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Outcome-Based Design for Circadian Lighting: An Integrated Approach to Simulation & Metrics

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ABSTRACT

Lighting practitioners are increasingly asked to quantify melanopic illuminance for phase shift and melatonin suppression at an hourly time scale for compliance with the WELL building Standard. This paper illustrates a workflow to achieve Equivalent Melanopic Lux (EML) goals based on the spectral qualities of daylight and electric light sources in the highly variable context of office design. The impacts of climate, view, color temperature, wall color, and orientation are considered.

INTRODUCTION

A daily rhythm of blue-rich irradiance in the morning hours followed by blue-deficient irradiance in the evening hours is correlated with natural circadian rhythms, improved sleep and overall health (Figueiro, Brainard, Lockley, 2008). The WELL Building Standard, known as the WELL, is one of the first human health design standards to codify a daily minimum threshold of 200 melanopic lux between 0900–1300 to entrain occupant circadian rhythms (International WELL Building Institute, 2017). Successful outcomes in design practice requires simulation of vertical illuminance from all sources of light, including electric, daylight and reflected light incident at the eye of the viewer, and consideration of the spectrum of each source, energy code, glare and cost. In WELL projects, circadian light systems are spot checked after occupancy in the field with spectrometer measurements taken at any desk at an unknown time of year. Therefore, designers must account for spectral power distributions (SPD) for glazing, materials, daylight, and electric sources, as well as accounting of the variable illuminance from daylight, daylight dimming, and shade deployment.

Simulation of vertical illuminance is accomplished with physically based rendering via Radiance (Ward, 1994) and Daysim (Reinhart, 2001), while post-processing for EML is conducted with Excel using melanopic ratios calculated with the WELL calculator (WELL, 2018). Additional luminance validation is provided via LARK Spectral Lighting (Inanici, Brennan, Clark, 2015).

This paper uses such parameters and metrics to build a composite understanding of predicted, hourly circadian light in an office space. Three climate zones based upon daylight availability are simulated. Two sets of SPDs are used for indoor and outdoor lighting that can be grouped into 4000K and 6500K (Fig. 1). To balance lighting power density goals with circadian lighting targets, this paper investigates task lighting solutions to fill in the circadian light deficit for hours that fall short of the goal. This process enables design validation for visual and non-visual light coupled with energy performance for energy code and WELL compliance.

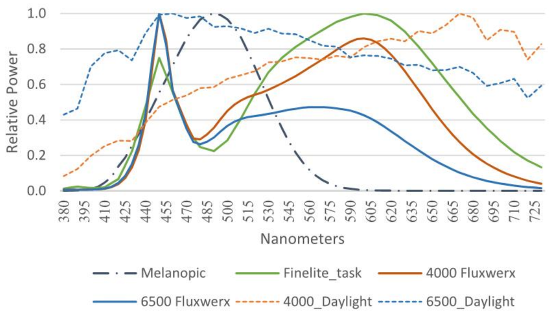

Fig. 1 Melanopic action spectrum & SPDs

Metrics

The WELL standard uses EML which is derived from the spectral action curve of the photopigment melanopsin, as the metric for circadian lighting. Calculating melanopic lux is a matter of multiplying the spectral power distribution of a light source by the melanopsin action curve which is normalized whereby 1 melanopic lux is equivalent to 1 photopic lux at 555nm (Enezi and others, 2011). The "Irradiance toolbox" allows a user to enter a source SPD along with the photopic illuminance normal to the eye to derive melanopic lux (Lucas and others, 2014). The WELL Melanopopic Ratio excel calculator allows the user to input an SPD to derive a melanopic ratio which can be multiplied by photopic illuminance for EML. The WELL prescribes 200 EML, equivalent to 6500K daylight at 182 lux (Fig. 2), as the threshold target. This can be derived using the melanopic ratio (MR) method or directly in the "Irradiance Toolbox". Lighting practitioners often employ the Circadian Stimulus (CS) metric developed at the Lighting Research Center (LRC) and derived from the interaction of rods, cones and retinal ganglion cells (Rea and others, 2005). Using the CS calculator, downloaded from the LRC website, a 6500K SPD for daylight at 182 lux translates to a CS of 0.3. This value causes circadian shift on a scale that ranges from 0.1 (threshold) to 0.7 (saturation). Though all light spectra have not been tested for melanopic stimulus (Enzei, 2011), higher MR can be expected from higher CCT light sources (Fig. 2).

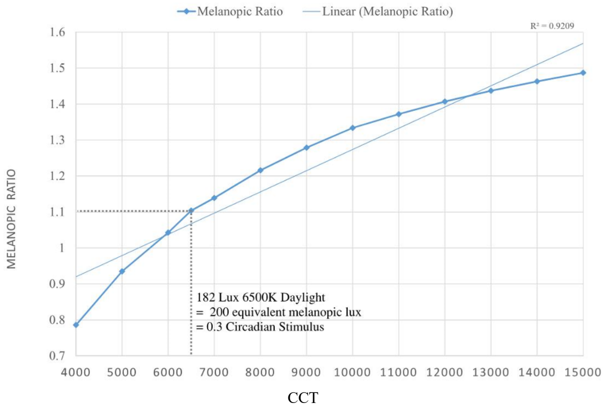

Fig. 2 Melanopic Ratio vs Daylight CCT
Sky spectra generated from the Munsell Color Science Laboratory Daylight Series Calculator, 2002

Previous Studies

Previous circadian light simulation studies for lighting practice have taken several approaches: (1.) point-in-time, multi-channel spectral simulation using Radiance (Geisler-Moroder, Krzysztof, Inanici); (2.) annual analysis with Daysim that is post-processed with SPD modifiers (Pechacek, Anderson, Mardaljevic); and (3.) point-in-time calculation of EML or CS using illuminance and spectral source data (Enzei, Lucas, Rea). The first approach has the benefit of accurate hourly analysis that accounts for full spectral interactivity, but is limited by known spectral sky data and extensive computing time based on channel count. The second is fast and allows for three sky spectrums (D65, D55, and D75) based on climate data and glazing optics. However, it assumes a neutral material palette for interior finishes that do not alter light source spectral reflectance. The third is similar to the second using illuminance data that is weighted by known spectral modifiers, but is typically applied solely to electric lighting scenarios.

Study Goals

This study aims to meet circadian light thresholds prescribed in the WELL within the constraints of current practice and after meeting the prerequisites of energy code and visual comfort objectives. There are several variables that drive the study: (1.) light sources, (2.) source spectrum, and (3.) views. The first of these looks to synthetically build up a composite EML from all the light sources found in an office. This breaks down into four areas: daylight, electric overhead lighting, devices (monitor) and task lighting. The second considers the impact of different spectral power distributions. The WELL standard assumes skies are D65 with a MR of 1.1 but, in reality, sky CCT is variable with values ranging from less than 4000K to more than 15000K (Hernandez-Andres, 2001). CCT measurements taken out the window of several offices found a consistent range of 4000K to 7000K (Bellia and others). To demonstrate relative impact of CCT on EML, a 4000K and 6500K sky was calculated using the Munsell Color Science Laboratory Daylight Series excel tool. For electric lighting, the typical 4000K office lamp was compared to a 6500K tunable source. Spectral data was provided by manufacturers (Fig. 1). The third variable considers the diversity of views in an office between 24 desk locations varied by three different furniture arrangements and four different orientations, which makes for 288 different views. The impact of color in the interior environment is considered in a separate experiment.

This study introduces a hybrid of workflows from previous studies using annual Daysim simulation for daylight with point-in-time Radiance for electic lighting that are modified by their respective melanopic ratios. Additional three-channel analysis for luminance images is tested.

SIMULATION EXPERIMENT

The Setting

The study tests an office floorplate 34.5' wide by 63' long with a ceiling and window head height of 9'-0" and single side of daylight with 56% window-wall ratio (Fig 3). Seattle's energy code mandates a lighting power density threshold of .59 for offices and daylight responsive controls for two interior sidelight zones (Seattle DCI, 2018).

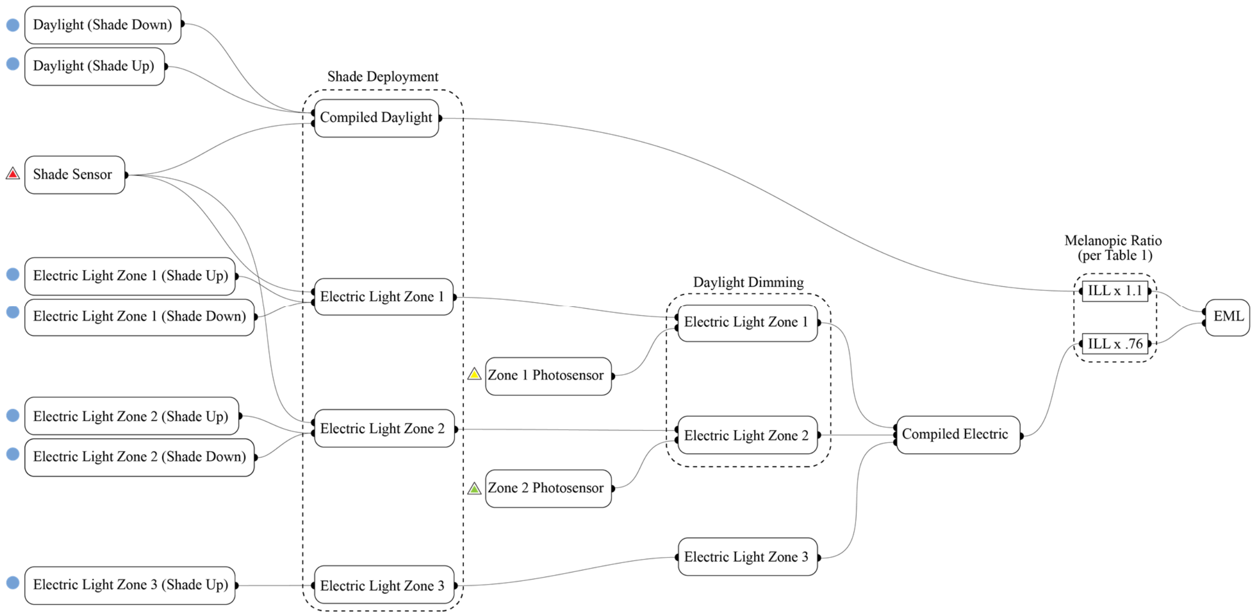

Fig. 3 Simulation Workflow

The lighting layout used for simulation achieves an average of 300 horizontal lux on the task plane with a lighting power density of .32. The two daylight zones are separately controlled by zone sensors with a ramp function that continuously dims electric lighting output between 0% for no daylight contribution and 80% for values => 500 lux (Fig. 3 & 4).

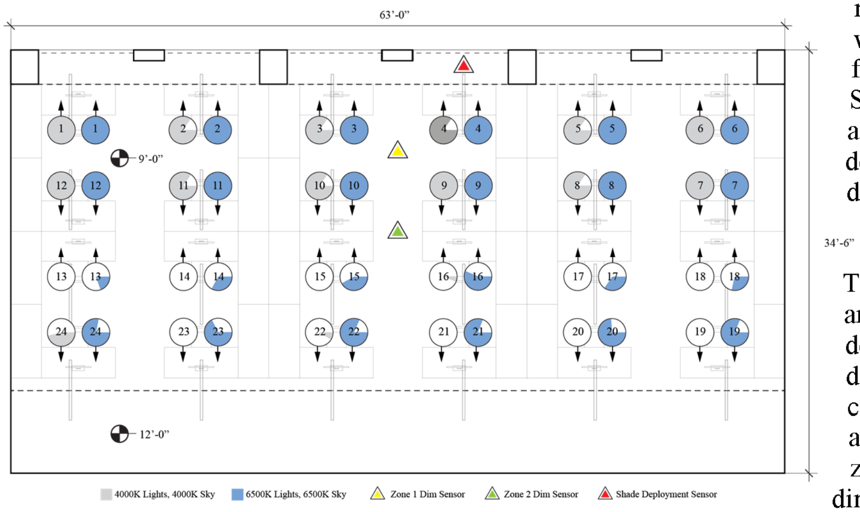

Fig. 4 EML_200 0900-1300 (Denver, 0, N)

Visual comfort is attained by deploying a 3% open factor shade cloth for vertical illuminance greater than 5000 lux incident on the interior of the façade. Material reflectance properties for all runs were 80:50:50:20 for ceiling, walls, furniture, and floor, respectively. Spectral data for sources and associated melanopic ratio is detailed in Table 1. Figure 3 describes the baseline office zone geometry, fenestration, lighting layout, and sensor placement. There are three variations in furniture arrangement: from 0, 90, and 120 degrees based on view orientation to daylight (Fig. 4, 9 & 10). Each case contains 24 desks, each of which has a vertical sensor at 54" AFF. The zone was arrayed to the four cardinal directions to test results from the north, east, south, and west. Three climates were chosen to simulate based on different annual global horizontal radiation (kWh/m2): Seattle (41,800), Chicago (51,900), and Denver (61,600). The *Profile* linear downlight from Fluxwerx was choosen for overhead lighting (Fluxwerx, 2018) . The *Curve* by Finelite was used for task lighting (Finelite, 2018). Both IES photometric files and SPDs for these sources were either provided by the manufacturer or dowloaded online. The monitor was modeled as a spectrally neutral 250cd/m2 glow source.

Table 1 Radiance Channel (Nanometers) and Melanopic Ratio (MR)

SOURCE	586-780	498-586	380-498	MR
Glazing	0.386	0.454	0.493	NA
Fluxwerx 4000k	0.833	1.153	0.384	0.718
Fluxwerx 6500k	0.405	1.278	0.788	0.976
Daylight 4000k	0.838	0.714	0.375	0.786
Daylight 6500k	0.641	0.872	0.823	1.104
Finelite	NA	NA	NA	0.564
Blue Wall	0.481	0.5162	0.515	NA
Green Wall	0.471	0.582	0.149	NA
Yellow Wall	0.630	0.518	0.083	NA

Simulation Results

An initial simulation established a baseline electric lighting layout that was used for all post-processing in all scenarios. The next step was to measure the percentage of annual hours for which each of the points reached the EML threshold of 200 lux. This annual method was proposed by Anderson and Mardalijevic in 2014 and visualized with a "Sombrero plot" for multiple view directions and hourly durations. In this case, one view (towards the monitor) and time slot (0900-1300) is considered for each occupant. A pair of pie charts located at each desk illustrates annual EML 200 based on both daylight and electric lighting for 4000K and 6500K CCT (Fig. 4). Slices of the pie express the percentage of the 1044 hours meeting EML_200. The front two rows of the room mostly meet the goal, while the back two fall short. However, this metric does not give a sense of the margin of failure which in some cases is 20 to 30 EML out of 200. Various strategies to address this challenge are discussed later.

Anderson and Mardalijevic also suggested averaging "circadian potential" of an entire zone to see performance trends (2014). Figure 5 presents one such example, in which the annual data for all 24 points per zone are averaged for all test cases. This was averaged for an all-4000K light source option and a 6500K option. The north and west orientations outperform east and west, as shades are not deployed as often in the morning. The 90-degree furniture layout performs best, followed by 120-degree and then 0-degree. There is a modest advantage to the sunnier climates in the 120- degree and 90-degree layouts. Overall, most spaces are failing during more than half the hours tested with 4000K light.

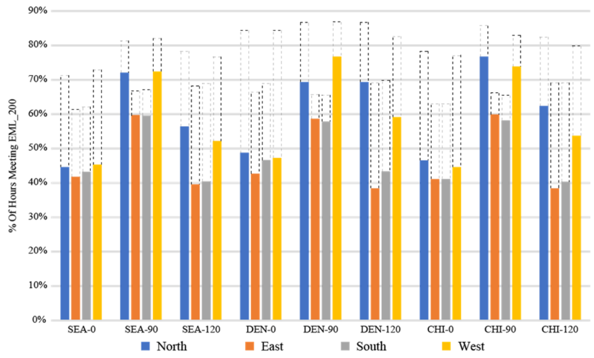

Fig. 5 Average Zone EML_200_0900-1300 4000K Sky + 4000K Light vs 6500K

Increasing the sky and electric lighting CCT to 6500K increases the "passing" hours dramatically (dotted lines in Fig. 5). However, increasing CCT alone does not reach annual EML_200. This metric is useful for annual trends, but gives no indication of the sensitivity of a zone to meeting EML_200.

Taking a closer look at an interior Denver point #17 at an hourly resolution across the first week of the year, we can examine each light source contribution (Fig. 6). In this case, all sources are set at 4000K except the monitor, which was assumed to be 6500K. Nearly three-quarters of the EML_200 target comes from overhead light, with minimal contribution from daylight. The final quarter of EML_200 is nearly satisfied by the monitor light, assuming 100% brightness. Seven of the 20 hours require some task light to fully comply with this target.

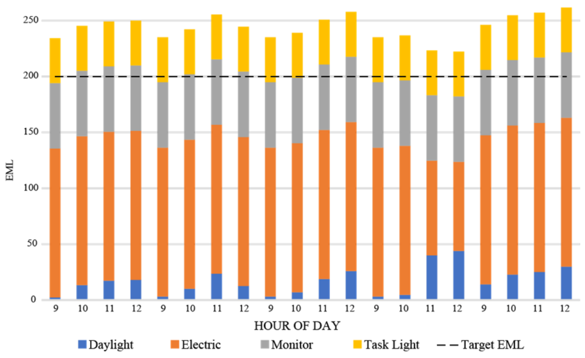

Fig. 6 Hourly EML_200 (Denver, 0, South, Point 17) 4000K: Sky/ Light/ Task + 6500K Monitor

Meanwhile, analysis at a perimeter Chicago point #4, looking straight out a north-facing window tells a different story in which daylight meets the goal for half of the hours in the week with overhead lighting filling the gap to EML_200 (fig. 7).

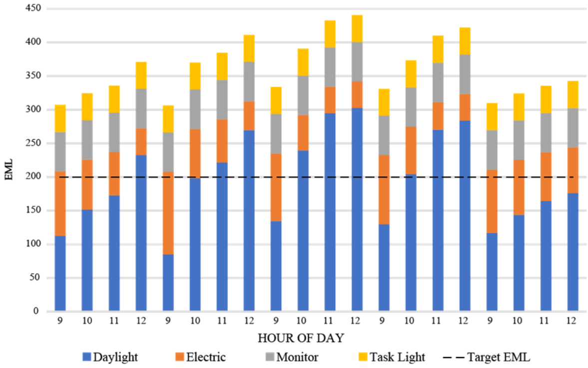

Fig. 7 Hourly EML_200 (Chicago, 0, North, Point 4) 4000K: Sky/ Light / Task + 6500K Monitor

For the interior locations such as point #17 in Denver, task lighting may be required for up to half of the hours to fill a 20-EML deficit. Assuming 8 watts per task light, Figure 8 shows predicted annual kWh consumption for each test case. 4000K (worst case) and 6500K (best case) options are compared such that 6500K is a baseline energy usage. 6500K monitor light is assumed to contribute to EML, but not added to the power load. Figure 9 is calculated by adding each point in a zone that fails to meet the threshold annually and multiplying by the source wattage. Switching to 6500K light sources cuts energy use nearly in half. Interestingly, the 0-degree option furniture layout does not require task lights with 6500K lighting and monitor light. This shows that many scenarios can be very close to meeting EML_200, but the sensitivity is difficult to discern from annual metrics alone. Furthermore, trends can be deceiving as the annual metric in Figure 6 shows the 0-degree layout as less performative compared to 90-degree and 120-degree layouts with the exception of some 120-degree east and south orientations that have shades deployed. Even though half of the seats look away from the window, the lighting layout happens to be optimized for electric lighting view. This was not intentional but rather the product of an efficent lighting scheme and furniture layout. The lighting layout is a difficult variable to control for as, in practice, lighting and furniture solutions are not always optimized together. This study aimed to overcome this by testing a diversity of arrangements with a range of lighting to view relationships.

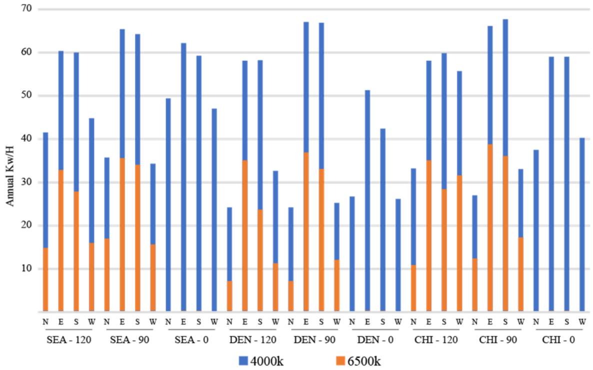

Fig. 8 Annual kWh from 4000K Task Lighting (4000K vs 6500K Lighting + Sky) + 6500K Monitor

Figures 9 and 10 show EML_200 0900-1300 in Denver North for the 90 and 120 furniture layouts at 6500K sky and lighting. Figure 5 shows both of these options are nearly equal in overall performance but here one can see the variation based on view to lights, windows and walls.

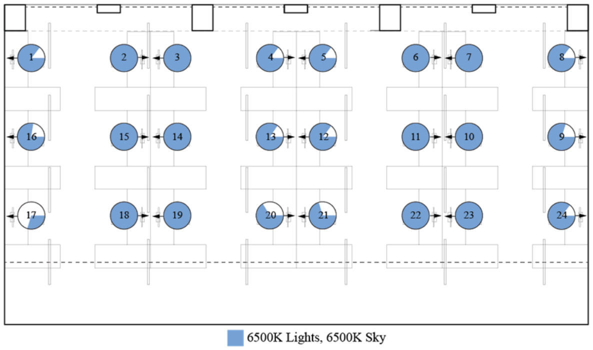

Fig.9 EML_200 0900-1300 (Denver, 90, N)

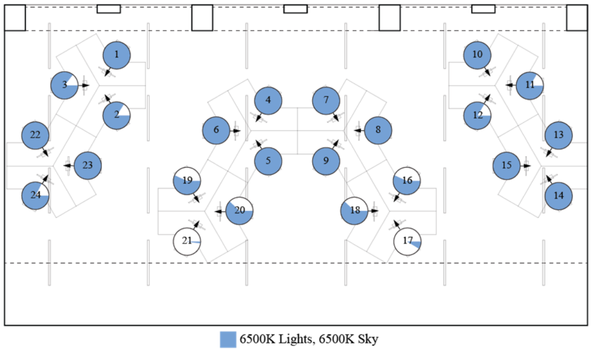

Fig.10 EML_200 0900-1300 (Denver, 120, N)

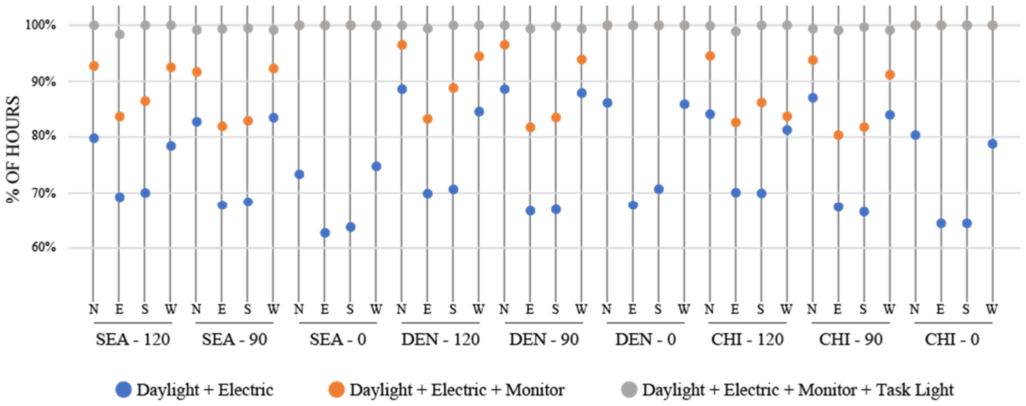

Fig.11_Average Zone EML_200 0900-1300 6500K Sky, Light, Monitor + 4000K Task

Figure 11 shows the cumulative contribution of each source to meeting the zonal average EML_200 0900-1300 for all scenarios. This assumes 6500K light from skies, overhead lighting and monitors, coupled with 4000K task lighting. As was shown in Figure 8, the 0-degree option satisfies EML_200 without task lighting for each city tested. Adding task lighting for all other scenarios nearly achieves 100% "passing" in all cases. This does make the unlikely assumption that the sky CCT does not dip below 6500K and there is color tunable controls for overhead lighting and monitors. Many tunable circadian systems increase light intensity as well as CCT during the day to meet ciradian light targets. As this study aimed to meet energy code, lighting output only dims down with daylight and never exceeds the design target.

Wall Color

The impact to EML from 6500K electric light reflecting from interior walls painted neutral grey, light blue, green and yellow was tested for all 24 views in the 90 furniture layout (Fig. 12) . The reflectances are 51, 50.7, 52.5, 52 percent respectivelly. Radiance definitions for the wall colors in table 1 were dowloaded from the Design for Climate and Comfort Lab. A 6500K fluxwerx Radiance definition was created from the data in table 1 such that an equal amount of lumens emits compared to a neutral source. The irradiance values from a five bounce Radiance simulation were post processed with LARK Spectral Lighting plugin for EML. Figure 12 plots the increase or decrease in EML from the neutral grey (0) with light blue nearly the same followed by modest decreases from green and yellow. Views in furniture layout 90 directed at the wall (1,8,9,16,17,24) showed up to 25% reduction in EML between light blue and yellow, whereas typical views in the open office lost 1-4%.

Circadian Luminance

The impact to EML from variations in 4000K and 6500K fluxwerx light sources in a scene was simulated for illuminance and luminance. Similar to the wall color study, the SPDs in table 1 were used to generate Radiance lights and post-processed with LARK. The baseline assumes 4000K sky and overhead lighting. The monitor spectrum was not altered.

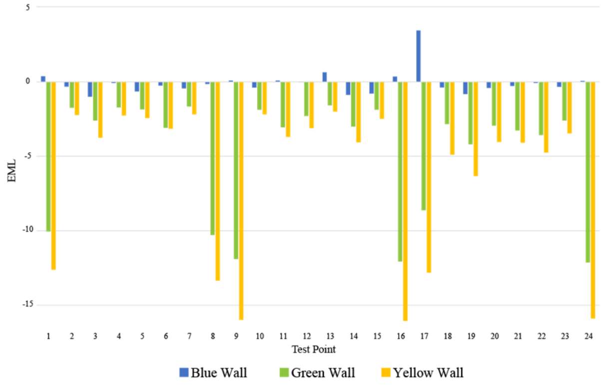

Fig.12 EML Comparison by Wall Color 6500K Light Furniture Layout 90

Figure 13 shows the relative increase of EML with higher CCT while the photopic illuminance remains constant. Figure 14 shows the same series as melanopic luminance falsecolor images. Each iteration was subtracted from the 4000K baseline using pcomb in Radiance. The second image isolates the contribution of the fluxwerx light source; the third isolates the sky; and the fourth shows the combination. The sky occupies a much larger view angle and therefore reflects more from interior surfaces. The combination of both sources has the greatest impact, and surface interaction begins to play a larger role.

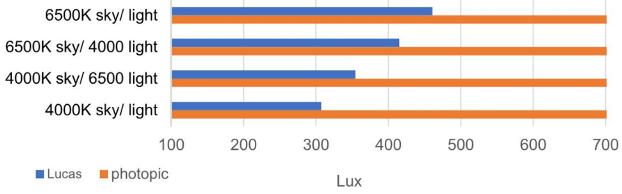

Fig. 13 EML & Photopic Lux based on CCT: Chicago, Jan 1, 10am, overcast, north zone, 0, seat 4

CONCLUSION

To achieve an annual EML_200 lighting design requires evaluation of all occupant views, orientation, light sources, a variation of source SPDs and the color and reflectance of the surrounding environment. View to light sources is the largest driver as was shown in layout 0, which inadvertently optimized desk orientation to overhead lighting. Views to daylight can be significant if there is proximity and the shades are up. Sunny climates like Denver can expect shades down in the east and south during the morning. Therefore, exterior daylight controls are advised to reduce heat gain and glare without deploying shading devices. Depending on brightness and CCT, computer monitors can deliver 25% of EML_200. It is likely that task lighting, which the WELL Standard recognizes as a pathway to compliance, will be required for many interior desk locations to consistently reach EML_200. Task lights are bit of a wildcard as they can deliver another 20% + but there is no guarantee of timely and efficacious use for non-visual requirements. Education, coupled with sensors that measure and communicate circadian lighting data to users, could be a solution.

It has been shown that there is a significant jump in EML from higher CCT sources (4000K to 6500K), both electric and daylight. One should not assume D65 daylight at an hourly resolution based on the dynamic effects of surrounding context, weather, and pollution. The workflow presented allows the designer to post process different assumptions for custom scenarios. As for electric lighting, 3500K – 4100K is typically specified in office design. However, the market is responding with high CRI, tunable sources that achieve 6500K with no energy penalty. It has been shown that energy can be saved with higher CCT sources by reducing task light hours. Monitors controlled by circadian color tuning software can close the gap further with guaranteed brightness levels and 6500K CCT during morning hours. Tunable task lighting would be another option for challenged locations.

This study is an attempt to integrate annual daylight analysis and point-in-time Radiance electric lighting simulation with melanopic ratio post processing. Further studies with multi-channel simulation evaluated the impact of wall color. It is by no means exhaustive and there are variations to explore to improve accounting of spectral interaction in the interiors. Overall, the findings point towards designs that maximize daylight, use high CCT sources in the morning and carefully orient the field of view to light sources. Where orientation is challenging, understanding the lighting contribution from monitors and task lights can prove to be highly beneficial.

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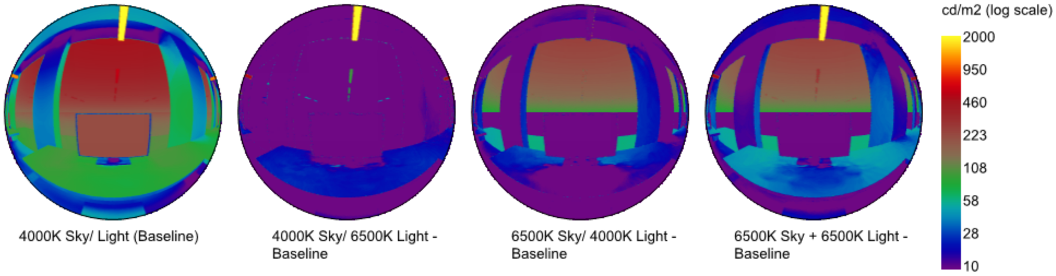

4000K Sky/ Light (Baseline)

4000K Sky/ 6500K Light - Baseline

6500K Sky/ 4000K Light - Baseline

6500K Sky + 6500K Light - Baseline

Fig. 14 Melanopic luminance based on CCT

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