively).

As expected, E_{WP} showed a different pattern when compared to EML. For ceiling-mounted distributions, E_{WP} was highest for the center occupant location within the space. This pattern could also be observed for the center wall-mounted distribution. For the right and left wall-mounted distributions, E_{WP} was highest when the desk was oriented towards the light source (i.e. 90° and 270°), similar to EML performance, and decreased for locations further away from the illuminated wall.

In order to investigate the relative impact of *Location* and *Orientation* in more detail for each condition, we calculated the maximum/minimum ratio of EML and E_{WP} across one factor within each level of the other factor (i.e. ratio across *Location* for each level of *Orientation* and vice versa). Then these ratios were averaged for each distribution. Note that a higher ratio indicates a stronger impact of the factor under consideration, whereas a ratio close to 1 indicates a low impact. As shown in Figure 6, both *Location* and *Orientation* had a stronger impact on EML for the left and right wall-mounted distributions than for the center wall-mounted, recessed, and suspended distributions. For all conditions, E_{WP} was more strongly affected by *Location* than *Orientation*; however, this effect was most pronounced for the left and right wall distributions since both *Location* and *Orientation* had a very small impact on E_{WP} for the recessed, suspended and center wall distributions.

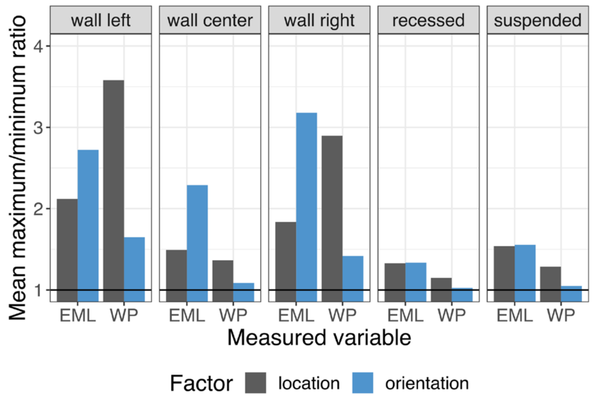


Figure 6: Relative impact (max/min ratio) of location and orientation on melanopic lux and EWP for each distribution. Note that a ratio of 1 indicates no impact.

While EML and E_{WP} varied substantially between conditions, only two conditions met the minimum WELL recommended eye-level EML of 150lux: the left wall-mounted distribution with the left desk location and orientation towards the left wall (270°), and the right wall-mounted distribution with the right desk location and orientation towards the right wall (90°). At the same time six conditions met the recommended work-plane illuminance of 300lux: the recessed and suspended distributions at center location. However, no condition achieved the minimum eye-level illumination and recommended work-plane illumination at the same time, nor did any condition achieve the WELL recommended eye-level EML of 240lux (see Figure 7A).

Step 3: Optimizing illumination

In order to meet recommended illumination targets both for the work-plane and at eye-level we adjusted the light spectrum and output intensity of the luminaires.

Spectrum

To investigate the impact of spectrum, we changed the spectrum to blue-enriched light at 6216K (see Figure 2), while keeping the output intensity constant at 5000lm. Figure 7B shows EML and E_{WP} for the 6216K spectrum. With this spectrum, similar work plane illuminance values as compared to the 3500K spectrum were achieved, while nearly twice as many conditions achieved the minimum WELL Building Standard threshold for EML of 150lux. However, while some conditions were close, none of these conditions met the recommended work-plane illuminance target of 300lux and minimum EML of 150 lux, or the recommended EML of 240 lux.

Intensity

To investigate the impact of a higher light output intensity, we adjusted the luminaire output from 5000 lumens to 8000 lumens (625 lm/ft to 1000 lm/ft), while keeping the spectrum constant at 3500K. Figure 7C shows EML and E_{WP} for an output intensity of 8000lm. With increased luminaire output intensity relating linearly to illuminance values, the majority of conditions achieve a recommended work-plane illuminance of 300lux as well as the minimum EML of 150lux. However, only two of these conditions achieve the recommended EML target of 240lux; both of these conditions being the left and right wall distributions.

Spectrum and Intensity

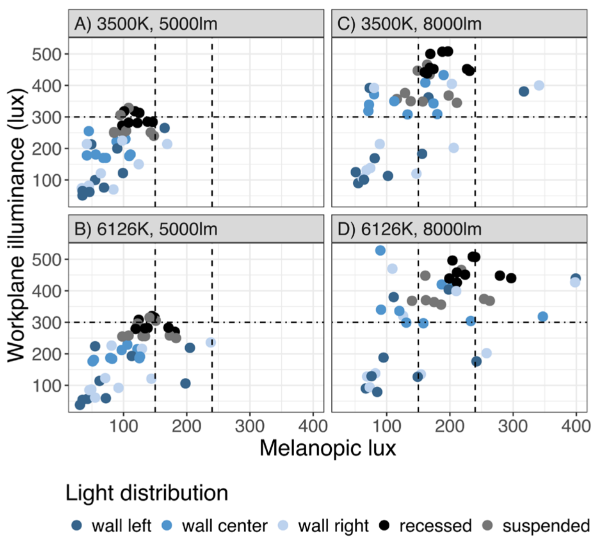


Figure 7: Melanopic lux and work-plane illuminance for A) the 3500K spectrum at 5000lm, B) the 6126K spectrum at 5000lm, C) the 3500K spectrum at 8000lm, and D) the 6126K spectrum at 8000lm for all conditions. Dashed lines indicate recommended eye-level EML (150 and 240lux) and work-plane illuminance (300lux).

In order to achieve more than two conditions that meet both the recommended work-plane and eye-level illumination targets we investigated the impact of adjusting the spectrum and output intensity of the luminaires together. Figure 7D shows EML and E_{WP} for the 6216K spectrum at an output intensity of 8000lm. With this combined adjustment of spectrum and intensity, seven conditions meet the recommended illumination targets.

Summary of findings

The results of the present study indicate that the installed lighting setup within the simulated office space – consisting of 8 linear feet of light fixture at 5000 lumens for a spectrum with CCT of 3500K –, is not sufficient for meeting the WELL Building Standard illumination recommendations for eye-level or work-plane at the same time. Although it was possible to achieve the minimum EML threshold of 150 lux with the wall-mounted light distributions, work-plane illuminance was below the recommended level of 300lux. While changing the light spectrum to more blue-enriched light allowed to achieve the recommended EML threshold of 240lux, both recommended work-plane and EML thresholds were only achieved with the left and right wall-mounted distributions when increasing the output intensity of the luminaires to 8000 lumens. When increasing the output intensity to achieve recommended EML, it simultaneously achieved the minimum 300lux threshold for work-plan illumination indicating that wall-mounted vertical illumination could satisfactorily achieve both lighting recommendations when ceiling-mounted distributions were unable to perform as such. In order to achieve recommended thresholds for ceiling-mounted luminaires, both spectrum and intensity had to be adjusted.

As hypothesized, the left and right wall-mounted light distributions consistently performed better in terms of ocular EML levels than the ceiling-mounted distributions. However, due to the impact of location and orientation on these results, there is very little flexibility in furniture arrangement based on occupant preference. To achieve the recommended EML threshold of 240lux for ceiling-mounted lighting distributions, both the intensity and spectrum of the luminaire would need to be altered. This would allow flexibility in furniture configuration if that was determined to be of high importance. Regardless of the luminaire distribution, seating location, and view direction, if the intensity and spectrum of selected sources are not sufficient, work-plane illuminance and eye-level EML will not achieve minimum current recommendations of 300lux and 150 lux, respectively.

Discussion

Our findings corroborate the findings of Jarboe et al. (2020), indicating that 500lux on the horizontal plane improved non-visual response more than that of 300lux.

Increased luminous output creates the challenge of increase in energy consumption and so further work is needed to determine optimal solutions for achieving energy efficient task plane illuminance *and* healthy eye-level exposure. Future work should consider the use of portable task-lighting, layers of lighting, or light sources closer to the occupant to achieve better eye-level exposure without adding extensive light overhead.

We should note several important limitations to this simulation-based study. First of all, the space used in our simulations is a single office type, therefore the impact of the lighting scenarios under consideration only impact a single occupant. The findings from this research may, however, be applicable to other similar small-scale spaces affecting more than a single person. Secondly, the lighting scenarios we studied were all considered as independent design options and as a result, we did not consider multiple layers of lighting through combined ceiling-mounted and wall-mounted fixtures. Layered light through multiple types of fixtures would allow the occupant to turn off a single layer of illumination in the afternoon in order to avoid any evening circadian disruption while continuing to achieve work plane illuminances throughout the entire day using a different fixture. Portable task lighting closer to occupant eye-level may provide a more optimal solution than those considered in this paper as depicted in Jarboe et al. (2020). The availability of daylight is another consideration that was outside the scope of this study but may have an impact on vertical EML regardless of how far the exterior curtain wall is from the individual office.

This research depicts the value that vertical illumination can have on ocular light exposure when weighted towards the non-visual system. When the lighting conditions remain constant, the eye-level exposures achieved for occupants are dependent on furniture configuration and occupant view direction. Therefore, in order to achieve an effective lighting scheme that meets work-plane and eye-level illumination targets, both luminaire placement and furniture arrangement must be considered. If a wall-mounted luminaire is selected with a CCT value of 3500K range, then furniture and view direction must be oriented appropriately to capture maximum intensity from the indirect lighting scheme. If flexibility of furniture and seating position is preferred, then luminaires with a higher intensity or a spectrum weighted towards shorter wavelengths should be recommended. Even with these recommendations, certain furniture and view configurations may perform just at or below the minimum threshold for equivalent melanopic lux (EML). In any case, a luminaire with 5000 lumens and 3500K is insufficient to achieve task-based *and* health-based targets for illumination. At a minimum, source intensity must be increased if selecting an indirect wall-mounted luminaire and spectrum would need to be tuned toward the blue range for ceiling mounted luminaires.

Conclusion

This paper investigates the impact of electric light distribution, furniture configuration, and view direction on work-plane and eye-level illuminance. This research aimed to further elaborate on spatial lighting distributions and the effect that occupant location and view direction has on lighting performance. As a result, the reported data is intended to further electric lighting design in meeting both health and task-based illumination targets for individual office spaces.

Our method was based on a three-step simulation process and allowed the evaluation of 1) wall reflectance as a linear model 2) the impact of light distribution, furniture configuration, and view direction on work-plane and eye-level illumination, and 3) adjustment of the luminaire spectrum and intensity output. As anticipated, wall reflectivity and EML were almost linearly related allowing the ability to estimate EML values at a lower reflectance when simulations were run at 74.7% reflectivity. Under the lighting conditions present in our base case, it was not possible to achieve minimum recommendation targets for work-plane illuminance (300 lux) and EML (150 lux or 240 lux) at the same time. In order to achieve both recommendations for E_{WP} (300lux) and EML (240lux), and maintain some furniture configuration flexibility within the space, both spectrum and intensity would need to be altered. As hypothesized, the wall-mounted direct/indirect luminaires reported higher values of EML due to vertical plane illumination but were more contingent upon occupant location and view direction than the ceiling-mounted lighting distributions. These results indicate that vertical plane illumination can act as an effective lighting design for *both* horizontal and vertical illuminance when furniture configurations are selected accordingly.

Acknowledgements

This paper was achieved in part with funding from the U.S. Department of Energy's Lighting R&D Program within the Office of Energy Efficiency and Renewable Energy (EERE), the Baker Lighting Lab at the University of Oregon, and the European Union's Horizon 2020 Marie Sklodowska-Curie Innovative Training Networks (ITN) grant No. 860613 (LIGHTCAP) with Laboratory of Light and Perception in Design at EPFL.

References

Acosta, I., Leslie, R., & Figueiro, M. (2017). Analysis of circadian stimulus allowed by daylighting in hospital rooms. *Lighting Research & Technology*, 49(1), 49–61.

Amundadottir, M., Lockley, S., & Andersen, M. (2017). Unified framework to evaluate non-visual spectral effectiveness of light for human health. Lighting Research & Technology, 49(6), 673–696.

Boyce, P. R. (2010). Review: The Impact of Light in Buildings on Human Health. *Indoor and Built Environment*, 19(1), 8–20.

Brown, T. M. (2020). Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. *Journal of Pineal Research*, e12655.

Cajochen, C., Freyburger, M., Basishvili, T., Garbazza, C., Rudzik, F., Renz, C., Kobayashi, K., Shirakawa, Y., Stefani, O., & Weibel, J. (2019). Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep. *Lighting Research & Technology*, 51(7), 1044–1062.

Chellappa, S. L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., & Cajochen, C. (2011). Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep Us Alert? PLoS ONE, 6(1), e16429+. https://doi.org/10.1371/journal.pone.0016429

Campano, M. A., Aguilar, M. T., Fernández-Agüera, J., & Domínguez, S. (2019). Optimization of the Window Design in Offices for a Proper Circadian Stimulus: Case Study in Madrid. *International Journal of Engineering and Technology*, 127–131.

CIE (2018) CIE S 026:2018 *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*

CIE (2019) *Position Statement on Non-Visual Effects of Light - Recommending Proper Light at the Proper Time, 2nd edition*

Dai, Q., Huang, Y., Hao, L., Lin, Y., & Chen, K. (2018). Spatial and spectral illumination design for energy-efficient circadian lighting. *Building and Environment*, 146, 216–225.

Danell, M., Ámundadóttir, M. L., and Rockcastle, S. F. (2020). Evaluating Temporal and Spatial Light Exposure Profiles for Typical Building Occupants. In *SimAUD 2020, Vienna Virtual Conference*.

Ewing, P. H., Haymaker, J., & Edelstein, E. A. (2017). Simulating Circadian Light: Multi-Dimensional Illuminance Analysis. *Building Simulation 2017*, San Francisco, CA Aug 7-9, 2017.

Figueiro, M. G., & Rea, M. S. (2016). Office lighting and personal light exposures in two seasons: Impact on sleep and mood. *Lighting Research & Technology*, 48(3), 352–364.

Figueiro, M. G. (2017). Disruption of Circadian Rhythms by Light During Day and Night. *Current Sleep Medicine Reports*, 3(2), 76–84.

IES - Illuminating Engineering Society (2012) Approved method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), IES LM-83-12, Illuminating Engineering Society of North America, NY, USA.

IES - Illuminating Engineering Society of North America (2013). *American National Standard Practice for Office Lighting,* ANSI/IES RP-1-12.

Inanici, M., Brennan, M., & Clark, E. (2015). Spectral Daylighting Simulations: Computing Circadian Light. In *Proceedings of International Building Performance Simulation.*

IWBI - International Well Building Institute (2021). WELL Building Standard, v2 pilot, Q1. https://v2.wellcertified.com/v/en/light

IWBI - International Well Building Institute (2014). WELL v1, Appendix C. Table L1: Melanopic Ratio. https://www.wellcertified.com/certification/v1/standard/tables

Jarboe, C., Snyder, J., & Figueiro, M. (2020). The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use. *Lighting Research & Technology*, 52(2), 167–188.

Kawasaki, A., Wisniewski, S., Healey, B., Pattyn, N., Kunz, D., Basner, M., & Münch, M. (2018). Impact of long-term daylight deprivation on retinal light sensitivity, circadian rhythms and sleep during the Antarctic winter. *Scientific Reports*, 8(1), 16185.

Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., Figueiro, M. G., Gamlin, P. D., Lockley, S. W., O'Hagan, J. B., Price, L. L. A., Provencio, I., Skene, D. J., & Brainard, G. C. (2014). Measuring and using light in the melanopsin age. *Trends in Neurosciences*, 37(1), 1–9.

Nowozin, C., Wahnschaffe, A., Rodenbeck, A., De Zeeuw, J., Hädel, S., Kozakov, R., Schöpp, H., Münch, M., & Kunz, D. (2017). Applying Melanopic Lux to Measure Biological Light Effects on Melatonin Suppression and Subjective Sleepiness. Current Alzheimer Research, 14(10), 1042–1052.

Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. LEUKOS, 3(1), 7–31.

Rockcastle, S., Ámundadóttir, M. L., & Andersen, M. (2019). The Case for Occupant-Centric Daylight Analytics: a Comparison of Horizontal Illumination and Immersive View. In *16th International Conference of the International Building Performance Simulation Association IBPSA*.

Rockcastle, S., Danell, M., Petterson, L., and Ámundadóttir, M. L. (2020). The Impact of Behavior on Healthy Circadian Light Exposure Under Daylight and Electric Lighting Scenarios, In *ACEEE Summer Study on Energy Efficiency in Buildings*.

Prayag, A. S., Münch, M., Aeschbach, D., Chellappa, S. L., & Gronfier, C. (2019). Light Modulation of Human Clocks, Wake, and Sleep. *Clocks & Sleep*, 1(1), 193–208.

Price, L. L. A., Udovičić, L., Behrens, T., van Drongelen, A., Garde, A. H., Hogenelst, K., Jensen, M. A., Khazova, M., Nowak, K., Rabstein, S., Romanus, E., & Wolska, A. (2019). Linking the non-visual effects of light exposure with occupational health. *International Journal of Epidemiology*, 48(5), 1393–1397.