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Tuning Hospital Lighting

Evaluating Tunable LED Lighting at the Swedish Hospital Behavioral Health Unit in Seattle

Prepared for the U.S. Department of Energy
Solid-State Lighting Program

August 2017

Prepared by Pacific Northwest National Laboratory

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Evaluating Tunable LED Lighting at the Swedish Hospital Behavioral Health Unit in Seattle

Final report prepared in support of the DOE Solid-State Lighting Technology GATEWAY Program

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Pacific Northwest National Laboratory
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Preface

The U.S. Department of Energy's Solid-State Lighting program documents the performance of SSL products and systems based on standardized laboratory test results, additional specialized testing, mock-up studies, and real-world field evaluations. This information is provided publicly for several purposes: 1) to track SSL technology performance improvement over time; 2) to identify technology challenges that impact performance and application of SSL; 3) to spur continued advancements in SSL technology, product design, and application; and 4) to maximize energy efficiency and decrease U.S. energy use, while improving lighting quality. DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products. SSL technology continues to evolve quickly, so evaluation results should always be understood in the context of the timeframe in which products were acquired, tested, installed, and operated. Especially given the rapid development cycle for SSL products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products. The two programs primarily involved in product evaluations are CALiPER and GATEWAY.

CALiPER

When CALiPER was launched, its role was largely to test products and compare actual performance to manufacturer claims and to benchmark technologies. Early CALiPER testing also contributed fundamentally to the development of standardized photometric test methods specifically for SSL and the associated accreditation of testing laboratories. As the SSL market has matured, CALiPER has transitioned its evaluations to new products and functions, such as OLED-based luminaires and color-tunable products, as well as long-term product performance. CALiPER continues to support the development of new test procedures and application guidance, with DOE investigations providing data that is essential for understanding the most current issues facing the SSL industry. Data are gathered primarily through laboratory testing and mock-up installations.

GATEWAY

GATEWAY conducts field evaluations of high-performance SSL products to collect empirical data and document experience with field installations. GATEWAY provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. GATEWAY typically documents pre- and post-installation light levels, color characteristics, energy intensity, and other performance attributes, and addresses application and maintenance of SSL products. In some cases, GATEWAY returns to projects after months or years of operation to take additional site measurements or remove luminaires and send to accredited laboratories for testing. While not possible for every project, such follow-up measurements have yielded useful data on dirt depreciation, color shift, luminous intensity distribution changes, and lumen depreciation over time.

For more information on the DOE SSL program, please visit https://www.ssl.energy.gov.

Acknowledgements
We are grateful for the contributions of Ian Cotton, electrical engineer for this project, along with support from Candela. Veca Electric and Technologies and Pacific Lighting Systems provided technical support to the project, including adjusting the controls and verifying technical details.

Executive Summary

The new Swedish Medical Behavioral Health Unit (BHU) in the Ballard neighborhood of Seattle serves patients struggling with mental health conditions. ZGF Architects and their design partners oversaw the design and construction of the new BHU, including the design of the lighting as a key element in creating an environment that connected staff and patients to nature and addressed the non-visual effects of light.

ZGF invited the U.S. Department of Energy Solid-State Lighting program to document the performance of the LED lighting systems as part of a GATEWAY evaluation. SSL technology provides new opportunities for controlling the intensity, distribution, and spectrum of light in healthcare and other applications. For DOE, this project was a chance to better understand how LED systems are delivering value to end users, and how these systems can be improved to deliver better quality and efficiency.

The lighting system for the corridors and dining/activity space was designed to operate according to a daily schedule developed by the ZGF design team, including a change in the spectral power distribution (SPD) of the downlights throughout the day. The correlated color temperature ranged from 2400 K at night to 6000 K midday, aligning with daily color variation of the sky. The intensity level also varied, with lower levels of light through the evening and night and higher levels in the morning and early afternoon.

An initial set of SPD and illuminance measurements was taken in May 2016, revealing that the design team's goals were not achieved, including higher than desired illuminance levels and a constricted SPD range. A second and third round of commissioning were required to meet the biophilic and circadian design goals.

Optimizing a tunable lighting system for biophilic and circadian goals, even on a small-scale, requires an understanding of the latest research related to circadian photobiology as well as an understanding of LED technology. The commissioning agents may not have the proper meters necessary for measuring both the SPD and illuminance, as was the case for this project. Developing a detailed specification of the desired control sequences and outcomes is necessary for these projects since estimating and measuring the SPD of light at expected eye locations is important for achieving circadian design goals, yet there is no easy way to currently estimate the effects at possible eye positions in an architectural space. Additionally, scientific evidence relating the medical effects of tunable lighting in architectural spaces to emerging lighting metrics has not been established, and the metrics themselves have not been standardized for use in lighting practice. Future projects would greatly benefit from collaborative design and research teams with expertise in biophilic design and in lighting and medical research.

Achieving design goals related to circadian and other biological and behavioral effects of lighting sometimes requires higher illuminances than those recommended for visual tasks, and consequently may increase the energy use of lighting during the hours when those high illuminances are needed. A given tunable luminaire may be less efficacious than a similar non-tunable model, which may contradict overall energy goals and require careful justification. Full-range dimming for LED systems provides significant energy saving opportunities that can help offset less efficacious luminaires and higher light levels. Allowing the building occupant some degree of manual control can potentially decrease energy savings. For this application, the reduced intensity levels specified for long periods of the day and night from the downlights enabled estimated annual energy savings of 41% relative to a non-tunable downlight system with the same number of luminaires. However, relative to a non-tunable system designed to only meet visual task illuminance criteria using half the quantity of luminaires, this tunable system increased estimated annual energy usage by 19%.

Contents

1. Introduction

The new Swedish Medical Behavioral Health Unit (BHU) in the Ballard neighborhood of Seattle, WA, incorporates color-tunable luminaires in common areas. The lighting system uses advanced controls for dimming and color tuning, with the goal of providing a better environment for staff and patients. ZGF Architects and their design partners incorporated color-tuning and dimming as part of the biophilic environment created to enhance the connection to nature for staff and patients.

The new BHU addresses the critical shortage of behavior health services in the Seattle region, and accepts voluntary and involuntary adult patients. The BHU is part of Swedish, the largest non-profit healthcare provider in the Seattle area, founded in 1908. The BHU is a 14,911 ft^2, 22-bed unit that required the renovation of two floors in a wing of the existing hospital. The patients struggle with mental health conditions, and are limited to the BHU during their stay that typically ranges from several weeks to a month. The previous 10-bed unit was across town at the Swedish Cherry Hill Campus. The unit occupied a floor of single-bed rooms, and patients had access to a behavioral-health-dedicated outdoor space and a large skylight in the common space. Since the new space was a renovation of existing infrastructure, the design sought to compensate for the differences between the new and old environments by leveraging biophilic design tenets.

ZGF invited the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) program to document the performance of the LED lighting systems as part of a GATEWAY evaluation. SSL technology provides new opportunities for controlling the intensity, distribution, and spectrum of light in healthcare and other applications. Tunable LED systems enable adjustments in spectral power distribution (SPD) and light output that are easier to implement than with conventional fluorescent lighting systems.[2] The availability of these new systems, combined with a growing understanding of the non-visual effects of light, has increased awareness and excitement. DOE previously published a CALiPER report summarizing laboratory testing of several color-tunable luminaires,[3] and a GATEWAY evaluation report documenting a trial installation of color-tunable luminaires in a few spaces at the ACC Care Center;[4] however, this is the first DOE documentation of a color-tunable system specified and installed by building industry professionals as part of a large-scale renovation project.

For DOE, this project was a chance to better understand how LED systems are delivering value to end users, and how these systems can be improved to deliver better quality and efficiency. This report reviews the design of this tunable lighting system, summarizes two sets of measurements, and discusses the circadian, energy and commissioning implications and lessons learned for this project.

[2] Definitions, testing, and other materials related to color-tunable LED products may be accessed at: https://energy.gov/eere/ssl/led-color-tunable-products.

[3] For further information, download the *CALiPER Report 23: Photometric Testing of White-Tunable LED Luminaires* prepared by the DOE SSL program: https://energy.gov/sites/prod/files/2016/01/f28/caliper_23_white-tunable-led-luminaires.pdf.

[4] For further information, download the *Tuning the Light in Senior Care* report prepared by the DOE SSL program: https://energy.gov/sites/prod/files/2016/09/f33/2016_gateway-acc.pdf.

2. Strategy and Design

This project was part of an ongoing effort by the ZGF design team to pinpoint the design attributes that affect human behavior, enabling these attributes to be adjusted to maximize positive outcomes. Evaluating how particular design elements impact human behavior, and then identifying successes and areas for improvement, is particularly important for projects that implement new concepts and technologies.

A tunable lighting system supported two new strategies integrated into this project: biophilic design attributes and circadian lighting, defined as lighting to support circadian rhythms. Biophilia, meaning love of nature, is a design approach that recognizes the innate human need to be a part of and within nature. There are many ways to apply biophilic design concepts, ranging from the subtle application of qualities of natural environments to overt inclusion of natural imagery and natural elements within buildings. The designers chose to highlight abstracted qualities of the Pacific Northwest environments by representing the progression through a stand of trees toward a well-lit, open clearing. Within the clearing, the darker ground plane gives way to the sky, with the transition represented by the dissolving patterns on the columns. The lighting in this space was designed to reinforce the passage of time by changing the spectrum and intensity of the lighting, with the goal of providing a sense of regularity in a care paradigm that can often be disorienting.

The tunable lighting is incorporated into the dining/activity area, shown in Figure 1, as well as corridors of the two-floor BHU. As part of the biophilic design strategy, the lighting was designed to largely mimic diurnal patterns of illumination, with changes in both intensity and SPD, providing a sense of the passage of time and a connection to natural rhythms. When the patients are awake, the majority of their time was expected to be spent in communal areas that are generally void of windows, including during the morning hours when light exposure can support the suppression of melatonin. Because of this, the dining/activity area was selected to incorporate white-tunable lighting. White-tuning cove lighting along the edges of the corridor represented glimpses of sky through a tree canopy. White-tuning cove lighting also encompassed the dining/activity area, representing a clearing in the forest, with white-tuning downlights providing task lighting that also mimics diurnal light patterns. Full-color-tunable lighting in small serenity rooms gave patients the option to adjust the SPD of the light to suit their mood. Serenity rooms were located at the end of three of the four corridors.

The design team implemented a tunable lighting system with the goal of reinforcing consistent circadian entrainment by providing tuned spectral content, with a specified intensity and duration. For the typical individual, the most important time to advance the circadian clock and promote earlier sleep times occurs in the morning hours. Since the patients were expected to spend their morning hours in the common areas that have limited daylight exposure, the circadian lighting system was installed in these areas.

Warmer material colors within the common area were avoided to improve the electric lighting efficiency, while supporting the biophilic design and the spatial experience. The final chosen wood panels and wood doors were light in color to improve reflectivity and are relatively neutral in color to reduce the depreciation of short wavelength content of the electric light. White tabletops were chosen to maximize the amount of light reaching the occupants' eyes while avoiding a considerable alteration of spectral content. Lighter walls and flooring were selected to benefit lighting efficiency. The limited ceiling height and limited space for ductwork made uniform spacing of fixtures impossible.

Figure 1. View of common areas. The nurse station (left) overlooks the dining/activity area, with views to the three corridors that connect to patient rooms, along with other spaces such as meeting rooms and examination rooms. A serenity room can be seen in the background on the left, illuminated by purple light. The tile patterns on the columns and the vertical lines and colors of the wallpaper provide references to natural elements such as trees, ground, and sky.

2.1 Lighting System Design

The lighting system was designed to operate according to a daily schedule developed by the ZGF design team for the common areas, including a change in the SPD of the downlights throughout the day. The correlated color temperature (CCT) ranged from 2400 K at night to 6000 K midday, in harmony with the natural color variation of the sky that occurs from sunrise to sunset. This schedule also included a variation in the intensity level, with lower levels of light through the evening and night and higher levels in the morning and early afternoon to reduce or increase, respectively, the possibility of melatonin suppression.[5] The short-wavelength content and intensity of the light was increased during the morning and afternoon to support melatonin suppression. The daily schedule initially included seven scenes, as shown in Figure 2. The Night and Afternoon scenes in the dining/activity area are shown side-by-side in Figure 3.

An Acuity Brands nLight® system was used to control the luminaires in the BHU, with multiple interfaces to meet the varying level of control desired in the different areas. The most comprehensive level of control was required for the corridors and the dining/activity area.

[5] For more information, see the DOE SSL Program Fact Sheet *Lighting for Health: LEDs in the New Age of Illumination,* May 2014, https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/light_and_health_fs.pdf.

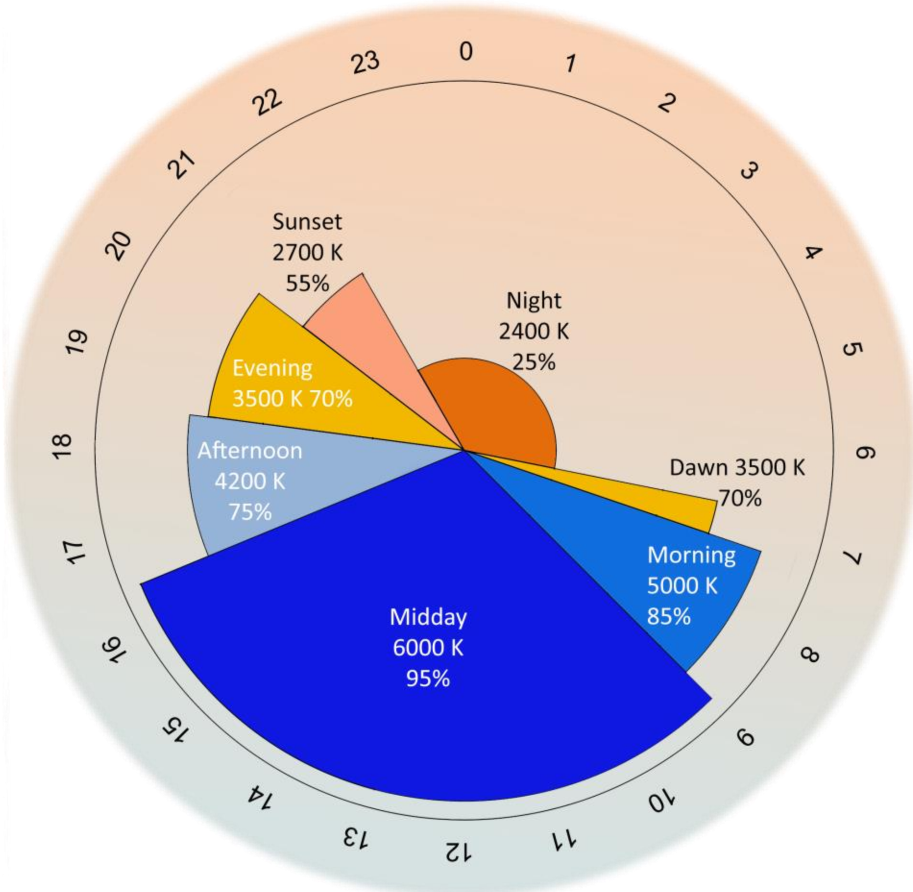

Figure 2. Daily schedule for the SPD and intensity level control setting: initial. The figure shows the initial schedule for the changes in SPD, indicated by CCT, and intensity level control setting throughout the day. The intensity level is expressed as a percentage of full output. The downlights and coves in the dining/activity area and the coves in the corridors initially changed according to this schedule.

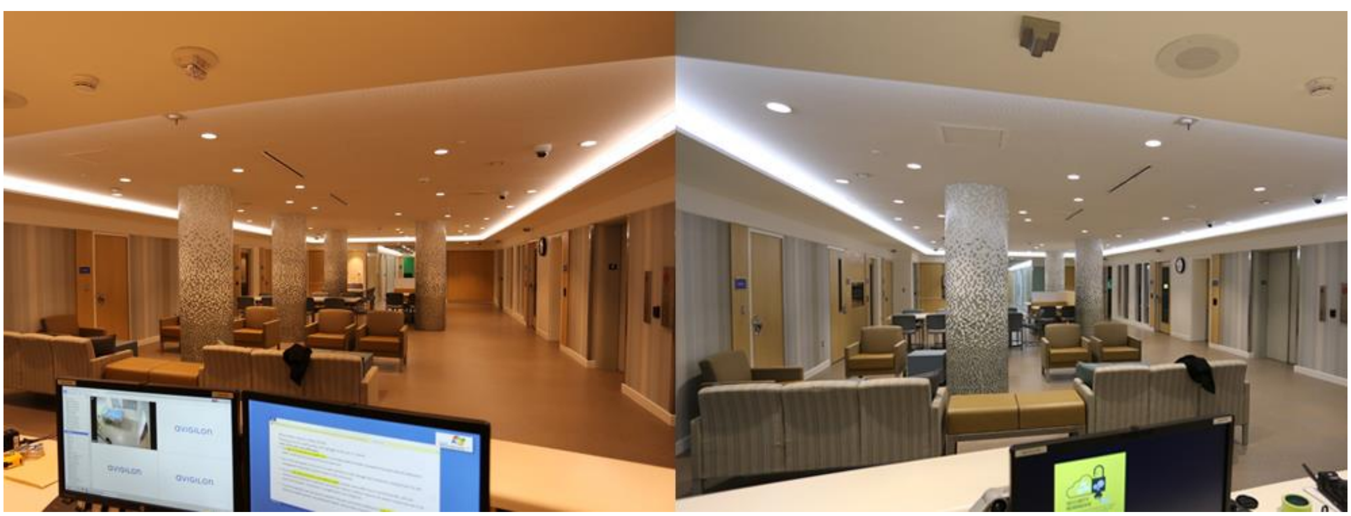

Figure 3. View of dining/activity area from nurse station. The change in SPD and intensity occurred throughout the day. The left shows the initial Night scene, and the right shows the Afternoon scene. The downlights were originally programmed to stay on all night (as shown here), but were later re-programmed to turn off at night, as preferred by the nursing staff.

2.1.1 Dining/Activity Area

The design team selected the USAI BeveLED® 2.0 Color Select downlights, which utilize a 0-10 V signal for intensity level and a separate 0-10 V signal for SPD.[6] The SPD and intensity of these downlights in the dining/activity area were primarily controlled by an automatic daily schedule to support the biophilic and circadian design goals. In addition, an nLight® nPod GFX Graphic WallPod[7] located near the nurse station allowed the medical staff to adjust the intensity level of the downlights via a touch screen. The SPD of the downlights could not be altered without a password.

2.1.2 Corridors and Serenity Rooms

The corridor cove lighting was controlled by a DMX-based Acuity Easyl™ DIN,[8] operating off the same time clock as the dining/activity area and following the same daily schedule. The intensity and SPD could not be altered by staff. Vision Light Worx Flex white-tuning LED flexible strip was used to light the cove. The design intent of the corridor was to provide cues of the passage of time and to tie together the common spaces. At the end of three of the four BHU corridors are serenity rooms where patients can enjoy a quiet space and adjust the SPD of the lighting on the walls, as shown in Figure 4. An Easyl™ DMX512 controller[9] was used to control the Vision Light Worx Flex full-color-tuning LED flexible strip product used to wash two walls with light in each serenity room. The occupant could set the desired intensity and color, or cycle through a preset color progression using the LCD touchscreen located outside of the room, next to the entrance. Ambient illumination was provided by a Luminaire LED, Inc. circular, ceiling-mounted LED fixture[10] with a 3500 K CCT and a 0-10 V dimming driver.

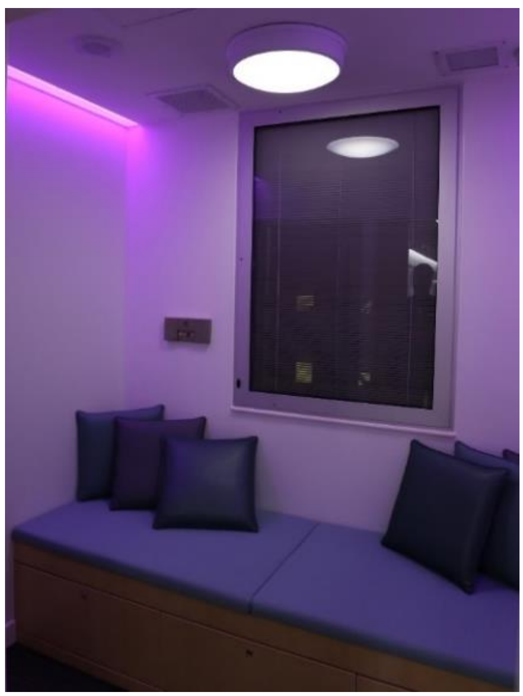

Figure 4. Serenity room. This small room provides a space for patients to spend time in a quiet space. The patients could adjust the SPD of the wall-wash luminaire to suit their mood.

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[6] USAI BeveLED® 2.0 Color Select Downlight. Round LED downlight, 1 in. regress, 32 W, 1875 lumens, 6000 to 2200 K tunable white light, 60° beam.
[7] Acuity Brands Lighting Graphic WallPod (nPOD GFX) controller with 3.5 in. color touchscreen.
[8] Acuity Brands Lighting Easyl™ DIN controlled by contact closure with input from the Acuity nLight® system.
[9] Acuity Brands Lighting Easyl™ Pro DMX512 controller with 3.5 in. color LCD touchscreen.
[10] Luminaire LED, Inc. ANYX ARV17 Series vandal-resistant LED luminaire, with polycarbonate lens. 26 W, 2155 lumens, 3500 K CCT, 80 CRI.

3. Measurements

3.1 Initial Measurements – May 23, 2016

An initial set of SPD and illuminance measurements was taken the evening of May 23, 2016, with measurements taken after dark to eliminate daylight contribution. The official opening of the BHU was scheduled for the next day, so this date was selected to avoid disrupting BHU operations. The goal of the measurements was to document the luminaire SPDs and floor illuminances produced by the tunable downlight and cove luminaires[11] in the dining/activity area, at each specified control setting. The research team did not have access to the system controls during this initial visit, and thus only could measure the schedule scenes that occurred during the measurement period. The scenes documented were Afternoon, Evening (identical to Dawn), Sunset, and Night. The Morning and Midday scenes could not be documented.

A calibrated Konica Minolta® CL-500A spectrophotometer[12] was used to measure the SPD of five downlights in the central portion of the dining/activity area, as the system cycled through the programmed schedule changes. The CL-500A software calculated CCT from the measured SPD, and the average CCT of the five luminaires was used for comparison to the schedule scenes. The CCT range was smaller than expected for the afternoon to nighttime scenes. The CCT range of the schedule was 1800 K, from 4200 K to 2400 K, but the measured range was just 937 K, from 3852 K for the afternoon (schedule 4200 K) to 2915 K for the night scene (schedule 2400 K). As explained later, this restricted range occurred due to the initial commissioning of the control system.

Horizontal illuminance was measured on the floor in the dining/activity area every 4 ft along a line parallel to the elevator wall and along another line perpendicular to the elevator wall in the middle of the room, as shown in Figure 5. The measured illuminances at each point, for each of the lighting scenes measured, are shown in Figure 6. The maximum-to-minimum illuminance ratios for the points measured ranged from 1.8 to 2.0 across the four scenes that were evaluated.

To compare the actual intensity level to the intensity level specified for dimming by the schedule, the illuminance at points 13 through 18 was measured for each scene, then was measured again with the downlights increased to full output with spectrum unchanged.[13] Due to time limitations, only six of the points were measured again at full output. As shown in Table 1, the magnitude of dimming, expressed as a percentage of the full light output, was less than the schedule, resulting in higher illuminance and less energy savings than intended by the design team.

[11] The cove light luminaires had not been properly commissioned at the time of the measurements, so they did not vary in spectrum or output during the programmed scene changes. This issue was later corrected, and the cove luminaires were evaluated for all schedule scenes during the second measurement visit.

[12] CL-500A Konica Minolta® Illuminance Spectrophotometer (10002008) calibrated July 8, 2016.

[13] The cove luminaires remained on during these measurements, but their contribution to the measured illuminance was subtracted out for these comparisons using cove-only illuminance measurements.

Figure 5. Dining/activity area illuminance measurements diagram: initial. The yellow line of the tape measure shows where the measurements were taken in the dining/activity area. The first line of 12 measurements was taken 4 ft 8 in. from the elevator wall at a spacing of 4 ft. The second line of 6 measurements (13-18) was taken perpendicular to the elevator wall in the center of the dining/activity area at 4 ft spacing.

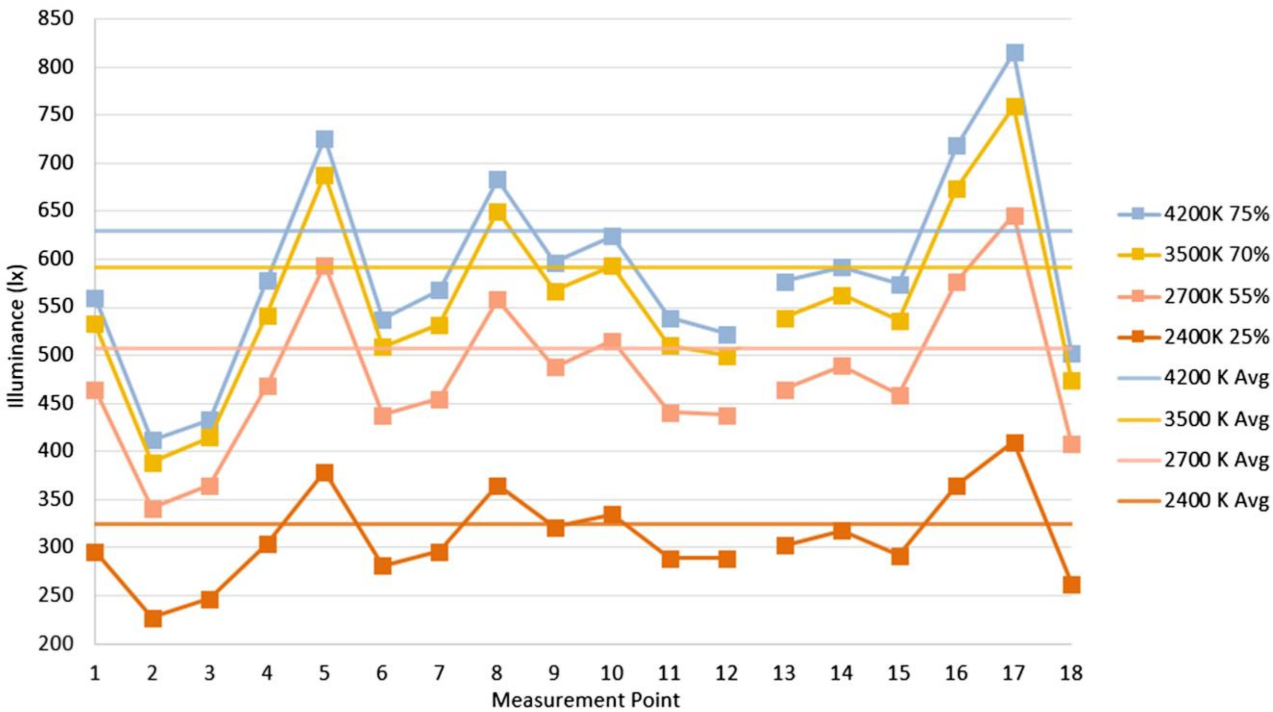

Figure 6. Dining/activity area illuminance measurements: initial. The illuminance measurements varied in part due to the irregular spacing of the downlights in the ceiling and the cove lighting. The average of the 18 illuminance measurements for each scene is shown by the solid lines. These measurements include contributions from both the downlights and the cove luminaires.

Table 1. Measured downlight illuminance levels compared to schedule intensity level settings. The measured illuminance of the downlights is an average of measurements points 13 to 18, with cove contribution subtracted out, measured at a 4 ft spacing perpendicular to the elevator wall at the center of the dining/activity area. The Morning and Midday scenes were not measured.

Lighting Scene (CCT)	Measured Average Illuminance (lx)		Intensity level (% of full output)	
	Full Output	Scene Output	Measured	Schedule
Afternoon (4200 K)	666	599	89.9	75
Evening (3500 K)	651	560	86.1	70
Sunset (2700 K)	635	477	75.0	55
Night (2400 K)	636	295	46.3	25

While documenting illuminance, DOE researchers noticed that the downlights created a pattern of blue-white light and orange-white light on the white tables in the dining/activity area. This pattern also occurred on the floor, but was less noticeable due to the brown, textured flooring. The design team discussed this concern with the luminaire manufacturer, and the cause was determined to be the use of clear polycarbonate lenses, which were custom manufactured for this project at the design team's request to provide greater durability for the behavioral health setting. Subsequently, the manufacturer created a diffusing polycarbonate lens that more closely aligns with the standard lens for the luminaire, and provided replacement lenses at no cost to the project. The lens replacement occurred after the second set of measurements, and solved the problem.

DOE researchers shared the initial measurement results with the project architects. Based on the discrepancies in CCT and illuminance between the schedule and the measurements, a second commissioning was considered necessary to fully implement the biophilic interior design attributes and tunable circadian lighting strategies.

3.2 Second Measurements – September 8, 2016

The results of the initial measurements led to a second round of commissioning in September 2016. The BHU was now fully operational, so access was limited to hours when patients were expected to be asleep, and when staff members were not expected to be active in the dining/activity area. In addition to the manufacturer's representative, the second round of commissioning included two of the project architects and a DOE researcher. All were integral in the iterative process of programming the control system to achieve project goals, including adjustment of the control system by the manufacturer's representative, SPD and illuminance measurements by DOE, and verification of target goals by the architects.

For each scene, the SPD of three downlights and the cove at two locations was measured in close proximity to the source. Table 2 compares the average CCT values of the initial and second measurements of the downlights, demonstrating that the desired range of 1500 K between the 4200 K and 2700 K scenes was nearly achieved after the second commissioning (range of 1413 K), and was greater than the range after the initial commissioning (801 K).

Table 2. **Comparison of downlight color temperature: initial and second measurements.** Due to furniture locations and to avoid disrupting the medical staff, different luminaires were measured during the second visit. The same CL-500A meter was used for both sets of measurements. The Morning and Midday scenes were not initially measured, and the Morning scene was changed during the second set of measurements to be equal to the Afternoon scene. The downlights were turned off for the second set of measurements due to a change in the schedule.

Lighting Scene (Intensity level)	Average CCT (K)		
	Schedule	Initial Meas.	Second Meas.
Midday (95%)	6000	---	5862
Afternoon/Morning (75%)	4200	3852	4272
Evening / Dawn (70%)	3500	3420	3302
Sunset / Sunrise (55%)	2700	3051	2859
Night (25%)	2400	2915	---

To evaluate the illuminances produced by the lighting system, horizontal illuminance was measured at two of the same points measured during the initial visit (points 13 and 14, shown in Figure 6).[14] As illustrated in Figure 7, the commissioning performed during the second visit resulted in a much greater range of illuminance for the four scenes assessed during both visits, and in general resulted in lower illuminances in the space. The commissioning process during the second visit was done in part to achieve illuminances that better matched the assumed task requirements in the space, and in part to achieve desired vertical illuminances to satisfy design goals related to human circadian response.

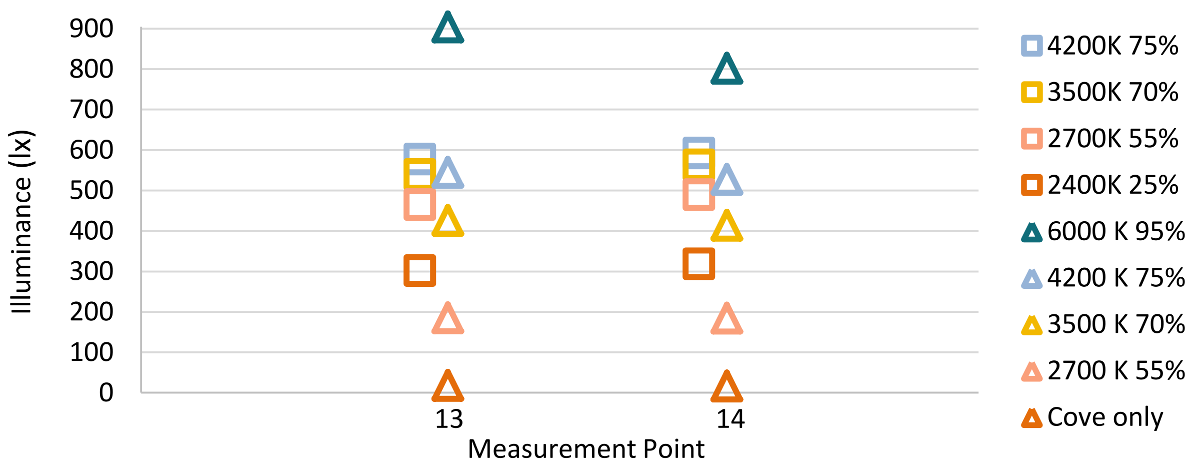

Figure 7. **Dining/activity area illuminance: initial and second measurements.** The initial illuminance measurements are indicated by the squares and the second set of illuminance measurements are indicated by the triangles. Two measurement points were repeated for both sets: 13 and 14.

Table 3 shows the initial and revised schedules and the measured downlight intensity levels for the four scenes evaluated during the initial and second measurements. The downlights in the dining/activity are turned off starting at 10:00 PM because after this time patients are rarely in the dining/activity area, while the nurse station and cove remains on at 2400 K CCT. The nurse station downlights could reach 2200 K, but the dining/activity area downlights could only go down to 2900 K due to differences between the relays used to control the SPD of the fixtures; this was a limitation of the controls installed and not of the luminaires. Further details are provided in Section 4, including the energy use implications of the dimming adjustments made during second commissioning.

[14] These two points were used for assessment during the second measurements because they could be accessed without moving furniture or disrupting BHU operations, and had illuminance values that were close to the average illuminance during the initial visit.

Table 3. Measured downlight intensity levels compared to schedule: initial and second measurements. Intensity level values are the average of measurement points 13 and 14. The four scenes were measured during the initial and second measurements, except Night since the downlights were turned off according to the revised schedule for the second measurements.

Lighting Scene (CCT)	Intensity Level (% of full output)		
	Schedule	Initial Meas. 13-14	Second Meas.
Afternoon (4200 K)	75	89.7	83.8
Evening (3500 K)	70	85.6	66.9
Sunset (2700 K)	55	75.2	29.8
Night (2400 K)	25	46.5	---

Additionally, vertical SPD and illuminance measurements were recorded for each of the five lighting scenes. The SPD and vertical illuminance were measured at seated eye height at a table in the dining/activity area, for the direction facing toward the seating area in the dining/activity area, and also in the opposing direction toward the back corridor. The SPD measurements recorded in the BHU (not the SPDs from the manufacturer) are shown in Figure 8, illustrating how the direction of an occupant's gaze in the space affects the intensity and SPD of the light entering the eye. The intensity is considerably lower when the occupant is facing the back corridor instead of the seating area, except for the night condition, when the downlights are off in the dining/activity area.

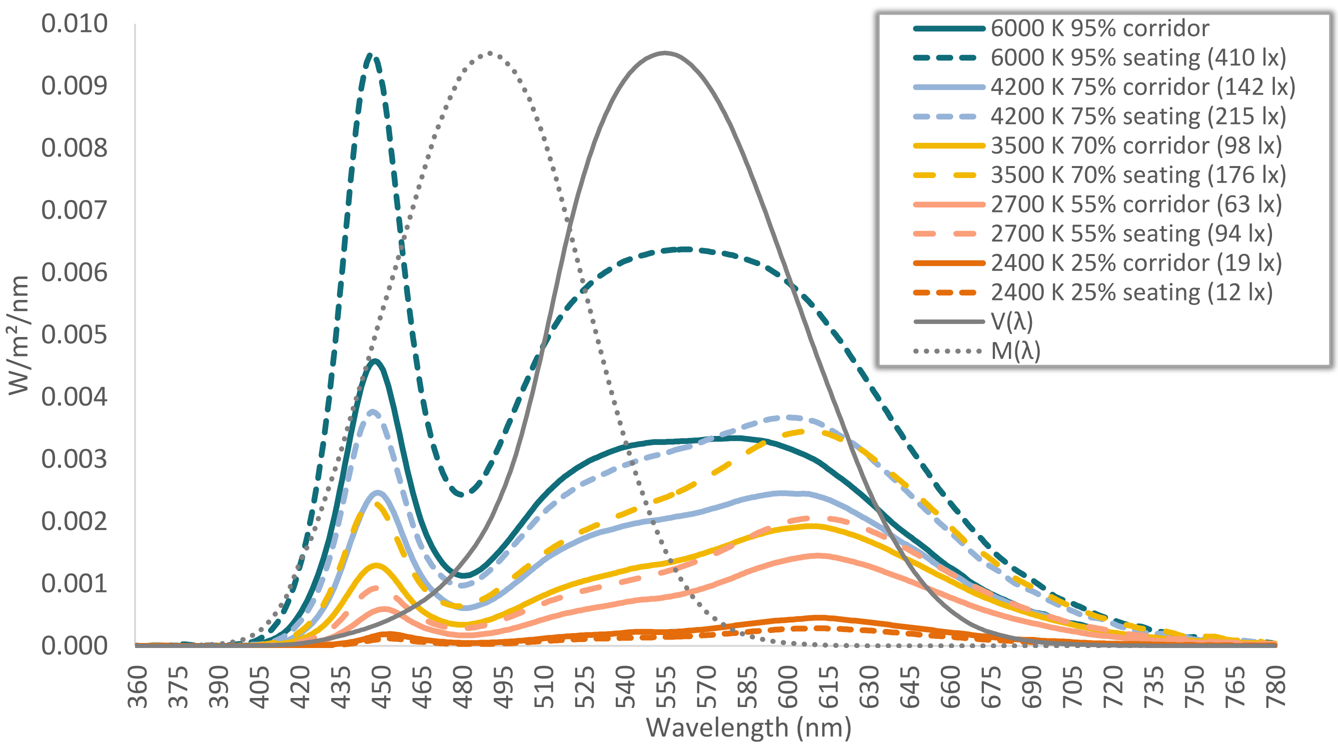

Figure 8. Dining/activity area vertical SPD measurements: second measurements. The SPDs were measured with the CL-500A positioned vertically at seated eye height for one of the seating locations at a table in the dining/activity area, facing toward the nearby seating area and also facing in the opposing direction toward the back corridor. Measurements were made for each of the five lighting scenes evaluated during the second commissioning. The photopic spectral luminous efficiency function, V(λ), and the melanopic efficiency function, M(λ),[15] are also plotted, normalized to the maximum spectral power value.

[15] Measuring and Using light in the Melanopsin Age, Lucas et al., *Trends in Neuroscience*, January 2014. International Commission on Illumination (CIE) TN 003:2015 Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013.

After the second set of measurements, the schedule needed further refinement. The design team decided that the 2-minute fade times from scene to scene created an obvious and mildly jarring shift in color and intensity, deemed inappropriate for the occupants in this application. The limited fade time of the control system for the downlights necessitated the application of multiple waypoints to smooth the transitions from specific set scenes. For instance, the initial schedule transitioned from settings for 6000 K at a 95% intensity level to settings for 4200 K at 75% in 2 minutes. To address this issue, the architects and a manufacturer's representative created multiple intermediate steps to create a less noticeable transition between scenes. The difference between the initial and revised schedules is illustrated in Figure 9. The DMX controller for the cove lights did not have a limitation in fade time, and fade times were programmed to closely correlate with the downlights. The scene end points were verified using a spectrophotometer to minimize any effect on the differences between the control techniques and fade times of the cove and downlight systems.

The revised schedule, as shown in Figure 9, also accounts for feedback from medical staff working in the BHU the same evening as the second round of commissioning. The staff said that they always turned off the downlights at night, since the cove lighting alone provided adequate and comfortable lighting. Based on their input, the Night scene was modified to only include the cove lighting.

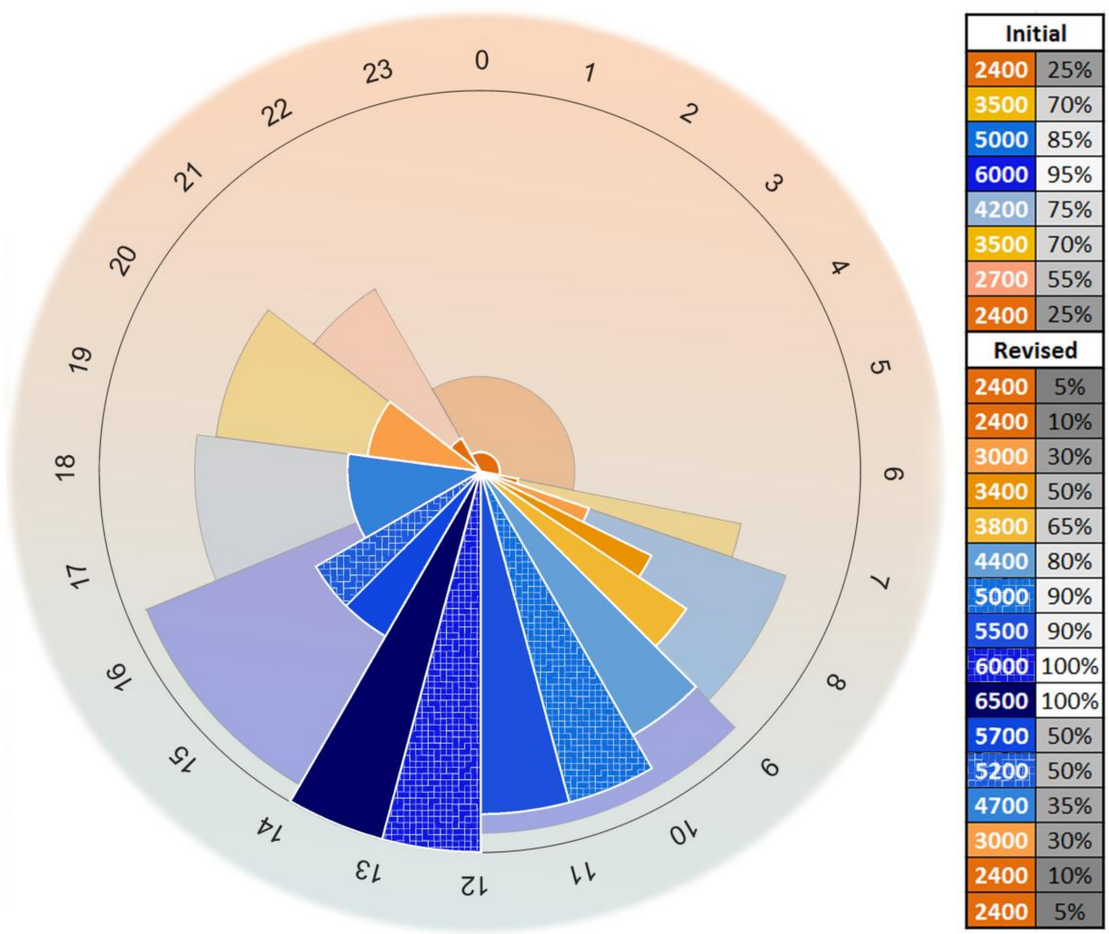

Figure 9. Daily schedule for SPD and intensity level control settings: initial and revised. The figure illustrates the final schedule in bold over the initial schedule in the background. The additional changes in SPD, indicated by color temperature, and intensity level control setting throughout the day created a smooth transition between scenes. The intensity level is expressed as a percentage of full output. The downlights and coves in the corridors and in the dining/activity area change according to this programming, except the downlights are off during the Night scene. The key shows the initial and revised schedule in order of occurrence, starting at midnight.

4. Discussion

Optimizing a tunable lighting system for biophilic and circadian goals, even on a small-scale, requires an understanding of the latest research related to circadian photobiology. Circadian response to light is affected by many factors, including the timing and duration of exposure, SPD, intensity, and physiological factors, such as whether the body's clock is phase-advanced or phase-delayed relative to the sleep/wake cycle. Implementing lighting that accounts for the non-visual effects of light also requires deeper knowledge of occupant behavior in a space and the characteristics of the space, including the materials' reflectance distribution and daylight contribution. Tunable lighting also increases the complexity of the controls and commissioning, particularly when designing systems that are innovative and unique. A given tunable luminaire may be less efficacious than a similar non-tunable model, which may contradict overall energy goals and require careful justification.

4.1 Circadian Response Design Goals and Assessments

Hospital patients often lose track of time of day and lack a routine that can ground them or instill a sense of normalcy. The lighting system for the Swedish Ballard BHU was envisioned to support the patient experience by creating a marker of the routine passage of time and indicating the day/night cycle by providing a consistent warm sunrise, a brightening and cooling of light by early morning, peaking by noon, and a sunset in the evening. This pattern provides visual cues that may help calm patients as they approach the end of the day and prepare for bedtime. The limited fade time length of the control system necessitated breaking up lighting scenes into multiple waypoints beyond what was specified in the initial sequence of operations, creating more subtle SPD and intensity transitions spread over longer periods, aligning with the biophilic design goals. This was suggested by the commissioning agent as a way to improve the occupant experience. The results are well aligned with the aesthetic and experiential expectation of the design team of the progression of light through the daily cycle.

During the second measurements, the design team calculated the circadian stimulus (CS) values[16] by using the measured CCT to select the corresponding SPD provided by the downlight manufacturer and using the measured illuminance. Ideally, the measured SPD would have been used to calculate CS since it represents the SPD at the eye, taking into account the interaction of the multiple sources and materials. However, the stand-alone CL-500A did not calculate CS, and connecting the CL-500A to a computer and using a separate program to calculate CS would have lengthened the measurement time and was not possible given the constraints of the BHU.

The CS calculator was used by the design team to determine the needed illumination level at the eye as well as approximate the SPD needed to advance the body clock (suppress melatonin) in the morning hours and not affect the circadian system for the typical individual in afternoon and evening hours. The specific design goal was to achieve a CS of 0.3 from 8:00 AM to noon and to provide a CS of less than 0.1 during evening and nighttime hours. Based on guidance by the Lighting Research Center, the design team decided the CS should be greater than 0.3 during the day, particularly in the morning, and less than 0.1 in the evening.

Figure 10 illustrates the change in CS due to SPD, intensity, and direction of gaze. CS decreases in the early afternoon and into the evening, avoiding a potentially negative effect on the sleep/wake cycle. This change in CS

[16] The circadian stimulus value is determined by a hypothesized model of circadian response developed by the Lighting Research Center (LRC). For more information and a copy of the Circadian Stimulus Calculator, visit the LRC Light and Health website: http://www.lrc.rpi.edu/programs/lightHealth/index.asp.

is primarily driven by the change in light level, with a decrease in illuminance from 410 to 214 lx (48%) resulting in a CS of 0.4 to 0.2 at 6000 K, while a change from 6000 to 4200 K at nearly the same illuminance (214 to 215 lx) resulted in the same 0.2 CS value. Additionally, 176 lx (3500 K) to 94 lx (2700 K) results in no change as both have a CS of 0.1. Although both are nominally 0.1, the CS at 2700 K and 55% is actually higher than at 3500 K and 70%. This is due to a recent revision in the CS calculation, with a different spectral sensitivity for "cool" sources than for "warm" sources.[17] This was not a concern for the overall design since CS remained at 0.1 and the system was still addressing both biophilic and circadian goals.

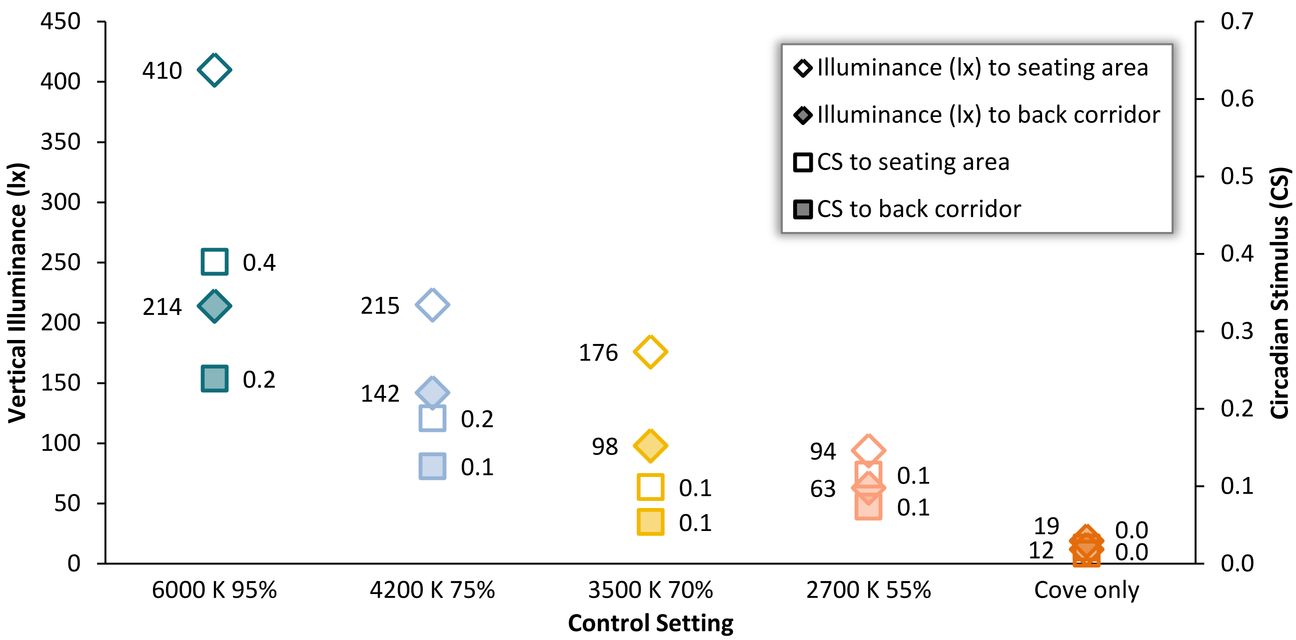

Figure 10. Scene Illuminance and CS: Second Measurements, September. The SPDs were measured with the CL-500A at seated eye height for one of the seating locations at a table in the dining/activity area in the direction facing toward the seating area in the dining/activity area and also in the opposing direction toward the back corridor. Measurements were made for each of the five lighting scenes evaluated during the second commissioning.

According to the design team, to provide the most potentially effective entrainment stimulus, the combination of intensity and SPD that produces the highest CS would have ideally occurred prior to 9:00 AM and continued until noon or a little later. The desire for gradual transitions delayed the occurrence of this combination. The design team made the decision to create additional scenes after experiencing the lighting transitions in the BHU.

Scene intensity and SPD were selected based on calculated CS levels; however, no confirmatory physiological, biological, or behavioral measurements were recorded. The calculated CS predicts what may occur based on a subset of published research, but there were no measurements documenting any realized effects.

4.2 Energy Implications of the Tunable Lighting System

Estimating the energy savings for tunable lighting systems in any application depends on comparison to a defined base case condition. The design team for this project selected the tunable lighting based on circadian and biophilic goals, so non-tunable alternative systems were not considered, and an energy analysis comparing the tunable lighting to an alternate base case was not part of the design process. DOE independently estimated

[17] For further information, see Light as a Circadian Stimulus for Architectural Lighting, MS Rea and MG Figueiro, *Lighting Research & Technology,* November 2016.

the energy implications of the USAI BeveLED Color Select 32 W tunable downlight system[18] relative to two base case conditions as part of the GATEWAY evaluation. The first defined base case condition included a similar downlight system, with the same number of luminaires (34) and locations, but with fixed CCT and light output. The second base case condition assumed a downlight system with fewer of the fixed-CCT downlights (17), since the number of downlights used in the design was selected for providing adequate circadian stimulation and resulted in illuminances that were about double those recommended by the Illuminating Engineering Society (IES) for the expected visual tasks in this application. Both base cases used the USAI BeveLED 24 W 3500K downlight, with similar light output to the 32 W Color Select downlight at 3500K.

The following assumptions were used in the energy estimates, based upon the programmed control settings and durations shown in Figure 9, and are summarized in Table 4:

- The base case downlight system was turned off during the nighttime hours of 10:00 PM – 6:30 AM (when only the cove lighting remained on), and was on at full output from 6:30 AM – 10:00 PM.
- The tunable system was turned off during the nighttime hours of 10:00 PM – 6:30 AM (when only the cove lighting remained on).
- During the six hours from 8:00 AM to 2:00 PM, the tunable system operated at a control setting of 65% or greater with the intention of providing adequate circadian stimulation during these hours, including operating at 90% or 100% output from 10:00 AM to 2:00 PM.
- During the 9.5 hours from 6:30 AM to 8:00 AM and from 2:00 PM to 10:00 PM, the tunable system operated at a control setting of 50% or less, both to provide gradual transitions in light level and spectrum in support of the biophilic design goals, and to avoid potentially suppressing melatonin in the late afternoon and evening.
- The power values for the tunable system at each control setting were derived based on prior CALiPER testing of a similar USAI BeveLED downlight.

Table 4. Control settings for energy savings comparisons of downlight system.

	Fixed (non-tunable) Downlight Base Cases	Tunable Downlight System	Percent of Daily Total Energy Use of Tunable Downlight System
10:01 PM – 6:30 AM	Off	Off	---
6:31 AM – 8:00 AM	100%	≤ 50%	4%
8:01 AM – 10:00 AM	100%	65% or 80%	19%
10:01 AM – 2:00 PM	100%	90 or 100%	55%
2:01 PM – 10:00 PM	100%	≤ 50%	22%

Based on these assumptions, the estimated annual energy use of the first base case downlight system with the same number of luminaires as the installed system was 138,500 kWh, and the estimated annual energy use of the installed tunable downlight system was 82,000 kWh. Therefore, the tunable downlights system reduced the annual energy use by an estimated 41%. These energy savings are attributed to the tunable intensity (i.e., dimming) and not to the tunable spectrum. The tunable downlights were less efficacious than the fixed downlights; however, the combination of tunable intensity and spectrum was necessary to achieve the biophilic

[18] The system of 34 downlights used for the energy estimates provided lighting within the dining area. Additional tunable downlights in the nurse station area and the tunable cove lighting system were not included in the energy evaluation.

and circadian project goals. The estimated annual energy use for the second base case system was 69,000 kWh; the tunable downlight system increased annual energy use by 19% relative to the second base case. This base case uses fewer luminaires to meet recommended illuminance based on visual tasks, but would not provide adequate illuminances for the desired circadian stimulation. However, it represents a more typical base case where circadian and biophilic goals were not part of the system design.

5. Conclusion: Lessons Learned

This project evaluated an early installation of a tunable LED lighting system designed to achieve biophilic and circadian lighting goals in a specialized healthcare application. As such, it provided an opportunity to document possible benefits as well as concerns in the design, installation, and operation of these systems. The following statements summarize some of the key observations from this GATEWAY project.

1. **Tunable LED systems can provide significant energy savings, but may increase energy use depending on the lighting system and application.** For this application, where biophilic and circadian design goals required a tunable lighting system with the ability to vary both spectrum and intensity, the reduced intensity levels specified for long periods of the day and night from the downlights enabled estimated annual energy savings of 41% relative to a non-tunable downlight system with the same number of luminaires. However, relative to a non-tunable system designed to only meet visual task illuminance criteria using half the quantity of luminaires, this tunable system increased estimated annual energy usage by 19%.
2. **Achieving design goals related to circadian and other biological and behavioral effects of lighting sometimes requires higher illuminances than those recommended for visual tasks, and consequently may increase the energy use of lighting during the hours when those high illuminances are needed.** In this project, 74% of the estimated annual energy use of the tunable lighting system occurred during the six hours each day when the control settings were established based on achieving the desired circadian stimulus. While the energy reductions that occur during the hours when the lighting was dimmed to lower intensity levels may offset the increases during these high intensity hours, it can be difficult to justify the increased cost and complexity of tunable systems while the evidence of the non-energy benefits are still emerging and not fully established.
3. **Allowing the building occupant some degree of manual control can increase energy savings***.* The original specification for the downlight system that was initially programmed into the automatic controls kept the downlights on at a dimmed level during the nighttime hours. But the nursing staff decided to turn off the downlights at night using the manual dimming option, based on their observation that adequate lighting from the cove system was provided in the space during the low-usage nighttime hours. This manual user behavior reduced energy use of the system and was then programmed into subsequent changes to the automatic controls.
4. **Commissioning of tunable systems remains a challenge given current field practices and capabilities.** Field commissioning today is often completed by establishing scene settings based on control settings and/or visual assessment of the scenes, rather than by confirmation with measured spectral and illuminance data. For this project, the initial commissioning did not provide the desired range of chromaticities or illuminances; the desired conditions were only achieved through a careful second phase of commissioning where chromaticity and illuminance were measured and adjusted for each scene, and then a third phase that was necessary to achieve the desired smooth transitions between the scenes. Without these additional commissioning phases, the energy savings realized would have been much less and the desired biophilic and circadian goals would not have been achieved.

5. **Developing a detailed specification of the desired control sequences and outcomes (SPDs, illuminances, circadian and other metrics) early in the design process can help identify potential shortcomings with the specified control solution, and can make the commissioning process more efficient.** Although the initial control specification for this project was more detailed than usual, the resulting iterations in commissioning, measurement, calculation, and system adjustments revealed the need for even greater specificity in the initial specification. Defining these details as early as possible can highlight the expected level of interoperability between different manufacturers' products, the need for early identification of eye positions and viewing directions for determining circadian effects, and the increased level of measurement and care required during commissioning.
6. **Estimating and measuring the spectral power distribution of light at expected eye locations is important for implementing circadian design goals, but there is currently no easy way to estimate the SPD at possible eye positions in an architectural space.** Common practice today for estimating circadian effects of lighting during design includes calculating the illuminance at the eye and then using the rated SPD of the luminaire to calculate related circadian metrics. But this project demonstrated that the actual SPDs at eye locations vary based on position, viewing direction, architectural surfaces, furnishing, and location of luminaires. Since any biological effect will occur based on the SPD at the eye, new techniques are needed to predict the SPDs at different eye locations during design and then to measure the SPDs during commissioning. Additionally, the entire design team needs to carefully consider the design of spaces where circadian response is important. In the near term, mock-ups that allow for the measurement of SPDs at typical eye locations for a variety of source SPDs and surface finishes may be necessary to accurately predict circadian metrics.
7. **Scientific evidence relating the medical effects of tunable lighting to emerging lighting metrics has not been established, and the metrics themselves have not been formally adopted for use in lighting practice.** While a growing body of literature exists related to the benefits of biophilic design and the circadian effects of light and several new lighting metrics have been developed and used in some studies, the established evidence on the medical effects of these techniques and metrics is very limited and has not yet been widely accepted within the medical community. Furthermore, the emerging metrics are still being revised and defined, and none of these metrics have yet been adopted by standards-setting organizations. This is not surprising, since the implementation of new technology and related new design approaches often precede the establishment of standards. But it is important to recognize that a sizable gap exists for evidence relating specific lighting metrics to biological and medical effects.
8. **Future projects would greatly benefit from collaborative design and research teams with expertise in biophilic design and in lighting and medical research.** At the outset of this project, the intention of the design team was to fully engage with the lighting research expertise available through the US DOE's SSL program, with the medical expertise available through the Swedish Medical organization, and with experimental expertise from psychology faculty at a local university. For a number of reasons, the inclusion of medical and psychology researchers and outcomes was not achieved, limiting the evidence of medical and psychological outcomes that could be documented. To facilitate the growing demand for evidence-based design practices that include the possible biophilic and circadian effects of tunable lighting, assembling design and research teams with the appropriate design, lighting and medical expertise is critical. This need will remain a challenge within the budgetary challenges of normal construction practices; identifying the research aspects of a project and possible sources of research

funding at the start of design will be important for achieving better quality of evidence in future projects.