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Measuring Light Exposure and its Effects on Sleep and Behavior in Care Center Residents

ACC Care Center – Sacramento, CA

November 2019

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Prepared in support of the U.S. Department of Energy's Building Technologies Office, Lighting R&D Program.

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Executive Summary

Nursing-care centers encounter daily instances of dementia behaviors and sleep issues among their residents. These instances affect not only the residents, but also care staff and families. This study examined tunable lighting implemented in a 99-bed nursing center in Sacramento, CA, with a large population of dementia patients. The objective was to test a strategy for measuring and documenting light exposure for typical residents, and to evaluate the collected data in terms of multiple metrics for human circadian responses over the course of a day. Research on effects and documentation of circadian light exposures is still in its infancy. Protocols for collecting these data are needed. Light-exposure measures used in the study included circadian stimulus (CS), melanopic/photopic (M/P) ratios of the light received at the eye of the resident, and equivalent melanopic lux (EML). Behavioral measures were also captured, including severity of sleep disturbances among all residents, and frequency of agitated behaviors among residents with dementia.

The positive effects of spectrally tunable and light-output-selectable LED lighting on sleep and dementia-related outcomes among residents have been postulated (Hanford and Figueiro 2013, van Someren et al. 1999). Research suggests that lighting color and pattern of intensity that mimic natural daylight over the course of the day can improve circadian rhythm entrainment and health outcomes. Compared to typical indoor lighting, natural daylight is much brighter during the day and is, of course, absent at night. However, while there have been several studies focusing on programmable, tunable LED lighting – including some in nursing centers specifically –most had significant methodological limitations, did not use current lighting technology, or did not report enough detail about light and spectral exposure to be comparable to models of circadian health.

This study involved a partnership between experts in lighting design, environmental design, and light measurement; experts in measuring resident behavioral outcomes in nursing centers; and leaders from a nursing center with previously installed programmable, tunable LED lighting. Nursing-center leaders were interested in evaluating the impact of the lighting and were willing to allow their long-term care corridors to feature settings that mimicked the facility’s former fluorescent lighting (static lighting) or that were programmed to change in spectrum and intensity (tuned lighting).

Figure 1. Three test corridors at the ACC Care Center, showing three of the programmed settings for the tunable lighting.

Figure 1 depicts various settings of the tunable lighting. The left photo shows the nighttime lighting mode, with overhead LED lights delivering 2700 K (warm) ambient light, dimmed to 21% output. The spectrum is designed to minimize blue-cyan energy. The right photo shows the daytime setting of 100% output at 6500 K (cool), designed to maximize energy emitted in the blue-cyan range. The center illustrates a transition period between the two, at 4100 K and 100% output. The center photo also illustrates the static lighting condition, tuned to the LED 4100 K spectrum at full output to visually simulate the previous non-dimmable T8 fluorescent lighting during the day. The lights would be dimmed to 50% output at night to simulate the staff's practice of switching off half the corridor fluorescent luminaires at night.

In order to simulate the light exposure of the typical wheelchair-bound resident over the course of a day, we collected spectral measurements in the plane of the eye at a 42" height in spaces where the residents spend time. This was performed for a baseline setting and for each of the tested settings of light level and color temperature. We also collected data in the rooms of sleeping residents who had provided informed consent.

Findings

The team hypothesized that residents were more likely to be affected by the nighttime tuned lighting than by the daytime tuned lighting, because the tunable lighting system was effective at dropping light levels and the blue-cyan content of the lights in corridors at night. Almost all resident rooms were open to the corridor at night so that staff could observe residents and provide help when needed, so corridor light straying into sleeping areas was likely to be a factor in sleep quality. Sleep was therefore our primary study focus. The results show that residents experienced fewer nighttime sleep disturbances on average when their corridors were assigned to the tuned and dimmed lighting.

Table 1. Resident sleep disturbances and agitation outcomes.

	Static Lighting (Control Condition)	Tuned Lighting (Treatment Condition)
	Mean (Standard Deviation)	Mean (Standard Deviation)
Sleep Disturbances* (higher scores = worse sleep)	3.6 (7.2)	1.8 (3.8)‡
Agitated Behaviors† (higher scores = more agitation)	36.9 (9.2)	36.2 (7.7)

*Sleep disturbances were measured for all residents in three study corridors (n=63)
†Agitated behaviors were measured in three study corridors for residents who had a dementia diagnosis (n=35)
‡p<.10

Other findings center on lessons learned and recommendations for future research. The pragmatic issues include variability of personal preferences among residents and the effects of those preferences on averaged data, and the questions of how to collect spectral data and process them into an intuitive and comparable set of metrics, and how to evaluate daily light exposure for health and wellbeing.

Conclusion

While the primary focus of this research was to establish feasibility and best-practice protocols for implementing tuned lighting in the nursing-home setting, results suggest that tuned lighting had a positive effect on residents' sleep. We were able to develop a methodology for collecting light-exposure data, analyzing those data using three different models for circadian health: EML, CS, and M/P ratios. This protocol will inform future work on programming and evaluating tuned lighting systems in an institutional setting.

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1. Introduction

In part because of aging vision, limited physical mobility, and facility lighting, residents of skilled nursing centers are at particular risk for circadian rhythm disorders, which affect sleep-wake cycles. While light is one of the most powerful cues for circadian rhythm, residents in institutional-care settings such as nursing centers experience very little daily exposure to bright light or daylight, and most such facilities are not designed to optimize natural light or to use electric lighting that is sufficiently bright. Research suggests that tunable LED lights, which can change in spectrum and intensity throughout the day to mimic natural cycles of daylight and darkness at night, can improve circadian rhythm entrainment and health outcomes (Figueiro et al. 2014). However, while there have been several studies focusing on this lighting – including some in nursing centers (specifically Ancoli-Israel et al. 2002 and Van Hoof et al. 2009) – most have significant methodological limitations, do not use current lighting technology, or do not report daily light exposures for residents in sufficient detail.

The purpose of this feasibility study was to test a strategy for evaluating the effects of tunable LED lighting on sleep and agitated-behavior outcomes among residents in the ACC Care Center, a single nursing center that had recently installed tunable LED lights. Characteristics of the facility and its residents are listed in Table 2. The participating center had 99 beds. Its residents were majority female (64.0%), and more than half of its residents had moderate cognitive impairment (64.2%). The facility was a high-performing nursing home with a predominately Asian-identifying resident population (72.1% non-white). Before-and-after sleep measurements were collected on all 63 residents of the facility's Azalea, Bamboo, and Cherry Lane residential corridors. Agitation measures were collected on 35 of the 63 residents identified as having dementia.

Table 2. Nursing center characteristics.

CHARACTERISTIC	
Facility	
Total beds, n	99
Not-for-profit, Y/N	Y
Payer mix, %	
Medicare	9.2%
Medicaid	63.2 %
Private pay	27.6%
Staffing, hours/residents/day	4.2
5-Star Nursing Home Compare rating, 1-5	5
Residents	
Age, mean	88.1
Female sex, %	64.0%
Non-white race, %	72.1%
Moderate to severe cognitive impairment, %:	64.2%

*Characteristics in table include 36 residents on the center's rehabilitation corridor, which was not part of the study. Rehabilitation residents were generally younger and experience shorter stays than the residents in the study.
Source: Publicly available data from LTCFocUS.org (2016) and NH Compare (2019)

The nursing center corridors were assigned settings that either mimicked the facility's former fluorescent lighting (static lighting) or were programmed to change in spectrum and intensity to support healthy sleep-wake cycles (tuned lighting). Detailed illuminance and spectral measurements taken at the residents' eye height were analyzed using three prominent models for human health response: EML, CS, and M/P ratios. Research staff assessed behavioral measures by interviewing caregivers. We hypothesized that residents' sleep would be better when exposed to tuned versus static lighting.

2. Methods

2.1 Research Team

The multidisciplinary team for this project included experts from Brown University School of Public Health Center for Long-Term Care Quality & Innovation (Q&I), American Health Care Association/National Center for Assisted Living (AHCA/NCAL)[1], the Center of Design for an Aging Society (CDAS), and Pacific Northwest National Laboratory (PNNL), a U.S. Department of Energy national laboratory with core capabilities in lighting science, technology, and application. Collectively, the team had expertise in nursing centers, lighting and design for the elderly, and research methods, including pragmatic studies and evaluation.

2.2 Intervention

The research study involved a lighting protocol implemented in the ACC Care Center (Figure 2). In 2015, the center collaborated with the Sacramento Municipal Utility District to install and pilot-test tunable LED lighting in select locations[2]. In 2018, nursing-center leaders expanded the installation of tunable lights to all five of the facility's corridors.

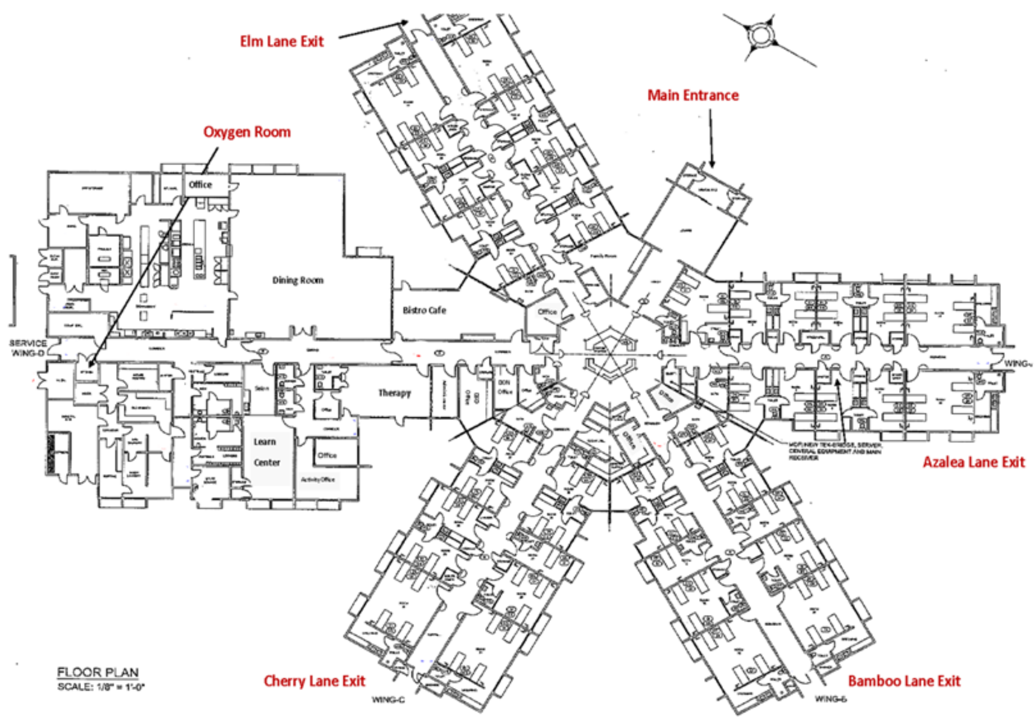

Figure 2. Floor plan of the ACC Care Center, showing the spoke-like pattern of four resident wings.

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[1] AHCA/NCAL represents 14,000 providers across the country, a unique partnership between academic researchers and the healthcare provider industry. Its goal is to catalyze research that establishes the evidence base for innovative practices such as tunable LED lighting, to improve care for older adults, with particular emphasis on those residing in nursing centers.

[2] Davis RG, Wilkerson AM, Samla C, Bisbee D, 2016. Tuning the light in senior care: Evaluating a trial LED lighting system at the ACC Care Center in Sacramento CA. DOE Gateway Study, https://www.energy.gov/sites/prod/files/2016/09/f33/2016_gateway-acc.pdf

The center agreed to assign the three long-term-care residential corridors (named Azalea Lane, Bamboo Lane, and Cherry Lane), which collectively housed a total of 63 residents, to two different lighting settings. Condition A was programmed to change in spectrum and intensity (tuned lighting), and Condition B was programmed to mimic the facility's former 4100 K fluorescent lighting (static lighting). A crossover research design was used, such that each corridor implemented one condition for a period of time and then switched to the other condition (see Figure 3).

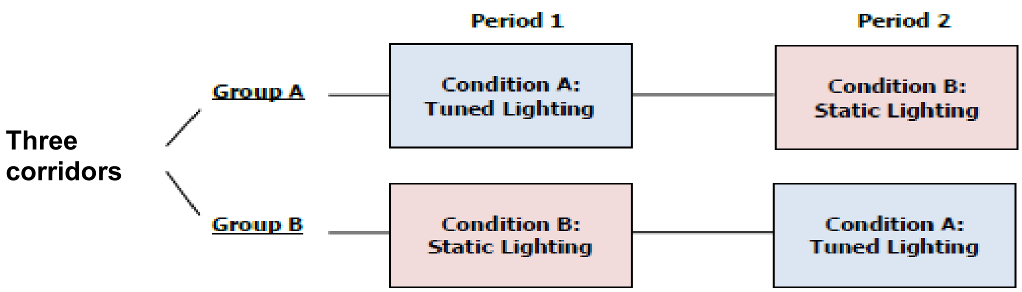


Figure 3. Crossover study design of programmable, tunable LED lighting.

The daily time settings for each color-spectrum and light-output change remained identical for both Period 1 and Period 2. The lighting protocol for static and tuned lighting conditions was as follows: Period 1 had one of the residential corridors on the tuned light settings (Condition A) for two months, and the two other corridors on the static/control light settings (Condition B) during those same two months. Light measurements were taken and data on the health and behavior of the residents were collected at the end of the two-month Period 1. For the two months of Period 2, the light settings were reversed, so that the two corridors that had had Condition B in Period 1 now had Condition A, and the other corridor had Condition B (Table 3).

- Period 1 was from December 2018 through January 2019. The Azalea Lane corridor received the tunable lighting intervention. The Bamboo Lane and Cherry Lane corridors received the control condition of static lighting.
- Period 2 was from February through March 2019. Bamboo Lane and Cherry Lane received the tunable-lighting intervention. Azalea Lane received the control condition of static lighting.

Table 3. Time, CCT, and light output for control and intervention lighting conditions.

CONDITION A: INTERVENTION (TUNABLE) LED LIGHTING CONDITIONS CORRIDORS: For specific hours, color spectrum and light output are tuned. A gradual color and output change occurs over a 30-minute period, beginning 30 minutes prior to the next color spectrum and output time.		
Time	CCT	Light Output
7:00 a.m. to 4:00 p.m.	6500 K	100%
4:00 p.m. to 8:00 p.m.	4100 K	100%
8:00 p.m. to 7:00 a.m.	2700 K	20% or less
CONDITION B: CONTROL (STATIC) LED LIGHTING CONDITIONS CORRIDORS: For specific hours, color spectrum and light output are fixed. A gradual output change over a 30-minute period is scheduled 30 minutes prior to the next output time.		
Time	CCT	Light Output
7:00 a.m. to 8:00 p.m.	4100 K	100%
8:00 p.m. to 7:00 a.m.	4100 K	50%

The control-condition settings were designed to mimic the previous static fluorescent lighting system, which delivered a 4100 K light spectrum 24 hours a day but had the capability of alternating lights being shut off during nighttime hours. This setting was simulated with the LED system set to 4100 K, but every LED luminaire was dimmed to 50% output at night. Light spectra for all settings are shown in Figure 4, and correlated color Temperature (CCT) is used as a shorthand way to describe the color of light.

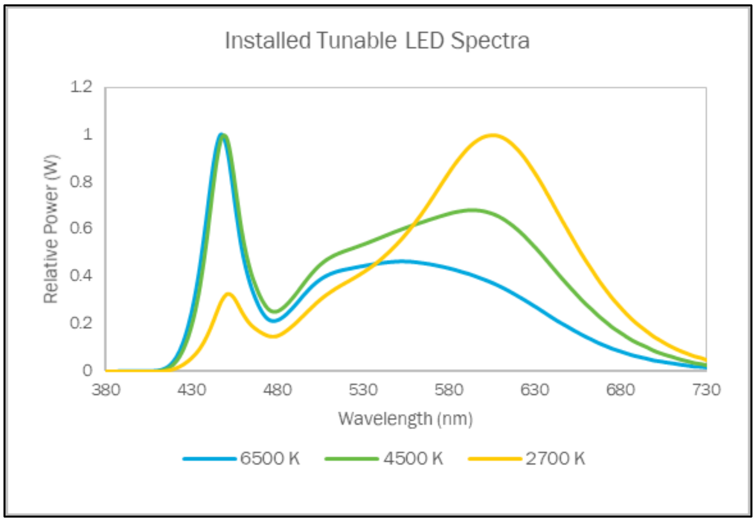


Figure 4. LED Spectral measurements, normalized to a maximum value of 1, for the maximum, midpoint, and minimum points on the available tunable CCT scale for the installed luminaire.

2.2.1 Description of Lighting System

Planled "Beetle" luminaires from Samjin (product code BT14-032-SK-CT-USR4) had been selected for one-to-one replacement of existing fluorescent wraparound luminaires in 2016 and had been modified for surface mounting to existing electrical boxes in the ceiling. Each Planled luminaire housed rows of two LED packages, one at 2700 K and one at 6500 K. A white translucent diffuser masked the visibility of the LEDs and produced the luminous-intensity plot shown in Figure 5. The Planled luminaires were spaced 12' apart on center in the Azalea and Bamboo corridors, and spaced either 10' or 14' apart on center in the Cherry corridor (see Figure 6). Each luminaire allowed a continuous variation of the CCT from 2700 K to 6500 K, with dimming possible at each CCT from 100% down to approximately 20% in steps of 1%. The manufacturer reported a minimum color rendering index (CRI) of 83.

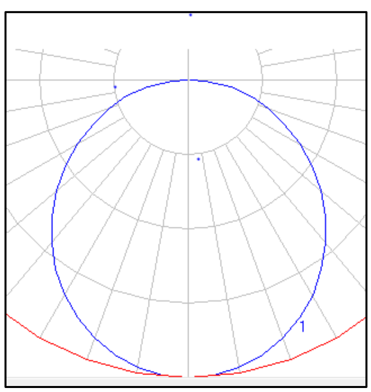


Figure 5. Photometric polar plot of LED corridor luminaire.

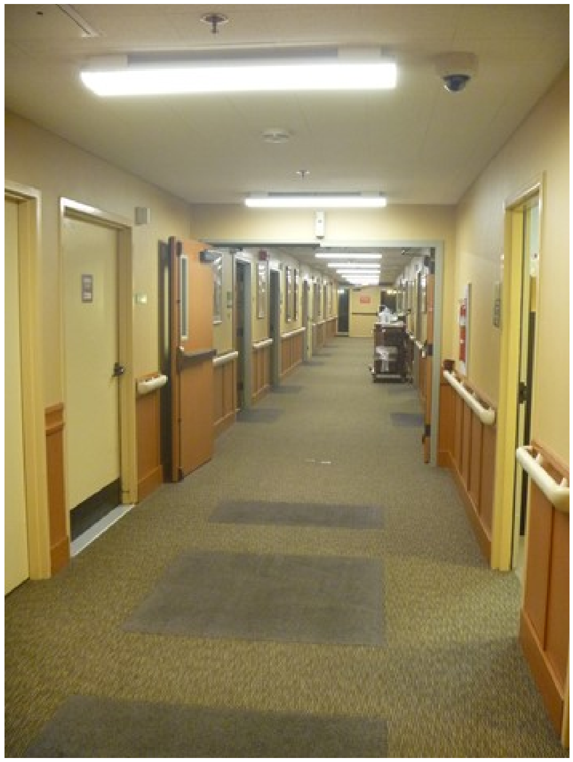


Figure 6. Photo of typical resident-room corridor, with LED color-tunable overhead lighting installed. Daytime setting with 4100 K color temperature and maximum light output is shown here, reflecting the fixed output setting intended to mimic the original undimmable fluorescent lighting.

2.2.2 Description of Automatic Lighting Controls

The Samjin VLTRA Smart Technology system provided the intensity and CCT programmability that allowed the facility manager/research team to customize the lighting environment. The ACC installation included a wireless wall control (WCRF-STUS) for each corridor (e.g., Azalea Lane) or space (such as the nurse's station or common rooms located on the Daisy Lane corridor). The central computer, which was provided by ACC and located in the facility manager's office on site, was used to program the lighting for each residential corridor and space. The wall controllers were daisy-chained (i.e., wired together) using CAT5e cable, with a final daisy chain to the central computer. An Ethernet converter gave Planled remote access to the central computer for programming or corrections, as needed (the programming of the settings was not a straightforward process, so Planled provided the programming by having one of its engineers remote into the computer).

Samjin partnered with Planled to provide the software for multiple presets for the static or tunable lighting settings. The system could not accommodate the programming of the combination of Period 1 and Period 2, so the Period 2 settings were reprogrammed by Planled at the end of Period 1.

2.3 Measurement of Sleep and Agitation

Two Q&I team members collected sleep and behavior data on site at the nursing center by interviewing staff members during each of the two intervention time periods. For the primary outcome, Q&I team members interviewed night-shift staff about all residents' nighttime sleep disturbances, using the Sleep Disorders Inventory (SDI) (Tractenberg RE et al. 2003), which asks eight questions about sleep behaviors and their frequency and severity. Frequency is assessed as rarely (1), sometimes (2), often (3), or very often (4); and severity is assessed as mild (1), moderate (2), or severe (3). The total SDI score is derived by summing the products of the frequency and severity ratings for each behavior, with higher scores indicating worse sleep.

For the secondary outcome, Q&I team members interviewed day staff about residents' agitated and aggressive behaviors, using the Cohen-Mansfield Agitation Inventory (CMAI; Cohen-Mansfield J 1997). These interviews focused on residents with a diagnosis of Alzheimer's and related dementias, since the CMAI was designed for residents with such a diagnosis. The CMAI asks about 29 verbally and physically agitated and aggressive behaviors, such as pacing, yelling, cursing, kicking, hitting, and calling out. Staff were asked how often each of these behaviors occurred in the previous two weeks, with their answers characterized as not applicable (0), never (1), less than once a week (2), once or twice a week (3), several times a week (4), once or twice a day (5), several times a day (6), or several times an hour (7). The total CMAI score is derived by summing the reported frequencies for all behaviors, with higher scores indicating more-agitated and/or more-aggressive behaviors.

2.4 Implementation – The ACC Resident Spaces

Most ACC residents spent their days indoors, and through conversations with staff, we were able to estimate how much time the typical resident spent in various rooms, and how much time they spent engaging in which activities. The spaces (such as resident rooms, dining room, corridors) are described in detail below, along with measurement details. The measurements were collected at times of day and under conditions as described below. Measurements were taken as the room or corridor was found; no modification of daylight or window shade position was made, in order to collect realistic light exposures.

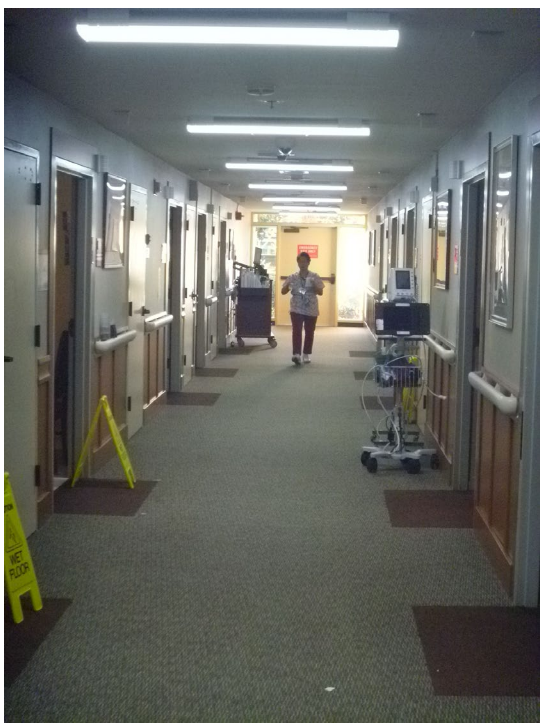


Figure 7. Daytime corridor lighting, showing 6500 K light setting and daylight from windows.

- *Corridor*. Spectral measurements were measured with a tripod, with the meter positioned at a height of 42” and mounted to simulate vertical illuminance at the eye of a resident in a wheelchair. These measurements captured the spectral radiance received at the eye, which took into account the luminaire spectrum and all the spectral characteristics of reflections and inter-reflections with walls, carpets, people, and medical care carts. Daytime measurements were taken along the centerline of the corridor and centered in the length of the corridor to minimize any contribution from daylight, from doors at one end of the corridor, or from the nurses’ station clerestory windows at the opposite end of the corridor. Nighttime measurements were taken during sleeping hours, or as close to sunrise as possible, in order to primarily characterize the electric lighting (see Figure 8).

Figure 8. Nighttime corridor lighting, showing 2700 K light setting dimmed to 20% output.

- *Resident bed, nighttime sleeping conditions* (Figure 9). Spectral measurements were taken with the instrument mounted on a tripod, with a horizontal extension so that the tripod could be located on the floor and the photometer head mounted on an arm over the bed to approximate the location of the sleeping or reclining resident’s eyes. The photoreceptor was centered 36” above the floor, aimed at an angle of 45° from vertical. Measurements were taken during the night, with care taken not to disturb the individual. Measurements accounted for all light directed or reflected from the corridor or, in some cases, from adjacent bathroom areas or nightlights. The light measured was most often light reflected from room and object surfaces, usually from above and below drawn privacy curtains. In one case, light from a poorly controlled outdoor wallpack luminaire entered through windows with partially drawn blinds.

Figure 9. View into two-resident room at night. Corridor doors remained open during nighttime for observation by care staff.

- *Resident room, daytime conditions*. Spectral measurements in the resident room during the day were taken in the vertical plane at 42”, to simulate the incident light on the residents’ eyes as they sat in a chair or wheelchair in their rooms. Most residents napped for at least an hour in their rooms after lunch (Figure 10). Light sources were daylight through windows and 4’-long over-bed lights that had one T8 4100 K fluorescent lamp directing light upward and one directing light downward from separate reflector chambers. There was no consistency in the state of the over-bed lighting during the day: some residents used upward light only, others had downward light only, some used both, and some preferred to have the lights off.

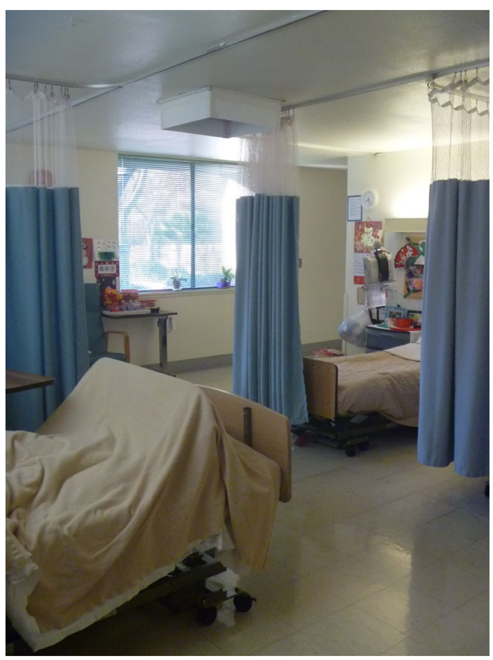


Figure 10. Photo of one four-bed resident room during the day. Note the over-bed light with upward light only.

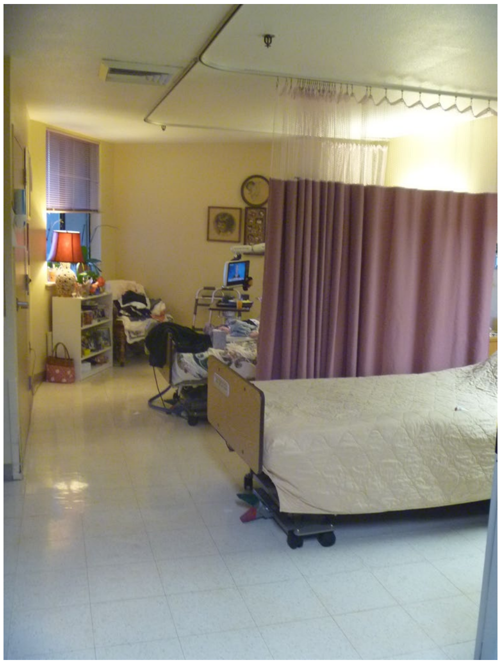


Figure 11. Photo of a two-bed resident room. Note a personal table lamp in use by one resident.

- *Dining room, daytime conditions*. The dining room was used by a majority of residents for three meals per day, plus morning and afternoon activities. (Figure 12) Windows contributed daylight and provided views. Measurements were taken in the center of the room, in multiple directions, and averaged to produce a general light exposure for residents.

Figure 12. Dining room with direct/indirect LED lighting. Although dimmable, it was fixed at 4100 K and was used at full output for mealtimes.

2.5 Implementation – Measuring Lighting Levels and Spectral Data

PNNL and CDAS team members collected lighting data to characterize light exposure for typical residents over the course of the 24-hour day by using meters to capture spectral power distribution (SPD) on-site at three time points: prior to the intervention (baseline) and during each of the two intervention time periods. Horizontal illuminance data were also collected to compare with measurements that had been taken in 2016.

Figure 13. Photo of tripod set up in ACC dining room. The spectrometer was mounted to take vertical measurements at a height of 42", the eye height of a typical resident in a wheelchair.

We captured spectral measurements in multiple spaces and lighting modes, using a Konica-Minolta CL-500a spectrometer that was within calibration and was able to record spectral energy data down to 0.5 lx (it also recorded data below that illuminance level, which are reported here as nighttime exposures for residents, although calibration tolerances for those measurements may not have been maintained). The meter and its software calculated illuminance and color metrics from the spectral data. Measurements were taken “as is,” without making any modifications to daylight or window-shade position, to collect realistic light exposures. Appendix B describes in detail the approach to capturing illuminance at the eye of residents. Since most residents were in wheelchairs, daytime illuminance and spectral data were collected in a vertical position at an eye height of 42” in corridors, dining areas, and resident rooms (Figure 13). At night, these data were collected at the approximate eye location and orientation of a sleeping resident. From this series of measurements, the “Lighting Day in the Life” profiles were compiled, by location, for typical residents.

The “Lighting Day in the Life” profiles included the three prominent models for estimating potential health effects from light: M/P ratios, CS values, and EML values; metrics based on these models are listed in Appendix A The key times when there were significant differences between the static and tunable conditions were 9:00 a.m. to 11:30 a.m. and 2:30 p.m. to 5:00 p.m. when the CCT was increased in the tunable corridors, and from 8:00 p.m. to8:30 p.m. when the CCT and illuminance were decreased significantly in the tunable corridors (Figure 14). The sleep conditions were also considerably different, since the light infiltrating the resident bedrooms from the corridors with the tunable lighting was warm in color (2700 K light setting) and dimmed to 20% of full output for the duration of the night, compared to the static condition of 4100 K and 50% of full output.

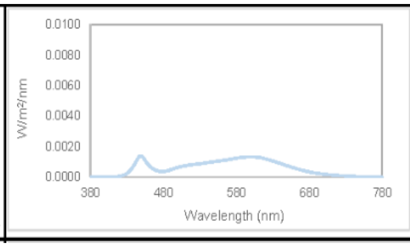
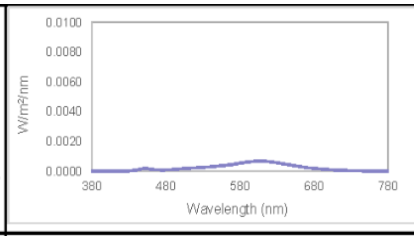
Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
8:00 p.m. - 8:30 p.m. Prep for Bed Light Setting: 4100K at 50%	Corridor *Observer seated in chair or wheelchair*		AVG.	73.3	3770	0.0640	0.664	48.9
			MAX	122.6	3882	0.1118	0.680	83.4
			MIN.	45.4	3622	0.0382	0.637	30.6
								n = 4
8:00 p.m. - 8:30 p.m. Prep for Bed Light Setting: 2700K at 20% in corridor	Corridor *Observer seated in chair or wheelchair*		AVG.	29.2	2526	0.0296	0.393	11.6
			MAX	49.4	2575	0.0521	0.404	19.9
			MIN.	16.6	2479	0.0160	0.382	6.5
								n = 5

Figure 14. An example of the difference between the control (static) lighting condition (above) and the tunable lighting condition (below) in Cherry Lane corridor between 8:00 p.m. and 8:30 p.m.

2.6 Implementation – Dates for Light Exposure and Interviews

The nursing center's three long-term-care residential corridors were assigned to static or tuned lighting, beginning in September 2018. One corridor was assigned to Condition A (tuned and then static lighting) and two were assigned to Condition B (static and then tuned lighting). Through regularly scheduled meetings with senior leadership and quality-improvement teams, and via staff in-service trainings, nursing-center leaders educated frontline staff about the purpose of the different settings in the corridors, the importance of proper implementation, and the goal of the research. Q&I took care not to set expectations as to which of the settings were likely to produce better outcomes, in order to minimize staff bias. For the first six weeks, maintenance staff tuned the lights manually in the mornings and evenings; after that, to lessen the staff burden, Q&I arranged for a controller to be installed to automatically tune the lights.

The static and tuned lighting conditions were scheduled to last for four-month intervals, from September to December 2018 and from January to April 2019. However, an October 2018 site visit to interview staff about residents' sleep and behaviors instead revealed that the lights were not properly tuned to the protocol settings, because the newly installed controller was not functioning as intended – most likely because the controller was installed on a computer that "went to sleep" during a staff member's vacation. As a result, the research team implemented an auditing process to monitor the light settings, restarted the study period using two-month intervals (from December 2018 to January 2019 and from February to March 2019), and conducted the staff interview process in January 2019 (replacing October 2018) and March 2019.

2.7 Health-Related Metrics from Light Intensity and Spectral Measurements

There are three main ways to evaluate potential health effects from the light:

- Melanopic/photopic (M/P) ratios
- Circadian stimulus (CS) values, and
- Equivalent melanopic lux (EML) values.

The M/P ratio is the melanopic content of the spectrum measured at the eye, divided by the photopic content (classical lighting units) of the spectrum measured at the eye. The M/P ratio (also sometimes called "blue-cyan content") simply provides the designer with a number describing its effectiveness at stimulating the intrinsically photosensitive retinal ganglion cell (ipRGC) photoreceptors and, thus, the nonvisual functions in the brain. High M/P ratios (roughly 0.9 and above, using the WELL Building Standard calculation method) are considered suitable for spaces where alertness is desired[3]; low M/P ratios (roughly 0.35 and below) are considered suitable for spaces where people are sleeping or getting ready for sleep. There are multiple ways to calculate M/P ratios, depending on how the melanopic and photopic response functions are normalized before the ratio is calculated. For this study, PNNL chose to calculate the M/P ratio according to the WELL Building v2 Q2 2019 Standard, where the two functions are normalized so that the area under the curves of each of the two functions equals one unit of radiant energy on an equal-energy spectrum. The normalized curves are then multiplied by the collected SPD of the light reaching the resident's eye, to yield the melanopic radiant watts and the photopic radiant watts. The melanopic radiant energy is then divided by the photopic radiant energy to yield the M/P ratio. An example of the calculation is shown in Appendix B.

EML, which is a measure of the radiant watts to which the ipRGC photoreceptors are sensitive, is calculated by multiplying the photopic illuminance at the eye by the M/P ratio. It effectively combines the ratio of blue-cyan light in the spectrum and the intensity of the light stimulus at the eye. The WELL Building Standard v.2 target for daytime office workers is 240 EML[4] for highest-tier achievement, and 150 EML for moderate achievement. To comply, the electric lighting and daylighting together must deliver this at least between 9:00 a.m. and 1:00 p.m. for both an alerting effect and circadian wellness. The standard offers no recommendation for pre-sleep or sleeping environments.

CS values are based on nocturnal melatonin suppression that result from a light stimulus. CS as a metric combines the inputs of all photoreceptors to affect the level of melatonin. According to the researchers who developed this metric, a CS of 0.3 equates to a combination of illuminance and spectrum that is appropriate for daytime use where alertness is desired (Rea and Figueiro 2017); a CS value of 0.1 or less is deemed appropriate for evening or sleeping spaces (Figueiro and Rea 2017). The WELL Building Standard offers a CS of 0.3 between 9:00 a.m. and 1:00 p.m. as an alternative to EML, to comply with the moderate level of performance for the credit.

CS is calculated by taking the SPD data measured at the eye, and the illuminance measured at the eye, and plugging these data into the CS online calculator[5]. Step 1 consists of selecting the "Custom Source" button and pasting in the SPD as two columns or rows of wavelengths and radiant-energy values. Step 2 consists of selecting that custom source from the list of sources and inputting the vertical illuminance measured at the eye. Two curves will be plotted under Step 3: the SPD of the source whose data file you have inputted, and the CS-warm or CS-cool Relative Spectral Contribution of the Circadian Response (this is the CS model's response curve for the specific SPD that has been inputted). The CS value is calculated automatically and appears in the table below the spectral plot.

CS, because of the two spectral-response functions used to evaluate warm and cool light environments, produces what appear to be anomalous values when the CCT of the light source is between 3500 K and 4500 K. Within this range, light sources produce a CS value lower than light sources at 3000 K or even 2700 K, which seems counterintuitive because the amount of blue-cyan energy is greater. Consequently, because the setting used to simulate ACC's earlier 4100 K fluorescent lighting system is within that range, the CS values for the static/control conditions appear low compared to the values of EML. It's not known whether CS is accurately evaluating the suppressed response of the circadian system to the source, or whether the model is less accurate in this range.

[3] Guidance provided by ALFA software, https://www.solemma.com/Alfa.html, accessed 10/23/2019.
[4] https://v2.wellcertified.com/v2.4/en/light/feature/3
[5] https://www.lrc.rpi.edu/cscalculator/

3. Results

3.1 Sleep and Behavior Outcomes

Q&I found that residents experienced significantly fewer nighttime sleep disturbances when their corridor was exposed to the tuned lighting condition than when their corridor was exposed to the static lighting condition (Table 4). On average, residents experienced about half as many nighttime sleep disturbances with tuned lighting as with static lighting (1.8 versus 3.6 disturbances, respectively). Sleep-disturbance data were highly skewed, with staff reporting that residents had no sleep disturbances or many severe disturbances. This skewness was reflected in the relatively low mean sleep disturbance average score and the large standard deviation, or variance around that mean. The intervention likely worked to reduce sleep disturbances in the 5% to 7% of residents with many severe sleep disturbances. However, in an institutional setting with shared rooms, such as the nursing center in this study, improving the sleep of a few residents may have a ripple effect on roommates and closely located others.

No meaningful improvement (decrease) was observed in agitated behaviors between the static and tuned lighting conditions (36.9 versus 36.2 behaviors, respectively).

Table 4. Resident sleep disturbances and agitation outcomes.

	Static Lighting (Control Condition)	Tuned Lighting (Treatment Condition)
	Mean (Standard Deviation)	Mean (Standard Deviation)
Sleep Disturbances* (higher scores = worse sleep)	3.6 (7.2)	1.8 (3.8)‡
Agitated Behaviors† (higher scores = more agitation)	36.9 (9.2)	36.2 (7.7)

*Sleep disturbances were measured for all residents in three study corridors (n=63)
†Agitated behaviors were measured in three study corridors for residents who had a dementia diagnosis (n=35)
‡p<.10

3.2 Lighting Levels and Effect of Spectral Changes Using Health-Related Metrics

In the corridors, we found that the tunable lighting system was very effective at reducing light levels and blue-cyan content of the light at night, as well as at providing higher blue-cyan content during the morning hours. Because the control/static setting at 4100 K provided very similar eye illuminances during the morning, the principal difference between the control and intervention conditions was nighttime light exposure. Expecting that low, warm-color light should help support residents' melatonin secretion levels and sleep quality, we made sleep our primary focus. During the nighttime light setting, light levels dropped to an average of around 33 lx at the eye (range: 20-45 lx) in the corridor, with a spectrum that dropped the M/P ratio to approximately 0.43, and with CCT averaging 2600K or less. This also resulted in far less light infiltrating the bedrooms from the corridors, since the doors to most resident rooms were left open to the corridor in order to facilitate easy observation by the staff. Appendix A presents "Lighting Day in the Life" results for residents by corridor and by the lighting condition (tuned or static/control). A typical day was estimated by talking to staff about normal times, locations, and activities that most residents experienced. "Wakeup" time, for example, was the hour spent going through normal dressing and ablutions in the resident room. "Breakfast" was the hour most residents spent in the dining room from 8:00 a.m. to 9:00 a.m. "Corridor" was the time many residents spent in the corridor during the morning period when their rooms were being tidied for the day. The time period is noted, because the duration of both bright light exposure and nighttime dim light exposure was a critical factor for healthy light and dark exposure. In some cases, the exposure is listed multiple times. The dining-room light exposure repeated for breakfast, lunch and activities, and dinner, for example. The corridor light exposure was the same high output at a high color temperature in the morning and afternoon, but in the evening before bed, the corridor lights were dimmed and warmed in color.

When examining residents' spectral and illuminance exposure, we found that the highest daytime light exposures as measured by illuminance at the eye (CS and EML) occurred in communal rooms (i.e., one of two dining areas). Most residents ate three meals a day in one or both rooms, and the light levels at the eye averaged 413 lx (range: 284-681) for one and 342 lx (range: 272-412) for the other. Both spaces were also used for activities such as singing, crafts, and puzzles, extending the time spent in the communal rooms - and therefore under relatively higher light levels - by one hour per day for more than half the residents. These spaces also had effective windows and attractive views of gardened areas. Short of going outdoors, this was likely the highest light exposure residents received during the day.

The nighttime exposures for sleep are the last time period listed in the "Lighting Day in the Life" tables. The amplitude of the SPD is quite low, since the exposures for most residents during sleeping hours were well below 5 lx at the eye, and the light that reached their eyes in the tunable setting was primarily from the lowest corridor setting at 2700 K, so the amount of blue-cyan energy in the spectrum was especially low. The amplitude of the SPD for the static/control setting was generally higher than that of the tuned setting, which was reflected in M/P ratios and EML values. There were exceptions, however. The measurement team (PNNL and CDAS) found several rooms where residents had their own table lamps and/or televisions operating all night, or where light from 4000 K exterior lighting shined through the window. These situations could be seen in the high maximum M/P ratios of 0.6 or more in both the Azalea and Bamboo resident rooms, even in the tunable lighting condition (Table 5).

Figure 15 is excerpted from Appendix C to show the graphics illustrating light and color exposure for an average resident over the course of a 24-hour day, for corridors with static/control lighting versus tuned lighting. It is shown in a radial plot, with the color of the light indicated by blue-white-yellow to illustrate 6500 K - 4100 K - 2700K, and the intensity of the light in illuminance (lx) shown as the distance from center to the outer line. In the morning and afternoon, the daytime light exposure was identical for both groups, because all residents spent similar time in common areas. The only differences to be seen in the graphics involve the periods of time when residents were in the corridors before bedtime, and the nighttime period, when the principal light exposure was from light reflected into their sleeping areas from the corridor.

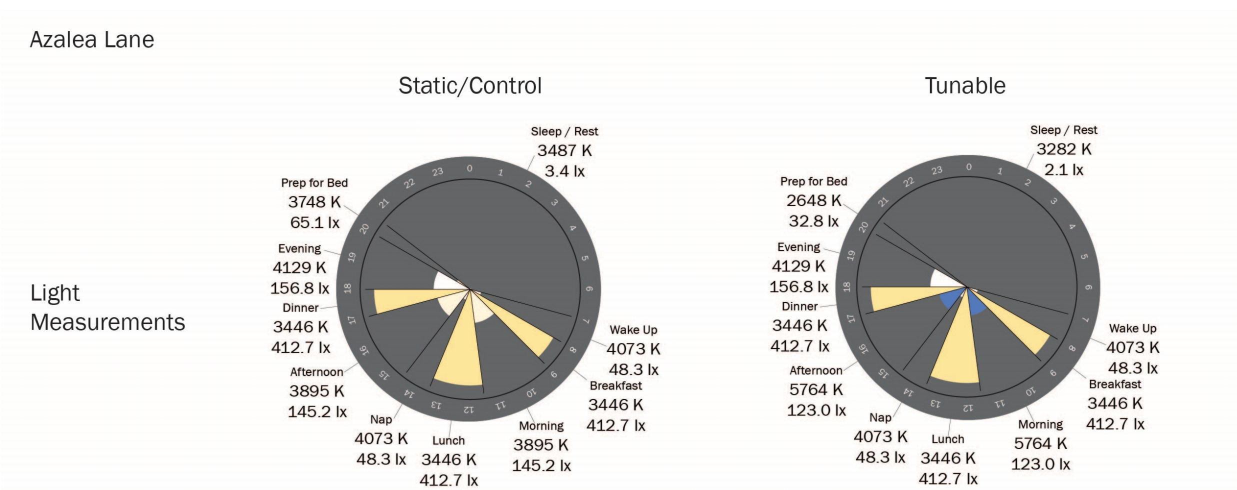


Figure 15. Graphics showing resident light exposure over 24-hour day.

The subsequent rows of radial plots in Appendix C do not use color to illustrate the light color. Instead, these plots use black-and-white graphics to illustrate the changing values of EML, CS, and M/P ratios over the course of the day in the three corridors. In terms of EML, the tunable light exposure in corridors just before bedtime and while in bed averaged less than half of the same exposure in static/control corridors. This may have played a critical role in the resident outcomes, since this exposure had a long duration (11 hours) and occurred during the critical hours of sleep. The CS values did not show that large a difference, likely because the static/control light setting was at 4100 K, where the CS model predicts the circadian stimulus to be much lower than its CCT would suggest.

Table 5. Summary of "Sleep" light measurements in resident rooms, with calculated circadian metrics. Values are shown for each of the three residential wings at the control/static setting and the tunable setting. On average, EML values calculated in the tunable corridors were 60% or less than those calculated during the control/static setting.

		Illuminance (Ev) (lx)	CS	M/P	EML
Azalea Control/Static	MAX	10.2	0.0141	0.687	5.7
	AVG	3.4	0.0039	0.605	2.0
	MIN	0.3	0.0001	0.540	0.2
Azalea Tunable	MAX	6.5	0.0035	0.731	4.3
	AVG	2.1	0.0015	0.603	1.3
	MIN	0.3	0.0002	0.454	0.2
Bamboo Control/Static	MAX	8.4	0.0044	0.681	5.7
	AVG	4.8	0.0031	0.582	3.0
	MIN	2.6	0.0022	0.498	1.3
Bamboo Tunable	MAX	4.9	0.0049	0.584	2.2
	AVG	3.1	0.0034	0.472	1.5
	MIN	0.9	0.0007	0.389	0.4
Cherry Control/Static	MAX	1.0	0.0010	0.621	0.6
	AVG	0.9	0.0005	0.615	0.5
	MIN	0.7	0.0003	0.608	0.4
Cherry Tunable	MAX	1.6	0.0011	0.409	0.6
	AVG	0.8	0.0005	0.387	0.3
	MIN	0.3	0.0002	0.360	0.1

3.3 Reading the Light Characterization Plots

Spectrophotometers collect radiant-energy data, generally in 1 nm or 5 nm intervals, over the visible range of 380 nm (short-wavelength violet) to 780 nm (long-wavelength red). Measured in radiant watts, this numerical data can be transferred to a spreadsheet, and a variety of response functions can be applied to the data to calculate photopic illuminance, melanopic irradiance, circadian stimulus, CCT, and color-quality metrics, for example. Figure 16 illustrates three response functions relevant to this work: the photopic sensitivity function (for calculating illuminance, centered at 555 nm), the melanopic response function (for calculating the response of the ipRGC photoreceptors for human non-image-forming physiological function), and the CS function (which characterizes the impact of multiple photoreceptors on melatonin suppression at night). The CS function is different depending on whether the light source is warm (CCT of approximately 3500 K or lower) or cool (CCT of approximately 3500 K or higher). All of these are illustrated on the plot below, normalized to a maximum value of 1, except for the CS-warm sensitivity curve, which is scaled to correspond to the normalized CS-cool sensitivity curve.

The photopic sensitivity curve is expressed with a peak of 683 W/nm when used to calculate classical lumens. It describes the human daytime sensitivity for central vision and is a combination of the response of the middle- and long-wavelength cones.

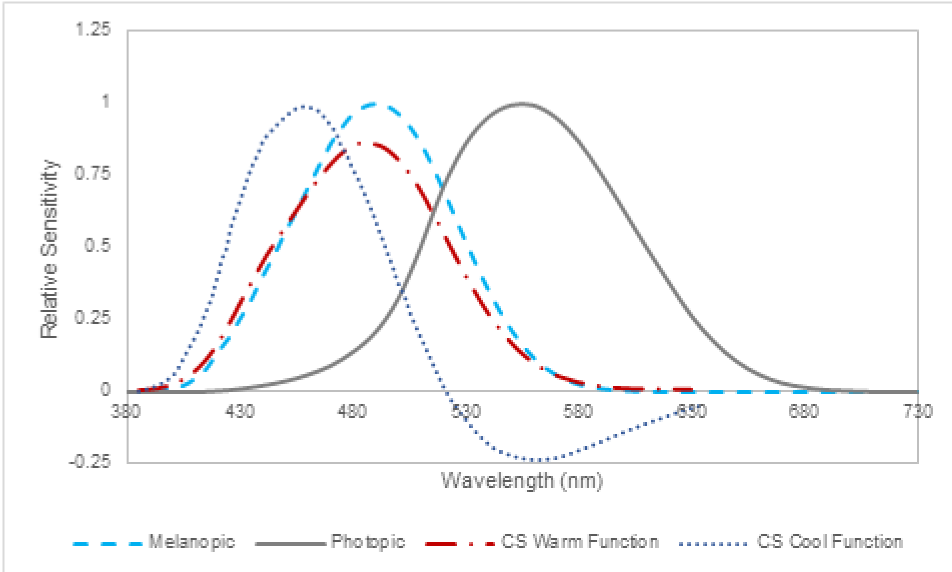


Figure 16. The circadian stimulus (CS) metric spectral sensitivity model for warm and cool light sources; the melanopic spectral sensitivity curve; and V(λ), the photopic sensitivity curve, which describes human spectral sensitivity for daytime vision.

To understand the different circadian metrics, it is helpful to superimpose the SPD received at the eye on a plot of the different response functions. As an example, the "Prep for Bed" lighting condition occurred between 7:30 p.m. and 8:00 p.m. Figure 17 shows on the left the Static/Control lighting condition that simulated the CCT of the older 4100 K fluorescent system (of course, the SPD of the LED was different from that of the previous fluorescent luminaires, so this was just an approximation). The SPD at the eye is in gray, showing a normalized peak of 1.0 at about 450 nm (blue) and a secondary peak at about 600 nm (yellow). The light-blue curve is the melanopic (ipRGC) response, which peaks at about 490 nm, or approximately where the light source has a trough in its output. The CS curve for cool light sources is drawn in dark blue and peaks at about 460 nm. According to the CS model, this light source would deliver relatively high CS values based on the SPD's peak in the blue, but that is counteracted by the yellow portion of the spectrum where the CS curve dips below the horizontal axis. Thus, it is hard to tell at a glance whether the SPD is beneficial or problematic for sleep based on its predicted effect on the melatonin level. According to the EML model, the SPD of light reaching the eye delivers moderate melanopic content (M/P ratios of approximately 0.6 – 0.7) because the peaks of the light blue and grey curves overlap somewhat but do not coincide. Both models depend on knowing the illuminance at the eye, since it is a combined effect of the spectrum and the intensity of light at the eye.

Similarly, the plot on the right shows the SPD received at the eye in the corridor when the tunable lighting system was set at 2700 K, so you can see that the gray curve delivers much less power in the shorter wavelengths. Comparing that to the red-colored CS-warm curve, this lighting condition would be expected to deliver much lower values of CS and, consequently, less melatonin suppression, depending on the light output. The same is true when comparing the gray curve to the melanopic response illustrated in light blue. The SPD with minimal blue-cyan content would be expected to deliver low M/P ratios (approximately 0.4) and, thus, low values of EML.

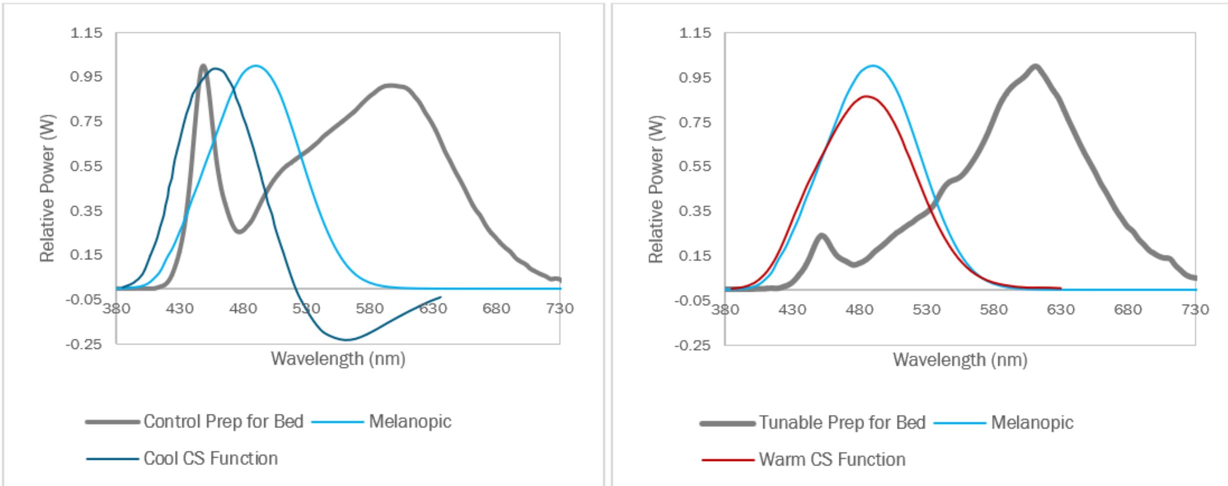


Figure 17. Control (left) and tunable (right) “Prep for Bed” SPD measurements. In both plots, the melanopic sensitivity curve and the appropriate CS sensitivity curve (cool or warm) are shown for comparison.

It’s important to reiterate that for both EML and CS calculations, the intensity of light at the eye is just as important, if not more so, than the SPD. There is a tradeoff, such that high levels of light with a low M/P ratio can produce a high circadian response, and very low levels of light with a high blue-cyan content (high M/P ratio) may not elicit any circadian response. For this reason, both CS and EML take the light intensity at the eye into account.

4. Discussion

4.1 Light Measurement Data

The science of light’s effect on the circadian system and other physiological and behavioral effects on humans is evolving. There are three prominent models for evaluating light exposure for physiological effect, all of which were used in this study. However, there is a lack of consensus on ideal lighting levels, spectral content, and duration of light exposure at different times of day. This study can inform that understanding, with the goal of formulating and implementing recommendations to improve care for nursing-center residents.

One lesson is how much the expected spectrum of a luminaire differs from what is measured at the eye of the resident, due to the finishes used in the space and the effect of inter-reflection of light from those surfaces. While the nighttime color selected for the tunable lighting in the study was 2700 K, the SPD received at the eye was 2600 K. Similarly, the 4100 K light source resulted in a received CCT of 3700, and 6500 K was reduced to 5800 K. Designers should consider both the color and reflectance of finishes used in care facilities.

Another lesson is that the circadian metrics of EML and CS do not track one another consistently, except when the SPD has higher blue-cyan content (e.g., when the CCT ≥ 5000 K). CS predicts much lower circadian metric values than EML does, when the CCT of light at the eye is around 4000 K. This can be seen in the CS and EML values calculated for the daytime corridor static/control settings in Appendix A for each of the corridors.

Collecting SPD data at the eye and running those data through online calculators or spreadsheets for different human health models was an onerous process. Of course, interpreting the data is also not straightforward, because this is still such a new area of design application. Metrics are still little tested in application, and recommended target values and durations are still moving. Targets for EML, for example, have shifted downward by almost 50% in the last few years. Our hope is that this effort can inform the research and design communities on what protocols for data collection yield the most useful results for the minimum of work.

4.2 Resident Outcome Data

Long-term-care residents residing in a nursing center that assigned three corridors to tuned or static lighting conditions experienced half as many nighttime sleep disturbances when their corridor lighting was tuned than when it was in the static/control condition. There was no meaningful improvement observed in agitated behaviors between the static and tuned lighting conditions.

The resident outcome data have several limitations. First, there were other co-occurring, light-based initiatives at the center, among them a "Sunshine Group" to bring residents outside daily, and a "Dream Team" to evaluate factors, including lighting, that could contribute to poor sleep. These initiatives made it difficult to isolate the impact of the tuned LED lights, since the effect may have been muted by other light exposure. Second, the tools we used to measure residents' sleep and behaviors, while validated and widely used in the nursing-center population, are dependent on staff speaking the same language as the residents they serve; whereas in this center, that was often not the case. Almost half of the residents in this facility spoke Japanese or Chinese exclusively, while only one staff member was fluent in each of those languages. This made it difficult for staff to answer several items on the agitation assessment, such as "Does the resident repeat the same phrase or question over and over?" and "Does the resident curse?" Third, we were not always able to interview the same staff member at follow-up. Given that every person perceives agitated behaviors differently, this may have affected our results.

4.3 Future Research Directions

Future research could leverage technology, such as individual light, sleep, and activity monitors, to accurately measure outcomes. This would offer resident-specific light-delivery data and present a potential for real-time clinical intervention to explain behaviors. These data could also change therapeutic approaches to residents with behavior issues.

Studies with more subjects and longer-term collected data could yield more-definitive results on which metrics for health-related outcomes were best predictors of improved sleep or reduced agitation. At present, researchers may harbor some bias in favor of their own preferred models, so research from third parties is needed.

4.4 Observations from the ACC Care Center Medical Director

During the review phase of this report, ACC's Medical Director contributed valuable observations and comments. These are paraphrased below.

This crossover study presents environmental lighting as a dose-related stimulus with physiological effects similar to drug therapy. Residents served as their own controls. The results may underestimate the potential for optimal photo-pharmacological effect, because differences in the light received by the residents were not clear, since each resident was in and out of different rooms, engaged in different activities, ate meals, and went outdoors throughout the day. One can visualize that a specific light prescription for individuals could be used to support restorative sleep; however, the negative effects of extended naptime and institutionally implemented lifestyle habits can mask the positive effects of tunable and dimmable light on sleep. As such, sleep-hygiene education for residents, families, and staff is critical in treating the elderly population, where the prevalence of inadequate restorative sleep is in the range of 45%.

Another benefit not measured in this study is that when there is a change in light color and intensity, the staff, families, and residents are exposed to a warm-color reminder that it is time for the residents to sleep. We have seen more of an awareness on the part of the staff, and an effort to be quieter and more respectful of sleep time.

Tunable lighting at ACC has presented energy-saving light therapy that is attractive to the eye and in no way interferes with our main goal, which is to maximize dignity and independence for our residents, and to provide a great place to work for our staff.

5. Conclusion

In this study of the measurement of light for health-related outcomes in a nursing center, we assessed whether we could capture the effects of tuned LED lighting on the residents' sleep and agitated behavior. The results suggest that tuned lighting had a positive effect on nursing-center residents' sleep. We were able to develop a methodology for collecting light-exposure data, analyzing those data using three different models for circadian health: equivalent melanopic lux (EML), circadian stimulus (CS), and melanopic/photopic (M/P) ratios. This protocol will inform future work on programming and evaluating tuned lighting systems in an institutional setting.

5.1 Lessons Learned from Study Protocols and Procedures

Table 6 includes recommendations for future research resulting from lessons learned during implementation of this study. Collectively, these lessons highlight not only the importance of routine, on-site monitoring to mitigate real-world issues encountered in field research, but also the ways the lighting in nursing-care environments can be improved for residents.

Table 6. Lessons learned from the study protocols, procedures, and lighting/controls installation.

Lessons Learned		
1	Set standards for calculating M/P ratios or EML and CS values, so that different institutes and sites can readily compare values.	To characterize residents' light exposure at different times of day, SPDs were measured and used to calculate M/P ratios, EML, and CS values. However, there are no widely accepted ways to calculate M/P ratios; we are aware of four methods, each one based on different ways to normalize the melanopic and photopic functions. PNNL is in the process of researching this issue and plans to raise the concern with the Illuminating Engineering Society's Light and Human Health Committee.
2	Use light-colored paint and wallcovering finishes in addition to white ceilings to increase light received at the eye of the resident.	Light reflectance value (LRV) is important for painted surfaces, acoustical tiles, and wall and floor coverings, because it affects how much light is received at the eye in all spaces. At the nursing center, a low wall light reflectance of 31% in the Cherry Lane corridor contributed to horizontal light levels on the floor that were 20% lower, on average, than those of the Bamboo Lane corridor, which had 52% wall reflectance. The comparatively warm wall and floor finishes also shifted the spectrum received at the eye to a lower color temperature, suggesting that the finish selection can reduce the daytime benefit of blue-cyan-rich spectrum and increase the effectiveness of nighttime lighting.
3	Pair residents with roommates who have similar lighting and sleep preferences.	Personal preferences in multi-bed resident rooms can negatively affect the roommates. One resident's choice of sleeping with the television, table lamp, and room vanity light on produced high ambient-light levels when the resident in the adjacent bed was trying to sleep. Even with the privacy curtain drawn between the two beds, the sleeping conditions were far from dark. Second-hand light may have consequences for the health and sleep quality of the neighbor.
4	Check baseline light settings and output to ensure accuracy of any prior measurements or assumptions, before starting a study.	During baseline measurements, we measured SPD in multiple spaces and lighting modes to characterize spectral and illuminance exposure for residents over a 24-hour period prior to the intervention's start. These data showed us that the system was not delivering the CS values conveyed to us by the Sacramento Municipal Utility District. We adjusted the light-output settings to adhere to our protocol (see Appendices Appendix A). We also adjusted the time settings at the medical director's request, to keep residents awake later in the evenings so that they would be readier for sleep.

Lessons Learned		
5	Ensure that the tunable LED lighting system can be automated, and that there is a quality-assurance process in place to verify that settings are correct and remain unchanged.	During a baseline site visit, we learned that the lighting system, which was supposed to offer the capability of programming each corridor for both light output and CCT at specific times, did not, in fact, allow users to program both. While the nursing-home staff initially proposed and implemented a manual process for changing the lighting settings in the morning and evenings, we felt that the manual process was too dependent on a single individual (the facilities manager) and could also be prone to human error, so a controller from Planled was purchased for automated lighting changes. The controller was installed in mid-October 2018 on a computer in the office of the nursing center's facility manager. During a first-period visit to collect resident outcome data, we observed lights tuned to incorrect settings. Root-cause analysis helped us to determine that the most likely reason was that the computer sending control signals "went to sleep" while a key staff person was on vacation. While this likely occurred just a few days before the visit -- meaning that the lights were functioning correctly for nearly the first two months of the first period -- our data collectors asked about sleep and behaviors in the prior seven days. As a result of our uncertainty about the validity of the data we captured, we not only implemented procedures to monitor the settings and prevent any problems from recurring, but "restarted" the first period in December 2018, shortening it from four months to two months, and added a third site visit, in January 2019, to capture data reflecting a seven-day period when we were certain the lights were functioning correctly.
6	Consider using sleep as the primary outcome, since daytime lighting exposure is highly variable and may not adhere to recommended lighting levels.	Characterizing light exposure for a typical resident was difficult, since some residents remained in their rooms (usually in bed) all day; some had shared rooms (up to four residents per room); some had physical therapy or other activities during the day; some went outside; some spent time near the nursing station, where there was abundant daylight; etc. The most reliable and consistent characterization we had was the nighttime light exposure, because then the room lights were generally off, and only the light from the corridors reached residents' eyes. However, even this varied, because some residents preferred sleeping with lights on, and some rooms had light trespass from the outdoors.
7	Systematically capture information on other, concurrent initiatives that may impact the same outcomes of interest (e.g., that may affect light exposure, sleep, and agitated behaviors).	Because of the nursing-center staff's strong belief in light's importance, their leaders had started other lighting initiatives to improve residents' exposure to light. These included arranging outdoor meals for residents and writing prescriptions for "time outdoors in natural light" for several of them. The concurrent nature of these initiatives made it difficult to isolate the impact of the tunable LED lights, since the effect may have been muted by other light exposure.
8	A facility should make decisions on the settings of the lighting and control systems before implementation.	Who is in charge of the settings of the control system and its ongoing maintenance? Where should the controls reside? Who gets access to change them, and at whose direction? Is there an IT person on staff to maintain/update the software on the computer or device in question and make needed modifications?

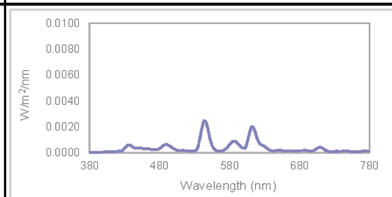
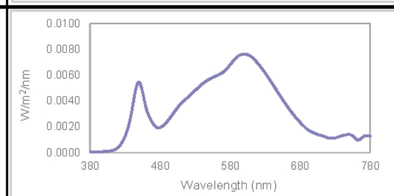
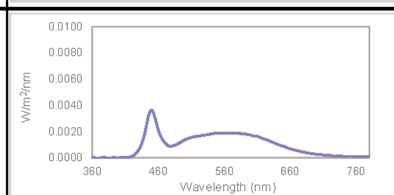
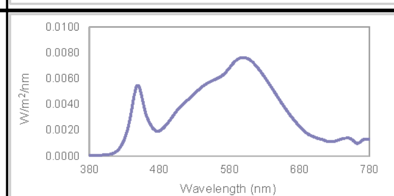
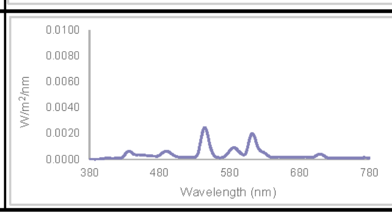
Lessons Learned		
9	Resident bedroom lighting should be capable of supporting circadian health.	Light from existing over-bed fluorescent luminaires did not provide color tuning or sufficient light levels to impact the circadian system during the day. The over-bed lighting provided both ambient up-light (typically controlled by a wall switch near the door) and downward task light (controlled by each individual resident via a pull chain). Rooms with typical over-bed lighting did not provide ceiling power outlets for additional lighting to be easily installed, to increase lighting levels or provide color-tuning.
10	Continuously illuminated lights for guiding residents to the bathroom in multi-resident bedrooms need careful design, to avoid too much light spill into sleeping areas.	The layout of the four-person bedroom located the bathroom down a short hallway. A ceiling light in the bedroom adjacent to the hallway was on all night to light the path to the bathroom and delivered excess light to one bed area. Instead, nightlights mounted low on the wall can be located within a direct line of sight of the bed and entry to the bathroom.
11	Under-bed lights that turn on when movement on the floor near the bed area is detected can provide helpful navigation light without disturbing residents, but time delays for automatic switch-off need attention.	The motion-sensor-activated nightlight provided light on the floor around the bed when the residents would get up at night, but did not stay on long enough for their return from the bathroom. The time delay after motion was detected needed to be adjusted for a longer duration. Although the CCT of the under-bed light was intended to be amber in color, a 3000 K white light product was installed instead. Amber or white light of 2700 K or lower is likely to be more supportive of good sleep, because of the reduced blue-cyan content. In this installation, floor illuminance of 2 lx was adequate to help residents and caregivers get safely to the bathroom in one- or two-bed rooms, but three- and four-bed rooms may need additional low-level nightlights.
12	Exterior lighting in the facility needs to be designed to minimize light infiltration into sleeping-area windows.	Some bedroom windows admitted stray light from streetlights and site lighting (wall packs). The existing mini-blinds were closed but did not totally block the light.

6. Appendices

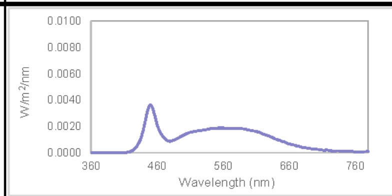
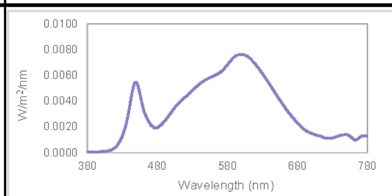
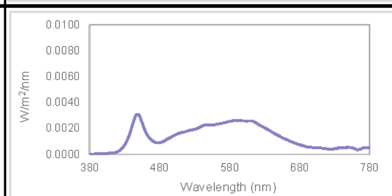
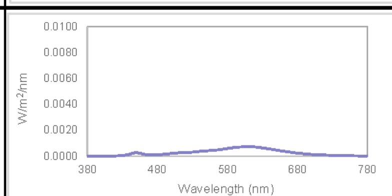
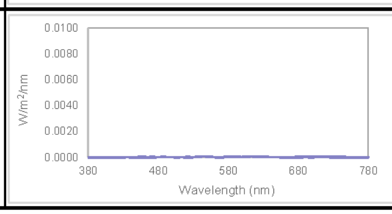
6.1 Appendix A

ACC resident light exposure data over the course of a day, for the Azalea, Bamboo, and Cherry Lane corridors. Separate tables show tunable light exposure and control light exposure. Columns show SPD, illuminance values, CCT, and three prominent metrics for health-related light exposure.

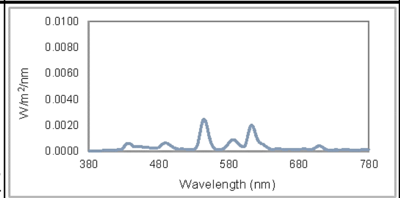
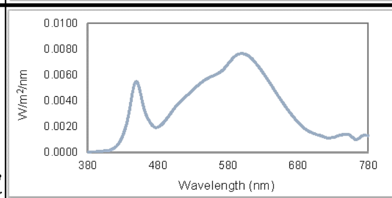
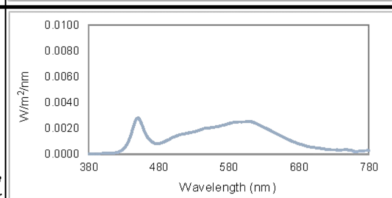
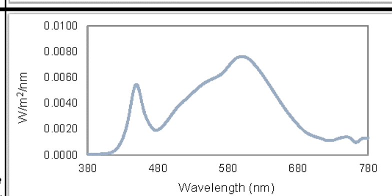
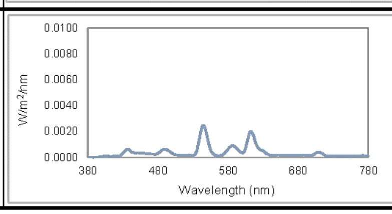
ACC Care Center
Azalea Corridor
TUNABLE

Time	Location	SPD		Illuminance (Ev) (lx)	CCT	CS (1 hr.)	M/P	EML (lx)
7:00 a.m. - 8:00 a.m. Wake Up Light Setting: 6500K at 100% in corridor	In Room *Observer seated in chair or wheelchair*		**AVG.**	48.3	4073	0.0532	0.634	29.2
			MAX	71.7	4672	0.1027	0.726	38.9
			MIN.	25.5	3483	0.0245	0.542	18.5
								n = 3
8:00 a.m. - 9:00 a.m. Breakfast Light Setting: 4100K at 100%	Dining Room *Observer seated in chair or wheelchair*		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
			MIN.	283.6	3296	0.2108	0.537	157.4
								n = 4
9:00 a.m. - 11:30 a.m. Morning Light Setting: 6500K at 100% in corridor	Corridor *Observer seated in chair or wheelchair*		**AVG.**	123.0	5764	0.1855	0.908	112.3
			MAX	163.4	5944	0.2419	0.924	151.0
			MIN.	82.5	5585	0.1290	0.891	73.6
								n = 2
11:30 a.m. - 1:30 p.m. Lunch and Activity Light Setting: 4100K at 100%	Dining Room *Observer seated in chair or wheelchair*		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
			MIN.	283.6	3296	0.2108	0.537	157.4
								n = 4
1:.30 p.m. - 2:30 p.m. Nap Light Setting: 6500K at 100% in corridor	In Room *Observer seated in chair or wheelchair*		**AVG.**	48.3	4073	0.0532	0.634	29.2
			MAX	71.7	4672	0.1027	0.726	38.9
			MIN.	25.5	3483	0.0245	0.542	18.5
								n = 3

ACC Care Center
Azalea Corridor
TUNABLE

Time	Location	SPD		Illuminance (Ev) (lx)	CCT	CS (1 hr.)	M/P	EML (lx)
2:30 p.m. - 5:00 p.m. Afternoon	Corridor		**AVG.**	123.0	5764	0.1855	0.908	112.3
			MAX	163.4	5944	0.2419	0.924	151.0
Light Setting: 6500K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	82.5	5585	0.1290	0.891	73.6
								n = 2
5:00 p.m. - 6:00 p.m. Dinner	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
6:00 p.m. - 8:00 p.m. Evening	Corridor		**AVG.**	156.8	4129	0.1506	0.696	111.9
			MAX	229.1	4325	0.2271	0.734	168.2
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	84.6	3932	0.0740	0.658	55.7
								n = 2
8:00 p.m. - 8:30 p.m. Prep for Bed	Corridor		**AVG.**	32.8	2648	0.0368	0.430	14.2
			MAX	45.2	2681	0.0517	0.435	19.7
Light Setting: 2700K at 20% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	20.3	2614	0.0218	0.425	8.6
								n = 2
8:00 p.m. - 7:00 a.m. Sleep	In Room		**AVG.**	2.1	3282	0.0015	0.603	1.3
			MAX	6.5	4197	0.0035	0.731	4.3
Light Setting: 2700K at 20% in corridor	*Observer lying in bed*		**MIN.**	0.3	2707	0.0002	0.454	0.2
								n = 5

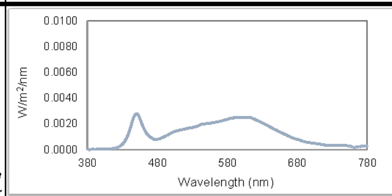
ACC Care Center
Azalea Corridor
CONTROL

Time	Location	SPD		Illuminance (Ev) (lx)	CCT	CS (1 hr.)	M/P	EML (lx)
7:00 a.m. - 8:00 a.m. Wake Up	In Room		**AVG.**	48.3	4073	0.0532	0.634	29.2
			MAX	71.7	4672	0.1027	0.726	38.9
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	25.5	3483	0.0245	0.542	18.5
								n = 3
8:00 a.m. - 9:00 a.m. Breakfast	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
9:00 a.m. - 11:30 a.m. Morning	Corridor		**AVG.**	145.2	3895	0.1340	0.697	101.5
			MAX	187.3	3966	0.1744	0.706	132.3
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	103.0	3824	0.0937	0.687	70.8
								n = 2
11:30 a.m. - 1:30 p.m. Lunch and Activity	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
1:.30 p.m. - 2:30 p.m. Nap	In Room		**AVG.**	48.3	4073	0.0532	0.634	29.2
			MAX	71.7	4672	0.1027	0.726	38.9
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	25.5	3483	0.0245	0.542	18.5
								n = 3

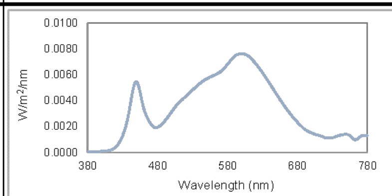
ACC Care Center
Azalea Corridor
CONTROL

<table>
<tr><th>Time</th><th>Location</th><th>SPD</th><th></th><th>Illuminance (Ev) (lx)</th><th>CCT</th><th>CS (1 hr.)</th><th>M/P</th><th>EML (lx)</th></tr>
<tr><td rowspan="4">2:30 p.m. - 5:00 p.m.
Afternoon

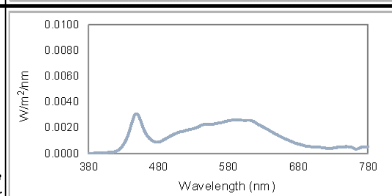
Light Setting:
4100K at 100%</td><td rowspan="4">Corridor

Observer seated in chair or wheelchair</td><td rowspan="4"></td><td>AVG.</td><td>145.2</td><td>3895</td><td>0.1340</td><td>0.697</td><td>101.5</td></tr>
<tr><td>MAX</td><td>187.3</td><td>3966</td><td>0.1744</td><td>0.706</td><td>132.3</td></tr>
<tr><td>MIN.</td><td>103.0</td><td>3824</td><td>0.0937</td><td>0.687</td><td>70.8</td></tr>
<tr><td colspan="6">n = 2</td></tr>
<tr><td rowspan="4">5:00 p.m. - 6:00 p.m.
Dinner

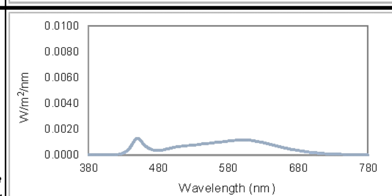
Light Setting:
4100K at 100%</td><td rowspan="4">Dining Room

Observer seated in chair or wheelchair</td><td rowspan="4"></td><td>AVG.</td><td>412.7</td><td>3446</td><td>0.3011</td><td>0.568</td><td>237.7</td></tr>
<tr><td>MAX</td><td>680.9</td><td>3689</td><td>0.3462</td><td>0.603</td><td>410.6</td></tr>
<tr><td>MIN.</td><td>283.6</td><td>3296</td><td>0.2108</td><td>0.537</td><td>157.4</td></tr>
<tr><td colspan="6">n = 4</td></tr>
<tr><td rowspan="4">6:00 p.m. - 8:00 p.m.
Evening

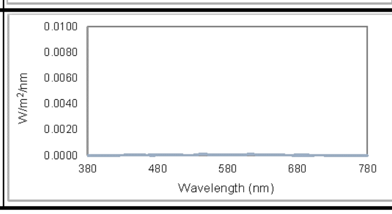
Light Setting:
4100K at 100%</td><td rowspan="4">Corridor

Observer seated in chair or wheelchair</td><td rowspan="4"></td><td>AVG.</td><td>156.8</td><td>4129</td><td>0.1506</td><td>0.696</td><td>111.9</td></tr>
<tr><td>MAX</td><td>229.1</td><td>4325</td><td>0.2271</td><td>0.734</td><td>168.2</td></tr>
<tr><td>MIN.</td><td>84.6</td><td>3932</td><td>0.0740</td><td>0.658</td><td>55.7</td></tr>
<tr><td colspan="6">n = 2</td></tr>
<tr><td rowspan="4">8:00 p.m. - 8:30 p.m.
Prep for Bed

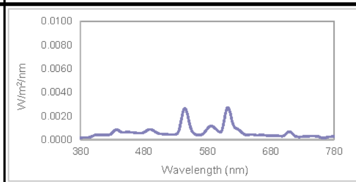
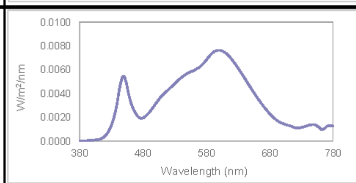
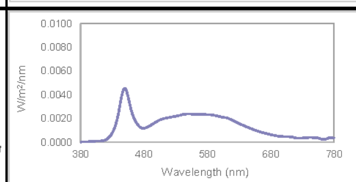
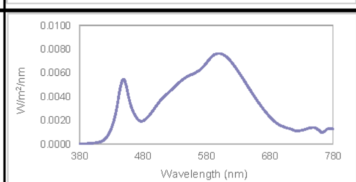
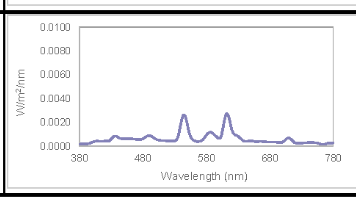
Light Setting:
4100K at 50%</td><td rowspan="4">Corridor

Observer seated in chair or wheelchair</td><td rowspan="4"></td><td>AVG.</td><td>65.1</td><td>3748</td><td>0.0593</td><td>0.671</td><td>44.4</td></tr>
<tr><td>MAX</td><td>92.9</td><td>3908</td><td>0.0895</td><td>0.696</td><td>64.6</td></tr>
<tr><td>MIN.</td><td>37.3</td><td>3589</td><td>0.0291</td><td>0.646</td><td>24.1</td></tr>
<tr><td colspan="6">n = 2</td></tr>
<tr><td rowspan="4">8:30 p.m. - 7:00 a.m.
Sleep / Rest

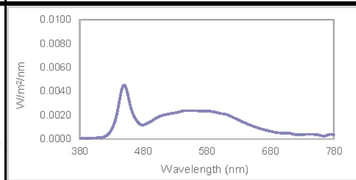
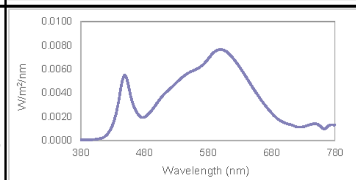
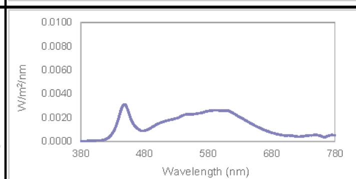
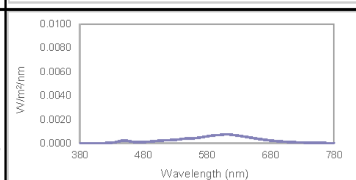
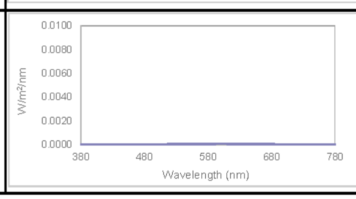
Light Setting:
4100K at 50%
in corridor</td><td rowspan="4">In Room

Observer lying in bed</td><td rowspan="4"></td><td>AVG.</td><td>3.4</td><td>3487</td><td>0.0039</td><td>0.605</td><td>2.0</td></tr>
<tr><td>MAX</td><td>10.2</td><td>3856</td><td>0.0141</td><td>0.687</td><td>5.7</td></tr>
<tr><td>MIN.</td><td>0.3</td><td>3213</td><td>0.0001</td><td>0.540</td><td>0.2</td></tr>
<tr><td colspan="6">n = 5</td></tr>
</table>

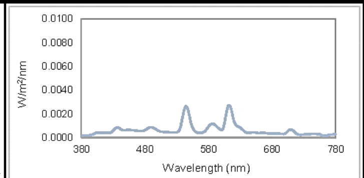
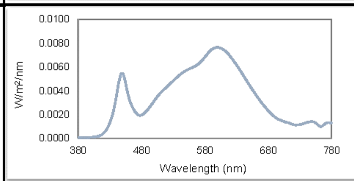
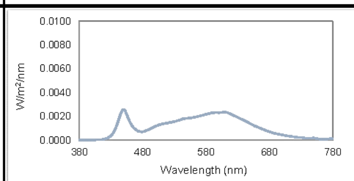
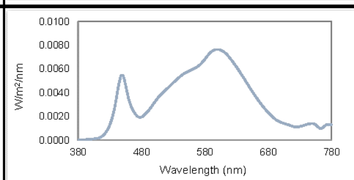
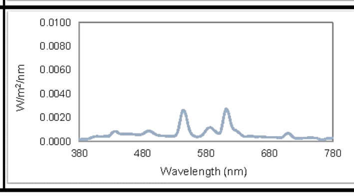
ACC Care Center
Bamboo Corridor
TUNABLE

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
7:00 a.m. - 8:00 a.m. Wake Up	In Room		**AVG.**	69.9	4000	0.1081	0.680	50.1
			MAX	88.1	5679	0.1539	0.981	86.5
Light Setting: 6500K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	53.0	3141	0.0818	0.487	30.4
								n = 3
8:00 a.m. - 9:00 a.m. Breakfast	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
9:00 a.m. - 11:30 a.m. Morning	Corridor		**AVG.**	155.5	5855	0.2304	0.923	143.7
			MAX	181.6	5933	0.2623	0.930	168.9
Light Setting: 6500K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	129.5	5777	0.1985	0.915	118.5
								n = 2
11:30 a.m. - 1:30 p.m. Lunch and Activity	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
1::30 p.m. - 2:30 p.m. Nap	In Room		**AVG.**	69.9	4000	0.1081	0.680	50.1
			MAX	88.1	5679	0.1539	0.981	86.5
Light Setting: 6500K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	53.0	3141	0.0818	0.487	30.4
								n = 3

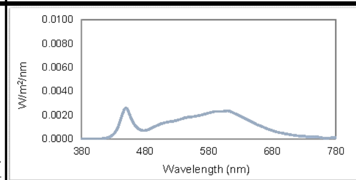
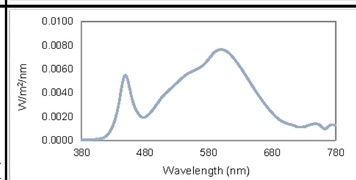
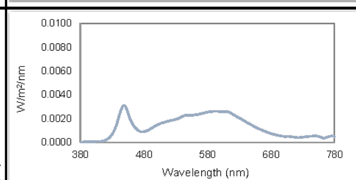
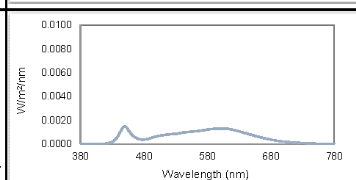
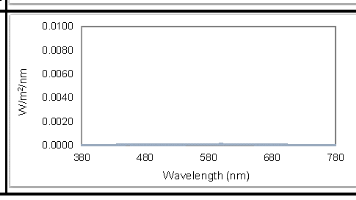
ACC Care Center
Bamboo Corridor
TUNABLE

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
2:30 p.m. - 5:00 p.m. Afternoon	Corridor		**AVG.**	155.5	5855	0.2304	0.923	143.7
			MAX	181.6	5933	0.2623	0.930	168.9
Light Setting: 6500K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	129.5	5777	0.1985	0.915	118.5
								n = 2
5:00 p.m. - 6:00 p.m. Dinner	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
6:00 p.m. - 8:00 p.m. Evening	Corridor		**AVG.**	156.8	4129	0.1506	0.696	111.9
			MAX	229.1	4325	0.2271	0.734	168.2
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	84.6	3932	0.0740	0.658	55.7
								n = 2
8:00 p.m. - 8:30 p.m. Prep for Bed	Corridor		**AVG.**	31.8	2555	0.0338	0.407	13.1
			MAX	43.7	2627	0.0484	0.423	18.5
Light Setting: 2700K at 20% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	19.8	2483	0.0192	0.390	7.7
								n = 2
8:00 p.m. - 7:00 a.m. Sleep / Rest	In Room		**AVG.**	3.1	2811	0.0034	0.472	1.5
			MAX	4.9	3382	0.0049	0.584	2.2
Light Setting: 2700K at 20% in corridor	*Observer lying in bed*		**MIN.**	0.9	2396	0.0007	0.389	0.4
								n = 3

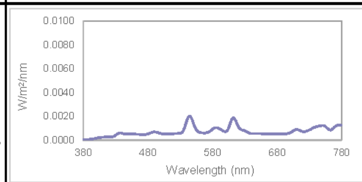
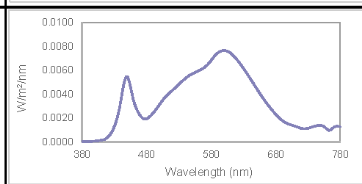
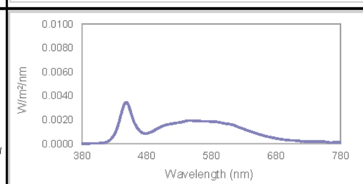
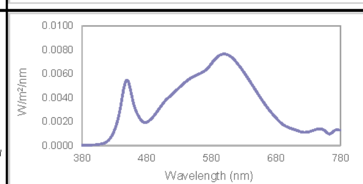
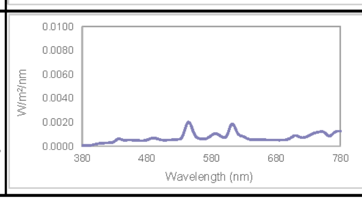
ACC Care Center
Bamboo Corridor
CONTROL

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
7:00 a.m. - 8:00 a.m. Wake Up	In Room		**AVG.**	69.9	4000	0.1081	0.680	50.1
			MAX	88.1	5679	0.1539	0.981	86.5
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	53.0	3141	0.0818	0.487	30.4
								n = 3
8:00 a.m. - 9:00 a.m. Breakfast	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
9:00 a.m. - 11:30 a.m. Morning	Corridor		**AVG.**	132.5	3820	0.1205	0.685	91.2
			MAX	175.3	3898	0.1611	0.696	122.0
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	89.8	3742	0.0798	0.673	60.4
								n = 2
11:30 a.m. - 1:30 p.m. Lunch and Activity	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
1:30 p.m. - 2:30 p.m. Nap	In Room		**AVG.**	69.9	4000	0.1081	0.680	50.1
			MAX	88.1	5679	0.1539	0.981	86.5
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	53.0	3141	0.0818	0.487	30.4
								n = 3

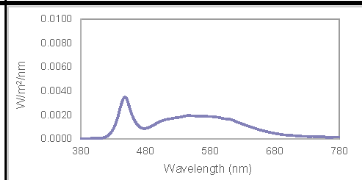
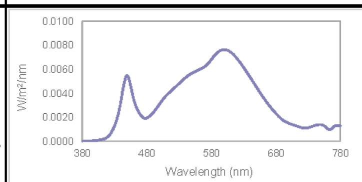
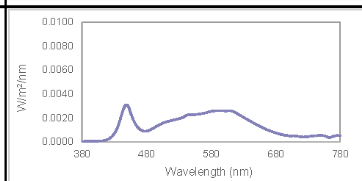
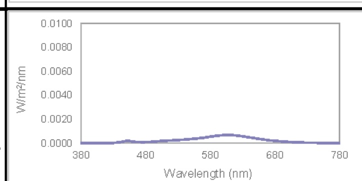
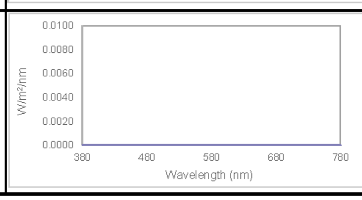
ACC Care Center
Bamboo Corridor
CONTROL

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
2:30 p.m. - 5:00 p.m. Afternoon	Corridor		AVG.	132.5	3820	0.1205	0.685	91.2
			MAX	175.3	3898	0.1611	0.696	122.0
			MIN.	89.8	3742	0.0798	0.673	60.4
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*							*n = 2*
5:00 p.m. - 6:00 p.m. Dinner	Dining Room		AVG.	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
			MIN.	283.6	3296	0.2108	0.537	157.4
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*							*n = 4*
6:00 p.m. - 8:00 p.m. Evening	Corridor		AVG.	156.8	4129	0.1506	0.696	111.9
			MAX	229.1	4325	0.2271	0.734	168.2
			MIN.	84.6	3932	0.0740	0.658	55.7
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*							*n = 2*
8:00 p.m. - 8:30 p.m. Prep for Bed	Corridor		AVG.	73.2	3801	0.0680	0.678	50.1
			MAX	97.1	3938	0.0949	0.699	67.9
			MIN.	49.2	3665	0.0411	0.657	32.4
Light Setting: 4100K at 50%	*Observer seated in chair or wheelchair*							*n = 2*
8:30 p.m. - 7:00 a.m. Sleep / Rest	In Room		AVG.	4.8	3268	0.0031	0.582	3.0
			MAX	8.4	3719	0.0044	0.681	5.7
			MIN.	2.6	2845	0.0022	0.498	1.3
Light Setting: 4100K at 50% in corridor	*Observer lying in bed*							*n = 3*

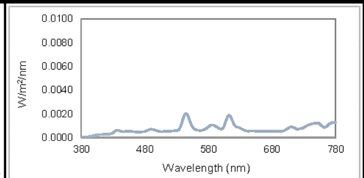
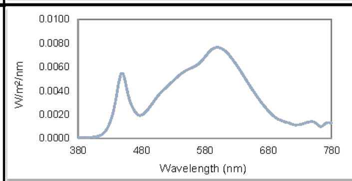
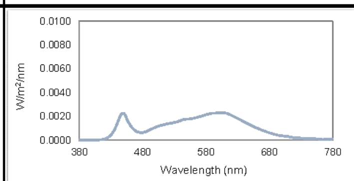
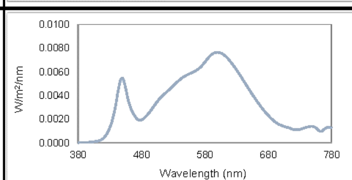
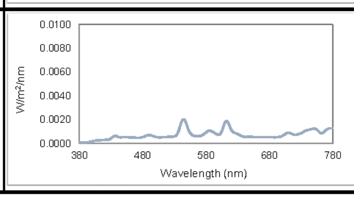
ACC Care Center
Cherry Corridor
TUNABLE

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
7:00 a.m. - 8:00 a.m. Wake Up Light Setting: 6500K at 100% in corridor	In Room *Observer seated in chair or wheelchair*		**AVG.**	65.9	4062	0.0661	0.641	42.2
			MAX	163.0	5633	0.1321	0.694	107.4
			MIN.	13.2	3137	0.0103	0.437	8.7
								n = 9
8:00 a.m. - 9:00 a.m. Breakfast Light Setting: 4100K at 100%	Dining Room *Observer seated in chair or wheelchair*		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
			MIN.	283.6	3296	0.2108	0.537	157.4
								n = 4
9:00 a.m. - 11:30 a.m. Morning Light Setting: 6500K at 100% in corridor	Corridor *Observer seated in chair or wheelchair*		**AVG.**	124.3	5816.8	0.1855	0.895	111.8
			MAX	185.0	6000.6	0.2629	0.912	168.7
			MIN.	72.4	5584.9	0.1123	0.877	63.5
								n = 4
11:30 a.m. - 1:30 p.m. Lunch and Activity Light Setting: 4100K at 100%	Dining Room *Observer seated in chair or wheelchair*		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
			MIN.	283.6	3296	0.2108	0.537	157.4
								n = 4
1:.30 p.m. - 2:30 p.m. Nap Light Setting: 6500K at 100% in corridor	In Room *Observer seated in chair or wheelchair*		**AVG.**	65.9	4062	0.0661	0.641	42.2
			MAX	163.0	5633	0.1321	0.694	107.4
			MIN.	13.2	3137	0.0103	0.437	8.7
								n = 9

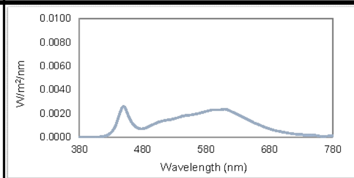
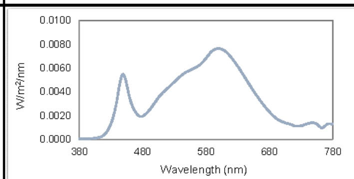
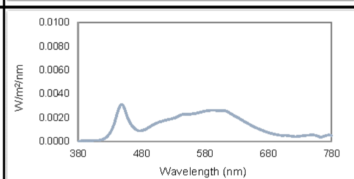
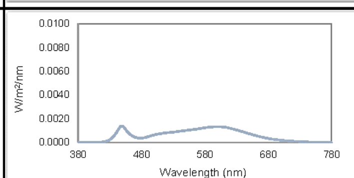
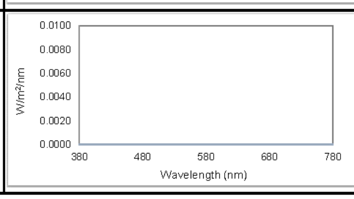
ACC Care Center
Cherry Corridor
TUNABLE

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
2:30 p.m. - 5:00 p.m. Afternoon	Corridor		**AVG.**	124.3	5817	0.1855	0.895	111.8
			MAX	185.0	6001	0.2629	0.912	168.7
Light Setting: 6500K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	72.4	5585	0.1123	0.877	63.5
								n = 4
5:00 p.m. - 6:00 p.m. Dinner	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
6:00 p.m. - 8:00 p.m. Evening	Corridor		**AVG.**	156.8	4129	0.1506	0.696	111.9
			MAX	229.1	4325	0.2271	0.734	168.2
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	84.6	3932	0.0740	0.658	55.7
								n = 2
8:00 p.m. - 8:30 p.m. Prep for Bed	Corridor		**AVG.**	29.2	2526	0.0296	0.393	11.6
			MAX	49.4	2575	0.0521	0.404	19.9
Light Setting: 2700K at 20% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	16.6	2479	0.0160	0.382	6.5
								n = 5
8:00 p.m. - 7:00 a.m. Sleep / Rest	In Room		**AVG.**	0.8	2483	0.0005	0.387	0.3
			MAX	1.6	2665	0.0011	0.409	0.6
Light Setting: 2700K at 20% in corridor	*Observer lying in bed*		**MIN.**	0.3	2415	0.0002	0.360	0.1
								n = 4

ACC Care Center
Cherry Corridor
CONTROL

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
7:00 a.m. - 8:00 a.m. Wake Up	In Room		**AVG.**	65.9	4062	0.0661	0.641	42.2
			MAX	163.0	5633	0.1321	0.694	107.4
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	13.2	3137	0.0103	0.437	8.7
								n = 9
8:00 a.m. - 9:00 a.m. Breakfast	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
9:00 a.m. - 11:30 a.m. Morning	Corridor		**AVG.**	127.5	3708	0.1061	0.652	84.2
			MAX	211.3	3852	0.1803	0.676	142.8
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	59.8	3565	0.0441	0.627	37.5
								n = 4
11:30 a.m. - 1:30 p.m. Lunch and Activity	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*		**MIN.**	283.6	3296	0.2108	0.537	157.4
								n = 4
1:30 p.m. - 2:30 p.m. Nap	In Room		**AVG.**	65.9	4062	0.0661	0.641	42.2
			MAX	163.0	5633	0.1321	0.694	107.4
Light Setting: 4100K at 100% in corridor	*Observer seated in chair or wheelchair*		**MIN.**	13.2	3137	0.0103	0.437	8.7
								n = 9

ACC Care Center
Cherry Corridor
CONTROL

Time	Location	SPD		Illuminance (Ev) (lx)	CCT (°K)	CS (1 hr.)	M/P	EML (lx)
2:30 p.m. - 5:00 p.m. Afternoon	Corridor		**AVG.**	127.5	3708	0.1061	0.652	84.2
			MAX	211.3	3852	0.1803	0.676	142.8
			MIN.	59.8	3565	0.0441	0.627	37.5
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*							*n = 4*
5:00 p.m. - 6:00 p.m. Dinner	Dining Room		**AVG.**	412.7	3446	0.3011	0.568	237.7
			MAX	680.9	3689	0.3462	0.603	410.6
			MIN.	283.6	3296	0.2108	0.537	157.4
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*							*n = 4*
6:00 p.m. - 8:00 p.m. Evening	Corridor		**AVG.**	156.8	4129	0.1506	0.696	111.9
			MAX	229.1	4325	0.2271	0.734	168.2
			MIN.	84.6	3932	0.0740	0.658	55.7
Light Setting: 4100K at 100%	*Observer seated in chair or wheelchair*							*n = 2*
8:00 p.m. - 8:30 p.m. Prep for Bed	Corridor		**AVG.**	73.3	3770	0.0640	0.664	48.9
			MAX	122.6	3882	0.1118	0.680	83.4
			MIN.	45.4	3622	0.0382	0.637	30.6
Light Setting: 4100K at 50%	*Observer seated in chair or wheelchair*							*n = 4*
8:30 p.m. - 7:00 a.m. Sleep / Rest	In Room		**AVG.**	0.9	3343	0.0005	0.615	0.5
			MAX	1.0	3504	0.0010	0.621	0.6
			MIN.	0.7	3198	0.0003	0.608	0.4
Light Setting: 4100K at 50% in corridor	*Observer lying in bed*							*n = 4*

6.2 Appendix B

The calculation of M/P ratios, using the procedures documented in the WELL Building Standard v2 Q2 2019.

The WELL Building Standard provides a downloadable Excel file to calculate M/P ratios. This Excel calculator utilizes an equal energy spectrum to equate the melanopic sensitivity curve and photopic sensitivity curve. All five photoreceptors, the equal energy spectrum, and the photopic sensitivity curve are illustrated in Figure 18, left. A sample measurement captured during nighttime conditions is also shown with melanopic and photopic sensitivity curves (Figure 18, right). Multiple captured SPD measurements, in 5 nm increments, can be entered into the tool for calculation. A sample calculation is shown in Table 7.

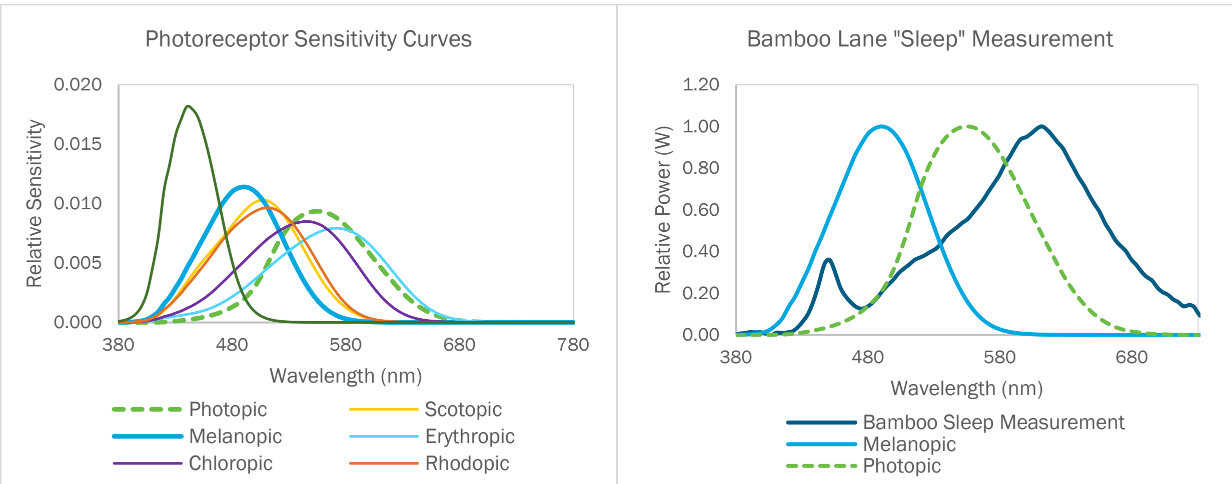


Figure 18. Five photoreceptor sensitivity curves, each shown to equal 1 W of radiant energy under the equal energy spectrum. The photopic sensitivity curve is shown here as well (left). A sample measurement taken during nighttime lighting conditions is shown with melanopic and photopic sensitivity curves overlaid (right).

Table 7. A sample M/P ratio calculation as specified in the WELL Building v2 Q2 2019 calculator. Captured measurement data are displayed in 5 nm increments, followed by tabulated melanopic and photopic sensitivity curves. The measurement data are multiplied by each of these functions to obtain weighted values representing the melanopic and photopic stimulus present in the measured SPD. These values are then divided, and that result is multiplied by an equal energy constant to obtain the final M/P ratio.

Sample M/P Ratio Calculation, WELL Building v2 Q2 2019 Standard					
λ (nm)	Measurement Data	Melanopic	Measurement * Melanopic	Photopic	Measurement * Photopic
380	2.57E-07	9.18E-04	2.36E-10	4.00E-05	1.03E-11
385	9.09E-07	1.67E-03	1.51E-09	6.00E-05	5.45E-11
390	1.47E-06	3.09E-03	4.56E-09	1.20E-04	1.77E-10
395	1.37E-06	5.88E-03	8.03E-09	2.17E-04	2.96E-10
400	1.26E-06	1.14E-02	1.44E-08	4.00E-04	5.02E-10
405	9.87E-08	2.28E-02	2.25E-09	6.40E-04	6.32E-11
410	1.06E-06	4.62E-02	4.91E-08	1.21E-03	1.29E-09
415	1.03E-06	7.95E-02	8.19E-08	2.18E-03	2.25E-09
420	1.46E-06	1.37E-01	2.00E-07	4.00E-03	5.84E-09
425	3.01E-06	1.87E-01	5.62E-07	7.30E-03	2.19E-08
λ (nm)	Measurement Data	Melanopic	Measurement * Melanopic	Photopic	Measurement * Photopic
430	6.65E-06	2.54E-01	1.69E-06	1.16E-02	7.72E-08
435	1.18E-05	3.21E-01	3.77E-06	1.68E-02	1.98E-07
440	2.08E-05	4.02E-01	8.36E-06	2.30E-02	4.79E-07
445	3.31E-05	4.74E-01	1.57E-05	2.98E-02	9.86E-07
450	3.98E-05	5.54E-01	2.20E-05	3.80E-02	1.51E-06
455	3.31E-05	6.30E-01	2.08E-05	4.80E-02	1.59E-06
460	2.36E-05	7.08E-01	1.67E-05	6.00E-02	1.42E-06
465	1.86E-05	7.85E-01	1.46E-05	7.39E-02	1.38E-06
470	1.53E-05	8.60E-01	1.32E-05	9.10E-02	1.39E-06
475	1.39E-05	9.18E-01	1.27E-05	1.13E-01	1.56E-06
480	1.52E-05	9.66E-01	1.46E-05	1.39E-01	2.11E-06
485	1.82E-05	9.91E-01	1.80E-05	1.69E-01	3.08E-06
490	2.24E-05	1.00E+00	2.24E-05	2.08E-01	4.66E-06
495	2.63E-05	9.92E-01	2.61E-05	2.59E-01	6.81E-06
500	2.99E-05	9.66E-01	2.88E-05	3.23E-01	9.64E-06
505	3.38E-05	9.22E-01	3.11E-05	4.07E-01	1.38E-05
510	3.65E-05	8.63E-01	3.15E-05	5.03E-01	1.84E-05
515	3.94E-05	7.85E-01	3.10E-05	6.08E-01	2.40E-05
520	4.10E-05	7.00E-01	2.87E-05	7.10E-01	2.91E-05
525	4.29E-05	6.09E-01	2.61E-05	7.93E-01	3.40E-05
530	4.48E-05	5.19E-01	2.33E-05	8.62E-01	3.87E-05
535	4.80E-05	4.33E-01	2.08E-05	9.15E-01	4.39E-05
540	5.26E-05	3.52E-01	1.85E-05	9.54E-01	5.02E-05
545	5.55E-05	2.79E-01	1.55E-05	9.80E-01	5.44E-05
550	5.83E-05	2.16E-01	1.26E-05	9.95E-01	5.80E-05
555	6.08E-05	1.62E-01	9.86E-06	1.00E+00	6.08E-05
560	6.49E-05	1.19E-01	7.69E-06	9.95E-01	6.45E-05
565	6.92E-05	8.43E-02	5.84E-06	9.79E-01	6.77E-05

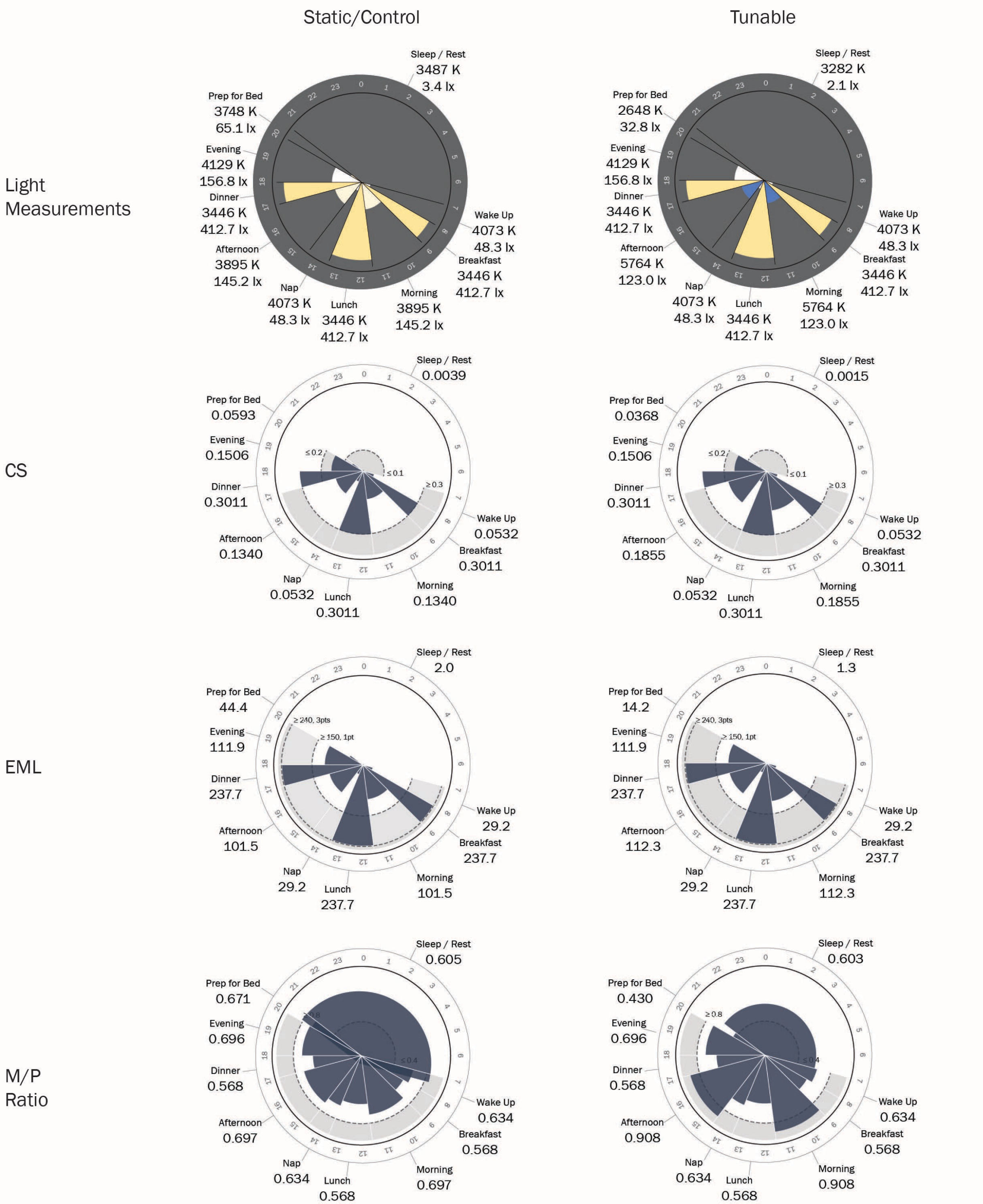
570	7.42E-05	5.87E-02	4.36E-06	9.52E-01	7.06E-05
575	7.95E-05	4.00E-02	3.18E-06	9.15E-01	7.28E-05
580	8.49E-05	2.69E-02	2.28E-06	8.70E-01	7.39E-05
585	9.15E-05	1.79E-02	1.63E-06	8.16E-01	7.47E-05
590	9.73E-05	1.18E-02	1.15E-06	7.57E-01	7.37E-05
595	1.03E-04	7.73E-03	7.94E-07	6.95E-01	7.14E-05
600	1.04E-04	5.07E-03	5.29E-07	6.31E-01	6.59E-05
605	1.07E-04	3.32E-03	3.55E-07	5.67E-01	6.07E-05
610	1.10E-04	2.18E-03	2.39E-07	5.03E-01	5.52E-05
615	1.09E-04	1.43E-03	1.56E-07	4.41E-01	4.79E-05
620	1.05E-04	9.47E-04	9.92E-08	3.81E-01	3.99E-05
625	1.01E-04	6.28E-04	6.31E-08	3.21E-01	3.23E-05
630	9.54E-05	4.18E-04	3.99E-08	2.65E-01	2.53E-05
635	8.90E-05	2.80E-04	2.49E-08	2.17E-01	1.93E-05
640	8.26E-05	1.88E-04	1.56E-08	1.75E-01	1.45E-05
645	7.71E-05	1.27E-04	9.81E-09	1.38E-01	1.06E-05
650	7.08E-05	8.66E-05	6.13E-09	1.07E-01	7.57E-06
655	6.54E-05	5.92E-05	3.87E-09	8.16E-02	5.34E-06
λ (nm)	Measurement Data	Melanopic	Measurement * Melanopic	Photopic	Measurement * Photopic
660	5.84E-05	4.07E-05	2.38E-09	6.10E-02	3.56E-06
665	5.28E-05	2.81E-05	1.48E-09	4.46E-02	2.35E-06
670	4.79E-05	1.96E-05	9.37E-10	3.20E-02	1.53E-06
675	4.45E-05	1.36E-05	6.07E-10	2.32E-02	1.03E-06
680	3.93E-05	9.58E-06	3.77E-10	1.70E-02	6.68E-07
685	3.54E-05	6.75E-06	2.39E-10	1.19E-02	4.22E-07
690	3.13E-05	4.79E-06	1.50E-10	8.21E-03	2.57E-07
695	2.88E-05	3.41E-06	9.83E-11	5.72E-03	1.65E-07
700	2.44E-05	2.44E-06	5.95E-11	4.10E-03	1.00E-07
705	2.20E-05	1.75E-06	3.85E-11	2.93E-03	6.43E-08
710	1.95E-05	1.75E-06	3.41E-11	1.46E-03	2.85E-08
715	1.74E-05	1.75E-06	3.05E-11	7.32E-04	1.27E-08
720	1.51E-05	1.75E-06	2.65E-11	3.66E-04	5.54E-09
725	1.56E-05	1.75E-06	2.74E-11	1.83E-04	2.86E-09
730	1.16E-05	1.75E-06	2.03E-11	9.15E-05	1.06E-09
Total			5.18E-04 (M)		1.43E-03 (P)

M/P =5.18E-04/1.43E-03 = 0.363 * 1.218 (EE constant) = **0.442**

6.3 Appendix C

ACC-resident light exposure and metric correlation over the course of a day for Azalea, Bamboo, and Cherry Lane corridors. In the top row of each page, radial plots show measured light color and intensity values over a 24-hour period for tunable and static/control conditions. Below these are plots showing the 24-hour measured light exposures as evaluated with CS, M/P, and EML. In all plots, distance from the center of the circle demonstrates intensity or an increase in value, where the center of the circle is 0. Dashed lines correspond to design target values being tested in the lighting community for healthy circadian rhythms or alertness.

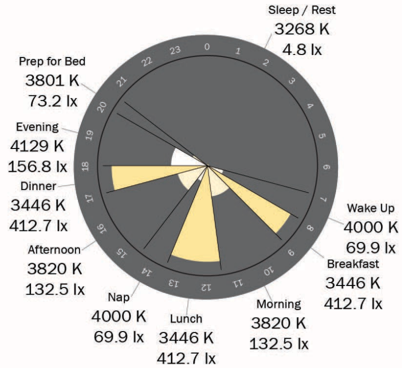
Azalea Lane

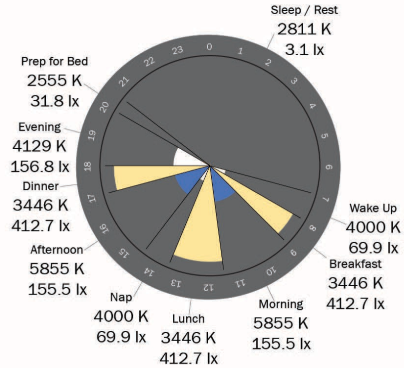

Static/Control
Tunable
Light Measurements
Sleep / Rest 3487 K 3.4 lx
Prep for Bed 3748 K 65.1 lx
Evening 4129 K 156.8 lx
Dinner 3446 K 412.7 lx
Afternoon 3895 K 145.2 lx
Nap 4073 K 48.3 lx
Lunch 3446 K 412.7 lx
Morning 3895 K 145.2 lx
Breakfast 3446 K 412.7 lx
Wake Up 4073 K 48.3 lx
Sleep / Rest 3282 K 2.1 lx
Prep for Bed 2648 K 32.8 lx
Evening 4129 K 156.8 lx
Dinner 3446 K 412.7 lx
Afternoon 5764 K 123.0 lx
Nap 4073 K 48.3 lx
Lunch 3446 K 412.7 lx
Morning 5764 K 123.0 lx
Breakfast 3446 K 412.7 lx
Wake Up 4073 K 48.3 lx
CS
Sleep / Rest 0.0039
Prep for Bed 0.0593
Evening 0.1506
Dinner 0.3011
Afternoon 0.1340
Nap 0.0532
Lunch 0.3011
Morning 0.1340
Breakfast 0.3011
Wake Up 0.0532
≤ 0.2
≤ 0.1
≥ 0.3
Sleep / Rest 0.0015
Prep for Bed 0.0368
Evening 0.1506
Dinner 0.3011
Afternoon 0.1855
Nap 0.0532
Lunch 0.3011
Morning 0.1855
Breakfast 0.3011
Wake Up 0.0532
EML
Sleep / Rest 2.0
Prep for Bed 44.4
Evening 111.9
Dinner 237.7
Afternoon 101.5
Nap 29.2
Lunch 237.7
Morning 101.5
Breakfast 237.7
Wake Up 29.2
≥ 240, 3pts
≥ 150, 1pt
Sleep / Rest 1.3
Prep for Bed 14.2
Evening 111.9
Dinner 237.7
Afternoon 112.3
Nap 29.2
Lunch 237.7
Morning 112.3
Breakfast 237.7
Wake Up 29.2
M/P Ratio
Sleep / Rest 0.605
Prep for Bed 0.671
Evening 0.696
Dinner 0.568
Afternoon 0.697
Nap 0.634
Lunch 0.568
Morning 0.697
Breakfast 0.568
Wake Up 0.634
≤ 0.4
Sleep / Rest 0.603
Prep for Bed 0.430
Evening 0.696
Dinner 0.568
Afternoon 0.908
Nap 0.634
Lunch 0.568
Morning 0.908
Breakfast 0.568
Wake Up 0.634
≥ 0.8
≤ 0.4

Bamboo Lane

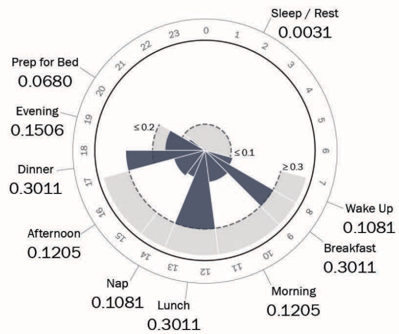
Static/Control | Tunable

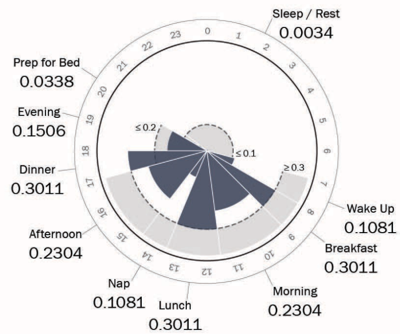
Light Measurements



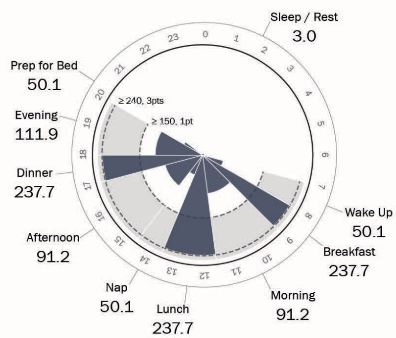


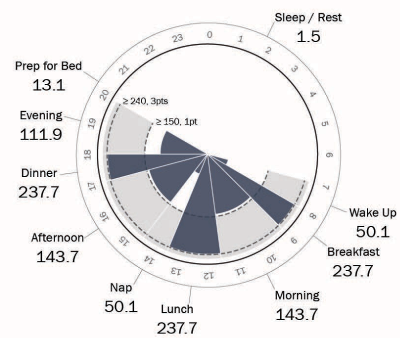
CS



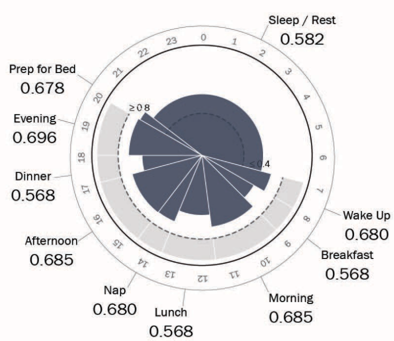


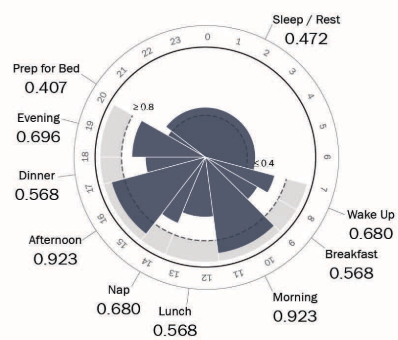
EML



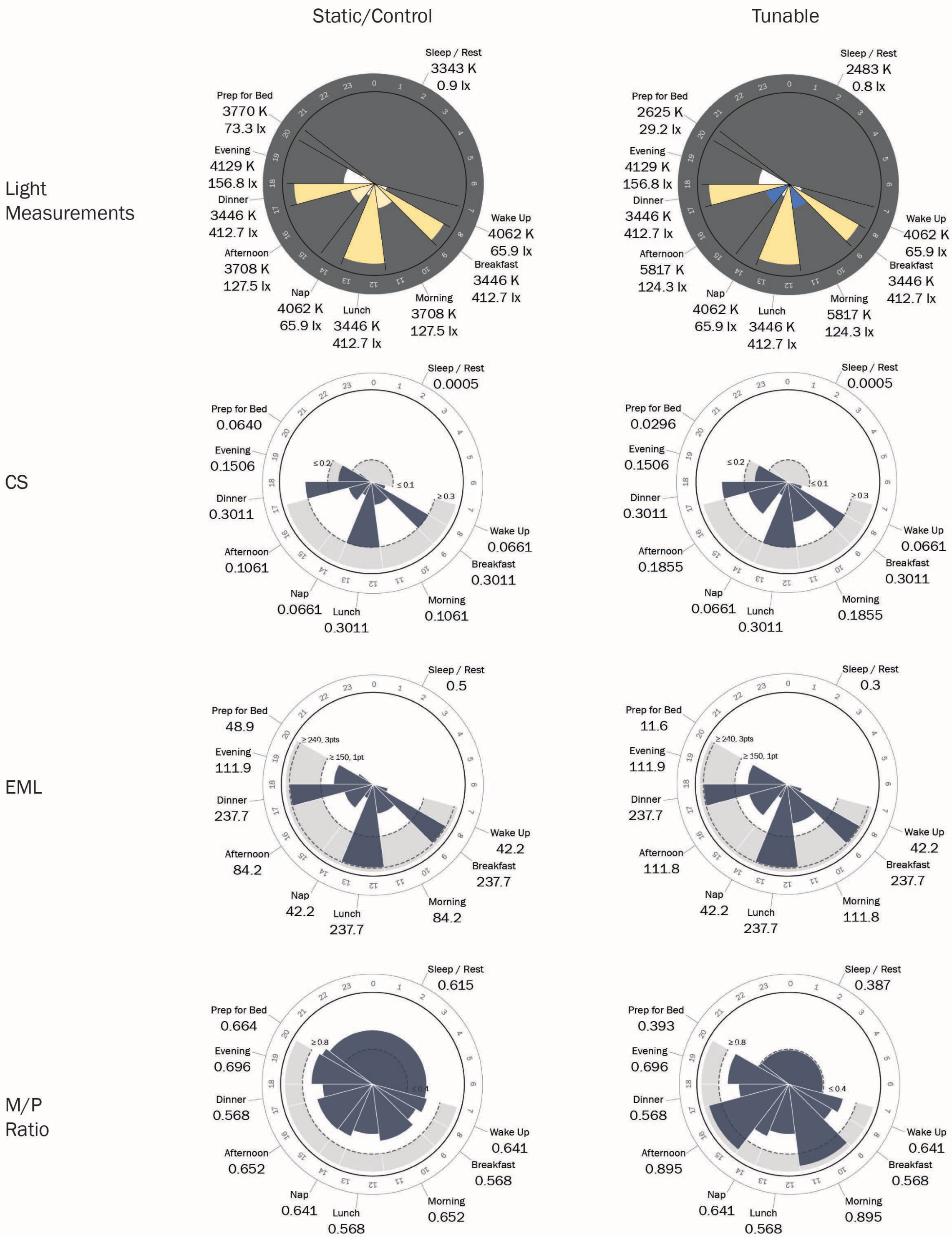


M/P Ratio





Cherry Lane



Static/Control
Tunable
Light Measurements
CS
EML
M/P Ratio
Sleep / Rest
3343 K
0.9 lx
Prep for Bed
3770 K
73.3 lx
Evening
4129 K
156.8 lx
Dinner
3446 K
412.7 lx
Afternoon
3708 K
127.5 lx
Nap
4062 K
65.9 lx
Lunch
3446 K
412.7 lx
Morning
3708 K
127.5 lx
Breakfast
3446 K
412.7 lx
Wake Up
4062 K
65.9 lx
Sleep / Rest
2483 K
0.8 lx
Prep for Bed
2625 K
29.2 lx
Evening
4129 K
156.8 lx
Dinner
3446 K
412.7 lx
Afternoon
5817 K
124.3 lx
Nap
4062 K
65.9 lx
Lunch
3446 K
412.7 lx
Morning
5817 K
124.3 lx
Breakfast
3446 K
412.7 lx
Wake Up
4062 K
65.9 lx
Sleep / Rest
0.0005
Prep for Bed
0.0640
Evening
0.1506
Dinner
0.3011
Afternoon
0.1061
Nap
0.0661
Lunch
0.3011
Morning
0.1061
Breakfast
0.3011
Wake Up
0.0661
≤ 0.2
≤ 0.1
≥ 0.3
Sleep / Rest
0.0005
Prep for Bed
0.0296
Evening
0.1506
Dinner
0.3011
Afternoon
0.1855
Nap
0.0661
Lunch
0.3011
Morning
0.1855
Breakfast
0.3011
Wake Up
0.0661
Sleep / Rest
0.5
Prep for Bed
48.9
Evening
111.9
Dinner
237.7
Afternoon
84.2
Nap
42.2
Lunch
237.7
Morning
84.2
Breakfast
237.7
Wake Up
42.2
≥ 240, 3pts
≥ 150, 1pt
Sleep / Rest
0.3
Prep for Bed
11.6
Evening
111.9
Dinner
237.7
Afternoon
111.8
Nap
42.2
Lunch
237.7
Morning
111.8
Breakfast
237.7
Wake Up
42.2
Sleep / Rest
0.615
Prep for Bed
0.664
Evening
0.696
Dinner
0.568
Afternoon
0.652
Nap
0.641
Lunch
0.568
Morning
0.652
Breakfast
0.568
Wake Up
0.641
≥ 0.8
≤ 0.4
Sleep / Rest
0.387
Prep for Bed
0.393
Evening
0.696
Dinner
0.568
Afternoon
0.895
Nap
0.641
Lunch
0.568
Morning
0.895
Breakfast
0.568
Wake Up
0.641

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