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Lighting in Senior Care Centers:

Comparing Tunable LED Systems to Conventional Lighting Systems in Four Senior Care Centers

March 2022

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Kate Wates, Oak Ridge Care Center

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Executive Summary

Lighting for senior care spaces not only provides for the demanding visual needs of the residents and care givers, but it can also play a role in supporting healthy sleep and wake cycles. Exposure to light, especially short-wavelength light, at high light levels during the day can help support normal sleep-wake cycles, while exposure to that same lighting during the evening or at night can disrupt this natural cycle.

The characteristics of light exposure received throughout a 24-hour cycle may influence sleep-wake cycles for the general population as well as for residents of senior care facilities, where disturbed sleep patterns are common and time spent outdoors is often limited. Further, normal aging processes and common ailments, such as Alzheimer’s disease, can also contribute to disruptions in the normal sleep-wake cycles, increasing the need to understand appropriate lighting conditions for senior populations.

This study was initiated to contribute to evidence-based practices for tunable light-emitting diode (LED) lighting upgrades in the future. The report summarizes Pacific Northwest National Laboratory (PNNL) evaluations of lighting conditions in four senior care centers in Wisconsin including energy savings analysis and non-image forming (NIF) response metric calculations.

Two of the care centers received lighting system upgrades that included the installation of white-tunable LED systems in common areas (e.g., corridors, dining rooms, activity rooms). The other two facilities had older, traditional fluorescent lighting systems and served as control locations. The tunable lighting systems provided a dynamic 24-hour schedule, delivering bright, cool morning light and warm, dim evening light, as shown in Figure ES-1, compared to the static light level and color provided by older fluorescent lighting.

Overall, the LED retrofits resulted in more than a 60% lighting energy use reduction, and greater energy savings were realized through a dimming schedule used to create an environment intended to support restful sleep. In the corridors and dining rooms, energy savings were even higher, at 79% compared to the fluorescent systems. Figure ES-2 shows the energy savings from just the LED conversion (green bars) and the additional savings from LED dimming (blue bars) for each area.

White-tunable LED lighting systems provide new opportunities for controlling the intensity, distribution, and spectrum of light sources that enable adjustments to the luminous environment and are much easier to implement compared to conventional fluorescent lighting technologies. Updating senior care centers to take advantage of the energy efficiency and potential benefits of tunable lighting to occupant well-being may be an important part of the future of senior care. However, incorporating newer technology into older care centers poses financial and practical constraints that can limit the effectiveness of the final solution. Tunable lighting systems can pose such a challenge when they are installed as a retrofit or renovation of an existing care center and are integrated with the existing electrical and control infrastructure.

The study was initiated by Midwest Lighting Institute (MLI). Staff from Energy Performance Lighting (EPL) coordinated and completed the design and installation of the LED systems, based on research completed by MLI and prior experience with other nursing home lighting upgrades. PNNL measured the tunable lighting system performance, calculated the energy implications of the retrofit solutions, and characterized resident light exposure over a hypothetical 24-hour schedule.

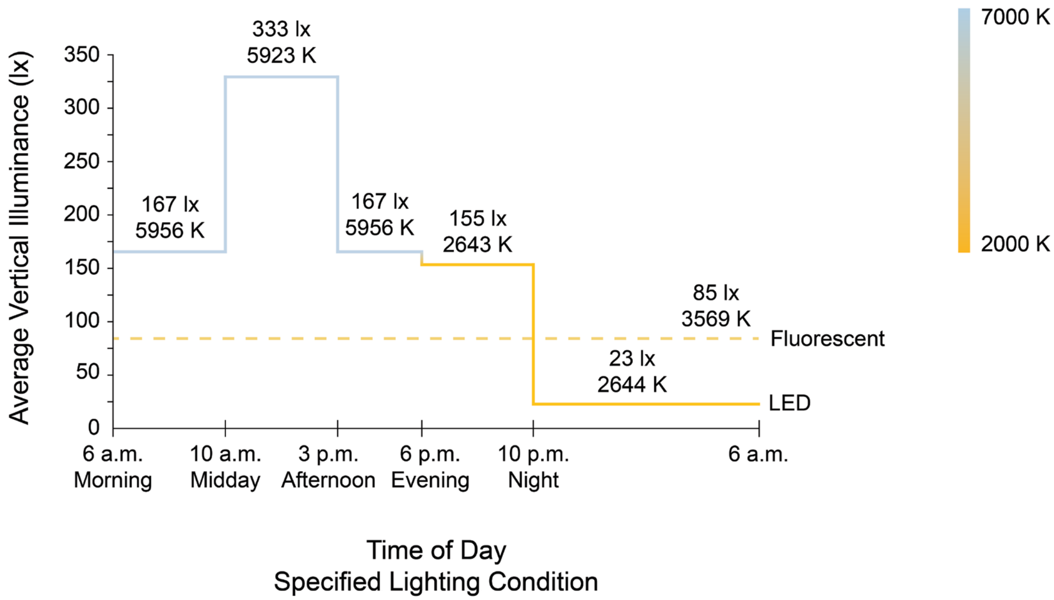

Figure ES-1. Average vertical illuminance and correlated color temperature (CCT) at eye positions in the activity rooms in two care centers. Compared to the traditional fluorescent lighting system (dashed line), the tunable lighting system (solid line) provided a dynamic lighting schedule over a 24-hour period with bright, cool daytime exposure and warm, dim nighttime exposure. The colors of the lines correspond to the measured CCT.

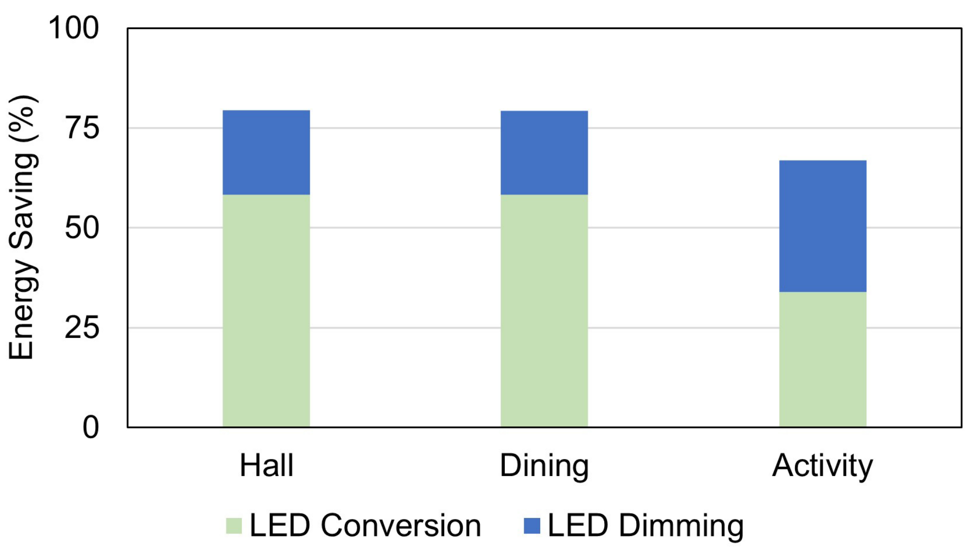

Figure ES-2. Energy savings comparisons between the baseline LED conversion (green) and the additional savings from the dimming schedule (blue). In the halls and dining room, dimming contributed to 21% energy savings while the remaining 58% energy savings were due to the transition to LEDs. In the activity area, dimming contributed to 33% energy savings while the remaining 34% energy savings were due to the transition to LEDs.

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1 Introduction

1.1 Project Background

This report summarizes evaluations of the lighting systems in four senior care centers located in Wisconsin. Two of the care centers received lighting system upgrades that included the installation of white-tunable light-emitting diode (LED) systems while the other two care centers served as control locations and maintained their existing fluorescent lighting systems during the study period. Midwest Lighting Institute (MLI), a 501c3 nonprofit organization in Cottage Grove, WI, coordinated the project and invited Pacific Northwest National Laboratory (PNNL) to document the performance of the lighting systems as a U.S. Department of Energy (DOE) GATEWAY evaluation. Energy Performance Lighting (EPL) staff coordinated and completed the design and installation of the LED systems based on research completed by MLI and prior experience with other nursing home lighting upgrades they have completed since 2016.

The white-tunable LED lighting systems were installed in both care centers that received upgrades in October of 2018. PNNL staff visited all four care centers to evaluate the performance of the systems in November 2019. MLI received a grant from the Wisconsin Department of Health Services to support the project, including funding to collect and analyze health and behavioral measures for residents at the care centers. PNNL staff were not directly involved in collecting or interpreting any health and behavioral data; therefore, those results are not included in this report.

The research project was designed such that each care center that received a lighting upgrade (the intervention care centers) was paired with a control care center with similar demographics that was operated by the same management company and maintained its existing lighting system during the study period. Characteristics describing all four care centers are listed in Table 1. Two of the care centers were managed by Wisconsin Illinois Senior Housing Inc. (WISH); these included the Maple Ridge Care Center in Spooner, WI (intervention, 75 beds, average age of 82[1]), and the Montello Care Center in Montello, WI (control, 50 beds, average age of 77). Two of the centers were managed by the Kuranz family; including the Oak Ridge Care Center in Union Grove, WI (intervention, 74 beds, average age of 77), and the Hope Health and Rehabilitation Center in Lomira, WI (control, 38 beds, average age of 83).

Table 1. Characteristics of the intervention and control care center pairings in the study conducted by MLI.

Care Center	Intervention or Control	Number of Beds	Average Age of Residents
WISH Properties			
Maple Ridge Care Center	Intervention	75	82
Montello Care Center	Control	50	77
Kuranz Properties			
Oak Ridge Care Center	Intervention	74	77
Hope Health and Rehabilitation Center	Control	38	83

Senior housing is often categorized as independent living, assisted living, or skilled nursing care depending on the level of care required. The four care centers included in this project are all skilled nursing care facilities and are typical of the existing building stock of older care center facilities. Unlike new construction, incorporating newer technology into these older facilities poses financial and practical constraints that can

[1] Data for the four care centers accessed June 19, 2020, at https://healthcarecomps.com/nursing-homes/wi/.

limit the effectiveness of the final solution. Tunable lighting systems pose such a challenge when they are installed as a retrofit or renovation of an existing care center and are integrated with the existing electrical and control infrastructure in the facility. However, updating these facilities to take advantage of the energy efficiency benefits and potential benefits to occupant well-being of tunable lighting will be an important part of the future of senior care. This project was initiated to contribute to the evidence-based practices for these types of upgrades in the future.

1.2 Lighting Energy Use in Senior Care

Healthcare facilities in the United States are among the highest ranked facility types in terms of energy use intensity (EUI). Hospitals, for example, have been estimated to have an average EUI of 259,000 British thermal units per square foot (Btu/ft2), ranking a close second to food service facilities. Assisted-living inpatient care facilities, such as nursing homes, have an average EUI of 143,000 Btu/ft2, ranking fourth in the U.S. behind food service, hospitals, and grocery stores. (For reference, the average EUIs for common facilities such as offices, schools, and retail stores are all less than 100,000 Btu/ft2.) Lighting systems represent the largest electricity end use in healthcare, over 40% according to a 2013 report from DOE (DOE 2013). While increasing adoption of solid-state lighting (SSL) since 2013 has most likely decreased this percentage, lighting remains a major electricity end use in healthcare.

The relatively high EUI of healthcare facilities, combined with a rapidly aging global population, indicates that energy use for this sector will almost certainly continue to increase, as the increased demand for healthcare drives a need for new facilities and renovations of existing facilities. The United Nations estimates that the percentage of the global population over the age of 65 will dramatically increase in the next 30 years, partly driven by the aging of those born during the post-World War II baby boom. That percentage is expected to increase from less than 10% in 2020 to 16% by the year 2050 (UNDESA 2015). The U.S. Census Bureau estimates that 46 million people living in the U.S. in 2014 were age 65 or older; that number is projected to increase to 98 million by 2060, representing 24% of the U.S. population at that time (Colby and Ortman 2014). This aging population almost certainly will require more healthcare facilities, with an expected corresponding increase in electricity use for lighting these facilities.

For senior housing and senior care, the approximately 74 million "baby boomers" born between 1946 and 1964 represent what is often referred to as the "silver tsunami" that will significantly affect the future needs for facilities. According to the National Investment Center for Seniors Housing & Care (NIC), nearly 50% of the more than 3 million housing units (beds) for seniors in the U.S are in skilled nursing care facilities. While many boomers are already in their 60s and 70s, the average age of people currently living in skilled nursing care facilities is 87 according to the American Seniors Housing Association, so the expected influx of residents for those facility types is still approaching. The 82- to 86-year-old age group represents the average move-in age of senior housing residents; the number of people in this group is expected to expand by 4.3% per year from 2021-2025 and then by 5.3% per year from 2026-2030. With skilled nursing care communities accommodating an estimated 10% of the 85+ population, these growth projections indicate a substantial future need for new facilities in the next few decades (NIC 2018).

As new facilities are opened, the pressure on older facilities to upgrade will continue to increase. NIC reports that while the median age of the existing buildings used for seniors in independent living and assisted living is less than 20 years, the current properties providing skilled nursing care have a median age of 38 years. These older facilities must be able to compete with newer facilities that offer up-to-date amenities. According to Jim Moore of Moore Diversified Services Inc., "Size and scale of many older communities are facing pressure in the marketplace by new communities. These new properties are offering innovative state-of-the-art designs responding to increased consumer preferences" (McKnight's Senior Living 2019).

This pressure on older facilities raises questions about the financial strategies that can support updates. For building systems, energy savings has often been one of those strategies, and that remains true for lighting, where LED lighting systems can provide opportunities for substantial energy and maintenance cost savings. In addition, emerging evidence about the potential health and well-being benefits of lighting in senior care facilities may further support the need for advanced lighting systems.

1.3 Health-Related Effects of Lighting in Senior Care

With the expected increase in demand for senior care centers and the corresponding lighting energy use in the future, there is growing understanding of the importance of lighting to the overall well-being of building occupants. Lighting for senior care spaces not only provides for the demanding visual needs of the residents and care givers, but it can also play a role in supporting healthy sleep and wake cycles. Exposure to light, especially short-wavelength light, at high light levels during the day can help support normal sleep-wake cycles, while exposure to that same lighting during the evening or at night can disrupt this natural cycle.

While the characteristics of light exposure received throughout a 24-hour cycle may contribute to sleep problems for the general population, health concerns are heightened for residents of senior care facilities, where disturbed sleep patterns are common and time spent outdoors is often limited. Normal aging processes and common ailments, such as Alzheimer's disease, contribute to disruptions in the normal sleeping and waking cycles, in part because the suprachiasmatic nucleus (SCN) of the hypothalamus deteriorates (Ancoli-Israel et al. 2002). The effects of aging-related diseases (e.g., Alzheimer) on circadian rhythms have created particular concerns regarding appropriate lighting for senior populations, whether in new or renovated facilities. These health concerns have led to research-based proposed guidelines for varying the light exposure in senior care facilities (Figueiro 2008).

SSL technology, more specifically a growing number of white-tunable or color-tunable LED lighting systems, provides new opportunities to control the intensity, distribution, and spectrum of light sources that enable dynamic adjustments to the luminous environment that are much easier to implement when compared to conventional fluorescent lighting technologies. A pilot study conducted as part of a previous DOE evaluation of a white-tunable LED lighting system in a skilled nursing care facility documented the potential for both substantial energy savings and improvements in behaviors and sleep patterns for three residents (Davis et al. 2016). Based on these pilot results, the care facility implemented tunable lighting throughout the facility, and a follow-up study conducted in conjunction with Brown University showed a significant reduction in sleep disturbances (Miller et al. 2019; Baier et al. 2020).

Other recent research provides further evidence of positive outcomes from tunable lighting in senior care facilities. In one pilot study, a tunable lighting system was installed for a period of three weeks in a hospital common area that was shared by 13 patients with dementia, then the lighting was removed for an additional three weeks of data collection with the standard room lighting. Results showed that the tunable lighting resulted in significant decreases in nighttime bed wandering and average time out of bed at night, while the average total sleep time at night increased significantly. Based on these results, the authors proposed that similar tunable lighting could serve as a non-pharmacological intervention to support better sleep patterns (van Lieshout-van Dal et al. 2019). Another study explored tunable lighting that was installed for eight weeks over the beds of 20 patients with dementia, comparing a number of patient outcomes with the tunable lighting to data collected during 8 weeks without the tunable lighting. The tunable lighting significantly improved the mood of patients in the mornings after waking, especially during the second four weeks (Bromundta et al. 2019). These studies indicate the potential advantages of tunable lighting systems for senior care residents. This project documented the tunable lighting system properties and energy implications of retrofits of two existing care centers.

1.4 Project Goals

PNNL selected this project for a GATEWAY evaluation because healthcare lighting represents a significant national energy use, tunable lighting is an important emerging aspect of SSL, and because advances in lighting technology provide opportunities to significantly improve both energy use and occupant outcomes in senior care centers.

MLI initiated the project to better understand how tunable LED lighting could be incorporated into older or existing skilled nursing care centers. They also aimed to investigate the extent to which lighting energy savings could be combined with improving occupant outcomes. MLI established goals related to the occupant outcomes, specifically in terms of the desired spectral content of light, melanopic to photopic (M/P) ratio and equivalent melanopic lux (EML) levels at different times of day, and selected and installed the tunable lighting systems based on those goals.

In this project, PNNL staff performed the following:

- Evaluations of lighting conditions in two control care centers: field measurements of illuminance and spectral power distribution (SPD) at various task and eye levels throughout the care centers.
- Evaluations of lighting conditions in the two intervention care centers: field measurements of illuminance and SPD at various task and eye locations throughout the care centers under the four designed lighting system settings (morning/afternoon, midday, evening, and night).
- Energy analyses: estimated energy use of the incumbent lighting systems compared to the new tunable lighting systems in the two intervention care centers.
- Analyses of light exposure patterns in common spaces in the care centers: characterize potential photopic and melanopic resident light exposure over 24 hours based on a hypothetical daily schedule.

PNNL was not involved in the selection and installation of lighting equipment in the intervention care centers, nor with the collection and analyses of measures related to resident outcomes.

2 Care Center Overview

2.1 Traditional Lighting Systems

2.1.1 Montello Care Center

Montello Care Center is divided into two nearly identical residential wings, shown in Figure 1. The hallway included in the study (Hall A) is designated for long-term care and has 16 double resident rooms and a lounge area for residents and visitors. The hallway is open to a central lounge space; there is no central nurse station in this care center and nurses use rolling carts with laptops for reporting and administration of medication. The facility has a communal dining room and an activity room that is also used for physical therapy. The activity room is only open to residents during the day and is locked around dinner time.

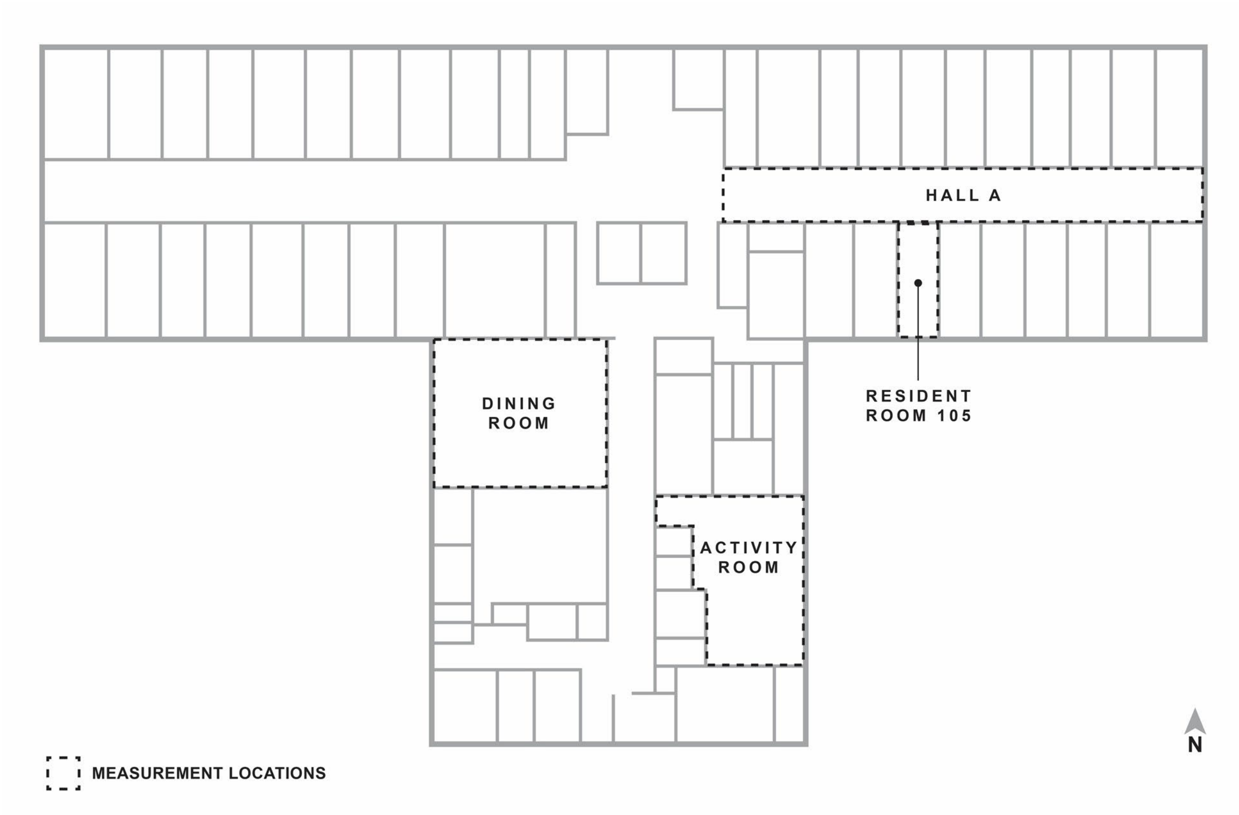


Figure 1. Montello Care Center schematic floor plan. Lighting measurements were taken in the rooms shown with a dashed outline. This plan is not to scale.

Lighting throughout the hallways and dining room consists of recessed 2 ft by 4 ft fluorescent luminaires, as pictured in Figure 2. All lamping in the 2 ft by 4 ft fluorescent luminaires is visually similar and expired lamps are rare. No effort was taken to relamp or clean luminaires before taking measurements. The SPD and color metrics, shown in Figure 3, are representative of the hallways and dining room in the facility. In all care centers included in the report, relevant color metrics were calculated using the measured SPDs captured approximately 2 in. away from the luminaire.

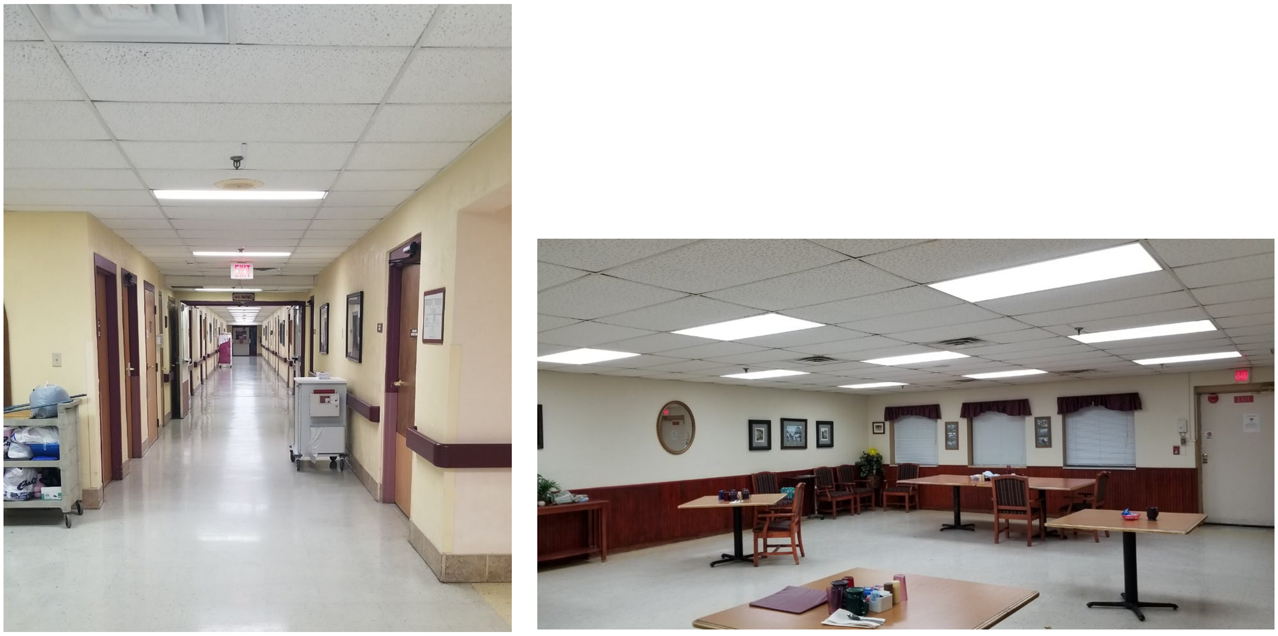
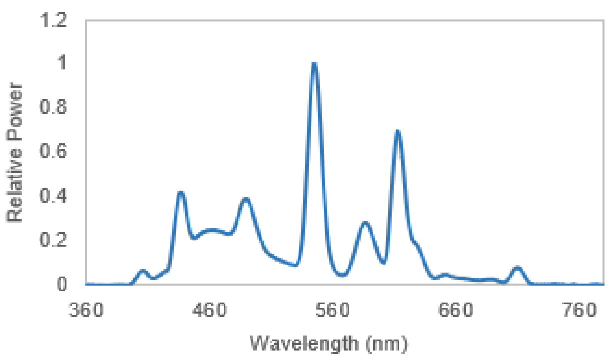


Figure 2. Montello Care Center hallway (left) and dining room (right).



CCT (K)	5775
R_f	88
R_g	97
D_{uv}	0.0090

Figure 3. Representative fluorescent luminaire SPD and color metrics.

The activity room has four ceiling fans with a diffused glass shade and three A19 lamps, as well as 1 ft by 4 ft wrap luminaires with two fluorescent lamps, sometimes not visually consistent in correlated color temperature (CCT) as shown in Figure 4. Lastly, the lighting in the resident rooms consists of a wall-mounted overbed luminaire typically seen in care environments, with separate direct or indirect switching and a secondary decorative wall sconce with a single A19 lamp, as shown in Figure 5. The lighting in the hallways is consistent over a 24-hour period, including overnight. The lighting system is not dimmable and does not have alternate nighttime switching to reduce light levels. Lighting in the dining room, activity room, and resident rooms is controlled locally with on/off switching.

Figure 4. Montello Care Center activity and physical therapy room.

Figure 5. Montello Care Center typical double resident room.

2.1.2 Hope Health and Rehabilitation Center

Hope Health and Rehabilitation Center is divided in two wings, a short-term rehabilitation center and a long-term care center. Lighting measurements were taken in the long-term care center wing, as shown in Figure 6. Within the long-term care wing, there are two residential hallways with single and double occupancy rooms, a central nurse station, a dining room, and an activity room.

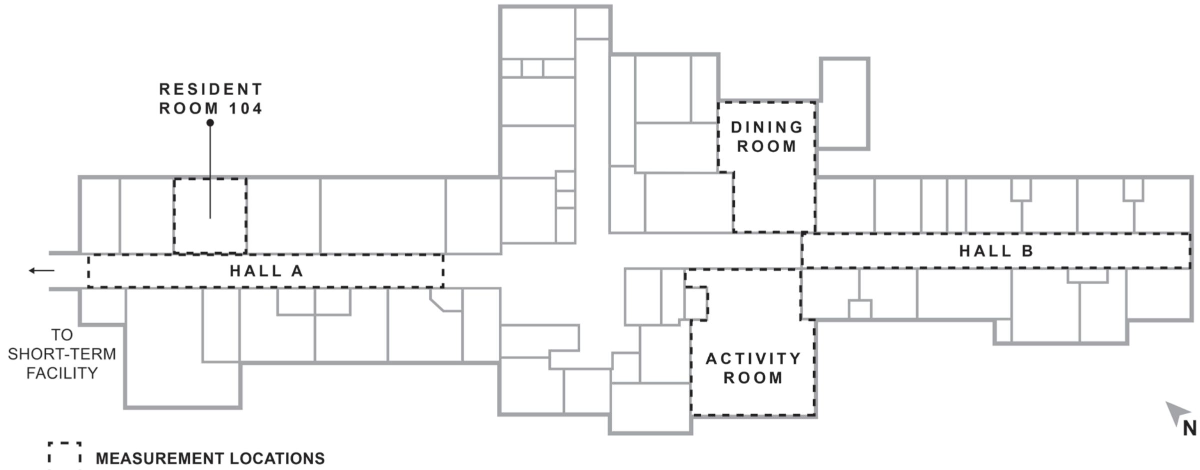


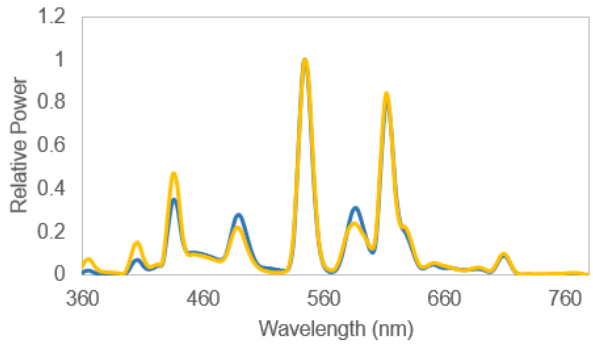
Figure 6. Hope Health and Rehabilitation Center schematic floor plan. Lighting measurements were taken in the rooms shown with a dashed outline. This plan is not to scale.

The lighting in Hall A consists of 2 ft by 2 ft recessed troffers and is shown in Figure 7. Each luminaire contains two u-bent fluorescent lamps. Lamp CCT is not always visually consistent within each luminaire or between luminaires. Luminaires are not evenly spaced, most likely due to location of other mechanical systems. Hall B has a series of 6 in. round aperture recessed downlights with two compact fluorescent lamps and an interior cross baffle. The right image in Figure 7 is representative of the lighting system but is not the hallway where data were collected. The SPDs and color performance summary shown in Figure 8 are consistent, despite differences in the luminaire type and lamping between the hallways. The lighting in the dining room consists of seven 2 ft by 4 ft fluorescent troffers with visually consistent lamping, as shown in Figure 9. The representative SPD and color performance data are shown in Figure 10.

Figure 7. Lighting in Hall A (left) consists of 2 ft by 2 ft fluorescent luminaires and Hall B (right) has recessed downlights. Note: Image shown for Hall B is for reference to lighting system only, lighting measurements were not captured in this space.

Hall A (2x2 Troffers)

CCT (K)	3911
R_f	82
R_g	99
D_{uv}	0.0040

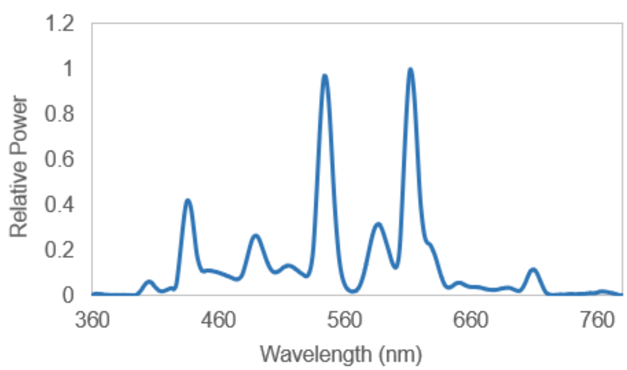


Hall B (Downlights)

CCT (K)	3881
R_f	77
R_g	102
D_{uv}	-0.0011

Figure 8. **Representative fluorescent SPDs and related color metrics for Halls A & B.** Although each hallway has a unique lighting system and lamping, the SPDs are consistent with one another.

Figure 9. **The Hope Health and Rehabilitation Center dining room.**



CCT (K)	3840
R_f	85
R_g	103
D_{uv}	0.0031

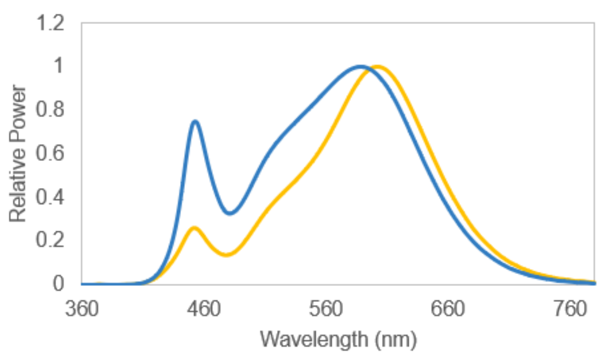
Figure 10. **Representative SPD and color performance of fluorescent luminaires in the dining room at Hope Health and Rehabilitation Center.**

The activity room is a large open space with a TV, a few tables for games or puzzles, and many reclining chairs around the perimeter of the room. The lighting consists of several ceiling-mount fixtures with three A19 LED lamps in each luminaire; see Figure 11 for reference. The same ceiling mount fixtures are used in the resident rooms, pictured in Figure 11. Many resident rooms also have table lamps or night lighting; however, only the ceiling-mount luminaires were included in the analysis. Measurements were taken at each ceiling-mount luminaire, summarized in Figure 12, and measurement data indicate that two different A19 LED lamps were installed in the luminaires. Similar to Montello Care Center, the lighting in the hallways does not vary in terms of CCT or intensity over a 24-hour period and the lighting system is not dimmable. Local on/off switching is provided in all spaces.

Figure 11. Hope Health and Rehabilitation Center typical double resident room. Luminaire A is on the left and Luminaire B is on the right; there was a perceptible chromaticity difference between the two luminaires; see Figure 12.

Luminaire A

CCT (K)	3962
R_f	82
R_g	91
D_{uv}	0.0083



Luminaire B

CCT (K)	2756
R_f	83
R_g	92
D_{uv}	0.0046

Figure 12. Two SPD measurements and color metrics captured at the ceiling mount luminaires in a resident room. A19 LED lamps of different CCTs were installed in the luminaires, producing a different visual environment on either side of the room; see Figure 11.

2.2 LED Lighting Systems

2.2.1 Maple Ridge Care Center

Maple Ridge Care Center has four hallways with single and double occupancy resident rooms as shown on the floor plan in Figure 13. Three hallways are long-term care, and the fourth hallway is short-term rehabilitation care; lighting measurements were taken in one of the long-term care hallways, labeled as “Hall A” in Figure 13. The facility also has a large dining room, an activity room, a centrally located nurse station, a separate TV room, and multiple areas for residents and guests to visit. EPL designed a retrofit lighting solution and replaced lamps and luminaires with LED sources in October 2018. Most sources were replaced with a static, non-dimmable source; however, luminaires in select locations were replaced with white-tunable LED lighting to provide dynamic lighting to residents and care center staff over a 24-hour period. Tunable lighting was installed in the hallways and around the nurse station while static, high CCT lighting was installed in the dining room and the activity room, as well as in additional seating areas, designated by shading in Figure 13.

Where tunable lighting was installed, the system was programmed to change CCT and intensity automatically throughout the day.

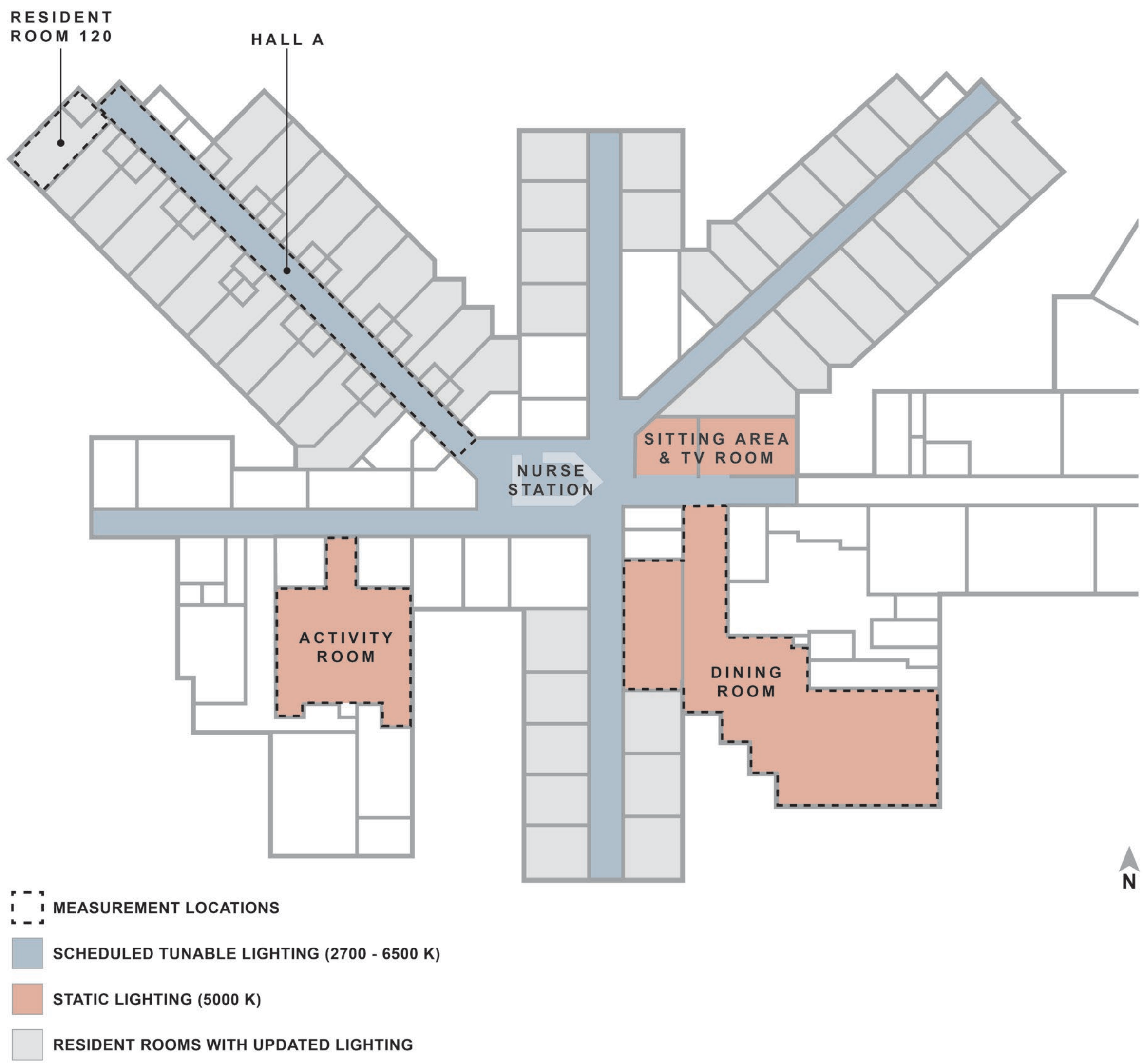


Figure 13. Maple Ridge Care Center schematic floor plan. Lighting measurements were taken in the rooms shown with a dashed outline. Programmed tunable lighting (intensity and CCT tuning) was installed in the blue shaded rooms and static intensity and CCT lighting was installed in the red shaded rooms. Lighting upgrades were also completed in the resident rooms, however they were not incorporated into the central control system. This plan is not to scale.

The programmed lighting schedule is illustrated in Figure 14, which shows the specified CCT, horizontal light level, and target M/P ratio value over a 24-hour period. EPL used M/P ratios during the specification process for both intervention care centers as a way to quantify the biological potential of the tunable lighting system; the preprogrammed lighting conditions were also specified in terms of horizontal illuminance and rated CCT. The tunable luminaires are capable of dimming to < 1% and use two primary LEDs (warm and cool) to create a tunable range between 2700 and 6500 K. The overall scheme proposed a bright, cool daytime environment (high EML and M/P) and a dim, warm evening/nighttime environment (low EML and M/P).

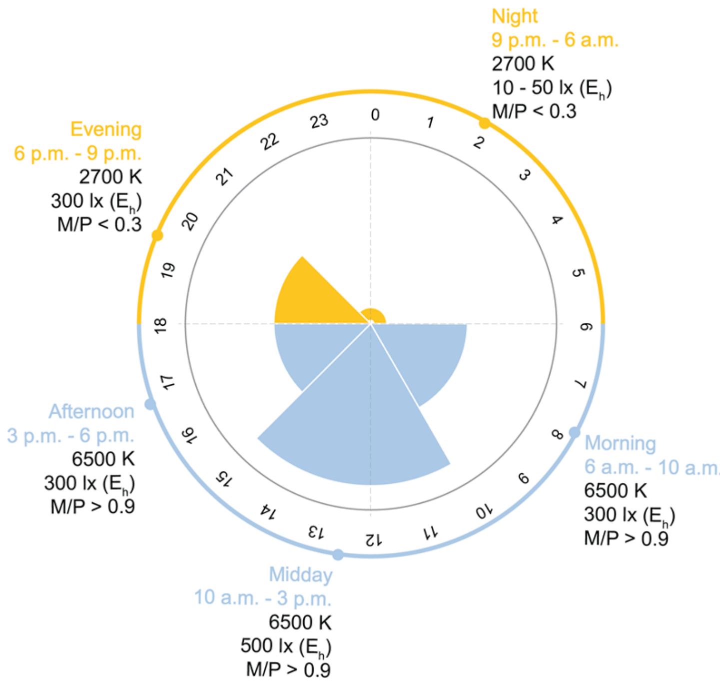


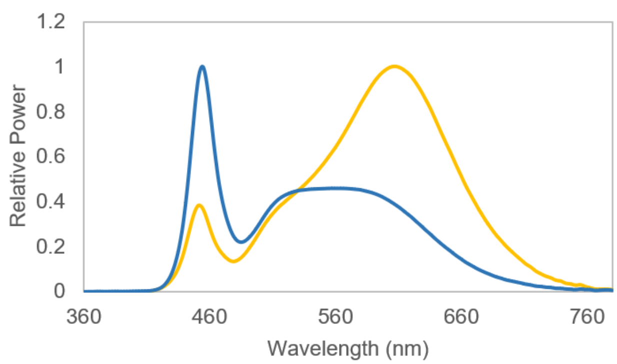
Figure 14. Maple Ridge Care Center tunable lighting schedule. This 24-hour radial plot shows the programmed settings for the tunable lighting system. The blue and yellow colors relate to the CCT and the radius of the plot shows target illuminance at the horizontal task plane. The M/P ratio design target used during design is also listed.

The tunable lighting in the hallway consists of 1 ft by 4 ft recessed Acuity® Whisper LED luminaires arranged in an alternating layout on the left and right sides of the hallway. Figure 16 shows the representative relative SPD measurements for the upper and lower limits of the tunable range, as both settings were used in the facility throughout the day. In addition to the recessed luminaires, this hallway has static 2700 K direct/indirect wall sconces, as shown in Figure 15. A custom LED board solution was created to retrofit the wall sconce, and the original housing remained. The wall sconces turn on automatically at 6 p.m. and stay on until 6 a.m.; overnight from 9 p.m. to 6 a.m. the tunable ceiling luminaires are off, and the hall is illuminated by the wall sconces alone.

Figure 15. The hallway in Maple Ridge Care Center has tunable recessed 1 ft by 4 ft LED luminaires (midday setting, left) and direct/indirect static LED wall sconces that were used in the evening setting (right) and overnight (not shown).

6500 K

CCT (K)	6436
R_f	83
R_g	94
D_{uv}	0.0035
M/P Ratio	0.98



2700 K

CCT (K)	2740
R_f	85
R_g	96
D_{uv}	0.0006
M/P Ratio	0.44

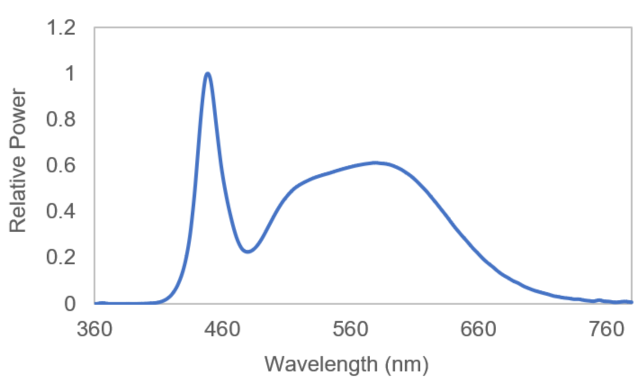
Figure 16. Representative SPDs and related color performance for the tunable lighting system installed in Maple Ridge Care Center. The upper and lower limits of the tunable range represent the CCT settings selected for use in the space over a 24-hour period. This luminaire was capable of meeting the M/P ratio design target at the upper end of the tunable range (6500 K) but exceeded the design target at the low end of the tunable range (2700 K).

There is one large dining space that includes a small room separated by a half-height wall where all residents have their meals. The lighting in this space consists of decorative pendants with five A19 LED lamps. Each pendant has four 5000 K "daylight" Cree® A19 lamps and one 5000 K Healthe® by Lighting Science Group A19 lamp. EPL specified a static high CCT so residents would be exposed to lighting conditions with greater melanopic content when outside their room during daytime hours. Additionally, there are wall sconces with two 5000 K LED Cree A19 lamps and static 5000 K LED Sylvania retrofit downlights in the smaller dining area, circulation spaces, and service areas. Figure 17 shows the three types of luminaires found in the dining room. The pendant luminaires are not always aligned with table location to allow for easier wheelchair access and circulation.

Figure 17. There are three types of luminaires in the dining room: recessed downlights, wall scones and decorative pendants.

The activity room has an evenly spaced grid of recessed 2 ft by 4 ft static 5000 K Acuity Whisper LED luminaires, as shown in Figure 18. Scheduled activities take place throughout the day and into the evening, and a static high CCT lighting system was specified to expose residents to lighting conditions with greater melanopic content. A representative SPD and related color performance are shown in Figure 19.

Figure 18. The activity room in Maple Ridge Care Center.



CCT (K)	5151
R_f	83
R_g	97
D_{uv}	0.0022
M/P Ratio	0.82

Figure 19. Representative SPD and related color performance of a static LED luminaire in the activity room at Maple Ridge Care Center.

The lighting in each double occupancy resident room consists of an overbed luminaire for each occupant that had a cool (6500 K) LED direct component and a warm (3000 K) LED indirect component, and two 3000 K recessed downlights in the circulation space in the room. Similar to the wall sconces, a custom solution was created to relamp the existing overbed fixture housing to reduce cost in the retrofit. The lighting configuration in a typical resident room is shown in Figure 20. Nurses manually switch the overbed luminaires on in the morning and are instructed to visually match the color of the overbed light to the hallway operating according to the programmed schedule. Lighting in the activity room and dining room is controlled locally with on/off switches. The tunable lighting system in the hallways is automated with a central controller.

Figure 20. A typical double occupancy resident room at Maple Ridge Care Center.

2.2.2 Oak Ridge Care Center

At Oak Ridge Care Center there are two wings of single and double occupancy resident rooms, a central nurse station, a dining room, and a TV room shown on the plan in Figure 21. Activities take place in this space or in the adjacent dining room. EPL replaced the incumbent lighting system with a white-tunable LED lighting system to provide dynamic lighting to residents and care center staff over a 24-hour period. In this care center, tunable LED lighting was installed in all common areas including the hallways, dining room, and activity room, as shown in Figure 21.

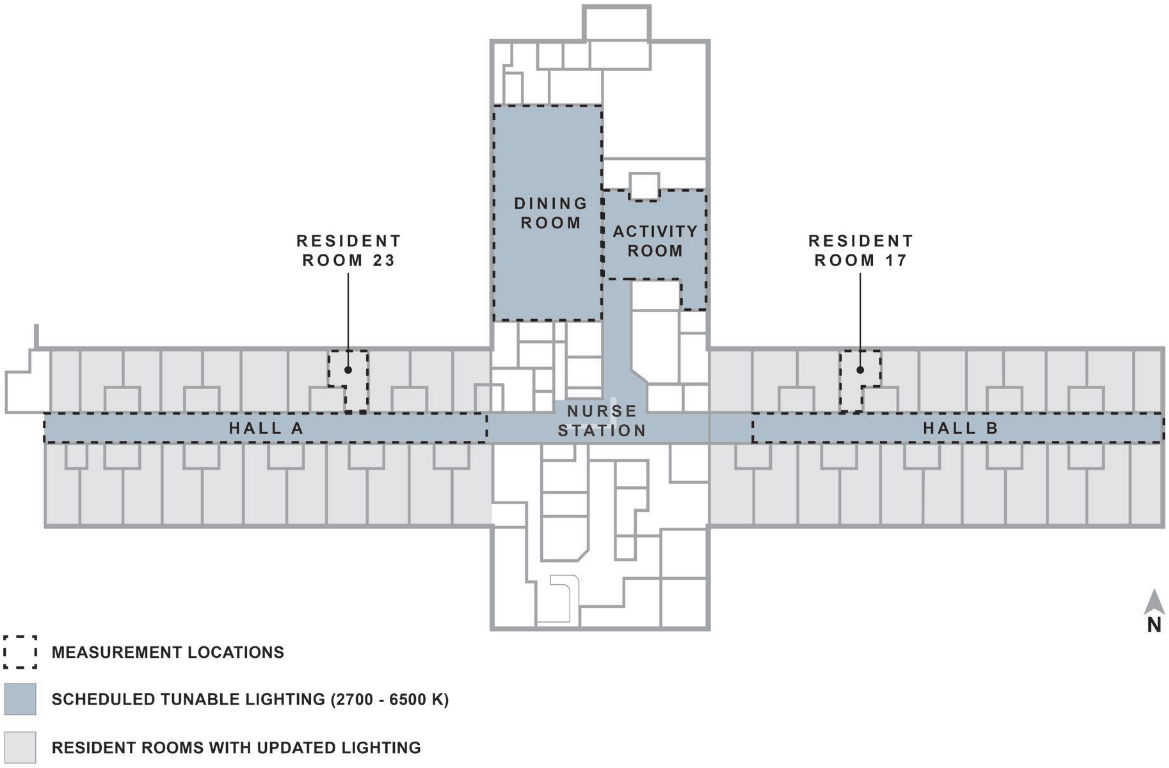


Figure 21. **Oak Ridge Care Center schematic floor plan.** Lighting measurements were taken in the rooms shown with a dashed outline. Programmed tunable lighting (intensity and CCT tuning) was installed in the blue shaded rooms. Lighting upgrades were also completed in the resident rooms; however, they were not incorporated into the central control system. The floor plan is not to scale.

As in Maple Ridge Care Center, the tunable lighting system in Oak Ridge Care Center is capable of tuning between 2700 to 6500 K and dimming to < 1%. The programmed lighting schedule, illustrated in Figure 22, is almost identical to Maple Ridge Care Center, aside from the scheduled time of the overnight setting which is 1 hour later (10 p.m.) at Oak Ridge Care Center to better align with resident's schedules.

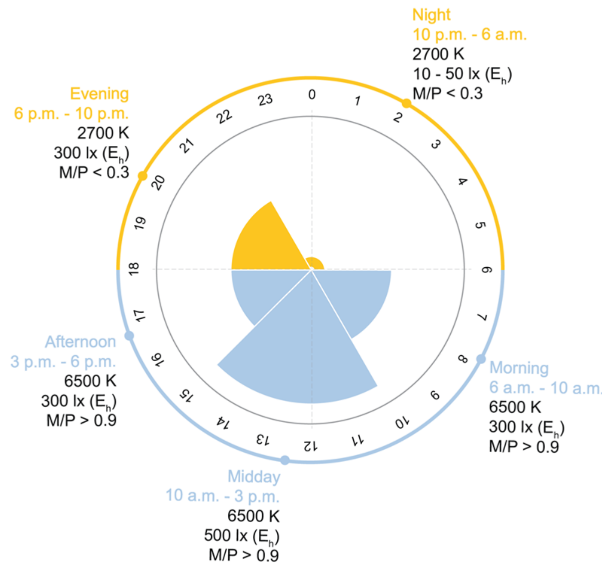
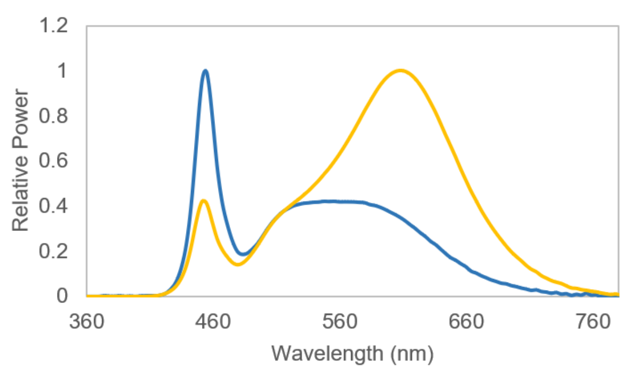


Figure 22. **Oak Ridge Care Center tunable lighting schedule.** This 24-hour radial plot shows the programmed settings for the tunable lighting system. The blue and yellow colors relate to the CCT, and the radius of the plot shows intended intensity at the horizontal task plane. The M/P ratio design target EPL used during design is also listed.

All common spaces with tunable lighting have 2 ft by 4 ft recessed Acuity Whisper LED luminaires. The hallways, dining room, and activity room are all visually connected, and the same tunable fixture was specified throughout these spaces in the care center. The lighting in Hall A, shown in Figure 24, consists of tunable luminaires spaced between 6 ft and 10 ft on center. In Hall B, luminaires followed a similar spacing, but the floor finish is much lighter compared to Hall A and the rest of the care center. Figure 23 shows SPD measurements taken at the two nominal CCT levels used in the space throughout the day. Since luminaires from the same family (Acuity Whisper) are installed in both locations, measurements align very closely with those presented in Figure 16. In both intervention care centers, the upper end of the Acuity Whisper tunable range produced an SPD with an M/P ratio within the daytime target (greater than 0.9), but the SPD at the low end of the tunable range had an M/P ratio of 0.45, slightly greater than the evening/nighttime design target of 0.3 or less according to the spectral measurements taken approximately 2 in. away from the surface of the luminaire.

6500 K

CCT (K)	6434
R_f	82
R_g	93
D_{uv}	0.0040
M/P Ratio	0.97



2700 K

CCT (K)	2736
R_f	85
R_g	96
D_{uv}	-0.0003
M/P Ratio	0.45

Figure 23. **Representative SPDs and related color performance for the tunable lighting system installed in Oak Ridge Care Center.** The upper and lower limits of the tunable range represent the CCT settings selected for use in the space over a 24-hour period. This luminaire was capable of meeting the M/P ratio design target at the upper end of the tunable range (6500 K) but exceeded the design target at the low end of the tunable range (2700 K).

Figure 24. Hall A (left) and Hall B (right) have the same tunable lighting system but different floor finishes.

The lighting in the dining room and activity room (not photographed) also consists of 2 ft by 4 ft LED luminaires and both areas had the same darker flooring as Hall A, shown in Figure 25. Local control is provided in the dining room, hallways, and activity space for emergencies; however, lighting control in these common spaces is automated and follows the schedule identified in Figure 22.

Figure 25. The dining room at Oak Ridge Care Center.

Overnight in Oak Ridge Care Center, the lighting system is switched so that roughly one out of three luminaires is on and operated at a reduced output in all spaces with tunable lighting. Figure 26 shows a photograph of Hall B during the overnight setting. Additional task lighting was provided within the nurse station that increased the amount of light to allow staff to complete visual tasks, but it was shielded from the resident's view and did not affect nighttime resident light exposure.

Figure 26. Oak Ridge Care Center night lighting condition with every third luminaire operating in Hall B.

Figure 27 shows a typical single occupancy resident room with an overbed LED luminaire with a cool (6500 K) direct component and a warm (3000 K) indirect component. There are also two 3000 K recessed downlights in the room that are not visible in Figure 27.

Figure 27. Oak Ridge Care Center typical single occupancy resident room.

3 Care Center Lighting System Evaluations

PNNL staff evaluated the lighting systems in the main areas of all four care centers, including a typical resident room, the dining room, the activity room, and one or two typical hallways, depending on the site. Measurements were taken between November 18 and 21, 2019 to evaluate two white-tunable LED lighting systems and two traditional lighting systems. The remainder of this report details the analyses of energy savings, variability of the lighting conditions, and hypothetical 24-hour light exposure patterns.

A calibrated Konica Minolta® CL-500A spectrophotometer[2] was used to measure vertical and horizontal irradiance. Spectral irradiance was measured 48 in. above the floor with the meter oriented vertically on a tripod at the eye position of a person seated in a wheelchair. When measuring in resident chair locations or where the tripod could not be fully extended, the meter was handheld. Measurements were taken facing multiple directions in each space and at typical furniture or task locations (i.e., a dining table) to characterize resident light exposure and realistic use of the space. Table 2 summarizes the vertical irradiance measurement location criteria in each care center.

Table 2. Vertical irradiance measurement locations by space type in each care center. Vertical measurements were taken 48 in. above the floor at seated eye height to characterize the lighting to which residents are exposed.

Space Type	Measurement Notes
Hallways	Maple Ridge Care Center: Every 15 ft, down the center of hallway, with two measurements at each point; one facing each of the two primary view directions. Oak Ridge Care Center, Montello Care Center and Hope Health and Rehabilitation Center: Under and between luminaires, down the center of hallway, with two measurements at each point; one facing each of the two primary view directions.
Dining rooms	Seated at several dining tables distributed throughout the space, facing four primary viewing directions at each table.
Activity rooms	Maple Ridge Care Center and Montello Care Center: Under and between evenly spaced luminaires facing four primary viewing directions. Oak Ridge Care Center and Hope Health and Rehabilitation Center: Seated at typical furniture locations throughout the space, facing multiple directions at task locations.
Resident rooms	Eye position of a resident sitting in bed or in a chair in a typical resident room.

Measurements were taken after dark in three of the four care centers to eliminate daylight contributions. Two sets of measurements (with and without electric lighting) were taken where daylight contributions could not be eliminated; the resulting electric lighting contribution is reported. In most cases, no furniture or medical equipment was moved, unless the object directly interfered with replicating a previous measurement point or if furniture (e.g., a dining chair) had to be moved for accurate tripod placement. To avoid disruption to resident space, the doors to resident rooms remained in their current status (open or closed) when measuring the hallways.

[2] Serial number 10002008

3.1 Energy Savings Analysis

The difference in the electrical energy consumption before and after LED replacement was analyzed in the Maple Ridge and Oak Ridge care centers. Data regarding lighting system energy consumption were not collected, and this analysis is estimated based on the programmed lighting schedule, rated luminaire wattage, and observations during the site visit. For the energy consumption calculations, operating hours were calculated for 365 days a year, and a linear dimming curve was assumed [e.g., 500 lx setting (midday) was 100% power intensity; 300 lx (morning/afternoon, and evening) setting was 60% power intensity]. The assumption of linear dimming was applied to all lighting settings, regardless of the CCT. Energy consumed by lighting was calculated in three locations (hall, dining room, and activity room) before and after LED replacement. Resident rooms were excluded from the calculations due to the variation in lighting use (residents were allowed to control overbed luminaires) and lack of a specified dimming or CCT tuning schedule.

3.1.1 Maple Ridge Care Center Energy Analysis

In Maple Ridge Care Center, previous light sources were replaced with LEDs, and an automated dimming and CCT tuning routine was introduced only in the hallways. Dining and activity rooms were manually controlled and did not have an automatic control schedule. The operating hours were estimated based on reports from facility management. Operation time assumptions before replacement were 15 hours per day for troffers in the hallway (Hall A only), 24 hours per day for the sconces in the hallway (Hall A only), 15 hours per day for the pendants, downlights, and sconces in the dining room, 12 hours per day for the troffers in the activity room and 6 hours per day for the track lights in the activity room. Operation time assumptions after the retrofit were 15 hours per day for the troffers in the hallway (Hall A only), 12 hours per day for the scones in the hallway (Hall A only), 15 hours per day for pendants, downlights, and sconces in the dining room, 12 hours per day for the troffers in the activity room, and 6 hours per day for the track lights in the activity room, as shown in Table 3. The sconces in the hallway are no longer used 24 hours a day because they are not tunable, and therefore would not be visually consistent with the daytime tunable 6500 K troffer setting. When the programmed tunable lighting shifts to 2700 K in the evening, the sconces turn on and remain on throughout the evening and overnight.

Table 3. Operation assumptions for light sources used in the energy calculations for Maple Ridge Care Center.

		Before		After	
		hr/year	hr/day	hr/year	hr/day
Hall A	Troffer	5,475	15	5,475	15
	Sconce	8,760	24	4,380	12
Dining	All	5,475	15	5,475	15
Activity	Troffer	4,380	12	4,380	12
	Track lighting	2,190	6	2,190	6

The energy consumption considering the programmed dimming schedule, where appropriate, in all three spaces was reduced by more than 50%, as shown in Table 4. The largest reduction in energy use was in the halls (77%) due to the fact that only the wall sconces were used overnight, in addition to replacing the incumbent luminaires with LEDs. Layering troffers and wall sconces in this hallway exemplifies how to utilize light distribution as a purposeful method of stimulus delivery, or lack thereof. Turning the troffers off overnight not only reduces the overall intensity of the environment which can help support restful sleep, but results in significant energy savings. The energy consumption as a function of the time of the day is shown in Figure 28.

Table 4. **Energy consumed by each space (hall A, dining room, and activity room) before and after LED replacement in Maple Ridge Care Center.** Total power represents the connected load for each room (using the rated luminare wattage). Energyy consumption per year includes programmed dimming schedule.

	Before		After		Energy savings (%)
	Total power (kW)	Energy consumption (kWh/yr)	Total power (kW)	Energy consumption (kWh/yr)	
Hall A	1.02	6,609	0.37	1,520	77
Dining	2.06	11,251	0.99	5,437	52
Activity	1.66	5,966	0.51	2,133	64
Total		23,826		9,090	62

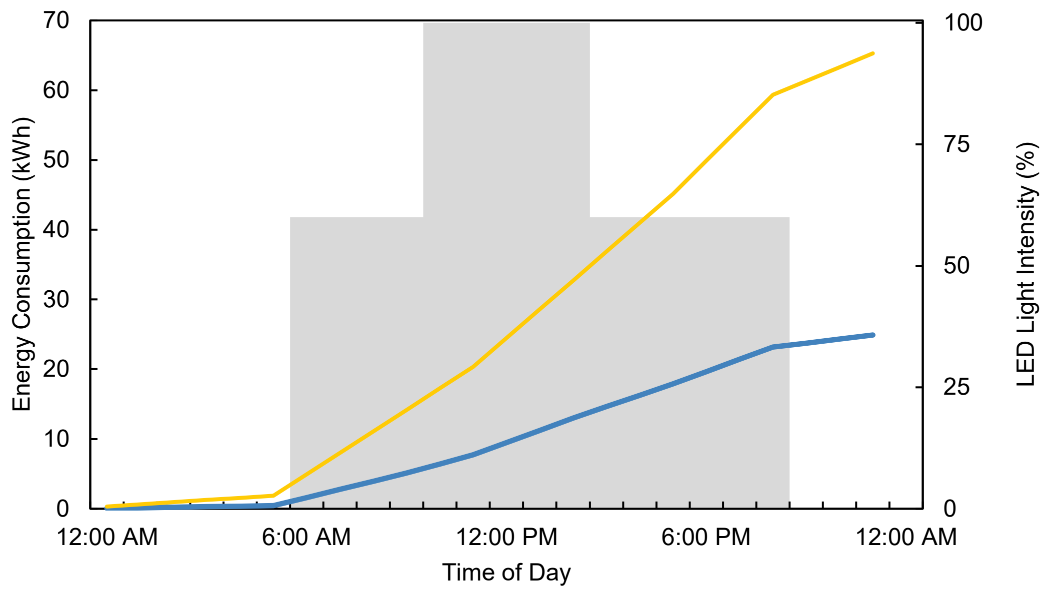


Figure 28. **Energy consumption as a function of the time of day before (yellow line, left y-axis) and after (blue line, left y-axis) LED replacement in the hallway, dining room, and activity room in Maple Ridge Care Center.** The light intensities of the LED lighting system are shown in grey bars (right y-axis).

3.1.2 Oak Ridge Care Center Energy Analysis

Similar to Maple Ridge Care Center, electrical energy consumed by lighting was calculated in three locations (hallway, dining room, and activity room) before and after LED replacement in Oak Ridge. However, there were several noted differences between Maple Ridge Care Center and Oak Ridge Care Center. Prior to the retrofit in Oak Ridge Care Center, the troffers in the hallway (Hall A only), dining room, and activity room were on for 16 hours per day. After the retrofit, the troffers were on for 24 hours per day in all three spaces, as shown in Table 5. The automated CCT and intensity tuning was introduced in the hallways, dining room, and activity room in Oak Ridge Care Center, instead of just the hallways as in Maple Ridge Care Center. Overnight, approximately one third of the luminaires are operated at a dimmed level and the rest are off completely; this is factored into the calculation through the dimming schedule. Although the lights were operated for a greater number of hours per day after the retrofit, the nominal replacement luminaire wattage and dimming schedule provide significant energy savings and provide a dynamic environment for residents.

Table 5. Operation assumptions for light sources used in the energy calculations for Oak Ridge Care Center.

		Before		After	
		hr/year	hr/day	hr/year	hr/day
Hall A	Troffer	5,840	16	8,760	24
Dining	Troffer	5,840	16	8,760	24
Activity	Troffer	5,840	16	8,760	24

The energy consumption in all three spaces was reduced by more than two thirds, as shown in Table 6. The largest reduction in energy use was in the hallway and the dining room (79%).

Table 6. Energy consumed by each space (hallway, dining room and activity room) before and after LED replacement in Oak Ridge Care Center. Total power represents the connected load for each room (using the rated luminaire wattage). Energy consumption per year includes programmed dimming schedule.

	Before		After		Energy savings (%)
	Total Power (kW)	Energy consumption (kWh/yr)	Total Power (kW)	Energy consumption (kWh/yr)	
Hall A	1.26	7,358	0.35	1,516	79
Dining	2.07	12,089	0.58	2,490	79
Activity	1.53	8,959	0.68	2,927	67
Total		**28,406**		**6,933**	**76**

The energy consumption as a function of the time of the day is shown in Figure 29. While operating hours were greater after the retrofit, renovating the lighting system reduced the energy due to the high efficacy of LEDs and the automated dimming schedule. The major contribution to energy savings was the transition from fluorescent lamps to LEDs. However, dimming schedules significantly contributed to energy savings when the light sources were operated for long hours (e.g., in the hall, the light intensity was 60% for 11 hours and 3% for 8 hours), as shown in Figure 30. In the halls and dining room, dimming contributed to 21% energy savings while the remaining 58% energy savings were due to the transition to LEDs. In the activity area, the contribution of dimming (11 hours at 60% light intensity and 3% for 8 hours) to energy savings was limited compared to the hall and dining area because a higher wattage replacement was used in this space. In the activity room, transition to LEDs provided 34% of the total energy savings, and dimming schedules resulted in 33% energy savings. For further energy analysis, see Appendix A.

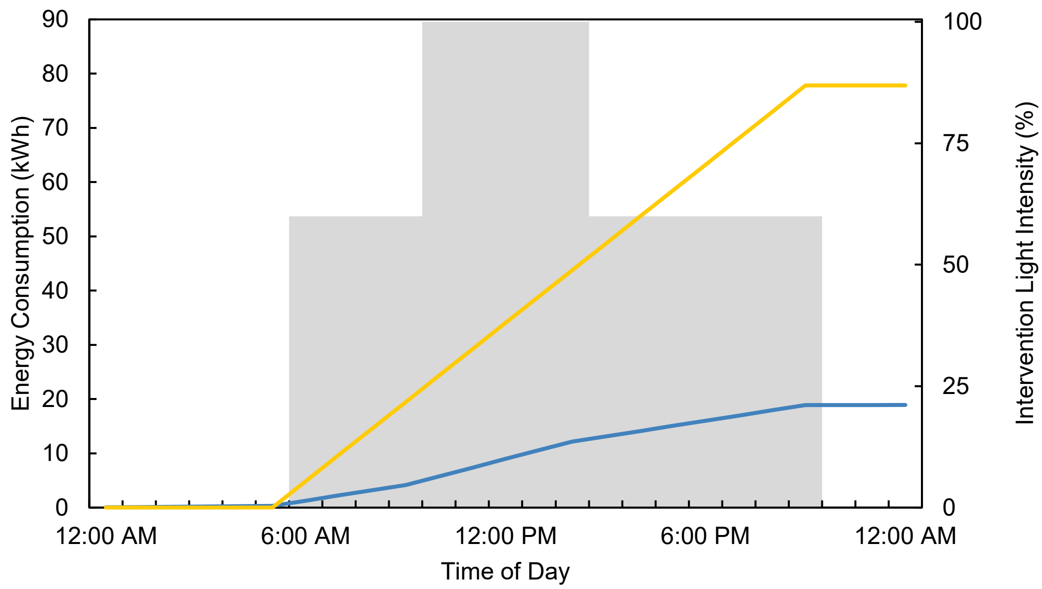


Figure 29. **Energy consumption as a function of the time of day before (yellow line, left y-axis) and after (blue line; left y-axis) LED replacement in hallway, dining room and activity room in Oak Ridge Care Center.** The light intensities of the LED dimming system are shown in gray bars (right y-axis).

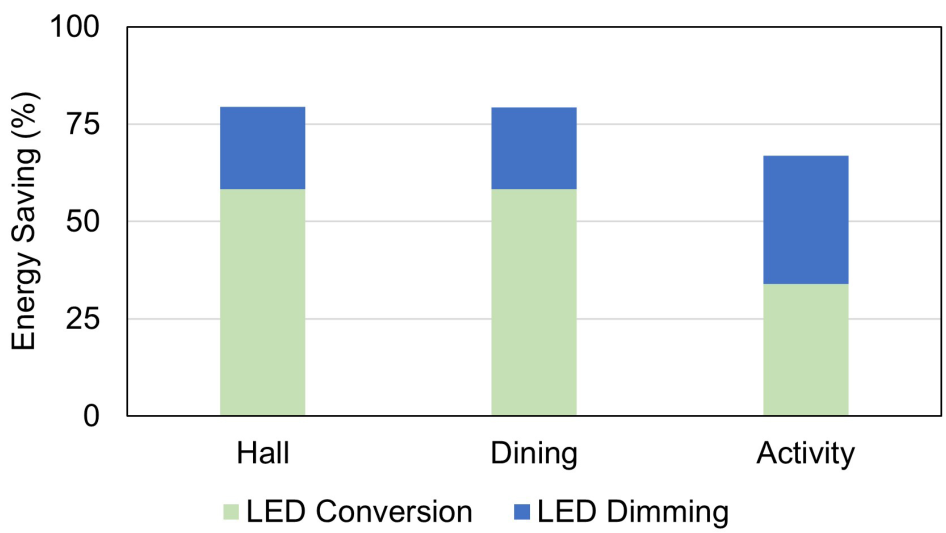


Figure 30. **Energy savings comparisons between the baseline LED conversion (green) and the additional savings from the dimming schedule (blue).**

3.2 Variability of Tunable Lighting

Prior to tunable LED lighting systems, practitioners relied on dimming and alternative lamping strategies to provide a dynamic lighting system for building occupants. LEDs offer a wide range of spectral tuning capabilities that are not possible with fluorescent technology. Recently, there has been increased interest in designing environments that support human health and wellness. While tunable lighting itself does not necessarily increase occupant well-being, it can more easily provide a dynamic schedule that may support occupant health and safety related outcomes. As shown in Figure 14 and Figure 22, the tunable lighting schedules in the intervention care centers were designed to provide bright, cool light during the day and dim, warm light in the evening and at night, similar to the natural light-dark rhythm of a 24-hour day.

3.2.1 Maple Ridge Care Center and Montello Care Center Hallway Comparison

A comparison between the vertical illuminance and CCT measured at assumed eye positions in a number of locations throughout the care centers revealed that the tunable lighting systems in the intervention care centers are generally capable of following the design scheme, providing residents with dynamic light exposure. Figure 31 shows the spectral variation measured at each tunable light setting (morning/afternoon, midday, evening, and night) in Maple Ridge Care Center in Hall A. The four distinct SPDs are the average of 20 vertical measurements taken at 48 in. above the floor to represent a resident's eye position in a wheelchair. This is contrasted with a singular fluorescent SPD that represents the static condition over 24 hours in the Montello Care Center hallway. In Maple Ridge Care Center, vertical electric light levels varied between a maximum of 151 lx under the midday setting and a minimum of 25 lx under the night setting. The static fluorescent system remained constant at 111 vertical lx over 24 hours, as shown in Figure 32.

Resident room doors are often left open to the hallway space overnight so nursing staff can check on residents and provide care if necessary. Therefore, it is important to reduce the light spilling from the hallways into the resident rooms at night as much as possible to not disturb residents' sleep. As the fluorescent system is not dimmable, it is not possible to decrease the intensity of light overnight without turning all the lights off, which is not a viable option considering staff needs and other safety concerns. During the morning/afternoon lighting conditions, both the fluorescent and tunable lighting systems produce similar vertical light levels, 111 lx and 126 lx, respectively, but the tunable lighting system provides cooler (higher CCT) light. During the evening hours at Maple Ridge Care Center, the hallway is illuminated by the recessed luminaires as well as the wall sconces, producing 140 lx at the vertical plane, which is slightly higher than Montello Care Center. However, the average CCT during the evening lighting condition for Maple Ridge Care Center is 2633 K, which is considerably warmer than Montello Care Center's average CCT of 4712 K.

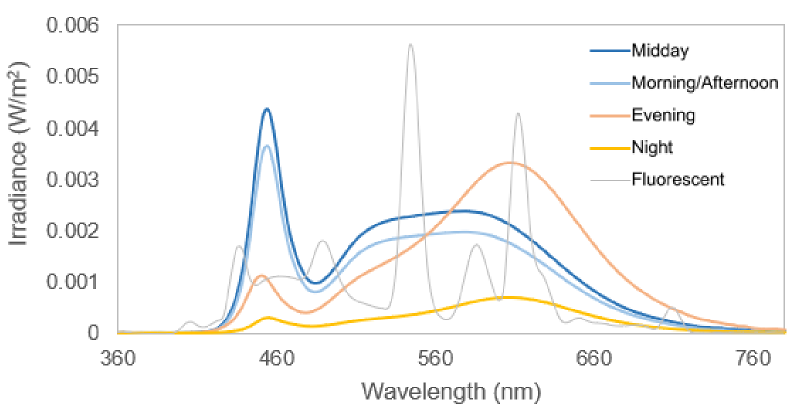


Figure 31. Average SPD measurements at eye positions in the hallways at Maple Ridge Care Center and Montello Care Center. These average SPDs represent the variations the tunable lighting system can provide, while the fluorescent lighting system provides static spectral content and intensity.

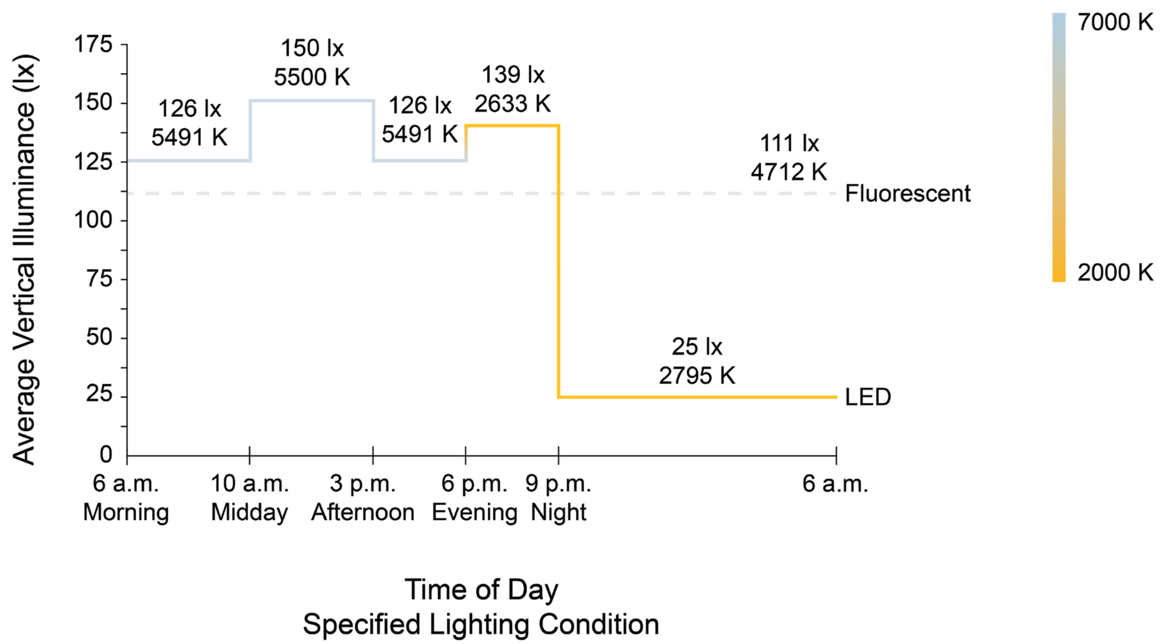


Figure 32. **Measured lighting conditions at eye positions in terms of vertical illuminance and CCT in the hallways at Maple Ridge Care Center and Montello Care Center.** The tunable lighting system provides variation in spectrum and amount of light at different times throughout the day. Importantly, the tunable lighting system (solid line) is capable of reducing the CCT and the amount of light overnight, while the fluorescent system (dashed line) operates consistently over 24 hours. Line colors in the graph correspond to the measured CCT.

3.2.2 Oak Ridge Care Center and Hope Health and Rehabilitation Center Activity Room Comparison

In addition to the hallways, Oak Ridge Care Center has tunable lighting throughout the dining room and activity space. These spaces have more flexible use throughout the day and are used by different residents at different times. With a static lighting system, each resident would generally receive the same amount of light, regardless of the time of day; a tunable lighting system with dynamic CCT and intensity settings can potentially offer more appropriate light exposure depending on the time of day in a more efficient manner than traditional lighting technologies. Similar to the previous example, the tunable lighting system in Oak Ridge Care Center is programmed to produce four unique lighting conditions over the course of a 24-hour period, while the lighting system in Hope Health and Rehabilitation Center remains static for the same period. Spectra across the four tunable lighting conditions and the static A19 LED lamp condition from Hope Health are shown in Figure 33.

Vertical illuminance levels at Oak Ridge vary between a maximum of 333 lx during the midday lighting condition and a minimum of 23 lx during the night lighting condition. The static fluorescent system is constant at 85 lx over 24 hours, as shown in Figure 34. The tunable system delivers a much cooler CCT during the day, about 5950 K, and is reduced to about 2640 K in the evening, while the static system in the control care center is 3570 K regardless of the time of day. Additionally, a shift in CCT occurs at 6 p.m. in Oak Ridge Care Center, but vertical illuminance is not substantially reduced. This results in a visual change in the environment that signals to occupants and visitors that the day is winding down but still provides enough light for residents to complete tasks.

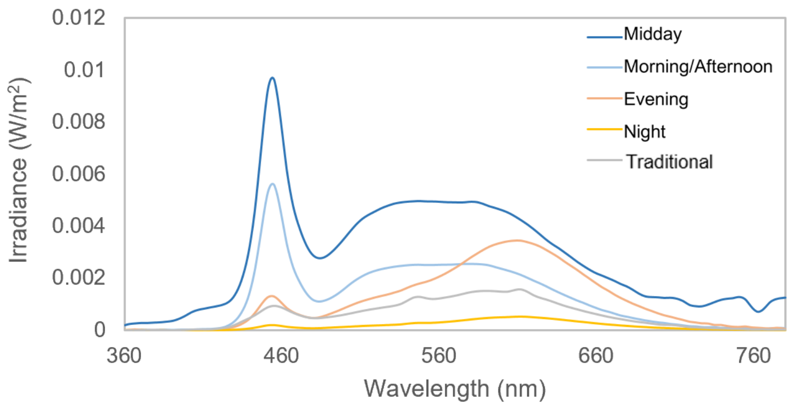


Figure 33. Average SPD measurements at eye positions in the activity rooms at Oak Ridge Care Center and Hope Health and Rehabilitation Center. These average SPDs represent the variations the tunable lighting system can provide, while the traditional lighting system provides static spectral content and intensity.

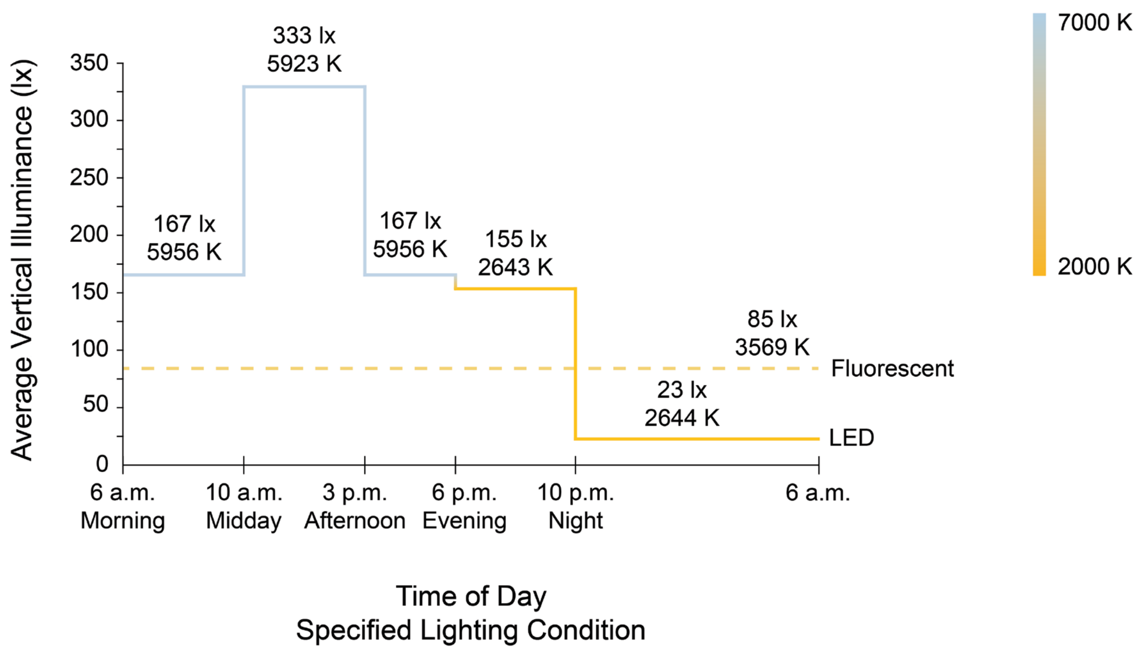


Figure 34. Average lighting conditions at eye positions in terms of vertical illuminance and CCT in the activity rooms at Oak Ridge Care Center and Hope Health & Rehabilitation Center. The tunable lighting system (solid line) provides variation in spectrum and amount of light at different times throughout the day. Compared to the tunable lighting system, the daytime light levels and CCT are much lower in Hope Health (dashed line). The colors of the lines correspond to the measured CCT.

3.2.3 Oak Ridge Care Center and Hope Health and Rehabilitation Center Dining Room Comparison

Measurements taken at multiple seating locations in the dining room at Hope Health and Rehabilitation Center indicate that the fluorescent lighting system delivers vertical illuminance levels more than double the vertical illuminance levels in the Oak Ridge dining room during the morning and afternoon tunable conditions. Over the tunable range, the control care center consistently delivers vertical illuminance of a much higher intensity, as depicted in the average SPD measurements in Figure 35. The tunable lighting system still produces four distinct lighting conditions with unique spectral qualities; however these differences seem less pronounced as a result of the high intensity lighting condition in the control care center.

The tunable lighting conditions shown in terms of illuminance and CCT in Figure 36 are not dissimilar to the tunable conditions shown in the previous examples, however, the difference in magnitude between the tunable conditions and the static control condition are apparent over the 24-hour schedule. The static fluorescent system provides an average CCT of 3417 K and 414 vertical lx, which was the highest average vertical illuminance recorded in all four care centers. During the midday tunable lighting condition, the system delivers a lower vertical illuminance of 232 lx, but at a cooler CCT of 6401 K. Without alternate switching and control strategies in the dining room at Hope Health and Rehabilitation Center, there is no way to reduce the potentially excessive vertical illuminance delivered to the residents throughout the day and into the evening. Although the tunable lighting system in Oak Ridge is scheduled, there is inherent flexibility that allows for varied lighting conditions. During typical breakfast and dinner times, the tunable lighting system delivered 159 vertical lx at 6058 K. After dinner, the lighting system is scheduled to reduce CCT, producing 140 vertical lx at 2645 K. This is followed by a reduction in intensity several hours later at 10 p.m., dropping average vertical illuminance levels to 35 lx with a CCT of 2635 K.

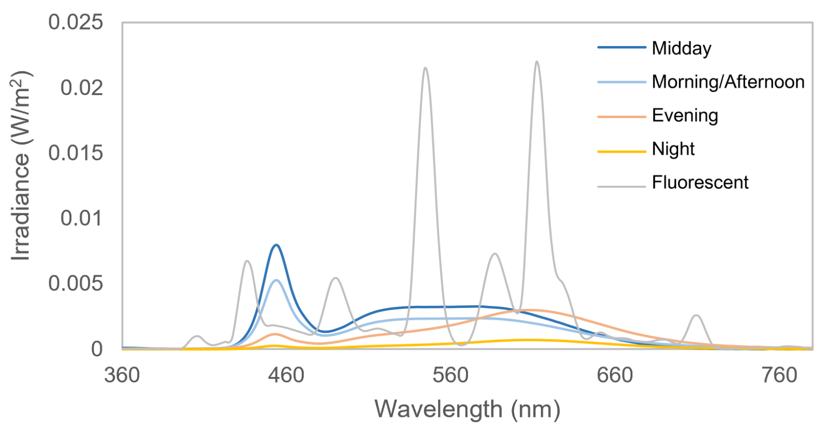


Figure 35. Average SPD measurements at eye positions in the dining rooms at Oak Ridge Care Center and Hope Health and Rehabilitation Center. These average SPDs represent the variations the tunable lighting system can provide, while the fluorescent lighting system provides static spectral content and intensity. In these care centers, the magnitude of irradiance delivered to occupant's eyes is much greater under the fluorescent conditions than under any tunable condition.

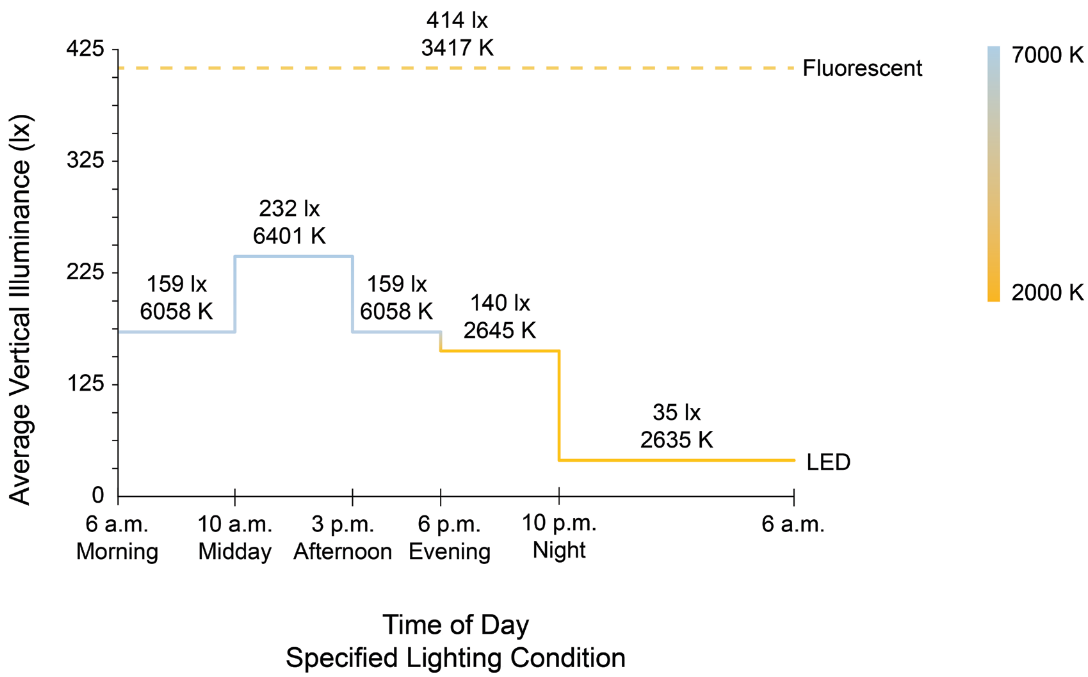


Figure 36. **Average lighting conditions at eye positions in terms of vertical illuminance and CCT in the dining rooms at Oak Ridge Care Center and Hope Health & Rehabilitation Center.** Though the tunable lighting system (solid line) provides variation in spectrum and amount of light throughout the day, the fluorescent lighting system in the control care center (dashed line) provides a greater amount of vertical illuminance over 24 hours. The colors of the lines correspond to the measured CCT.

3.2.4 Discussion

Both tunable lighting systems in the intervention care centers were capable of providing a dynamic lighting schedule over a 24-hour period with bright, cool daytime exposure and warm, dim evening exposure. The lighting systems in the control care centers did not allow for a dynamic schedule and cannot reduce light exposure in common spaces at night. However, several spaces in the control care centers delivered higher daytime illuminances than the intervention care centers, although with different spectral qualities than the tunable LED systems (see Appendix B for additional space-by-space comparisons). This presents a challenge for retrofit projects attempting to increase energy efficiency while providing lighting conditions suitable for supporting human health and well-being. Whenever illuminances in existing buildings exceed IES recommendations for visual tasks, common practice has been to maximize energy savings with a retrofit to more efficient products by also reducing the illuminances.

However, because emerging metrics related to health and well-being are affected by both spectrum and intensity, this reduction in illuminance may reduce the resulting metric values as well, even if the spectrum of the retrofit system might be better suited for occupant needs at a given time. The variation and flexibility supported by tunable LED lighting systems are important technological advances that can contribute to creating a bright daytime environment and a dark nighttime environment in support of preliminary metrics regarding non-image forming (NIF) response to light, but only when spectrum and intensity are considered together. NIF metrics that account for the intensity and spectrum of light are discussed in Section 3.3 of this report. Until consensus standards are adopted for the use of these metrics, lighting retrofits that seek to save energy while also improving the dynamic nature of the environment with tunable spectrum and intensity face this difficult trade-off without an accepted way to balance the competing demands.

Lastly, it is important to note that the spectral content received at the occupant's eyes is not equivalent to the spectral content leaving the luminaire due to interactions between the light and the room surfaces. Using CCT to illustrate this point, the tunable lighting systems were programmed at 6500 K and were measured on site at the luminaire ranging between 6434 K and 6454 K, but resulted in a received CCT around 5500 K in the Maple Ridge Care Center hallway and 5900 K in the Oak Ridge Care Center activity room. The lower CCT setting was less affected, due to the use of warm finishes, but was reduced from 2700 K from the luminaires to 2600 K at eye positions in both intervention care centers. This highlights a potential downside to the trend of using warmer finishes in care centers – those surfaces absorb the shorter wavelength light that is most efficient for desired NIF responses.

3.3 A Spectral Day in the Life of a Care Center Resident

Although both intervention care centers used similar lighting equipment, the lighting design and physical space characteristics were different which provided varied lighting conditions in each space throughout the day. In the previous section, the variation was presented in each space over the course of the day in terms of CCT and vertical illuminance. The following section reports light exposure as potentially experienced by a resident living in the care center moving from space to space in the same common photopic terms as well as emerging NIF response metrics.

Several metrics have been proposed to aide researchers and practitioners in determining the potential NIF response to light exposure. Additionally, there are several ways to calculate and use these metrics (Miller and Irvin 2020). Practitioners may need to increase light levels to achieve the recommended design targets, particularly if the selected luminaires have a direct distribution intended to light the horizontal task plane (Safranek et al. 2020). Metrics used in simulations during the design phase calculated from a manufacturer SPD or a sample SPD can differ when implemented in a real setting, due to different surface reflectance interactions, the spatial relationship to luminaires, and the luminaire distribution. Note that common methods used to calculate these metrics do not consider the spectral reflectance of objects, which affects the light reaching the eye (Durmus 2019).

Among these metrics, circadian stimulus (CS), melanopic daylight equivalency ratio (mDER), melanopic equivalent daylight illuminance (mEDI), melanopic to photopic ratio (M/P), and equivalent melanopic lux (EML) are currently used to predict or quantify the NIF response to light, such as melatonin suppression and alertness. Several factors can be manipulated to achieve these effects: intensity, spectral content, distribution, timing, and duration of light exposure.

Of these factors, CS considers intensity and spectral content, and it is based on nocturnal melatonin suppression that occurs as a result of one hour of light exposure (Rea and Figueiro 2018). Both mDER and the M/P ratio only consider the spectral content of light, and evaluate the ratio between the melanopic content of the SPD (blue-cyan region) and the photopic content of the SPD to provide an understanding of a source's potential to provide NIF effects. The mDER and M/P ratios are then typically combined with illuminance at the eye to generate the metrics of mEDI or EML, respectively, which consider both the spectrum and the intensity of the light.

EML and mEDI as metrics were created for practitioners designing for NIF effects as their values are similar to photopic illuminance. Both pairs of metrics (mDER and mEDI, M/P and EML) are effectively the same calculation, however M/P and EML reference the equal energy spectrum and mDER and mEDI reference the standard CIE D65 illuminant, which may be a more appropriate or familiar visual reference (CIE 2018; Lucas et al. 2014). While these melanopic metrics only account for the response of the ipRGCs to the lighting stimulus, Brown (2020) showed that melanopic illuminance serves as a good predictor for a range of NIF effects.

Characterizing typical resident light exposure over a 24-hour period can be helpful to understand holistic light exposure. As many NIF metrics do not inherently consider the time and duration of exposure, it is important to evaluate this separately so all factors influencing the potential NIF response are considered.

3.3.1 Hypothetical Resident Schedules

For the analyses described below, a hypothetical resident schedule was developed showing the amount and spectrum of light a resident may receive over 24 hours in typical photopic terms and as a function of NIF metrics. Recommendations regarding timing and duration are sometimes created separately to accompany metrics accounting for other variables such as intensity and spectrum. Creating a 24-hour schedule can allow a designer or practitioner to understand light exposure over time as a resident moves throughout the care center throughout the day. It can also allow the medical and administrative staff to adjust residents' schedules for the use of different spaces in the facility based on desired light exposure patterns. For example, the tunable systems may deliver light with greater potential for NIF response under the midday lighting condition, but residents may not spend time in those spaces at the appropriate time of day. Therefore, an accurate representation of stimuli that an individual is exposed to requires a schedule representing the day in the life of a care center resident.

In this example schedule, a resident starts their day in their room, goes to the dining room for breakfast, socializes in the hall, has lunch in the dining room, returns to their room for a nap, participates in a scheduled activity in the activity room, has dinner in the dining room, returns to the hallway, and finally goes to their room to rest, as summarized in Table 7. A summary of average spectral measurements taken in the care centers at seated eye positions following this schedule can be found in Appendix C.

Since measurements representing sleeping conditions were not captured in the control care centers, the percentage of the day does not include the hours between 9 p.m. and 6 a.m. Instead, the total (100%) of the day represents the time between 6 a.m. and 9 p.m. In summary, a resident who follows this schedule would spend about 17% of their day in the activity room, 20% of their day in their room, 27% in the hallways, and 36% in the dining room.

Table 7. A hypothetical care center resident daily schedule. While the resident room lighting produced several environments with different combinations of luminaires, a representative daytime and evening settings have been specified for use here.

Time	Tunable Lighting Setting (where applicable)	Description	Location	Percent of Day[b]
6 a.m. – 8 a.m.	Daytime Resident Room	Wake Up	Resident Room	13%
8 a.m. – 10 a.m.	6500 K 300 lx	Breakfast	Dining Room	13%
10 a.m. - 11 a.m.	6500 K 500 lx	Hallway	Hall A	7%
11 a.m. - 1 p.m.	6500 K 500 lx	Lunch	Dining Room	13%
1 p.m. - 2 p.m.	Evening Resident Room	Nap	Resident Room	7%
2 p.m. - 4:30 p.m.	6500 K 300 lx	Activity	Activity Room	17%
4:30 p.m. - 6 p.m.	6500 K 300 lx	Dinner	Dining Room	10%
6 p.m. - 9 p.m.	2700 K 300 lx	Hallway	Hall A	20%
9 p.m. - 6 a.m.	Evening Resident Room	Sleep / Rest	Resident Room	--

[b] In this table, "Day" is defined as the hours between 6 a.m. and 9 p.m.

For this analysis, CS was calculated according to the procedure outlined in UL Design Guideline 24480 (UL 2019), mDER and mEDI were calculated according to the procedure outlined in CIE S 026/E:2018 (CIE 2018) and M/P ratio and EML were calculated according to the procedure outlined in Lucas et al. (2014). Respective radial plots are shown for each care center in Figures 37 through 40 in typical photopic terms and NIF response metrics.

3.3.2 Resident Hypothetical Schedule Analysis

3.3.2.1 Morning

As residents wake up and receive morning care, the nurses in both intervention care centers were instructed to turn on the cool component of the overbed luminaire. To increase daytime light exposure in resident rooms, both intervention care centers also have multiple downlights in the resident rooms. Not considering any daylight contribution, the lighting system in Maple Ridge Care Center (intervention) provided residents with almost 90 lx at the assumed eye position. The static, traditional lighting system in Hope Health and Rehabilitation Center (control) provided residents with the greatest vertical illuminance of 118 lx and was the only room with surface mount luminaires instead of more traditional overbed luminaires.

In Montello Care Center (control), the lighting system produced the highest M/P ratio (0.64), but also produced the lowest vertical illuminance of the four care centers (32 lx). As a result, the M/P ratio in both intervention care centers is lower than Montello, however the EML values produced in the intervention care centers are greater than Montello because of the higher illuminance. Although the lighting system in Hope provided the greatest illuminance, the CCT was lower than the other care centers, at 2810 K. To maximize the current NIF response metrics, it is important to consider the combination of spectral content and intensity provided at the eye. The importance of delivering light to resident rooms that is capable of providing NIF effects during daytime hours is especially relevant for residents with limited mobility or access to abundant daylight.

Though the cool component in the overbed luminaire is rated at 6500 K, the measurements taken at the luminaires and resident's eye position during the daytime setting showed lower CCTs. In Maple Ridge Care Center, the CCT measured at the luminaire was 6233 K, but the CCT measured at the resident's eye position was 2986 K. The daytime Maple Ridge measurements did include contribution from the 3000 K downlights in the room, which reduced the resulting CCT at the eye but increased the light levels in the room.

Next, the example schedule assumes that residents go to the dining room for breakfast. In both intervention care centers, residents experience a greater change in CCT moving from their room to the dining room, and residents in both control care centers experience a greater change in illuminance. The lighting system in Hope Health and Rehabilitation Center delivered the highest vertical illuminance (414 lx) in all spaces across the four care centers; this resulted in the highest average CS (0.37) in any dining room. Due to the static lighting conditions in the control care centers, residents repeat this experience during all meals. This high vertical illuminance is not evident in the M/P or mDER radial plots, because only spectral content is considered in these metrics, while the large peaks at breakfast, lunch, and dinner can be easily identified in the CS, EML, and mEDI radial plots, which consider light intensity as well as spectral content.

3.3.2.2 Midday

During lunch at Oak Ridge Care Center (intervention), the average CS is lower than Hope (0.37) at 0.32, however this lighting system delivered far less vertical illuminance at a higher CCT to deliver the CS value more efficiently. This efficiency is also reflected in the mDER and M/P ratio values, which are 0.88 and 0.97, respectively, in Oak Ridge Care Center. The high illuminances that in turn produced the high CS values in Hope indicate that the system's spectrum is not as efficient for NIF effects; the spectral content produced mDER and M/P ratio values that were slightly more than half those of Oak Ridge, at 0.49 and 0.54.

Although the lighting conditions and CS values were different in Oak Ridge and Hope Health and Rehabilitation Center dining rooms during lunch, the resulting average mEDI values (Oak Ridge 203 lx, Hope Health 206 lx) and EML (Oak Ridge 224 m-lux, Hope Health 226 m-lux) are consistent between care centers. Because there is a unique relationship between illuminance and spectral content in the metric calculations, different combinations of CCT and illuminance can produce similar values within metrics, but communicate different results between metrics.

After lunch, residents may return to their rooms to take a nap or rest. In addition to the lighting conditions, other factors like noise level, thermal comfort, and physical pain or discomfort can influence how well a person can rest.

The activity room in Maple Ridge delivered the greatest vertical illuminance of 286 lx, CS of 0.24, mEDI of 185 lx, and EML of 204 m-lux compared to all other spaces and lighting conditions in Maple Ridge Care Center. For this hypothetical scheduling exercise, residents in Oak Ridge do not spend time in the activity room when the tunable lighting system is set to the midday (6500 K 500 lx) condition. If the goal for activity rooms is to maximize NIF response metric values and provide increased stimulus, static lighting, as applied in Maple Ridge Care Center may be a more appropriate solution. However, it may be possible to alter the tunable control strategy to maximize light intensity when the activity is being used during the day. Tunable lighting also provides flexibility to create different environments, which is particularly helpful when the space may be occupied 24 hours a day.

3.3.2.3 Evening

Regardless of the lighting system, residents in all care centers experienced the same electric lighting conditions during breakfast and dinner (all dining rooms except for Oak Ridge had static lighting conditions). In addition to eliciting a NIF response, tunable lighting can also provide simple visual cues alerting residents to the time of day. The tunable lighting systems in both intervention care centers were scheduled to reduce CCT from 6500 to 2700 K just after residents had their dinner and returned to the hallways or their rooms to socialize or rest.

With automated control systems, it is possible to design meaningful transitions that can be applied to individual care center needs that not only consider CCT and intensity, but distribution of light as well. In Maple Ridge Care Center, part of the transition between dinner and residents return to the halls included switching on the direct/indirect wall sconces and reducing the intensity of the overhead luminaires. The change in distribution from mostly direct lighting to mostly indirect lighting can also provide a visual cue to residents, while creating a more visually comfortable environment when preparing for rest.

Additionally, it is important to consider the duration of the transition between lighting conditions with the control system; a quicker transition that happens over seconds (as was the case in the intervention care centers) may be useful as a visual cue for marking time or altering the visual environment to influence behaviors or mood, while slower transitions that happen over the course of the day may seem more natural, but may not be as useful as a communication tool.

3.3.2.4 Overnight

For measurements representing the overnight environment in resident rooms in both tunable care centers, all room lighting was assumed to be switched off, leaving only spill light from the hallway (which was turned to the appropriate lighting condition). These measurements, taken at the eye position of a resident in bed, indicated that spill light was effectively lowered in the tunable care center resident rooms overnight resulting in 2 lx in Maple Ridge Care Center and 1 lx in Oak Ridge Care Center[3]. Although the intensity of the light in resident rooms at night was low, the M/P ratio was much greater than the design target of 0.3, as shown in the radial plots. This exposes a limitation of metrics that only consider spectrum (M/P ratio and mDER); to characterize lighting conditions with NIF responses in mind, consider the amount, spectral qualities, timing, and duration of light exposure.

Lastly, even though representative night time measurements were taken with all room lighting off, many residents kept their overbed or bathroom vanity luminaires or their televisions on at night, which may reduce or negate the potential benefits of reducing the lighting levels in the rest of the care center. During data collection, it was observed that of the 15 resident rooms in the 100 hallway in Maple Ridge Care Center, two

[3] Meter inaccuracies may increase in light levels below 5 lx.

residents closed their doors, four residents left their doors open and did not have any room lighting on, nine residents left their doors open and had either the room nightlight (a small nightlight recessed in the wall mounted about 18” above the floor), a table lamp, the bathroom vanity luminaire, or a television on. Among the 38 resident rooms in Oak Ridge Care Center, seven residents shut their doors and 11 residents left their doors open and did not have any room lighting on. Seven residents in Oak Ridge Care Center had the warm uplight component of their overbed luminaire on, and nine residents had all room lighting off but had the television on. The four remaining residents had some other combination of their room lighting operating, including two with the cool downlight component of the overbed luminaire. This exemplifies not only the variability that exists in realistic settings and personal preference, but also to the flexibility of the luminous conditions in a resident room.

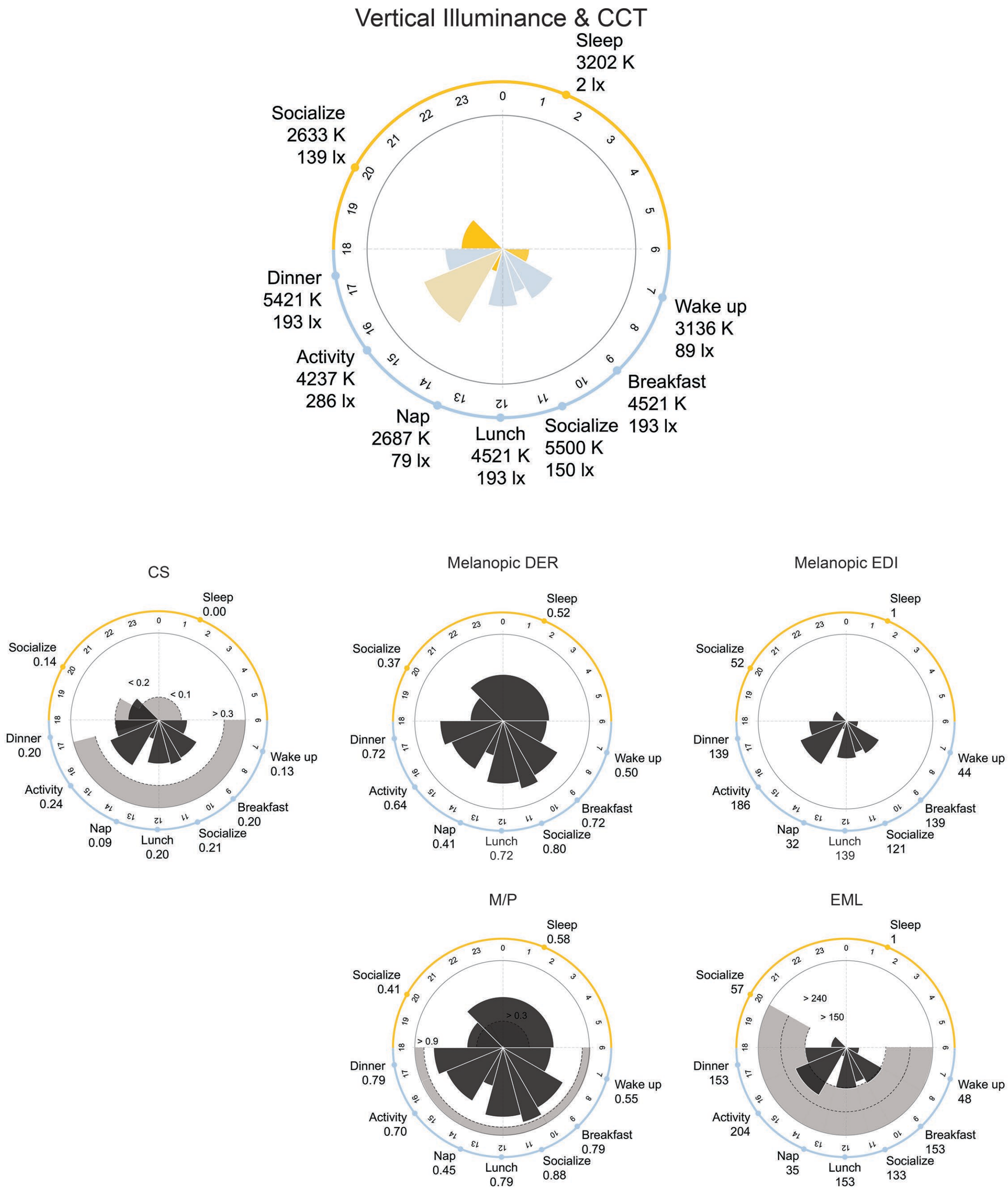


Figure 37. Radial plots showing hypothetical daily resident light exposure in photopic terms and several NIF metrics characterizing the biological potential of the electric lighting system for Maple Ridge Care Center. The radius of each section corresponds to the average value of the metric or measurement. The light gray fill and dotted line mark the boundary conditions for common design recommendations. The outermost blue and yellow circle around each plot shows a generalized warm (yellow) and cool (blue) tunable lighting scheme. In the top radial plot, the sections are colored to provide a visual representation of CCT.

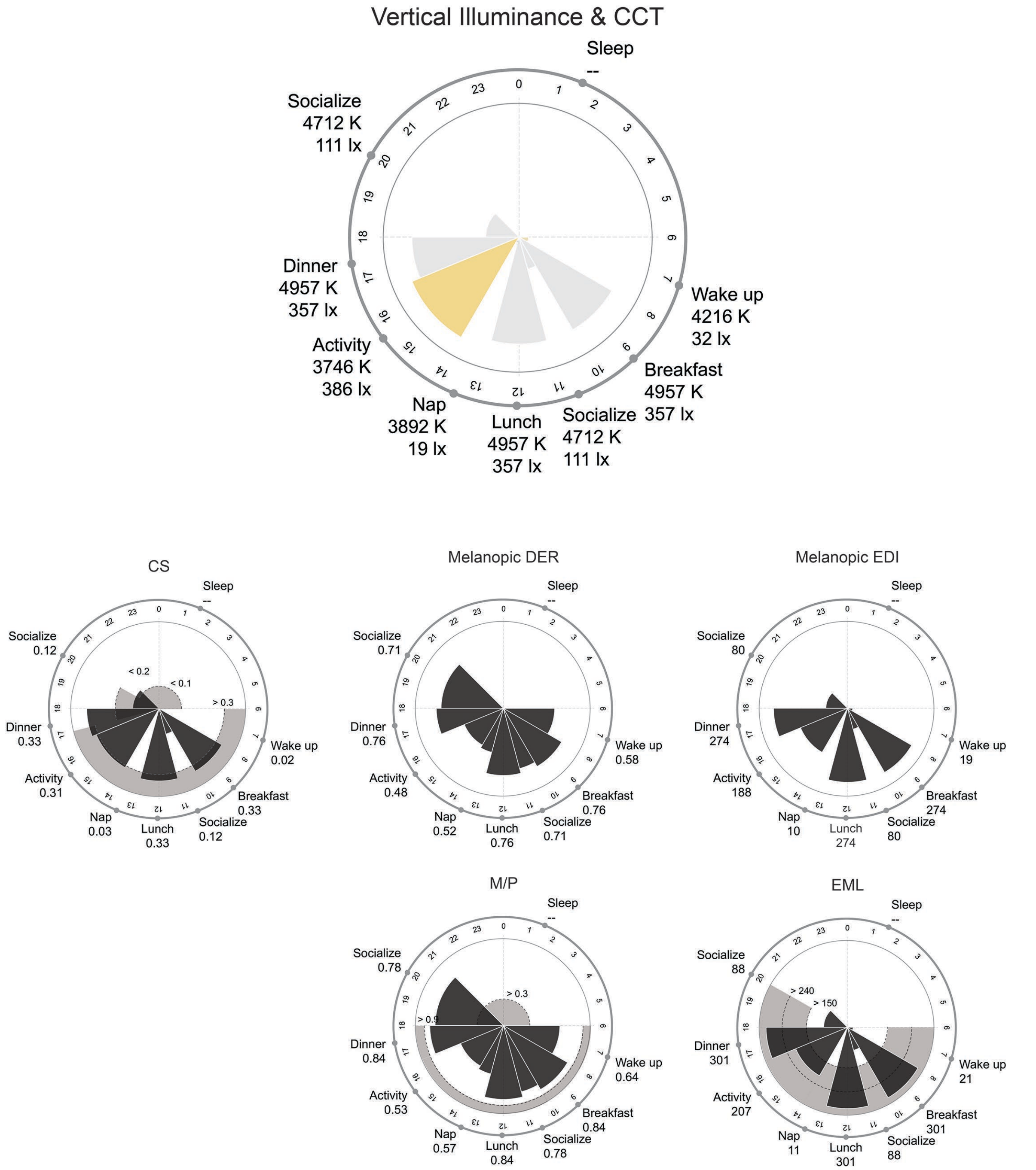


Figure 38 Radial plots showing hypothetical daily resident light exposure in photopic terms and several NIF metrics characterizing the biological potential of the electric lighting system for Montello Care Center. Radial plots showing hypothetical daily resident light exposure in photopic terms and several NIF metrics characterizing the biological potential of the electric lighting system for Montello Care Center. The radius of each section corresponds to the average value of the metric or measurement. The light gray fill and dotted line mark the boundary conditions for common design recommendations. Where "--" appears, data were not collected.

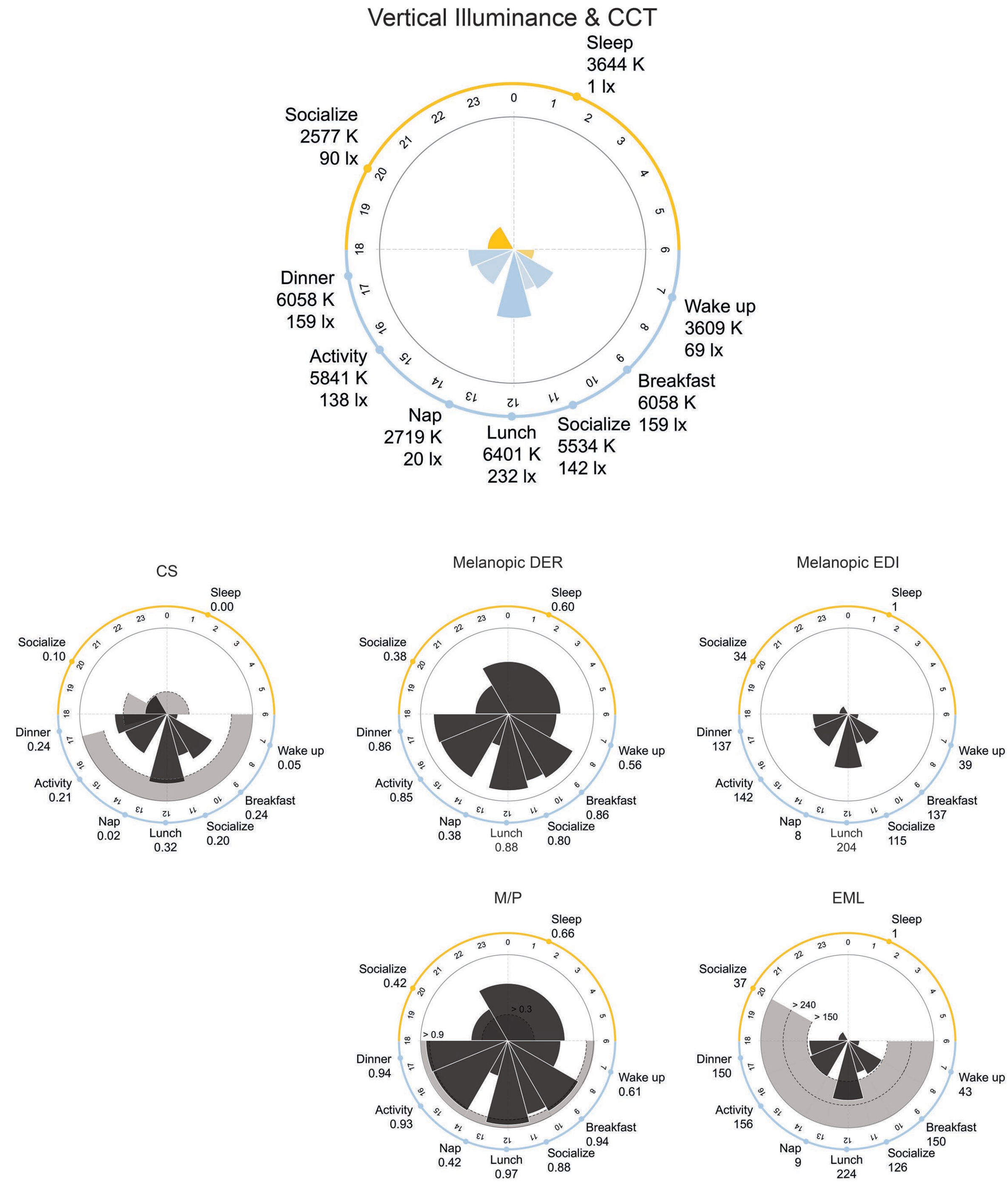


Figure 39. Radial plots showing hypothetical daily resident light exposure in photopic terms and several NIF metrics characterizing the biological potential of the electric lighting system for Oak Ridge Care Center. The radius of each section corresponds to the average value of the metric or measurement. The light gray fill and dotted line mark the boundary conditions for common design recommendations. The outermost blue and yellow circle around each plot shows a generalized warm (yellow) and cool (blue) tunable lighting scheme. In the top radial plot, the sections are colored to provide a visual representation of CCT.

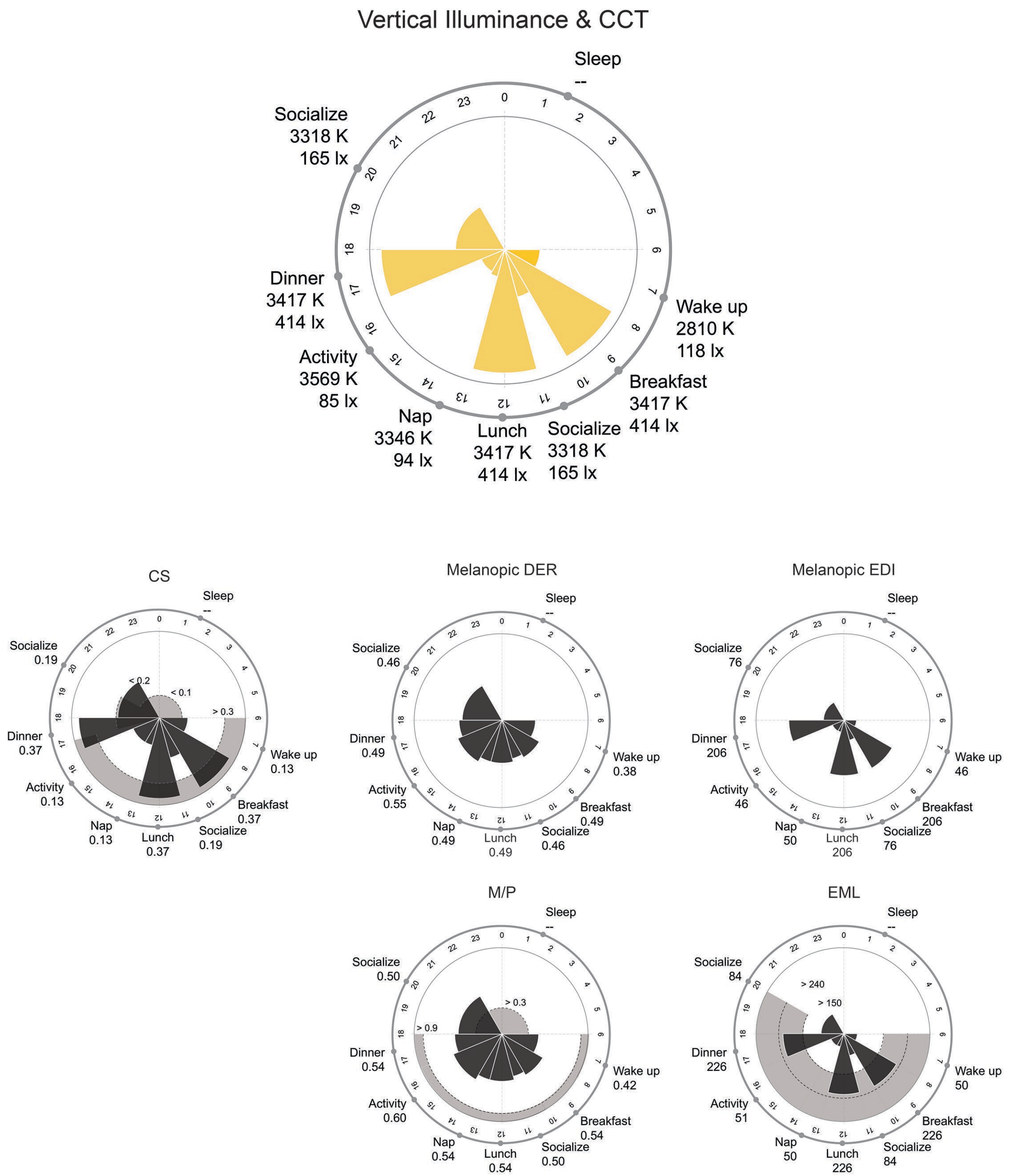


Figure 40. Radial plots showing hypothetical daily resident light exposure in photopic terms and several NIF metrics characterizing the biological potential of the electric lighting system for Hope Health and Rehabilitation Center. The radius of each section corresponds to the average value of the metric or measurement. The light gray fill and dotted line mark the boundary conditions for common design recommendations. Where "--"appears, data were not collected.

3.3.2.5 Discussion

The tunable lighting system in Maple Ridge Care Center exhibited greater variation in the spectrum of light delivered to residents, but less variation in the amount of light delivered. In Montello Care Center, the average vertical illuminance residents experience in the proposed schedule varied between 19 and 386 lx, while Maple Ridge residents receive between 2 and 286 lx. The average CCTs in Montello Care Center varied between 3746 and 4957 K (range of 1211 K), while Maple Ridge average CCTs varied between 2633 and 5500 K (range of 2867 K). In Oak Ridge, resident exposure varied between 1 and 232 lx (vertical) with a CCT range of 2577 to 6401 K (3824 K difference), compared to Hope Health, where resident exposure varied between 85 and 414 lx (vertical) with a CCT range of 2810 to 3569 K (759 K difference). The lighting conditions in Oak Ridge were able to maintain the desired M/P ratio targets in the dining room and activity rooms, unlike Maple Ridge, where no lighting conditions met the target values with the same tunable lighting system.

The lighting system in Oak Ridge Care Center resident rooms was capable of delivering the largest range of metric results between the daytime and evening settings, which could be important even though the daytime setting was not providing a similar intensity compared to other spaces in the care center. Both tunable lighting systems provided flexibility to vary the lighting conditions between daytime and evening light settings. The variation in lighting conditions was also evident in the NIF metric calculations CS, mDER and mEDI, as well as M/P and EML.

In Maple Ridge Care Center and Oak Ridge Care Center, residents experience greater variation in the spectrum of light, but less light intensity overall when compared to the control care centers. Resident lifestyle may influence any NIF effects depending on activity level, mobility level, and diet. For outcomes related to sleep quality, the relative effects of light exposure and duration are largely still a question. For example, does increasing light intensity first thing in the morning for a few hours with lower intensity during the rest of the day produce different effects than receiving consistent high-intensity light throughout the day? Is reducing light intensity and CCT in the evening and at night more important than generally increasing light intensity and CCT during the day? Though the care centers with tunable lighting were receiving less light in certain spaces, they delivered a more consistent intensity and spectrum of light exposure during the day, while the fluorescent lighting systems' spectrum was consistent, but the amount of light varied greatly between spaces. Understanding the relative effects of these complex combinations of spectrum, intensity, timing, and duration require further study.

3.3.3 NIF Response Metric Discussion

Design recommendations generally propose a design scheme similar to MLIs intended design – cool, bright light in the morning and throughout the day, and dim, warm light in the evening. While the design recommendations are typically used in office applications, there are no consensus-based design recommendations for senior care applications. UL Design Guideline 24480 for daytime office workers recommends that CS be greater than or equal to 0.3 from 7 a.m. to 4 p.m., then gradually reduced to less than or equal to 0.2 from 5 p.m. to 7 p.m., and finally reduced further to less than or equal to 0.1 after 8 p.m. (UL 2019).[4]

The WELL Building Standard (v2 Q2 2020) provides guidance "for all spaces" but provides measurement and verification guidance for "workstations," suggesting offices as the primary application (WELL v2 Pilot; IWBI 2019). This standard recommends at least 150 EML to receive 1 point and 250 EML to receive three points toward the overall score and WELL rating of the space. WELL suggests providing these EML levels at least

[4] In these senior care centers, the tunable transitions happened over seconds, instead of transitioning over one hour between settings as described in the design guideline. For this hypothetical analysis, PNNL adjusted the design targets to reflect CS > 0.3 from 6 a.m. to 5 p.m., CS < 0.2 from 5 p.m. to 8 p.m., and CS < 0.1 from 8 p.m. to 6 a.m.

between the hours of 9 a.m. and 1 p.m. While light levels may be lowered after 8 p.m., no further guidance is provided for nighttime exposure levels.

At this time, no lighting standards body has adopted any design recommendations and the recommendations are discussed here as a way to evaluate the technological capabilities of the lighting systems installed in the care centers. The guidelines and recommendations are illustrated in the respective radial plots as light shaded areas with dashed borders and are for reference only. There are currently no design recommendations surrounding M/P ratios, mDER, or mEDI; however, for this project MLI targeted M/P ratios greater than 0.9 during the day and M/P ratios less than 0.3 overnight. MLI was not seeking a WELL rating and the UL Design Guideline was not published when the design was completed. MLI faced challenges finding readily available, affordable products that met their design requirements and complied with the requirements of the grant. The following analysis is intended to discuss the similarities and differences between the current NIF metrics and highlight one way to evaluate the effectiveness of a design that includes timing, duration, and occupant schedules.

Based on the hypothetical schedule proposed here, residents in Maple Ridge Care Center may spend 20% of their day (from 6 a.m. to 9 p.m.) exposed to CS values that meet design recommendations and 53% of their day exposed to EML values that meet design recommendations; none of the spaces in Maple Ridge Care Center met the established M/P ratio targets as a result of limited technology selection and other architectural factors like luminaire placement, distribution, and surface reflectance, for example.

In Oak Ridge Care Center, residents may spend 33% of their day exposed to CS values and 30% of their day exposed to EML values that meet design recommendations. The daytime (morning/afternoon and midday), high CCT lighting condition in Oak Ridge produced M/P ratios that met or exceeded the design requirements, where residents may spend 53% of their day. The M/P ratio in the evening and overnight exceeded the design recommendations, but illuminance was effectively lowered.

In Hope Health and Rehabilitation Center, residents spend 40% of their day exposed to CS values and 36% of their day exposed to EML values that meet design recommendations. Lastly, residents in Montello Care Center spend 47% of their day exposed to CS values and 53% of their day exposed to EML values that meet current design recommendations.

Depending on the metric used in design or verification, the results could differ substantially, as shown in Table 8. This is not only due to the differences in timing guidance between the metrics, but is also a result of characterizing the same information, primarily spectral quality and light intensity, differently. As the research and science supporting the recommendations for a variety of applications and populations continues, the consequences of these scenarios should become clearer.

Table 8. Summary of percentage of day (between 6 a.m. and 9 p.m.) residents spend time in spaces that meet design recommendations for CS, M/P, and EML. M/P ratio design targets are project specific and are not included in the published standards. Depending on which metric is used in design or verification, conclusions and results could differ substantially.

	Maple Ridge Care Center	Oak Ridge Care Center	Hope Health	Montello
CS	20%	33%	40%	47%
M/P	0%	53%	--	--
EML	53%	30%	36%	53%

The result of applying a schedule emphasizes the importance of specifying lighting conditions according to how the space might be used over the duration of a day. The midday tunable lighting condition was available to residents in Maple Ridge and Oak Ridge for 5 hours of the day, between 10 a.m. and 3 p.m. The morning/afternoon lighting condition was available to residents for 7 hours a day, between 6 a.m. and 10 a.m., and 3 p.m. and 6 p.m. However, based on this hypothetical schedule, residents only spend 3 hours, or 20% of their day, in spaces with the midday tunable lighting condition, yet they spend 6 hours, or 40% of their day, in spaces with the lower, morning/afternoon lighting condition. The lighting schedule or resident schedule could be adjusted to be sure residents are in the spaces when appropriate lighting conditions are provided or vice versa.

Although the time residents spent sleeping was not counted in the summary analysis above, the M/P ratios were consistently higher than 0.3 in both tunable care centers, varying between 0.58 and 0.66 in Maple Ridge and Oak Ridge, respectively. M/P ratios are often used in isolation as specification tools, but should be accompanied by an EML value for a more accurate characterization. Even though the M/P ratios were higher than the design target, the vertical illuminance was very low in both care centers, producing very low EML values. Spectral content and intensity of light are both important factors; however, the reduction or absence of any amount of light at night, regardless of spectrum, is likely to support more restful sleep.

4 Conclusion

This report summarizes the lighting conditions in four senior care centers in the upper Midwest of the United States in terms of spectral and intensity information of installed light sources, estimated energy savings, and hypothetical residents' daily exposure to light. The retrofit project designed by MLI aimed to reduce energy use and increase resident health and safety in two care centers. While medical outcomes are not reported here, it is estimated that each intervention care center experienced more than a 60% reduction in energy consumed by the lighting system. Additionally, the tunable lighting systems installed were capable of providing a dynamic schedule delivering bright, cool daytime light exposure and warm, dim evening and night light exposure with the goal of supporting natural sleep-wake cycles for residents and reducing nighttime disturbances.

Research into the NIF effects of light on occupants progresses as senior care centers are being built or upgraded. Installing a tunable lighting system now offers flexibility in the future to alter lighting conditions to meet changing design targets or recommended lighting conditions. However, care should be taken in the design stage to ensure that these systems can deliver the high corneal light levels required to stimulate the biological effects. Future studies are needed to evaluate tunable lighting strategies in relation to medical outcomes, and to provide evidence-based lighting recommendations for residents with dementia or other medical conditions. Additionally, work with portable technologies, such as sleep mats or other light monitoring devices, could be used to evaluate individual sensitivities and subsequently provide resident level feedback to doctors and nursing staff. Appropriate timing and duration of effective light throughout the day is just beginning to become established. Individual sensitivities, lifestyles, and behaviors may play a role in determining the "ideal" light exposure.

Evaluation of the senior care center lighting systems provided the following key results:

- Completing the LED retrofit in both tunable care centers resulted in more than a 60% lighting energy use reduction, and greater energy savings were realized through a dimming schedule used to support occupant health and safety by creating an environment intended to support restful sleep.
- The tunable lighting systems were capable of providing a dynamic 24-hour schedule delivering comparatively brighter, cool daytime light and warmer, dim evening and nighttime light. However, in many cases, the amount of light received at the eye in the control care centers was more than that received in the intervention care centers. This is desirable during the day, but unless the high light levels can be reduced in the evening, it may be more than is needed for visual tasks by the staff and may not support healthy sleep.
- A one-to-one luminaire replacement, regardless of tunable capabilities, may make it difficult to increase light levels or NIF metrics. Light distribution, lumen output, luminaire location, view direction, and surface reflectance are important factors to consider when designing an efficient lighting solution for health and well-being of the occupants.
- Effective light delivery may mean illuminating ceilings and walls with light surface finishes to reflect light to occupant's eyes and avoid glare or a direct view of luminaire lenses. Wall and floor finishes typically associated with residential interiors are being used more frequently in care center applications to reduce the institutional feeling of the environment, but these finishes may decrease available light due to lower reflectances and should be carefully considered during design.
- Current NIF metrics consider spectral content and intensity of light, but do not inherently consider duration or timing related to light exposure. Tunable lighting routines should be synchronized, where possible, to accommodate the schedules and health needs of the occupants and provide appropriate lighting conditions at the correct time of day, regardless of the particular space they are occupying.

This can be accomplished during design and commissioning by understanding how occupants use the space over a 24-hour period.

- If practitioners decide to use the NIF metrics melanopic daylight efficacy ratio (mDER) and the melanopic to photopic ratio (M/P), melanopic equivalent daylight illuminance (mEDI) and equivalent melanopic lux (EML) should accompany these values, respectively, as mDER and M/P only consider the spectral content and do not take intensity into consideration. EML, mEDI, and circadian stimulus (CS) consider both spectral content and intensity.
- Depending on the metric used in design or verification, the metric calculation results could differ substantially. This is not only due to the differences in timing guidance between the metrics, but is also a result of characterizing the same information, primarily spectral quality and light intensity, differently. Additionally, it is unclear at this time how or if using any of the NIF metrics discussed here provide can provide accurate guidance for supporting patient outcomes in senior care environments.

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Appendix A: Extended Energy Analysis

Table A.1. Energy consumed by luminaire type in each space (hallway, dining room and activity room) before and after LED replacement in Maple Ridge Care Center.

		Hall		Dining				Activity	
		Troffer	Sconce	Sconce	Downlight	Downlight	Pendant	Pendant	Troffer	Track light
Before	Number of luminaires	12	12	11	27	2	76	10	9	4
	Luminaire power (W)	59	26	10	26	100	13	5.5	118	150
	Total power (kW)	0.71	0.31	0.11	0.70	0.20	0.91	0.06	1.06	0.6
	Operation time (hr/year)	5475	8760	5475	5475	5475	5475	5475	4380	2160
	Energy (kWh)	3876	2733	602	3843	1095	4999	301	4652	1314
Total power per room (kW)			1.02					2.06		1.66
Total annual energy (kWh)			6609					11251		5966
After	Number of luminaires	12	12	11	27	2	76	10	9	4
	Luminaire power (W)	25	6	13	13	13	5.5	5.5	52	9.5
	Total power (kW)	0.30	0.07	0.14	0.35	0.03	0.42	0.06	0.47	0.04
	Operation time (hr/year)	5475	4380	5475	5475	5475	5475	5475	4380	2190
	Energy (kWh)	1643	315	783	1922	142	2289	301	2050	83
Total power per room (kW)			0.37					0.99		0.51
Total annual energy (kWh)			1958					5437		2133

Table A.2. Energy consumed by each space (hallway, dining room, and activity area) before and after LED replacement in Oak Ridge Care Center.

		Hall A	Hall B	Dining	Activity
		Troffer	Troffer	Troffer	Troffer
Before	Number of luminaires	14	14	23	13
	Luminaire power (W)	90	90	90	118
	Total power (kW)	1.26	1.26	2.07	1.53
	Operation time (hr/year)	5840	5840	5840	5840
	Energy (kWh)	7358	7358	12089	8959
Total power per room (kW)			2.52	2.07	1.53
Total annual energy (kWh)			14717	12089	8959
After	Number of luminaires	14	14	23	13
	Luminaire power (W)	25	25	25	52
	Total power (kW)	0.35	0.35	0.58	0.68
	Operation time (hr/year)	8760	8760	8760	8760
	Energy (kWh)	3066	3066	5037	5922
Total power per room (kW)			0.7	0.58	0.68
Total annual energy (kWh)			6132	5922	5922

Appendix B: Variation of lighting conditions, a space-by-space comparison

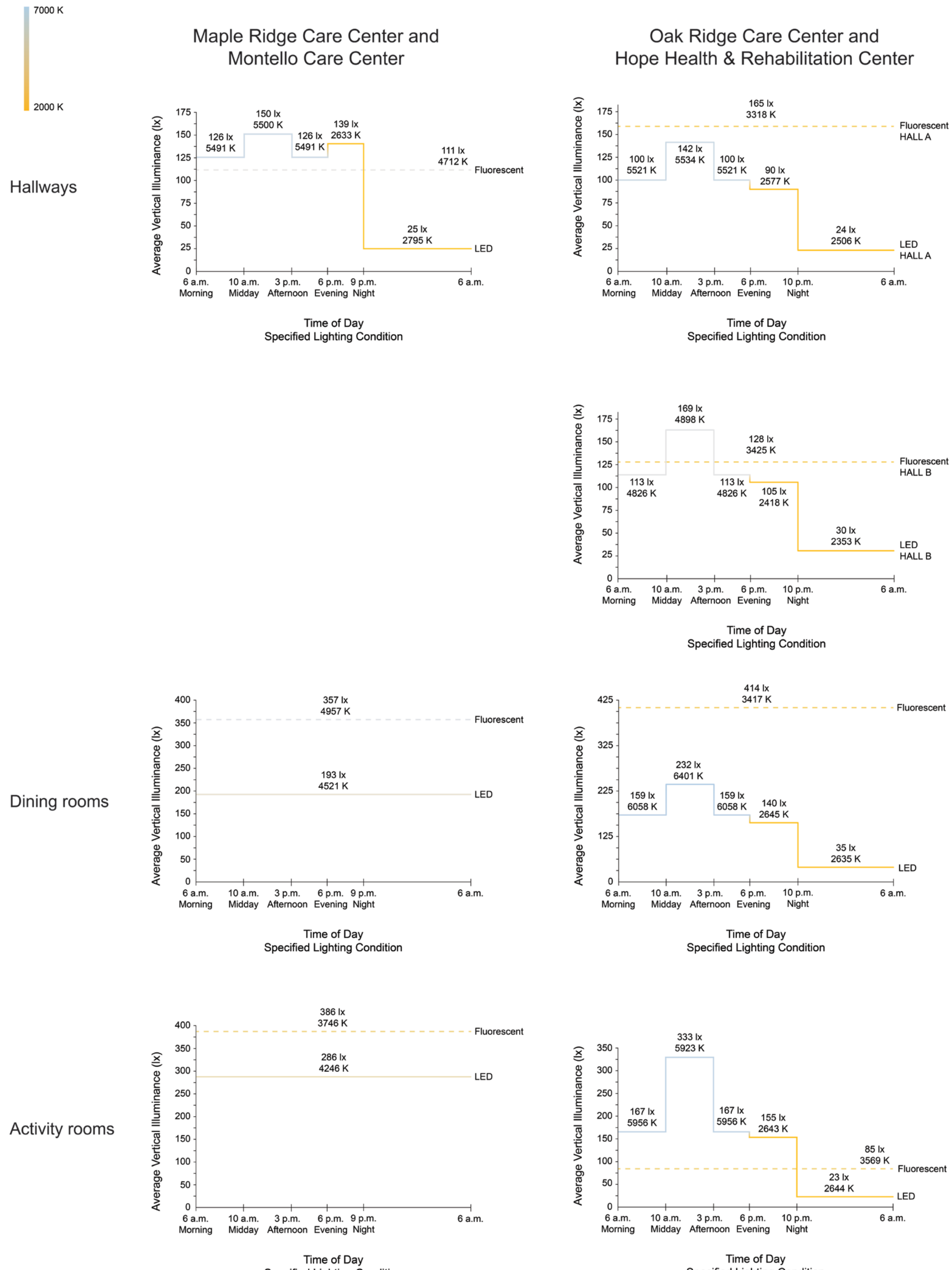

Figure B 1. A summary of space-by-space comparisons showing measured lighting conditions in terms of average vertical illuminance (y-axis) and average CCT (line color). The tunable lighting systems (solid line) are capable of varying both spectral content and intensity over 24 hours while the lighting systems in the control care centers (dashed line) remain static. As tunable lighting was not installed in the Maple Ridge dining or activity rooms, lighting conditions remained static in those spaces over 24 hours**.**

Appendix C: A Spectral Day in the Life of a Care Center Resident

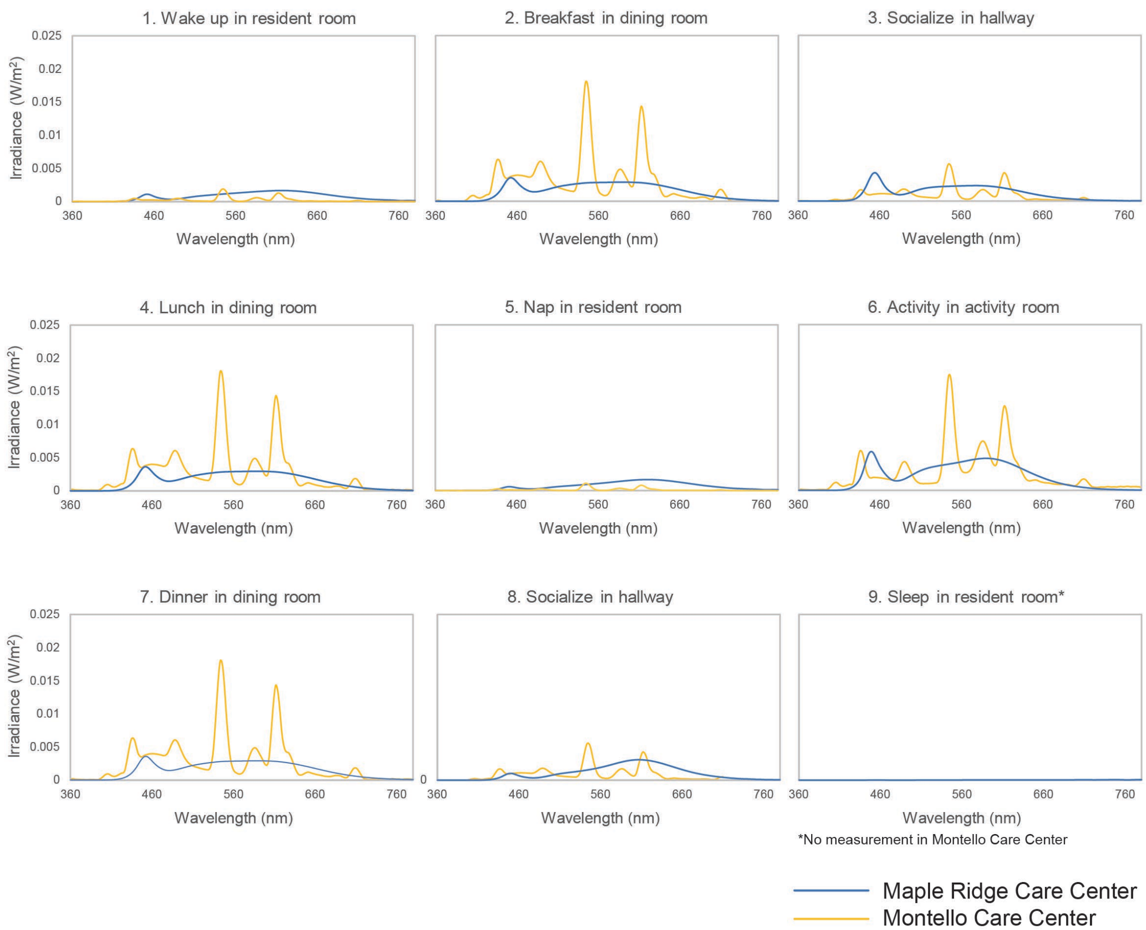

Figure C 1. **Summary of SPD measurements collected at eye height used to characterize a resident's light exposure over a 24-hour period following a representative resident schedule.** The intervention care center (blue lines) residents are typically exposed to less light than residents in the control care center (yellow lines). Exposure to higher intensities of light during the day may be preferred to support NIF effects, however only the tunable lighting systems were capable of purposefully reducing light intensities and shifting CCT during the evening and overnight.

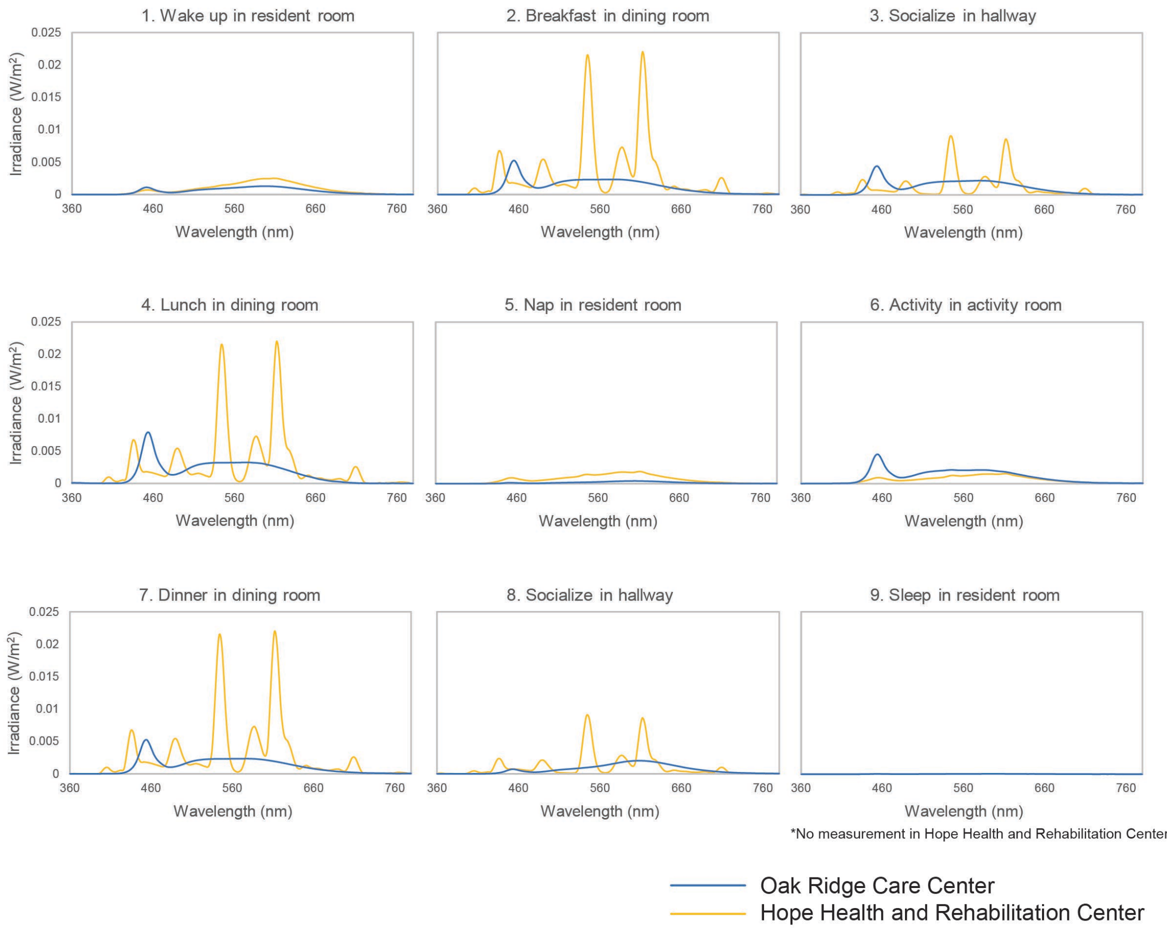

Figure C 2. A summary of SPD measurements collected at eye height used to characterize a resident's light exposure over a 24-hour period following a representative resident schedule. The intervention care center (blue lines) residents are typically exposed to less light than residents in the control care center (yellow lines). Exposure to higher intensities of light during the day may be preferred to support NIF effects, however only the tunable lighting systems were capable of purposefully reducing light intensities and shifting CCT during the evening and overnight.

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