# Energy impact of human health and wellness lighting recommendations for office and classroom applications

Sarah Safranek
Jessica M. Collier
Andrea Wilkerson
Robert G. Davis

Pacific Northwest National Laboratory
620 SW 5th Avenue, Suite 810
Portland, OR 97204
Sarah.Safranek@pnnl.gov

**This is an archival copy of an article published in *Energy & Buildings.* Please cite as:**

Safranek S, Collier JM, Wilkerson A, Davis RG. (2020): Energy impact of human health and wellness lighting recommendations for office and classroom applications. *Energy & Buildings.* 226 (1) 110365. doi: 10.1016/j.enbuild.2020.110365

# Abstract

The goal of this investigation was to evaluate potential energy impacts of circadian lighting design recommendations that are gaining attention in a variety of common applications such as offices and classrooms. The renewed focus on health along with advances in solid-state lighting technology capabilities has underscored that there is still much to learn regarding the relationship between light and human physiology. The energy implications of designing to address these possible physiological effects are not yet fully understood. Beyond the fact that the basic metric of luminous efficacy (lumens per watt) does not cover these other effects, the emerging science seems to indicate that addressing a holistic view of the human needs in most applications may mean a need for increased light and associated energy use by electric lighting systems. Two applications, an open office and a classroom, were simulated and lumen output, spectral characteristics, surface reflectance distribution, and desk orientation were varied to explore the magnitude of potential effects. Meeting current Illuminating Engineering Society (IES) illuminance recommendations did not satisfy existing equivalent melanopic lux and circadian stimulus recommendations for any of the office and classroom simulations. In some cases, satisfying circadian metric recommendations required an average illuminance that was more than double the IES recommendations, which may negatively impact lighting quality. Using results from 45 unique simulation conditions, it was estimated that lighting energy use may increase between 10% and 100% because of increased luminaire light levels used to meet circadian lighting design recommendations listed in current building standards such as WELL v2 Q2 2019, UL Design Guideline 24480, and CHPS Core Criteria 3.0.

# 1. Introduction

The amount of light needed for various interior and exterior applications has traditionally been expressed in terms of luminous flux, which accounts for the relative brightness sensitivity of human vision to wavelengths of the electromagnetic spectrum, as defined by the visual efficiency function V(λ) (Dilaura et al., 2011). Emerging evidence from the medical research community has linked lighting to physiological responses that go beyond visual performance, such as circadian synchronization and acute alerting effects. Research in the past 20 years has demonstrated that these responses have spectral sensitivities that differ from those used to define the luminous flux. Although luminous flux and metrics derived from it may be helpful for specifying the quantity of light needed for visual tasks, they are not sufficient for engineering and specifying lighting for non-image-forming human responses.

New circadian metrics, including equivalent melanopic lux (EML, units of m-lux) and circadian stimulus (CS, unitless), have been proposed in recent years to quantify the potential effect of light (used here to refer to optical radiation from 380 to 780 nm) on the human circadian system. Both EML and CS weight the spectrum of light using a different weighting functions than the accepted visual response (V(λ)) weighting function, with light intensity as a scaling factor. The EML metric is based on the melanopic response of the intrinsically photosensitive retinal ganglion cells (Lucas et. al., 2014) with a peak response at 480 nm. The CS metric is the calculated effectiveness of light at suppressing melatonin, using a more complex model of human phototransduction, including data from human melatonin suppression experiments combined with estimates of rod and cone photoreceptor responses, (Rea and Figueiro, 2018). EML has been adopted in a slightly modified form to align with SI unit requirements by the International Commission on Illumination (CIE) (CIE, 2018), while CS has not yet been adopted by CIE or the Illuminating Engineering Society (IES). EML will be used throughout this document as it was the initial criteria used by the design community and is still widely referred to in the lighting industry today.

Studies by Bellia et al. (2014), Dai et al. (2018) and Jarboe et al. (2019) reported that higher light levels than typically recommended for visual tasks are likely if EML and CS recommended values are met. Optimizing architectural lighting systems for either of these metrics and their unsubstantiated design targets may negatively impact current metrics related to lighting energy efficiency, which focus on luminous efficacy.

Predicting EML and CS in the built environment requires view-dependent lighting simulations that account for the spectral reflectance distribution (SRD) of room surfaces and spectral power distribution (SPD) of all light sources. The metrics are aimed at characterizing the intensity and spectrum of light reaching the eye of a potential occupant, and authors investigating daylit spaces found that the field of view considered has a significant influence over calculated EML and CS values (Konis, 2018; Mardaljevic et al., 2014). The SPD of light sources in the direct view of the calculation point impacts both metrics, although the exact spectral sensitivities of EML and CS vary based on the underlying assumptions of each metric. Cai et al. (2018) reported that room surface reflectance is an important design consideration as it can significantly influence EML and CS values with minimal energy consequence when compared to other potential design strategies, like increasing luminaire lumen output or window surface area. Further, Bellia et al. (2017) found that common lighting calculation methods reduce the SRD of room surfaces to an average value, which may be consequential when calculating EML and CS as the spectrum of light may shift differently when reflecting between room surfaces, even if they have equivalent average reflectance values.

There are currently three primary organizations with recommendations for designing lighting to account for the human circadian system: The International WELL Building Institute™ (IWBI™), UL, and the Collaborative for High Performance Schools (CHPS) (IWBI 2019, UL 2019, CHPS 2019). The WELL building framework covers 11 “concepts,” including water, materials, thermal comfort, and light, with the goal of defining design features that support and advance human health and wellness. There is a WELL recommendation for generic spaces (WELL v2 Pilot; IWBI 2019) and a separate recommendation for classrooms (WELL Education Pilot). UL Design Guideline 24480 is focused on describing how circadian-effective lighting designs for offices are to be accomplished and field verified. CHPS operates on the same foundational concepts as WELL, focused on defining effective design, construction, and operation strategies with the goal of reducing energy consumption and therefore operating costs in K-12 educational facilities. The specific recommendations for circadian lighting differ among documents and the primary characteristics are summarized in Table 1.

**Table 1: Circadian metric recommendation summary for office and classroom applications. Each recommendation has specific EML and/or CS requirements. To meet the recommendation, the circadian metrics must be met at the specified percent of viewing locations at the listed viewing height. The published recommendations provide minimum durations for which circadian metric values should be achieved. None of the included documents were developed by IES or CIE.**

| Document | Recommendation | Viewing Locations (%) | Measurement Height AFF[1] (m) | Minimum Duration (hours) |
|---|---|---|---|---|
| WELL v2 2019 Q2 | 1 point: EML ≥ 150 m-lux *OR* CS ≥ 0.3<br>3 points: EML ≥ 240 m-lux | 100 | 1.22 | 4<br>9 a.m.–1 p.m. |
| WELL Education Pilot (2019) | 1 point: EML ≥ 125 m-lux | 75 | 1.22 | 4<br>9 a.m.–1 p.m. |
| UL Design Guideline 24480 (2019)[2] | CS ≥ 0.3 | N/A | 0.91-1.22 | 2<br>7 a.m.–4 p.m. |
| CHPS Core 3.0 (2019)[3] | 1 point: EML ≥ 250 m-lux *OR* CS ≥ 0.3 | 75 | 1.22 | 4 |

[1] Above finished floor

[2] UL Design Guideline 24480 is not a point-based system; therefore, no additional criteria regarding percentage of view locations needed to achieve the recommendations are provided.

[3] Specific values are unclear due to typographical errors in the CHPS document

Although the metrics and prescribed quantities vary among documents, all require that circadian metrics be met at a specified number of view locations, view height, and daily duration in the built environment. Meeting WELL and CHPS recommendations earns points toward an overall numerical score while the UL Design Guideline 24480 does not include a numerical rating systems. Other organizations such as Fitwel and U.S. Green Building Council, through its Leadership in Energy and Environmental Design (LEED) program, are offering building design strategies to improve occupant health or environmental impact. Currently, both organizations have recommendations for utilizing daylighting and access to views, and LEED specifies some electric lighting quality guidelines, but neither organization makes any specific recommendations regarding circadian lighting design or wellness benefits (Fitwel 2020, USGBC 2019).

## 2. Methods

Common practice for calculating circadian metrics includes calculating or measuring the illuminance at the eye and then using the manufacturer-provided SPD of the luminaire to calculate EML or CS. This method does not consider valuable information pertaining to the view direction, architectural surfaces, furnishing, and location of luminaires. There can be a significant difference between the SPD of the luminaires and the SPD measured vertically at the eye, caused by spectral absorption and reflection of light as it moves throughout space and interacts with surfaces and objects, as well as by the possible mixture of daylight and multiple electric light sources. To lessen this issue, the simulations detailed in this article used the software tool Adaptive Lighting for Alertness (ALFA) (Solemma LLC), which considers SRDs for surfaces and SPDs for light sources, both of which are discretized into 81 values, about 5-nm increments, across the visible spectrum.

## 2.1 Model Parameters

For this report, three-dimensional computer models were developed for two space types: an open office space and a classroom space. Additional parameters for ALFA simulations include SRDs, luminaire distribution, luminaire lumen output, luminaire SPD, and designation of calculation points and view directions. The office and classroom spaces are illustrated in Figure 1. The office was 192 $m^2$ with five rows of desks and eight desks in each row. One long wall had floor-to-ceiling windows, although daylight contributions were not considered to simplify this initial analysis. The 70-$m^2$ classroom space was based on an existing elementary school classroom, which had a unique desk layout with 31 seating positions, no windows, and two teaching locations; at the north and south walls. One wall in the classroom had dark maroon upper and lower cabinets that covered most of the wall. In both models, desks were assumed to be 0.76 m tall. Horizontal and vertical calculation points were assigned for each desk at 0.76 m and 1.22 m above the floor, respectively. The vertical calculation points had a 180° field of view facing forward, used to represent the field of view of a person seated at each desk.

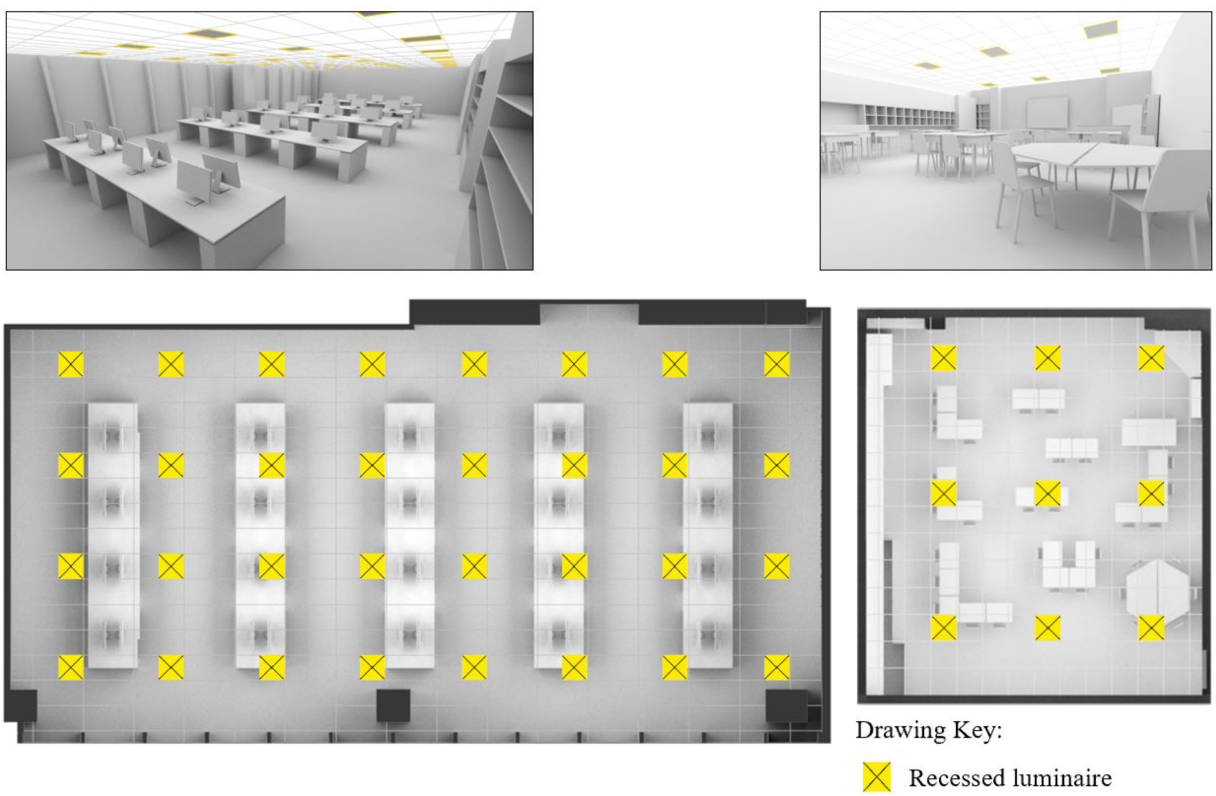



**Figure 1: Floorplans and images of office (left) and classroom (right) model spaces.**

Both models used the same white-tunable LED 0.61 by 0.61 m luminaire on a grid designed to uniformly light the horizontal task surface. The luminaire was evaluated in an integrating sphere [accredited by the National Voluntary Laboratory Accreditation Program to perform IES LM-79 testing]; measurements summarizing photometric, colorimetric, and electrical data are given in Table 2. Three SPDs, shown in Figure 2, were selected from the set of test data to represent the actual range of color settings available for the luminaire. For the remainder of this article, the differences in these three SPDs will be described using the nominal correlated color temperature (CCT) values for each. The maximum luminaire power draw was measured to be 40.5 W, regardless of the SPD. ALFA simulations where the lumen output was adjusted to less than 100% assumed a linear relationship between the luminaire power and lumen output. The photometric file used was taken from the manufacturer's website and was manually edited to adjust lumen output. No additional light loss factor was applied.

**Table 2: Laboratory testing summary of a new luminaire.**

| | |
|---|---|
| Luminaire size | 0.61 m by 0.61 m |
| White-tuning type | Linear |
| No. of LED primaries | 2 |
| Maximum lumen output | 4028 – 4588 |
| CCT (K) | 2722 – 6188 |
| Power (W) | 39.2 – 41.6 |
| Luminous efficacy (lm/W) | 100 – 114 |
| Luminous efficacy of radiation (LER; lm/Wrad) | 310 – 320 |

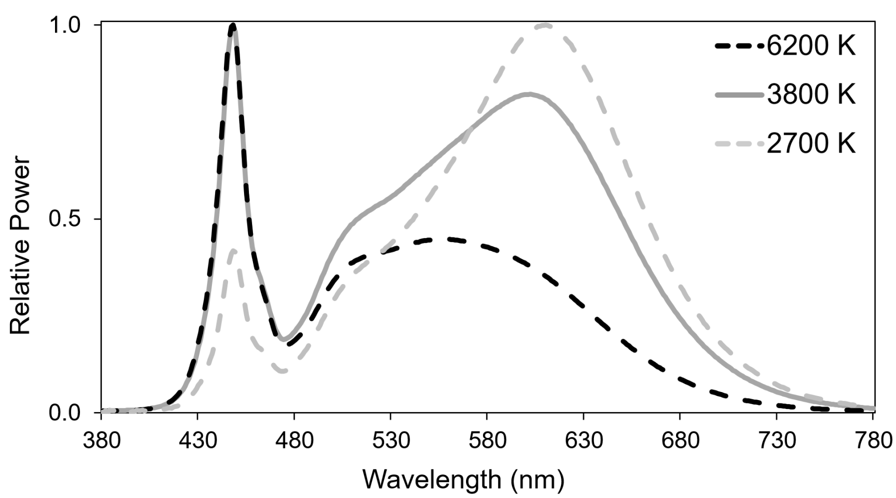
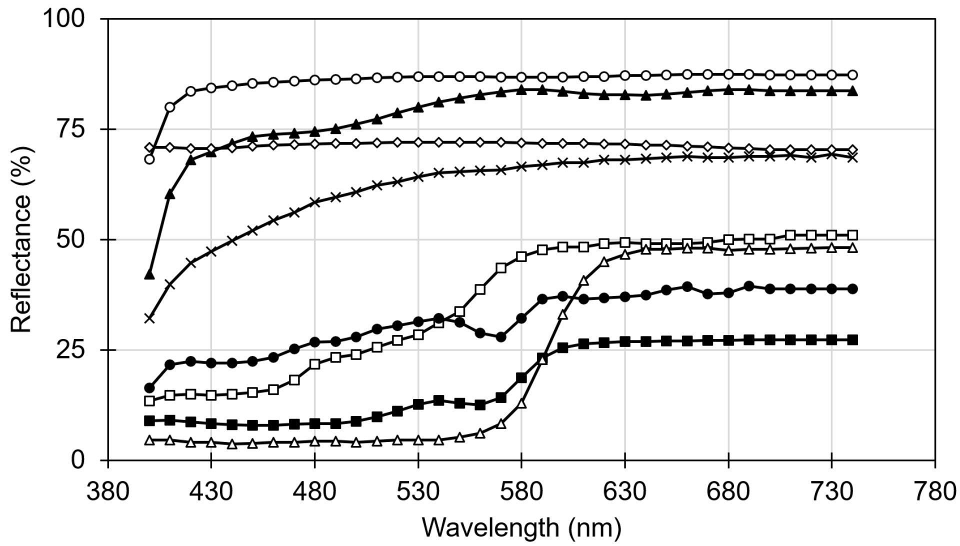



**Figure 2: Spectral power distributions of the luminaire. To compare the SPDs without the contribution of room surfaces, at 100 lx the 2700 K source equates to an EML of 44 m-lux and a CS value of 0.11; the 3800 K source equates to an EML of 66 m-lux and a CS value of 0.09 CS; and the 6200 K source equates to an EML of 92 m-lux and a CS value 0.16.**

The average reflectance values and SRDs used in the models are presented in Figure 3 for all surfaces. These SRDs all represent real objects or surfaces; the floor, walls, and ceilings for both models were assigned the same SRDs (neutral grey and white surfaces).




| Surface Material | Average Reflectance |
|---|---|
| White Ceiling Tile | 86% |
| White Wall Paint | 78% |
| Maroon Cabinets | 13% |
| Aluminum Window Frame | 71% |
| White Plastic | 66% |
| Blonde Wood | 36% |
| Warm Wood | 18% |
| Grey Flooring Tile | 32% |

**Figure 3: Reflectance definitions for model surfaces. The surfaces used in the ALFA models are listed in the table (left) and the full SRDs are plotted (right). The meter used to capture the SRDs has a measurement range from 400 to 740 nm. It is important to note the variation that can occur across the range of wavelengths in relation to a material's average reflectance.**

Baseline lighting conditions for both space types were created for initial system performance to meet the IES recommendations for horizontal and vertical illuminance. To achieve the recommended illuminance, luminaires were adjusted to 50% and 70% lumen output for the office and classroom models, respectively. For both models, CCT was held constant at the range midpoint, 3800 K, and the desks were assigned a medium-tone wood finish (referred to as blonde wood in this article). Additional simulations investigated the impact of different model parameters. For the office, 27 simulations were run using different combinations of nine parameters, as shown in Table 3. Surface reflectance values were held constant for the classroom model and the classroom layout was varied to investigate the influence of view direction and furniture arrangement, also shown in Table 3. Two layouts were evaluated as shown in Figure 4, contrasting the existing, unique layout with a traditional forward-facing desk layout, in accordance with WELL recommendations for circadian metric evaluations.

**Table 3: Summary of model parameters used in the office and classroom simulations. A total of 27 simulations were evaluated for the office space, and 18 were evaluated for the classroom, utilizing all combinations of model parameters listed below.**

| Office Model Parameters | | |
|---|---|---|
| **Desk Surface Material** | **Luminaire Parameters** | |
| | **CCT (K)** | **Lumen Output (%)** |
| Blonde wood<br>Warm wood<br>White plastic | 2700<br>3800<br>6200 | 50<br>75<br>100 |
| **Classroom Model Parameters** | | |
| **Desk Layout** | **Luminaire Parameters** | |
| | **CCT (K)** | **Lumen Output (%)** |
| Existing<br>Traditional | 2700<br>3800<br>6200 | 70<br>85<br>100 |


**Figure 4: Classroom desk layouts. The existing desk layout (left) reflects flexible space use, while the traditional desk layout (right) is a more standard design.**

# 3. Results and Analysis

The simulations were compared using average horizontal illuminance at the desk work plane, vertical illuminance at eye level, EML at eye level (calculated within ALFA), CS at eye level (manually calculated using the method detailed in UL Design Guideline 24480), and estimated annual energy use. Calculations at eye-level assume a seated position at a desk with the occupant facing forward, with a 180° field of view, referred to as seated view position. Calculated EML and CS values were compared with the WELL v2 2019 Q2 and UL Design Guideline 24480 recommendations for the office simulations, and WELL Education Pilot and CHPS Core Criteria 3.0 for the classroom simulations, summarized in Table 1. The WELL Circadian Lighting feature is tiered such that projects may earn either 1 point or 3 points, contributing to an overall numerical score, while the WELL Education Pilot and CHPS Core 3.0 do not have tiers. Although UL Design Guideline 24480 provides a recommendation for achieving circadian entrainment, it is a design guideline document and no points are awarded for following the guidelines.

## 3.1 Open Office Model

A summary of the simulation results is plotted in Figure 5, comparing the luminaire CCT with the calculated average vertical illuminance, EML, and CS values. A table of all model parameters and simulation results can also be found in Table A.1 of Appendix A. The IES Lighting Handbook (Dilaura et al., 2011) recommends average illuminances of 300 lux (lx) horizontal and 50 to 150 lx vertical for typical office applications, but some simulated light levels were more than double these recommendations, as shown in Figure 5. Average horizontal illuminance values from the 27 simulation conditions, calculated at each of the 40 desk locations, ranged from 375 to 818 lx. Average vertical illuminance above each desk ranged from 166 to 449 lx. The maximum horizontal and vertical illuminance values occurred with the highest reflectance desk surface, neutral white plastic, at 100% lumen output. Conversely, the minimum horizontal and vertical illuminance values occurred with the lowest reflectance desk surface, warm wood, and with luminaires operated at 50% output.

Average EML ranged from 69 to 382 m-lux and EML values were generally largest for the simulation conditions with higher CCTs and vertical illuminance levels. Desk surface reflectance affected EML averages, but it was still possible to achieve average values as high as an EML of 284 m-lux with the warm wood. Average CS values ranged from 0.12 at 3800 K and 50% output to 0.40 at 6200 K and 100% output. An average CS of 0.33 was possible with a CCT of 2700 K at 100% output for the neutral white desk surface. The 3800 K CCT parameter did not achieve an average CS value greater than 0.26 under any set of conditions.

Only one office simulation condition (#10, Table A.1) met the requirement for EML ≥ 240 m-lux for all seated view positions. The model parameters for that simulation included high surface reflectance, high CCT, and 100% lumen output, resulting in a horizontal illuminance of 812 lx and an average EML of 382 m-lux. A second simulation condition (#1, Table A.1) had 39 of the 40 viewpoints meet the EML ≥ 240 m-lux requirement but failed to qualify for 3 points because of a single non-compliant viewpoint. Nine simulation conditions were able to achieve EML ≥ 150 m-lux at all view locations using any of the desk surfaces, a CCT of 6200 K or 3800 K, and a lumen output of 100% or 75%. Only two simulation conditions (#1 and #10, Table A.1) met the WELL CS requirement.

For each lumen output parameter, annual energy estimates were calculated as shown in Table 4. It was assumed that the office lighting system operated for 4,000 hours per year. The first annual energy calculation assumed that when luminaires were operating, they were operating at the listed lumen output. The second calculation assumed that luminaires were operating at the listed lumen output 4 hours per day and at the baseline condition lumen output (50%) for the remaining hours of the occupied day.

All conditions met the ANSI/ASHRAE/IES Standard 90.1-2016 requirement of 8.72 $W/m^2$ (0.81 $W/ft^2$) for the lighting power density in an open office. The annual energy usage for the baseline condition, with lumen output at 50%, was 2590 kWh. Increasing lumen output throughout the office to meet the specific circadian metric requirements may double annual energy usage to 5180 kWh. If the circadian metric recommendations are met for the minimum 4-hour requirement, the annual energy usage estimate was 3400 kWh, a 31% increase from the baseline condition.

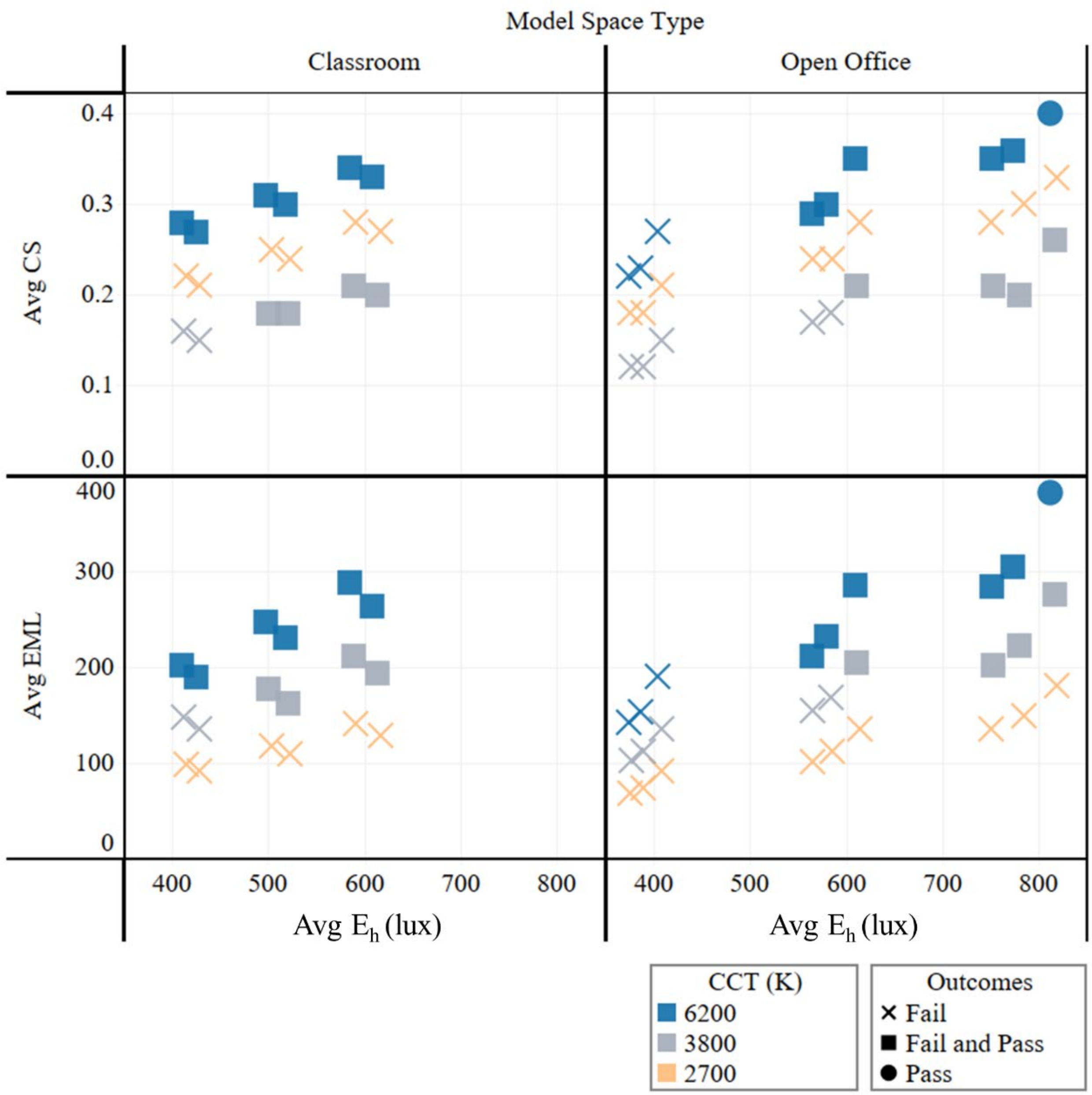



**Figure 5: Outcomes of meeting design recommendations for different simulation conditions. Only one simulation condition between both environments met all design recommendations. Note that increasing horizontal illuminance and/or CCT does not always result in meeting design recommendations.**

**Table 4: Comparison of energy requirements for the different lumen output conditions used in the office simulations. For each lumen output condition regardless of CCT, active power per area ($W/m^2$) and annual energy estimates were calculated assuming the lighting system is operated 4,000 hr/year. One annual energy calculation was done assuming luminaires always operate at the listed lumen output and a second calculation was done assuming luminaires operate at the listed lumen output for 4 hr/day, as suggested by WELL v2 Q2 2019. The estimates for the baseline condition (50% lumen output) are shown in bold text.**

| Output (%) | $W/m^2$ | $W/ft^2$ | Annual Energy Usage (kWh) | % Increase from Baseline | Annual Energy Usage w/ 4-hr Limit (kWh) | % Increase from Baseline |
|---|---|---|---|---|---|---|
| 100 | 6.76 | 0.63 | 5183 | 100% | 3402 | 31% |
| 75 | 5.04 | 0.47 | 3887 | 50% | 2997 | 16% |
| **50** | **3.33** | **0.31** | **2591** | ---- | **2591** | ---- |

## 3.2 Classroom Model

A summary of the classroom simulation results can also be found in Figure 5. A complete summary of the model parameters and simulation results for the classroom model can be found in Table 2 of Appendix A. As in the office model, metric results for the classroom simulations were compared against circadian lighting design recommendations in CHPS Core Criteria 3.0 and the WELL Education Pilot 2019. Lumen output was set to 70% for this simulation to meet the baseline visual requirements. For general classroom applications, the IES recommends 400 lx horizontal and 150 lx vertical (Dilaura et al., 2011). All simulation conditions met or exceeded these visual requirements; average horizontal illuminance ranged from 411 to 617 lx, and average vertical illuminance ranged from 222 to 351 lx.

For all classroom simulation conditions, average EML varied between 92 and 288 m-lux, while average CS varied between 0.15 and 0.34. Simulation conditions with high CCT and lumen output settings produced the highest EML and CS values regardless of desk arrangement. As modeled, the highest average EML and CS values were 288 m-lux and 0.34, respectively, corresponding to a lighting condition of 6200 K at 100% lumen output with the existing, unique desk layout. Conversely, the minimum average EML value of 92 m-lux occurs at 2700 K and 70% output with a traditional desk layout. The minimum average CS value of 0.15 occurs at the baseline visual condition of 3800 K at 70% lumen output with a traditional desk layout.

Although the baseline simulation condition did not satisfy the WELL Education Pilot circadian lighting design recommendation, just over half of the conditions (#1-5 and #10-14, Table A.2) provided enough light stimulus at the eye to satisfy the recommendation. The same five lighting conditions for both desk arrangements met the required EML threshold to satisfy the design recommendation, including two CCT settings (3800 K and 6200 K) and all three lumen output settings, although 70% output can only satisfy the recommendation at 6200 K. With the current lighting layout and room characteristics, it was not possible to achieve any points using EML or CS for the CHPS Core 3.0 criteria. To meet this criteria, additional luminaires would need to be installed or a different luminaire with a higher lumen output would need to be selected. Either option will very likely increase energy consumption in this space.

The existing desk layout in this classroom had 31 possible seating positions arranged in small groups facing multiple directions. Assuming one view direction parallel to the desk, it was possible to satisfy the recommendations for the WELL Education Pilot 2019 at 3800 K and 80% lumen output with 81% of view positions achieving EML ≥ 125 m-lux. At the same lighting condition with the secondary desk layout assuming one primary view direction towards the front of the classroom, the recommendation could no longer be achieved, with only 74% of the view positions achieving EML ≥ 125 m-lux. The effect of these results is illustrated in Figure 6.

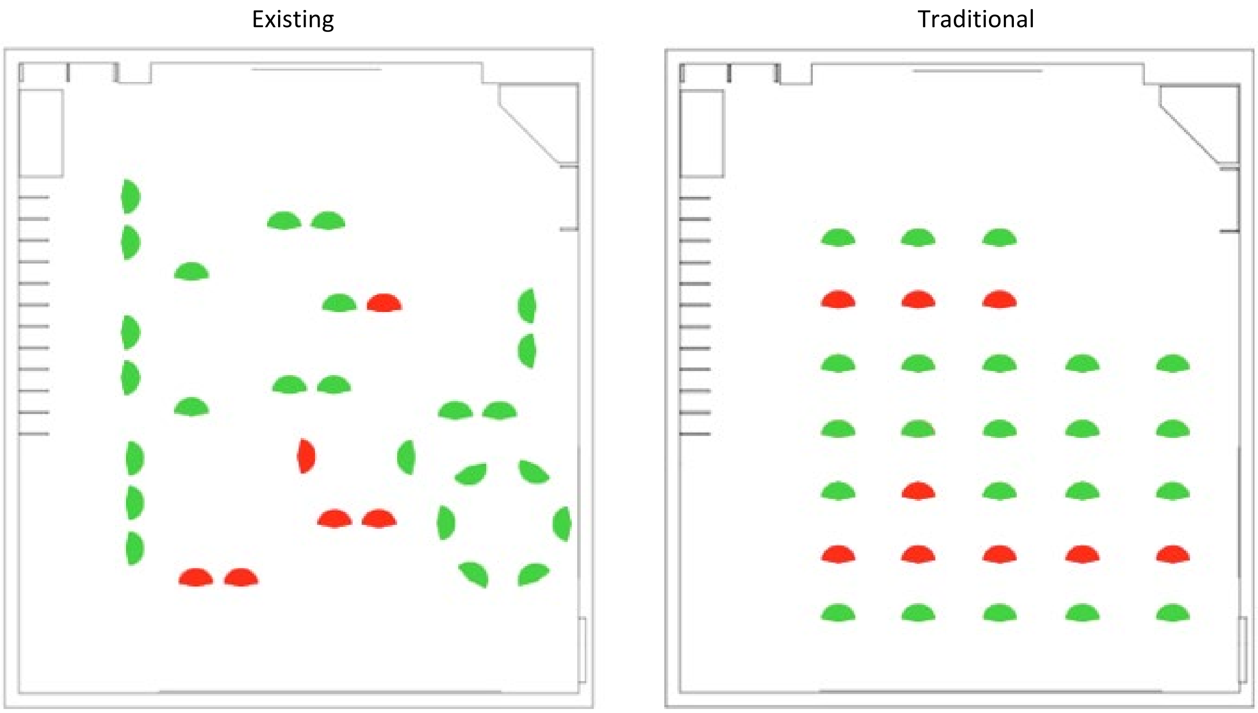



**Figure 6: Images comparing success and failure rate of desk layout. The WELL Education Pilot 2019 circadian lighting design criteria states that 75% or more viewing positions must achieve EML ≥ 125 m-lux to satisfy the recommendation. Each seat is color coded, green = satisfactory and red = unsatisfactory, for both desk layouts (existing, left, and traditional, right).**

Energy estimates are provided in Table 5, assuming 1,500 annual operating hours with the secondary condition of operating at a higher lumen output for only 4 hours per day. The classroom model met the ANSI/ASHRAE/IES Standard 90.1-2016 lighting power density limit of less than 9.90 $W/m^2$ (0.92 $W/ft^2$). At 70% lumen output, the baseline annual energy consumption per classroom is 383 kWh. If lighting systems were operated at full output instead of the baseline, it is projected that lighting energy consumption would increase to 547 kWh. With more sophisticated controls, lighting may be adjusted throughout the day to meet circadian metric requirements for the suggested 4-hour duration, then decreased to the baseline visual condition. In this scenario, lighting energy usage may increase by 21%, using 465 kWh per classroom.

**Table 5: Comparison of energy requirements for the different luminaire lumen output conditions used in the classroom simulations. For each lumen output condition regardless of CCT, active power per area (W/m2) and annual energy estimates were calculated assuming the lighting system is operated 1,500 hr/year. One annual energy calculation was done assuming luminaires always operate at the listed lumen output and a second calculation was done assuming luminaires operate at the listed lumen output for 4 hr/day, as suggested by the WELL Education Pilot 2019. The estimates for the baseline condition (70% lumen output) are shown in bold text.**

| Output (%) | $W/m^2$ | $W/ft^2$ | Annual Energy Usage (kWh) | % Increase from Baseline | Annual Energy Usage w/ 4-hr Limit (kWh) | % Increase from Baseline |
|---|---|---|---|---|---|---|
| 100 | 5.14 | 0.48 | 547 | 42% | 465 | 21% |
| 85 | 4.39 | 0.41 | 465 | 21% | 424 | 10% |
| **70** | **3.64** | **0.34** | **383** | ---- | **383** | ---- |

# 4. Discussion

Meeting current IES illuminance recommendations did not satisfy existing EML and CS recommendations for any of the office and classroom simulations. In some cases, satisfying circadian metric recommendations required an average illuminance that was more than double the IES recommendations, along with CCTs that were higher than those typically used for office and classroom settings. In the case of the office, only one set of parameters was able to achieve 3 points for the WELL v2 2019 Q2 Circadian Lighting Design feature, with a recommendation of EML ≥ 240 m-lux at all seated view positions. This simulation condition had average CS and EML values of 0.4 and 382 m-lux, respectively, at 6200 K and 100% lumen output and white plastic desktops, increasing energy use by 30% even at the minimum suggested duration. None of the classroom simulation conditions were able to meet the CHPS Core Criteria 3.0 recommendations of EML ≥ 250 m-lux or CS ≥ 0.3 at 75% of seated view positions. The highest average EML and CS values in the classroom, 288 m-lux and 0.34, respectively were achieved at 6200 K and 100% lumen output with the existing desk layout, resulting in greater energy consumption and likely an undesirable visual environment due to the high CCT and lumen output (Davis and Wilkerson 2017; Safranek et al., 2018).

## 4.1 Energy Impacts of Circadian Lighting Recommendations

The results of the office simulations estimate a 15% to 100% increase in annual energy usage depending on the duration of occupied hours that the circadian metric recommendations are met. These estimates would be larger if light loss factors were considered. The more conservative energy estimates, closer to 15%, assume that the installed luminaires are capable of changing the spectral and lumen output settings using an advanced control system. For lighting systems that use luminaires with CCTs in the range of 3000 to 4000 K, increased light levels are needed to meet circadian metrics, which increases the potential energy use estimates. If the installed luminaires are tunable-white, capable of adjusting the light levels and CCT as needed for 4 hours per day, an appropriate control system is necessary, which may introduce complexity to the overall lighting system as well as the commissioning process and can increase the overall electrical load of the lighting system.

Incorporating daylight may be a possible design strategy to reduce electric lighting energy consumption; however, it may also increase the complexity of the lighting controls and commissioning process as well as the simulation methods. Determining the spectral contributions of daylight is complex given the variability of daylight availability, sky conditions, and window glazing. Figuerio et al. (2017) found in a study collecting personal light exposures of federal employees working in five different buildings that reaching 0.3 CS at the eye was difficult, despite four of the buildings designed to maximize daylight, and the authors highlighted the need to consider office furniture locations, window shades, and occupant visual and thermal comfort. As mentioned above, the foundation of CHPS is to reduce energy consumption and operational costs for educational facilities; however, no classroom simulation was able to meet the provided circadian lighting recommendations. In order to meet the criteria in the realistic classroom model, additional luminaires or luminaires with a higher lumen output would have to be installed; both solutions will increase the connected electrical load and potentially negate other energy saving efforts recommended in CHPS Core Criteria 3.0.

Although the design recommendations presented in this report explore the impacts of effectively implementing circadian metrics, a consensus decision has not been developed on the lighting requirements for achieving potential non-visual lighting effects on occupants. At this time, it is difficult to understand what “effective implementation” means and how the metrics apply to a realistic space because the design recommendations are still in transition. For example, the WELL Education Pilot suggests that EML ≥ 125 m-lux for 4 hours per day is an appropriate stimulus in a classroom environment, yet CHPS Core Criteria 3.0 suggests that twice that amount (EML ≥ 250 m-lux) is needed.

Not only does this make it challenging for designers or educational facility managers to understand which guideline to follow, but it also has the potential to substantially increase energy consumption.

According to the current circadian metric models, it is important to increase lighting stimulus in intensity and short wavelength spectral content during the day, particularly in spaces absent of daylight, and reduce light levels and short wavelength spectral content in the evening and at night to support healthy sleep. The relative importance of increasing daytime light levels in relation to reducing nighttime light levels in realistic settings is unknown. In fact, if reducing light levels and limiting short wavelength content at night is more effective, greater energy savings could be realized and light levels during the day would not need to increase as shown in the simulations. Additional research is needed to optimize lighting energy use to achieve the effective stimulus characteristics and exposure times required for circadian health.

## 4.2 Influence of Surface Reflectance and View Direction

In the office model, varying the surface reflectance parameter affected the vertical illuminance and spectral content of light predicted at the defined viewpoints. Conditions using the neutral white plastic material definition achieved the largest circadian metric values. The only condition that achieved 3 points towards the WELL v2 2019 Q2 Circadian Lighting Design feature used the white plastic SRD in combination with the maximum CCT and lumen output model parameters.

To demonstrate the effect of surface reflectance on circadian metrics, Table 6 compares the results of three conditions where the surface reflectance distribution is the only parameter that has been changed between simulations. For these conditions, CCT and lumen output have been set to 3800 K and 75%, respectively. If the desk surfaces are set to the neutral white plastic, 100% of the view positions meet the 1 point requirement in WELL v2 2019 Q2. Once the surface reflectance is changed to the blonde or warm wood materials, the number of view positions meeting the same requirement fall to 70% and 58%, respectively. This difference can be explained in part by the decrease in average reflectance, but is also influenced by the SRDs of the surfaces. For these same conditions, Figure 7 compares the ALFA-predicted SPDs for one viewpoint in the model, demonstrating the influence of different desk materials on final SPD. The neutral white plastic surface material reflects more energy in the shorter wavelengths, around 440 nm, as compared to the wood materials. It is important to be aware of the potential effect of surface materials on the spectral content reaching the designated view positions if meeting circadian metric recommendations is a priority for the space.

**Table 6: Comparison of office simulation results with surface reflectance as the changing variable. For these conditions, CCT and lumen output have been set to 3800 K and 75%, respectively. When comparing the simulation results, surface reflectance (B = blonde wood, N = neutral white plastic, W = warm wood) had a significant influence on the number of view positions meeting WELL v2 2019 Q2.**

| **Model Parameters** | | | | **Average Illuminance** | | **Circadian Metric Averages** | | **Percent of View Positions Meets WELL v2 Yes or No** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cond. | Desk Surface | CCT (K) | Lumen Output (%) | $E_h$ (lx) | $E_v$ (lx) | EML (m-lux) | CS | EML ≥ 150 m-lux 1 pt | EML ≥ 240 m-lux 3 pt | CS ≥ 0.3 1 pt |
| 14 | N | 3800 | 75 | 611 | 333 | 205 | 0.21 | 100% | 10% | 0% |
| 5 | B | 3800 | 75 | 584 | 289 | 169 | 0.18 | 70% | 0% | 5% |
| 23 | W | 3800 | 75 | 565 | 253 | 155 | 0.17 | 58% | 0% | 0% |

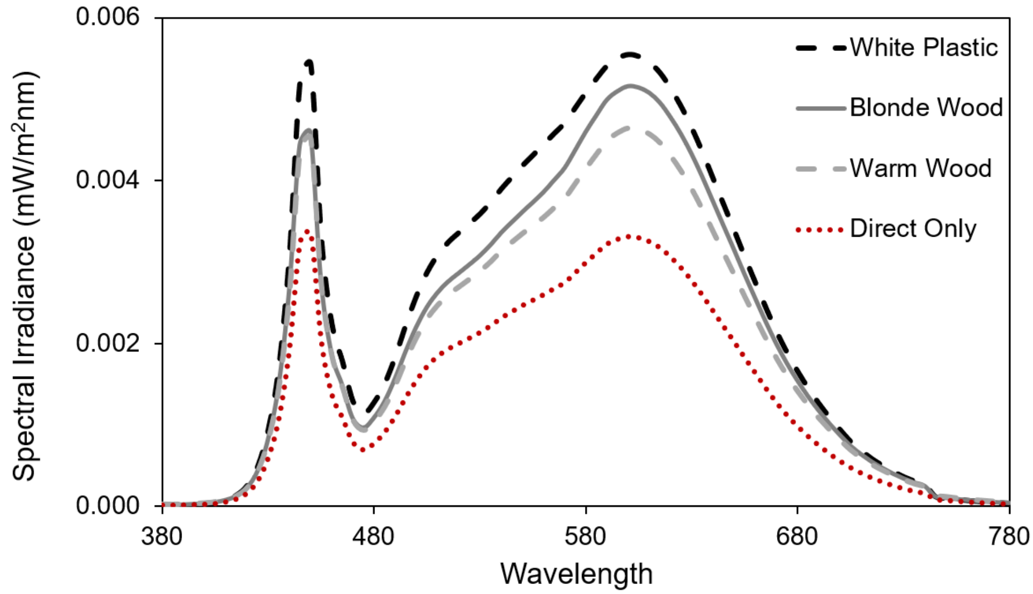



**Figure 7: Comparison of SPD at the eye with surface reflectance as the changing variable. SPDs reflected from white plastic, blonde wood, and warm wood are given at 3800 K and 75% lumen output. Also included is the SPD at the same location resulting from the direct contribution of the luminaires (no interreflection of light between room surfaces).**

ALFA provides the additional ability to vary the number of view directions for any desk. Increasing the view directions from one to four provides insight to how variability in desk arrangement, teaching location, or classroom focal point can influence circadian metric calculations within the same space. When the number of view directions was increased from one to four in the classroom model, to simulate the many possible ways the space could be used, the number of view positions meeting the recommendation decreased regardless of desk layout. Figure 8 illustrates the amount of light stimulus variation that can occur at two desk locations in the existing classroom layout. EML values were highest when the view direction was facing a luminaire nearby or directly overhead and lowest when the view direction was facing left or right between rows of luminaires. View positions facing the maroon cabinets (left) were noticeably lower than those facing the opposing white wall (right). Five of the eight illustrated view directions comply with the WELL Education Pilot recommendations, yet overall EML values ranged from 86 to 210 m-lux. The results demonstrate how circadian metrics can vary depending on what is in the observer's field of view. Though design recommendations discussed here use language suggesting any calculations be conducted assuming students face forward, this may not be realistic use of a classroom setting, and meeting recommendations with alternate seating arrangements or view positions is not guaranteed. If circadian synchronization is a design goal, it is advised to conduct analyses that reflect multiple realistic classroom or flexible open office use cases, regardless of building standards suggesting one primary view direction.

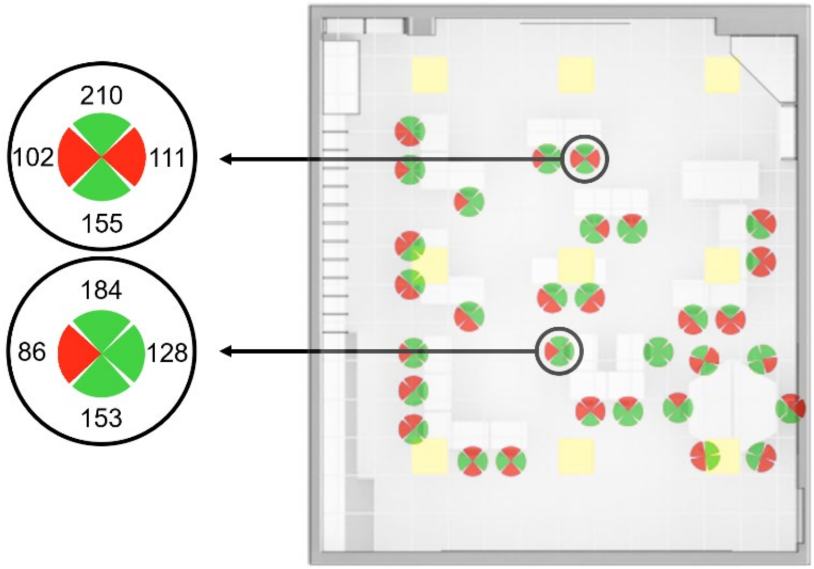



**Figure 8: Variation in EML values for two desk locations. Language in the WELL Education Pilot and CHPS Core Criteria 3.0 suggest measurement should be taken "facing forward." However, realistic use of a classroom is more flexible, and circadian metrics can vary significantly depending on what is in the occupant's field of view. For the two highlighted desk positions, EML values ranged from 86 m-lux when facing the maroon cabinets to 210 m-lux when facing forward. Each of the four view directions per seat is color coded, green = meets and red = does not meet, for WELL Education Pilot circadian lighting design recommendations of EML ≥ 125 m-lux.**

## 4.3 Additional Model Parameters

The variables considered for the investigation detailed in this report were limited in an effort to minimize the complexity of the simulation process. Future investigations could benefit from considering the potential effects of additional variables on the calculated circadian metrics and annual energy estimates. These variables include (but are not limited to):

- Space characteristics
- Daylight contributions
- Luminaire distribution, output, and CCT setpoints
- More complex existing or theoretical SPDs
- Luminaire depreciation and fluctuation factors
- Different calculation methods

# 5. Conclusion

The goal of this investigation was to evaluate potential energy impacts of circadian lighting design recommendations that are gaining attention in a variety of common applications such as offices and classrooms. Within the two applications considered, parameters like surface reflectance distribution and desk orientation were also evaluated to explore the magnitude of potential effects. Using results from 45 unique simulation conditions, it was estimated that energy use may increase between 10% and 100% because of increased luminaire light levels used to meet circadian lighting design recommendations listed in current building standards such as WELL v2 Q2 2019, UL Design Guideline 24480, and CHPS Core Criteria 3.0.

Results from further research may show more efficient ways to meet design recommendations through varied light distribution or optimized spectral characteristics or continue to express the energy penalties that these recommendations present in realistic settings. For example, researchers are working to understand the relationship between daytime and nighttime exposure levels and relative effect as energy savings might be realized in reducing nighttime light levels instead of substantially increasing daytime light levels. Until circadian design metrics and effective delivery of light stimulus have been thoroughly understood in realistic settings with recognizable health and well-being benefits, the trade-offs between meeting design recommendations mentioned here and satisfying energy efficiency goals cannot be fully expressed.

# 6. References


Bellia, L., A. Pedace and F. Fragliasso (2017). "Indoor lighting quality: Effects of different wall colours." *Lighting Research & Technology* 49: 33-48.

Bellia, L., A. Pedace and G. Barbato (2014). "Indoor artificial lighting: Prediction of the circadian effects of different spectral power distributions." *Lighting Research & Technology* 46(6): 650-660.

Cai, W. J., J. G. Yue, Q. Dai, L. X. Hao, Y. Lin, W. Shi, Y. Y. Huang and M. C. Wei (2018). "The impact of room surface reflectance on corneal illuminance and rule-of-thumb equations for circadian lighting design." *Building and Environment* 141: 288-297.

CHPS - Collaborative for High Performance Schools (2019). Core Criteria. https://chps.net/chps-criteria.

CIE. 2018. S 026/E:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light. e. Vienna, Austria: Commision Internationale de L'Eclairage. doi: 10.25039/S026.2018.

Dai, Q., W. Cai, L. Hao, W. Shi and Z. Wang (2018). "Spectral optimisation and a novel lighting-design space based on circadian stimulus." *Lighting Research & Technology* 50(8): 1198-1211.

Davis, R.G. and A. Wilkerson (2017). *Tuning the Light in Classrooms: Evaluating Trial LED Lighting Systems in Three Classrooms at the Carrollton-Farmers Branch Independent School District in Carrollton, TX*. PNNL-26812, Pacific Northwest National Laboratory, Richland, WA.

Dilaura, D., K. Houser, R. Mistrick and G. Stetty (2011). *The Lighting Handbook Reference and Application. 10th ed*. The Illuminating Engineering Society, New York, NY.

Figueiro, M., B. Steverson, J. Heerwagen, K. Kampschroer, C. Hunter, K. Gonzales, B. Plitnick and M. Rea (2017). "The impact of daytime light exposures on sleep and mood in office workers." *Sleep Health* 3.

Fitwel (2020). Fitwel v2.1 Scorecard for Workplace. https://www.fitwel.org/resources.

IWBI – International Well Building Institute (2019). WELL v2™ pilot. https://v2.wellcertified.com/v/en/overview.

Jarboe, C., Snyder, J. and Figueiro, M. (2019) 'The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use', *Lighting Research & Technology*. doi: 10.1177/1477153519834604.

Konis, K. (2018). "Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities." *Building and Environment* 135: 112-123.

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

Mardaljevic, J., M. Andersen, N. Roy and J. Christoffersen (2014). "A framework for predicting the non-visual effects of daylight - Part 2: The simulation model." *Lighting Research & Technology* 46: 388-406.

Rea, M. S. and M. G. Figueiro (2018). "Light as a circadian stimulus for architectural lighting." *Lighting Research & Technology* 50(4): 497-510.

Safranek, S.F., R. G. Davis, and A. C. Irvin (2018). *Evaluating Tunable Lighting in Classrooms: Trial LED lighting systems in three classrooms in the Folsom Cordova Unified School District*. PNNL-27806, Pacific Northwest National Laboratory, Richland, WA.

UL (2019). DG 24480. *Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People. Edition 1*. Northbrook, IL.

USGBC – U.S. Green Building Council (2019). LEED v4 for Building Design and Construction. https://www.usgbc.org/.

# Appendix A

**Table A.1: Summary of office simulation results. The model parameters include desk surface (B = blonde wood, N = neutral white plastic, W = warm wood), CCT, and lumen output of luminaires. Calculated average horizontal illuminance ($E_h$,) at the desk work plane and vertical illuminance ($E_v$), EML, and CS values are listed for 40 view positions. The percent of seated view positions meeting the EML and CS recommendations determine points allotted for the Circadian Lighting Design feature. The simulation results for the baseline model are shown in bold text. No simulation results meet any recommendations at the baseline energy consumption.**

| Model Parameters | | | | Average Illuminance | | Circadian Metric Averages | | Percent of View Positions Meets WELL v2 Yes or No | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cond. | Desk Surface | CCT (K) | Lumen Output (%) | $E_h$ (lx) | $E_v$ (lx) | EML (m-lux) | CS | EML ≥ 150 m-lux 1 pt | EML ≥ 240 m-lux 3 pt | CS ≥ 0.3 1 pt |
| 1 | B | 6200 | 100 | 773 | 369 | 305 | 0.36 | 100% | 98% | 100% |
| 2 | B | 6200 | 75 | 579 | 282 | 232 | 0.30 | 100% | 48% | 55% |
| 3 | B | 6200 | 50 | 387 | 186 | 153 | 0.23 | 53% | 0% | 0% |
| 4 | B | 3800 | 100 | 780 | 378 | 223 | 0.20 | 100% | 30% | 0% |
| 5 | B | 3800 | 75 | 584 | 289 | 169 | 0.18 | 70% | 0% | 5% |
| **6** | **B** | **3800** | **50** | **389** | **191** | **112** | **0.12** | **0%** | **0%** | **0%** |
| 7 | B | 2700 | 100 | 785 | 386 | 150 | 0.30 | 53% | 0% | 53% |
| 8 | B | 2700 | 75 | 586 | 286 | 112 | 0.24 | 0% | 0% | 0% |
| 9 | B | 2700 | 50 | 390 | 191 | 74 | 0.18 | 0% | 0% | 0% |
| 10 | N | 6200 | 100 | 812 | 448 | 382 | 0.40 | 100% | 100% | 100% |
| 11 | N | 6200 | 75 | 609 | 335 | 286 | 0.35 | 100% | 93% | 98% |
| 12 | N | 6200 | 50 | 405 | 224 | 191 | 0.27 | 95% | 0% | 5% |
| 13 | N | 3800 | 100 | 817 | 449 | 276 | 0.26 | 100% | 90% | 3% |
| 14 | N | 3800 | 75 | 611 | 333 | 205 | 0.21 | 100% | 10% | 0% |
| 15 | N | 3800 | 50 | 409 | 221 | 136 | 0.15 | 23% | 0% | 0% |
| 16 | N | 2700 | 100 | 818 | 444 | 181 | 0.33 | 95% | 0% | 93% |
| 17 | N | 2700 | 75 | 614 | 335 | 136 | 0.28 | 25% | 0% | 18% |
| 18 | N | 2700 | 50 | 408 | 226 | 92 | 0.21 | 0% | 0% | 0% |
| 19 | W | 6200 | 100 | 751 | 331 | 284 | 0.35 | 100% | 93% | 98% |
| 20 | W | 6200 | 75 | 564 | 248 | 212 | 0.29 | 100% | 15% | 50% |
| 21 | W | 6200 | 50 | 375 | 166 | 142 | 0.22 | 40% | 0% | 0% |
| 22 | W | 3800 | 100 | 752 | 331 | 202 | 0.21 | 100% | 10% | 0% |
| 23 | W | 3800 | 75 | 565 | 253 | 155 | 0.17 | 58% | 0% | 0% |
| 24 | W | 3800 | 50 | 377 | 168 | 103 | 0.12 | 0% | 0% | 0% |
| 25 | W | 2700 | 100 | 750 | 336 | 136 | 0.28 | 28% | 0% | 28% |
| 26 | W | 2700 | 75 | 565 | 254 | 102 | 0.24 | 0% | 0% | 0% |
| 27 | W | 2700 | 50 | 376 | 172 | 69 | 0.18 | 0% | 0% | 0% |

**Table A.2: Summary of classroom simulation results. The model parameters describe the desk layout options (E = existing, T = traditional), CCT, and lumen output of luminaires. Calculated average horizontal ($E_h$) and vertical illuminance ($E_v$) values are shown. Average EML and CS values are calculated for 31 view positions. The view positions are evaluated using the specific EML and CS requirements to determine whether the space receives credit for the WELL Education Pilot Circadian Lighting Design feature or the CHPS Core Criteria 3.0. UL Design Guideline 24480 does not have recommendations for classrooms. The simulation results for the baseline model are shown in bold text.**

| Model Parameters | | | | Average Illuminance | | Circadian Metric Averages | | Percent of View Positions: WELL (Yes or No) | Percent of View Positions: CHPS Core 3.0 (Yes or No) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cond. | Desk Layout | CCT (K) | Lumen Output (%) | $E_h$ (lx) | $E_v$ (lx) | EML (m-lux) | CS | EML ≥ 125 m-lux 1 pt | EML ≥ 250 m-lux 1 pt | CS ≥ 0.3 1 pt |
| 1 | E | 6200 | 100 | 585 | 341 | 288 | 0.34 | 100% | 61% | 74% |
| 2 | E | 6200 | 85 | 498 | 292 | 247 | 0.31 | 100% | 42% | 52% |
| 3 | E | 6200 | 70 | 411 | 239 | 202 | 0.28 | 100% | 19% | 39% |
| 4 | E | 3800 | 100 | 589 | 350 | 211 | 0.21 | 100% | 29% | 0% |
| 5 | E | 3800 | 85 | 501 | 294 | 177 | 0.18 | 90% | 3% | 0% |
| **6** | **E** | **3800** | **70** | **412** | **245** | **148** | **0.16** | **65%** | **0%** | **0%** |
| 7 | E | 2700 | 100 | 591 | 351 | 141 | 0.28 | 61% | 0% | 39% |
| 8 | E | 2700 | 85 | 504 | 296 | 118 | 0.25 | 42% | 0% | 13% |
| 9 | E | 2700 | 70 | 416 | 246 | 98 | 0.22 | 16% | 0% | 0% |
| 10 | T | 6200 | 100 | 608 | 311 | 264 | 0.33 | 100% | 52% | 74% |
| 11 | T | 6200 | 85 | 518 | 272 | 231 | 0.30 | 100% | 45% | 52% |
| 12 | T | 6200 | 70 | 426 | 222 | 190 | 0.27 | 84% | 19% | 29% |
| 13 | T | 3800 | 100 | 613 | 319 | 194 | 0.20 | 90% | 16% | 0% |
| 14 | T | 3800 | 85 | 521 | 268 | 163 | 0.18 | 81% | 0% | 0% |
| 15 | T | 3800 | 70 | 429 | 225 | 136 | 0.15 | 52% | 0% | 0% |
| 16 | T | 2700 | 100 | 617 | 322 | 129 | 0.27 | 52% | 0% | 29% |
| 17 | T | 2700 | 85 | 523 | 272 | 109 | 0.24 | 32% | 0% | 6% |
| 18 | T | 2700 | 70 | 429 | 228 | 92 | 0.21 | 10% | 0% | 0% |