# Lighting System Control Data to Improve Design and Operation: Tunable Lighting System Data from NICU Patient Rooms

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**This is an archival copy of an article published in *LEUKOS*. Please cite as:** Andrea Wilkerson, Sarah Safranek, Lia Irvin & Lauri Tredinnick (2023): Lighting System Control Data to Improve Design and Operation: Tunable Lighting System Data from NICU Patient Rooms, *LEUKOS*, 19:1, 94-109, DOI: https://doi.org/10.1080/15502724.2022.2059669

# Abstract

The advancement of LED and controls technology, computing capacity, and software provides new opportunities for researchers and designers to work together to further optimize spaces for occupant benefit. Lighting system control data from five neonatal intensive care unit patient rooms was collected over a 25-week monitoring period and analyzed to better understand occupant response to a tunable lighting system with automatic transitions throughout the day. Lighting systems are very rarely refined after installation based on actual use. Objective data detailing how the lighting system is used by the actual occupants highlights the opportunities for optimization after installation and provides insight for improving the next design. As use of the data becomes more commonplace, it can be leveraged for design recommendations. The collection of the data required no additional cost beyond the time for examining the data. The analysis revealed several clear opportunities for improvement, including adjustments to the default control setting at night, re-labeling of the control stations, and adjustments to the nighttime fade rate. The patient room occupants were active users of the different zones, dimming options, and manual overrides made available by the lighting system.



**Keywords:** controls, solid state lighting, behavioral response

# 1. Introduction

Despite the building industry changing relatively slowly during the 20th century compared to other industries, the 21st century has brought an increasing adoption of new products and practice. The increased pace of transformation is expected to continue, ultimately changing the way buildings are designed, built, and maintained. Building owners, managers, contractors, and designers are looking for ways to leverage the growing availability of data collected by various building systems, sensors, and network-connected devices to deliver data for decision making. Design firms are starting to incorporate augmented reality and virtual reality as part of the design process to aide in decision making and project coordination. The role of the lighting industry in this data-driven future remains to be seen; however, there is potential for advanced lighting control systems (LCSs) to share data with other buildings systems to improve energy and operational efficiency, human comfort, and occupant well-being.

Researchers have learned more about biological responses to light over the past 40 years, and this paired with advancements in LED lighting and controls technology has increased interest in altering intensity and spectrum for light and health considerations and biophilic design trends. This has resulted in a growing number of tunable lighting installations that vary light intensity and spectrum throughout the 24-hour day to support occupant well-being. Varying of light spectra in healthcare environments was explored prior to LED technology, but researchers had to use the constrained spectra of fluorescent lamps (Engwall et al. 2014; van Hoof et al. 2009), limiting any modification of the spectrum to using lamps separately, in combination, or placing sleeves over the lamps. More recent studies have explored the potential health benefits of using LED tunable lighting (Baier et al. 2020; Gimenez et al. 2017; Shishegar et al. 2021). For example, in a study based in the Netherlands, researchers explored the effect of tunable lighting on sleep, mood, and overall satisfaction of hospitalized cardiology patients, finding improvement in some aspects of lighting satisfaction and sleep (actigraphic) compared to the standard room lighting (Gimenez et al. 2017).

In neonatal intensive care units (NICUs), the varying of light levels was first documented in the 1980s (Mann et al. 1986), with additional studies building evidence that changing the intensity of light during the 24-hour day has potential benefits (Brandon et al. 2002; Miller et al. 1995; Mirmiran et al. 2003). The recommendations for neonatal infants by the Consensus Committee for NICU Design (White et al. 2013) include the topic of cycled lighting, with the Committee noting that there has been no demonstrated benefit of cycled light before 28 weeks gestation, but after this period there is some evidence of potential benefit. (For infants born at a gestational age of 38-42 weeks, circadian rhythms of melatonin do not appear until 2-3 months after birth [Glickman 2010].) Morag and Ohlsson (2016) systematically reviewed the relevant literature regarding NICU cycled light for preterm and low-birth-weight infants, finding only a few outcomes that reached statistical significance, including cycled light resulting in a shorter stay versus continuous bright light or near darkness; however, Morag and Ohlsson also found that the quality of evidence for cycled light was low.

While recommendations for NICU environments are still in early stages of development, there are recommendations detailing how to vary intensity and spectrum in adult patient room environments. There is still a lack of research supporting and validating these early recommendations. Some researchers have sought to add to the evidence base using pilot or mock-up patient rooms. Gleason and colleagues (2019) detailed the installation of a tunable lighting system in a hospital patient room as proof of principle, incorporating advanced sensors, computing, and communication infrastructure in an active clinical environment. Graves and colleagues (2021) sought to understand how nurses respond to tunable lighting while completing simulated daily tasks, finding nurses did not object to different correlated color temperatures (CCTs) in a mock patient room setup. There remains opportunity to better understand occupant response to tunable lighting systems in patient rooms.

An additional way to understand the response of occupants in active clinical environments is to track how they use the tunable lighting system. Software companies have long been tracking how consumers use their products as they value real-world feedback, but tracking of occupant use of lighting systems thus far has been limited. A previous paper presented the potential for using the occupant use control data to reduce lighting energy consumption (Safranek et al. 2021), showing how small changes to the control system could result in considerable energy savings. This paper explores the ways that tunable lighting system data can be used to improve operation of an installed system, and also provides feedback that can improve the next design and ultimately design recommendations.

# 2. Lighting System Design

Neonatal infants were exposed to cycled lighting in hospitals during the 1950s and 1960s by happenstance, since infants were placed in adult patient rooms with lights that were brighter during the day and darker at night. In the 1970s, there was a transition to continuous bright light as specialized NICUs became more common; however, in the 1980s there was another transition to continuous dim light due to eye health concerns and a desire to create an environment similar to the womb (Rivkees 2004). Aligning with this trend, the University of Kentucky (UK) opened its first nursery dedicated to premature infants in 1972, initially placing two infants per standard adult bed. Subsequent NICU expansions in 1974, 1981, and the mid-1990s increased the total to 66 beds (UK HealthCare 2018). The 66 beds were split among shared rooms, with standard practice being to keep the lighting dim, with a few downlights on in each room, blinds closed, and with blankets coverings the infant beds, as shown in Fig. 1.

In April 2018, the UK NICU moved to the spacious Betti Ruth Robinson Taylor NICU at Kentucky Children's Hospital, in a renovated portion of the Albert B. Chandler Hospital. The UK NICU provides the highest level of care for premature infants, regularly operating near capacity. Sixty-eight patient rooms were distributed among six hallways with each patient room having one bed, except for two rooms for twins. Due to renovation constraints, the patient rooms had no windows.


**Figure 1.** Photographs of the Old UK NICU. These photographs were taken prior to the transition to the new NICU in April 2018.

The design team relied on the Recommended Standards for Newborn ICU Design, Eighth Edition (White et. al 2013) for many of the design parameters. Recommendations include providing adjustable ambient lighting ranging from approximately 10 to 600 lx, with immediate darkening of the entire room for certain examinations. The design team considered these NICU recommendations, along with input from patient families and staff and the UK facilities guidelines, and also had to work around many architectural constraints. Additionally, UK staff wanted to incorporate a tunable lighting system. This request coincided with recent advances in solid-state lighting (SSL) technology, although tunable lighting product options were still limited when the system was installed.

The UK NICU nurses work 12-hour shifts, changing shifts at 7:00 a.m. and 7:00 p.m. The white-tunable lighting system was pre-programmed so that changes in luminaire intensity and CCT would align with the clinical schedule of the NICU. A linear luminaire was located in the soffit as shown in Fig. 2, providing the base level of ambient illumination. The infant beds were located under the soffit, with the bed perpendicular to the headwall. The linear luminaire would automatically turn on at 7:00 a.m. at a nominal 3000 K (a visually warmer appearance), aligning with the start of the day shift, then at 7:30 a.m. the linear luminaire slowly transitioned to a nominal 5000 K (a visually cooler appearance). At 7:00 p.m., just as guest hours were beginning, the linear luminaire transitioned to 3000 K and then automatically turned off at 9:00 p.m., when guest visiting hours were over, remaining off for 10 hours. This specific schedule, detailed in Table 1, is herein referred to as the cycled-lighting program (CLP) mode, which operated 24 hours a day, 365 days a year, unless the lighting was manually overridden by a patient room occupant. The intensity remained static throughout the duration of each mode, with a slight decrease in intensity during CLP Dawn and Dusk modes compared to the CLP Day mode.

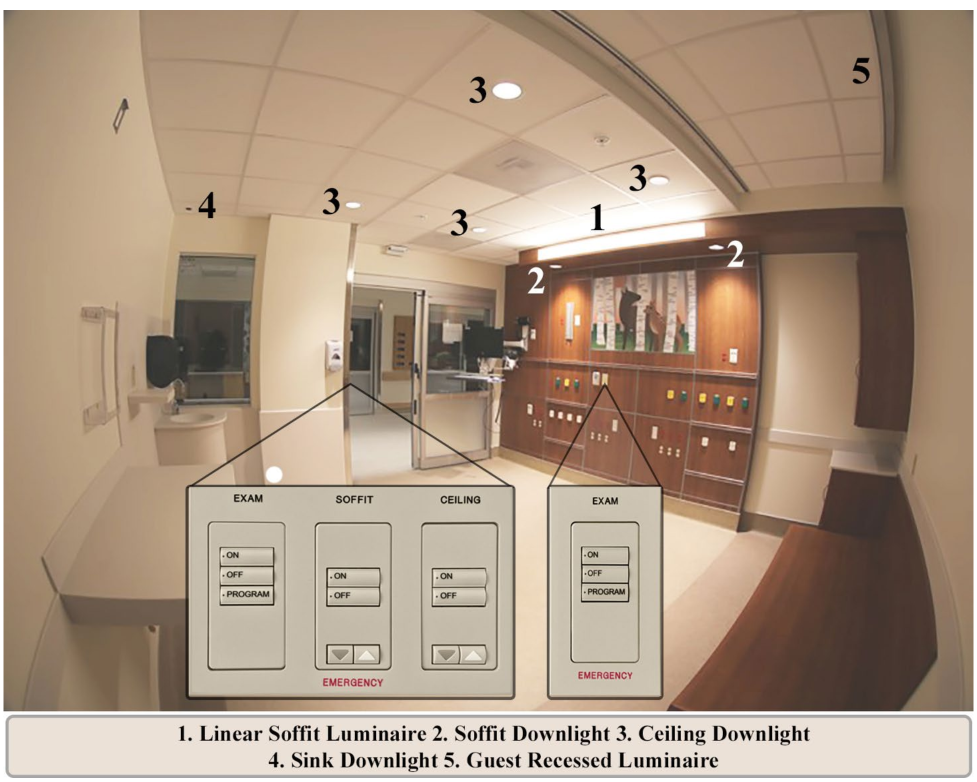



**Figure 2.** NICU Patient Room Prior to Occupancy. The white-tunable luminaires connected to the LCS are all operating in this photo. The infant bed (not pictured) is placed perpendicular to the headwall, under the soffit.

The occupants could manually override the CLP mode at any time, including turning off all luminaires. If an occupant entered the room during the day while the system was in CLP mode, the occupant could also turn on four downlights located in the ceiling and the two downlights located at the headwall in the soffit. A 2 in. aperture downlight over the sink was always on, as required by the hospital, with an output less than 200 lumens. Additionally, a guest recessed luminaire over the seating area could be turned on with a toggle switch. The sink downlight and guest recessed luminaire were not connected to the LCS, and so are not considered for the remainder of this paper.

**Table 1.** Patient Room Lighting Mode Summary. The table lists the different lighting modes possible in the patient room, with the CLP operating the linear luminaire according to the programmed schedule. The programmed schedule was disabled by pressing any button other than Program on the control station. The spectral power distribution (SPD) of a light source may vary at the same CCT, with the downlights having a slightly different SPD than the linear luminaire, while still having the same nominal CCT. The CCT of the custom mode is determined by the CCT of the CLP mode prior to being selected.

| **Lighting Mode** | | **Programmed Schedule** | **Luminaires** | **CCT (K)** |
|---|---|---|---|---|
| **CLP** | Off | 9:00 p.m. – 7:00 a.m. | - | - |
| | Dawn | 7:00 a.m. – 7:30 a.m. | Linear | 3000 |
| | Day | 7:30 a.m. – 7:00 p.m. | Linear | 5000 |
| | Dusk | 7:00 p.m. – 9:00 p.m. | Linear | 3000 |
| **Manual** | Off | - | - | - |
| | Exam | - | Linear, Soffit Downlights, and Ceiling Downlights | 5000 |
| | Custom | - | Linear, Soffit Downlights, and/or Ceiling Downlights | 3000 – 5000 |

In each patient room there were two control stations: a primary control station at the room entrance and a more limited secondary control station at the patient headwall that could be reached while standing adjacent to the infant. The secondary control station had Program, Exam, and Manual Off modes, while the primary control station (Fig. 3) had these options plus the ability to turn on and dim the soffit and ceiling downlights independently. Turning the lights off manually was required for certain examinations, and all luminaires would remain in the Manual Off mode until another mode was enabled. The lighting system would only return to the CLP mode once the Program button was selected on a control station. If the lighting system was not in either the Exam, CLP, or Manual Off modes because one of the Soffit or Ceiling buttons was pressed, the system was considered to be in a Custom mode.

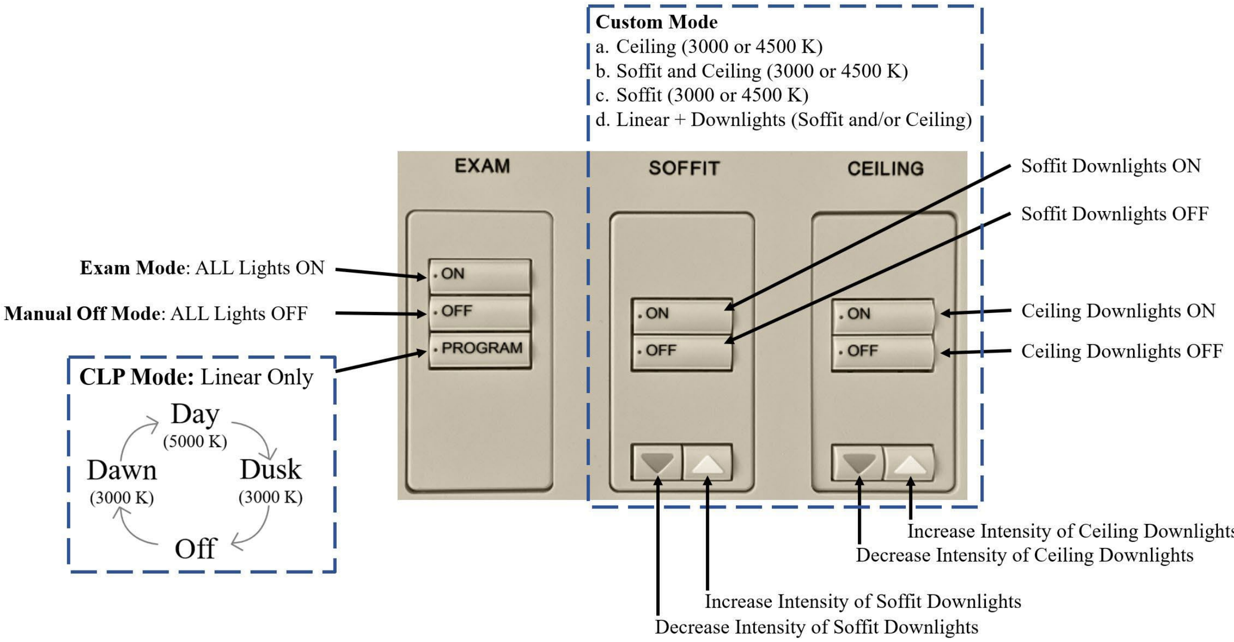



**Figure 3.** Control Mode Diagram for the NICU. The system operated in the CLP mode, as long as the Program button was the most recently pressed in the patient room. Selecting Manual Off turned all luminaires off, and all luminaires were turned on when in Exam mode. Additional adjustment of intensity was possible if the Soffit or Ceiling raise and lower buttons were selected. The CCT of the custom mode is determined by the CCT of the CLP mode prior to being selected. If On, Off or Program were selected, the LCS would override any downlight setting. The downlights were set to 4500 K to provide a better visual color match to the linear luminaire at 5000 K.

The downlights were also tunable, adjusting based on the time of day to the same nominal CCT as the linear luminaire. If the downlights were turned on at night, they would come on at 3000 K. If the Exam button was pressed, all luminaires would transition to full output at 5000 K no matter the time of day. There was no individual control for the linear soffit luminaire because it changed based on the programmed settings unless the Exam button was pressed. The color temperature and intensity of the downlights were controlled via separate channels; however, the linear luminaire had both a warm channel and a cool channel. The warm channel was a nominal 2200 K and the cool channel was a nominal 6000 K. This limited the ability to reach all color temperatures at all light levels due to a limit on how low these channels could dim. This resulted in the CLP Dusk and Dawn mode light levels being higher than initially desired because in order to reach 3000 K, the 5000 K channel had to be operating at 10% output. The different control methods also made it more difficult to match the visual color appearance of the LED luminaires.

# 3. Data Collection

All aspects of the patient room luminaires were controlled by the LCS with a processor to command and track the lighting modes. The lighting control protocol was a proprietary system, similar to the Digital Addressable Lighting Interface (DALI). A live connection between the processor and the building automation system (BAS) allowed for data to be pulled by the BAS at a chosen interval using the BACnet protocol.

For five patient rooms in the NICU facility, lighting control system data was collected every 5 minutes (totaling 288 collections per day, per room). Roughly 250,000 timestamps were collected for 25 consecutive weeks (175 days) from May to November 2019. The collection of the data did not require the use of any additional software or hardware beyond what was already installed for the project. The BAS automatically emailed the authors weekly, and all data was analyzed using Tableau.

The data included the lighting mode in use at the time of collection as well as the corresponding intensity and color settings of the linear luminaire and soffit and ceiling downlights. Table 1 summarizes the possible lighting modes. Lighting power estimates were also included in the dataset but are not a focus of this article. A field visit was made to the NICU to observe the functionality of the patient room lighting and programmed lighting modes and to confirm the accuracy of the collected data.

# 4. Lighting System Control Data

The collection of control data provides the opportunity to better understand how occupants use the lighting system, providing rare objective and detailed feedback that enables optimization of the actual lighting system while also helping to inform future lighting system designs. During the design process, hundreds of decisions related to the lighting system design are made. Lighting designers rely on the assumptions from prior projects, recommended practice documents, and the collective knowledge of the larger design team from electrical engineers to architects and manufacturers' representatives. With the increasing number of options made possible by tunable lighting systems, designers have even more decisions to make; however, when it comes to tunable lighting, there is typically less experience with the technology and limited guidance in recommended practice documents.

This tunable lighting system was novel at the time of design, and commercial tunable lighting products were just becoming a standard option at the time the luminaires were selected for the project. The ability to have pre-programmed changes in intensity and spectrum, along with manual override, was very rare for a patient room setting when it was installed. The sequence of operations for the lighting system was initially developed by the lighting designer in coordination with UK NICU staff and the lighting controls manufacturer to address the interactions between CLP mode and the override options.

## 4.1 The Cycled Lighting Program

The CLP mode was intended to be used the majority of the day, with the assumption that temporary overrides of the CLP mode would be necessary throughout the day for minor procedures and routine exams. The CLP mode automatically varied the color temperature of the luminaires and also turned luminaires on and off, a distinct departure from traditional and even contemporary lighting system design, where luminaires typically remain static in color temperature and do not change while a room is occupied. Since an occupant can manually override the CLP mode at any time, understanding how much the CLP mode was used indicates how well the design intent aligned with the needs and preferences of the occupants.

Operation of the lighting system varied across rooms on any given day, influenced by the individual needs of a patient along with the preferences and needs of the staff and patients' families. An example of this variation is shown in Fig. 4, where use of the lighting system in two patient rooms is compared to a hypothetical scenario where only the CLP is operating over 4 weeks. No interaction with the lighting system results in the CLP modes cycling through the Dawn, Day, Dusk, and Off modes automatically at the scheduled transition times. Occupant interaction with the lighting system through the Manual modes (i.e., Exam, Manual Off, Custom) caused notable deviation from the CLP that varied day to day and across rooms. There were visible patterns in how Manual modes were used. For example, the nurses conducted patient checks and examinations multiple times per night, often using the Custom or

Exam modes. These patient checks and examinations occurred at roughly the same time each night and lasted for similar durations; how these observed patterns can be quantified using lighting data is explored in this paper.

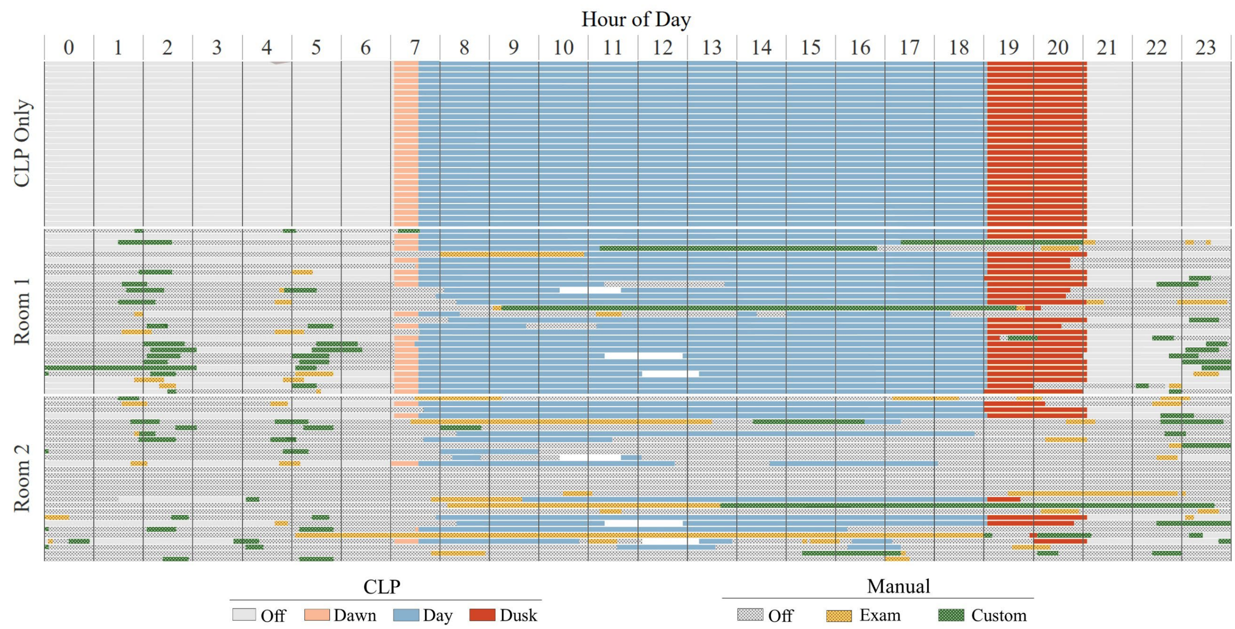
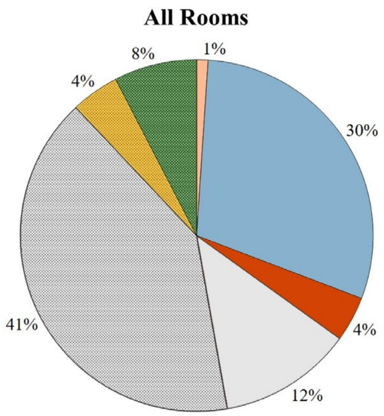



**Figure 4.** Daily Lighting System Use in Two Patient Rooms during a 4-Week Period. The lighting mode is plotted every 5 minutes over a 4-week duration in two patient rooms and compared to a hypothetical CLP Only scenario. Each row represents a day, and the color of the row corresponds to the lighting mode recorded by the lighting system. The CLP Only scenario demonstrates what the data would look like if there was no use of the Manual modes.

Despite daily differences between rooms, general trends emerged when combining the durations spent in each lighting mode during the 175-day collection period. Figure 5 shows the total percentage of time spent in the available lighting modes for each patient room as well as all five rooms combined. Between 38-56% of the collection period was spent in a CLP mode, with remaining time spent in Manual modes. Of the Manual modes, the most time was spent in the Manual Off mode, with one patient room using this mode for almost 50% of the collection period. There were instances where a patient room would be in the Manual Off mode for several days; an example of this can be seen for Room 2 in Fig. 3, where the Manual Off mode was engaged for more than 3 consecutive days. There were no exterior windows in the patient rooms and so it is assumed that the rooms are unoccupied when the Manual Off mode is used for more than 24 hours; however, overall the NICU operated near capacity. Across all five rooms, the Exam mode is used between 3-5% of the monitoring period, per room and the Custom modes are used for 6-10%. This equates to an average of 1 hour and 2 hours per 24-hour day, respectively.




| | Lighting Mode | Room 1 (%) | Room 2 (%) | Room 3 (%) | Room 4 (%) | Room 5 (%) |
|---|---|---|---|---|---|---|
| CLP | Dawn | 1 | 1 | 1 | 1 | 1 |
| | Day | 34 | 29 | 33 | 29 | 24 |
| | Dusk | 5 | 3 | 5 | 4 | 3 |
| | Off | 15 | 13 | 12 | 11 | 10 |
| Manual | Off | 33 | 42 | 36 | 43 | 49 |
| | Exam | 3 | 4 | 5 | 6 | 3 |
| | Custom | 7 | 8 | 7 | 6 | 10 |
| Totals | CLP Modes | 56 | 46 | 51 | 45 | 38 |
| | Manual Modes | 44 | 54 | 49 | 55 | 62 |
| | Off Modes (CLP + Manual) | 48 | 55 | 49 | 54 | 59 |

**Figure 5.** Lighting Mode Summary for 25-week Monitoring Period. The use of the lighting modes across the five patient rooms is summarized over the 25-week monitoring period. The top portion of the table divides the use by lighting mode for the five patient rooms, and the bottom shows the total for CLP, Manual, and Off modes. This summary includes the 14 days (out of 875 days) that it is assumed the rooms were unoccupied, based on less than 3 button presses in a 24-hr period (midnight to midnight).

Nurses were initially discouraged from touching the lighting system unless necessary, particularly when they first moved into the unit in April of 2018. Parents and visitors were also discouraged from doing the same, so that the system would remain in the CLP mode. Collection of the control data did not start until May of 2019, a year after the new unit was occupied, giving nurses time to adapt to the new lighting system. The data seem to indicate that the nurses became more comfortable with the lighting system over time and used the flexibility of the lighting system to meet occupant needs.

## 4.2 Daytime and Nighttime Use of Lighting System Modes

The lighting system data was used to identify when and for how long different lighting modes were used across multiple patient rooms. Table 2 summarizes the total number of times the available lighting modes were used across the five patient rooms as well as the average duration, depending on if the modes were activated during the daytime (7:00 a.m. to 8:59 p.m.) or nighttime hours (9:00 p.m. to 6:59 a.m.). Of the available modes, the Manual Off mode is initiated the most often, with an average duration of nearly 6 hours. The CLP mode is commonly initiated during the daytime hours, but during the nighttime it is only used half as often as the Manual Off mode. The Exam and Custom modes were initiated about the same number of times, but the Custom mode had a longer average duration than the Exam mode during both the daytime and nighttime hours.

**Table 2.** Summary of Lighting Mode Use during Daytime and Nighttime Hours. Instances are recorded for the timeframe in which a mode was initiated. The duration of each instance is calculated and averaged for daytime (7:00 a.m. to 8:59 p.m.) or nighttime hours (9:00 p.m. to 6:59 a.m.) across the 25-week monitoring period. The CLP mode instances and duration do not consider any automatic transitions, only physical presses of the Program button. This summary includes the 14 days (out of 875 days) it is assumed the rooms were unoccupied, based on less than 3 button presses in a 24-hr period (midnight to midnight).

| **Lighting Mode** | **No. of Instances** | | | **Avg. Duration (h: mm)** | | |
|---|---|---|---|---|---|---|
| | **Daytime** | **Nighttime** | **Total** | **Daytime** | **Nighttime** | **Total** |
| **CLP** | 1,061 | 630 | 1,691 | 5:35 | 6:15 | 3:42 |
| **Off** | 1,086 | 1,220 | 2,306 | 4:24 | 3:08 | 5:50 |
| **Exam** | 405 | 887 | 1,292 | 1:12 | 0:30 | 0:42 |
| **Custom** | 305 | 902 | 1,207 | 3:08 | 0:42 | 1:19 |

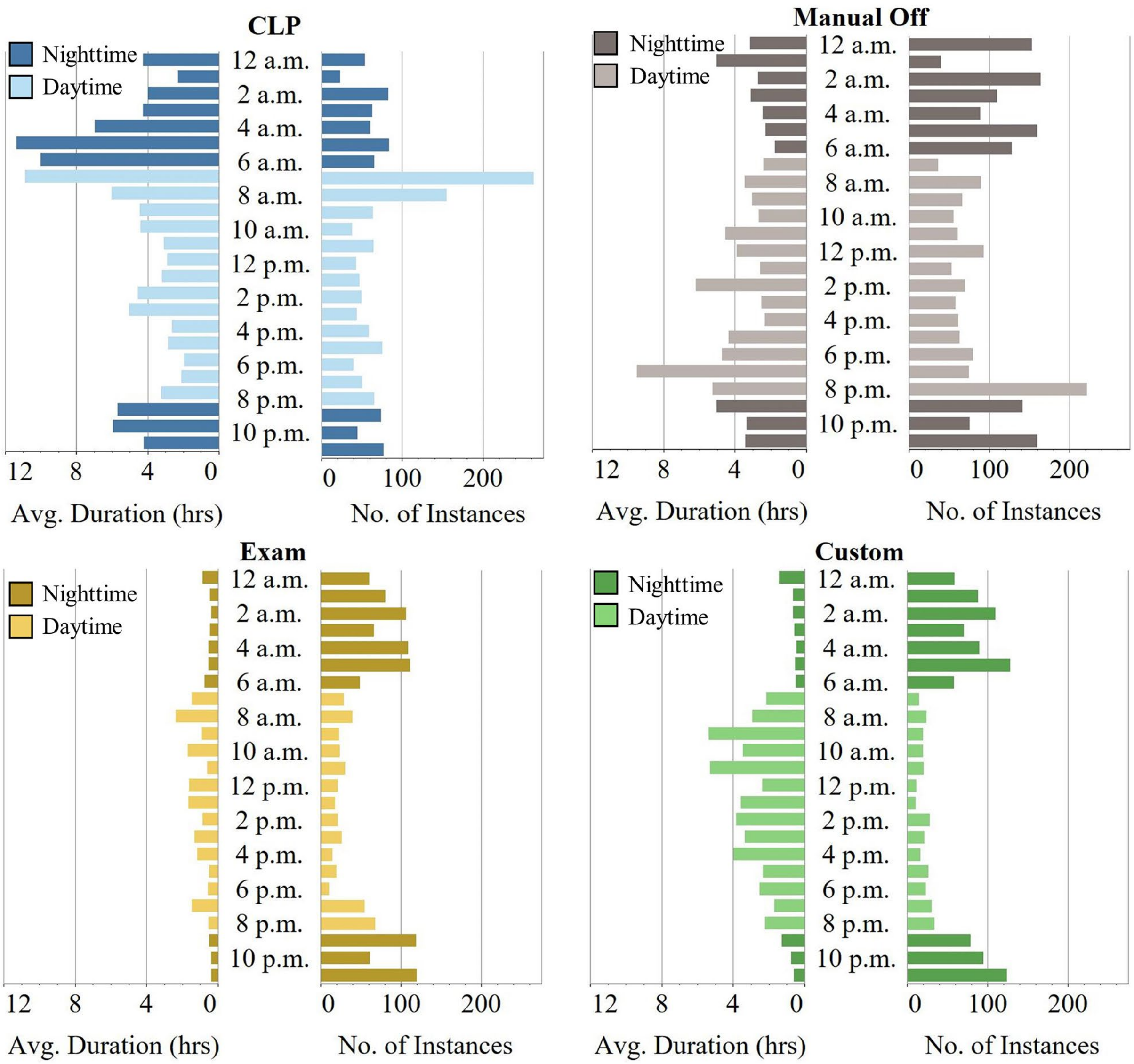



**Figure 6.** Hourly Lighting Mode Use. Instances are recorded for the timeframe in which a mode was initiated. The instances are summed over the entire monitoring period, with the duration averaged for each of these instances per hour for daytime (7:00 a.m. to 8:59 p.m.) and nighttime hours (9:00 p.m. to 6:59 a.m.). This summary includes the 14 days (out of 875 days) that it is assumed the rooms were unoccupied, based on less than 3 button presses in a 24-hr period (midnight to midnight).

Further investigation of the number of instances and average durations of the lighting modes per hour more clearly reveals the occupant patterns throughout the 24-hour day, as illustrated in Fig. 6. The CLP mode is initiated most often around 7:00 a.m. when the lights are scheduled to turn on automatically. Often the lights do not turn on automatically because of the extensive use of Manual Off during the nighttime. When the CLP mode is initiated between 5:00 and 7:59 a.m., it stays in this mode for more than 10.5 hours on average, while if initiated between 8:00 a.m. and 8:59 p.m., the average drops to less than 4 hours. The long duration of the CLP mode indicates that the lighting is sufficient for routine checks and other activities within the patient rooms during the day. After 9:00 a.m., it is generally more common for the Manual Off mode to be initiated compared to all other modes. Manual Off mode was most frequently initiated during the 8 p.m. hour before the CLP Off transition was scheduled to occur at 9:00 p.m.

The use of Manual Off mode instead of CLP mode at night was initially surprising; however, it reveals how labels on the lighting keypads may have affected occupant use of the lighting system. As shown in Fig. 3, pressing the button labeled Off would initiate the Manual Off mode and all lights in the patient room would turn off immediately. Alternatively, pressing the Program button at night would initiate the CLP Off mode, slowly fading the lights to off over 15 seconds. Both the labeling and the fade rate used for the Manual Off mode were likely more intuitive for occupants at night when they are trying to turn the lights off.

Viewing the duration and instances of Exam and Custom modes compared to the CLP and Manual Off modes reveals how these modes were used differently depending on the time of day. Exam and Custom modes were used twice as often during the nighttime hours, but for much shorter durations compared to the daytime use. As discussed in the previous section, these patterns are likely due to the patient checks and examinations that were conducted multiple times per night. During the daytime hours, the average duration of Exam mode increased from 30 minutes to over an hour, and the Custom mode increased from about 45 minutes to over 3 hours. While the duration of use for Exam and Custom modes increased during the daytime hours, these modes were selected less often during this timeframe. The considerable use of Exam mode at night was unexpected, as during the design phase it was assumed that the downlights would be used more to avoid the brighter light at night. A closer look at the use of the downlights reveals why Exam mode may have been used more than expected.

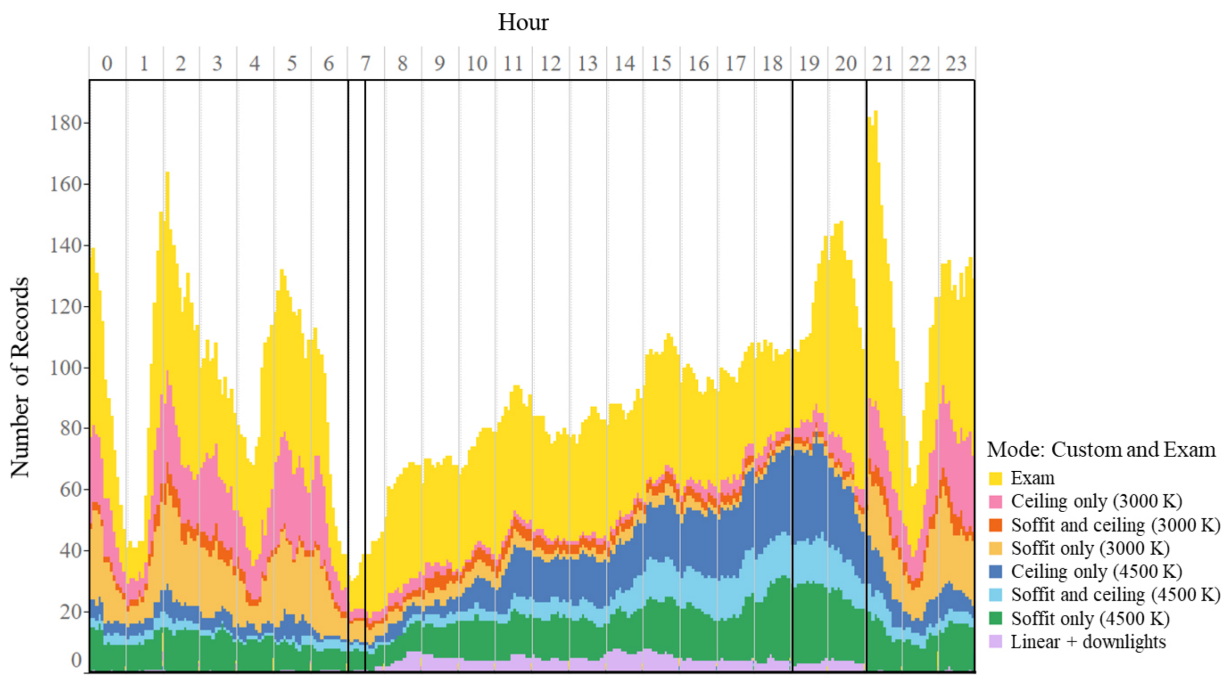



**Figure 7.** Occupant Use of Custom and Exam Mode across 24-hour Day during Monitoring Period. Black vertical lines denote the times of day at which the CLP changes scene. The data is plotted at 5-minute intervals for the 24-hour day, summed across the 25 weeks and five patient rooms.

While each occupant is making an individual selection to meet the needs and preferences of the moment in the NICU, a clear pattern emerges from these individual daily decisions throughout the 24-hour day, shown in Fig. 7. Plotting the mode for each 5-minute interval reveals the increase in the use of Custom modes during the daytime, while the use of Exam mode largely stays the same with brief increases during what are likely routine checks. It also shows how the differences in duration between Exam and Custom modes, shown hourly in Fig. 6, build throughout the daytime.

The largest peak occurs from 9:00 to 9:20 p.m., with an increase in both Exam and Custom modes. This peak is at the beginning of the CLP Night mode when the lights automatically turn off and indicates that the room occupants do not want the lights to be off. At this peak, the increase in Exam mode is greater than Custom mode. If the occupant happens to be near the infant bed, the only option for keeping the lights on is to select the Exam button on the secondary control station, unless the occuapnt can walk over to the room entrance where the primary control station is located. The occupants may have also wanted the higher CCT provided by the Exam mode.

During the nighttime if an occupant needed light, the only options were the Custom modes and the Exam mode. There are three peaks during the nighttime, as seen in Fig. 7, starting at 11 p.m., 2 a.m., and 5 a.m., indicating times at which the nurses would check on the patient. For half of the instances at these peak times, the occupants were using a Custom mode.

There is a small, but consistent number of records that have a CCT opposite of the CLP mode, as shown in Fig. 7. This was partially due to the control system not knowing to change CCT unless the system was in CLP mode during scheduled transitions. Some occupants also found a workaround with the control station that allowed the color temperature to switch to 3000 K during the daytime.

The use of ceiling and soffit downlight during the daytime varied, with the four ceiling downlights being used more than the two soffit downlights. This could be for many reasons, such as more light being desired throughout the room. Additionally, the word “Emergency” is written at the bottom of each of the control stations (both primary and secondary, as seen in Fig. 2) and on the primary control station directly below the soffit control buttons, so occupants may have been hesitant to use the soffit downlight control buttons. The “Emergency” wording was required to indicate the lights were on a circuit that would provide power in case of an emergency.

## 4.3 Occupant Response to Automatic Transitions

A unique feature of this lighting system design is the automatic transitions in light intensity and CCT, so understanding the response to these transitions was of high interest. During a brief discussion with the nurses, addressed later in this paper, they indicated the automatic transitions throughout the unit were generally viewed as a positive feature. The data collected from the lighting control system supports this verbal feedback. Figure 8 summarizes the occupant adjustments made to the lighting within 15 minutes of the CLP Dawn, Day, Dusk, and Night mode transitions. The morning transitions into Dawn and Day modes do not show any notable occupant customization of the lighting, indicating a level of acceptability of these transition periods. The same is true for the transition into CLP Dusk mode at 7 p.m. For the Night mode transition at 9 p.m., when the lighting system is scheduled to dim-to-off over 15 seconds, there is a notable increase in the use of Manual modes. During the 175-day data collection period, there are 148 instances across the five rooms where the lights are turned back on within 15 minutes using the Exam or Custom modes. This highlights an opportunity to refine the control protocol to better meet occupant needs.

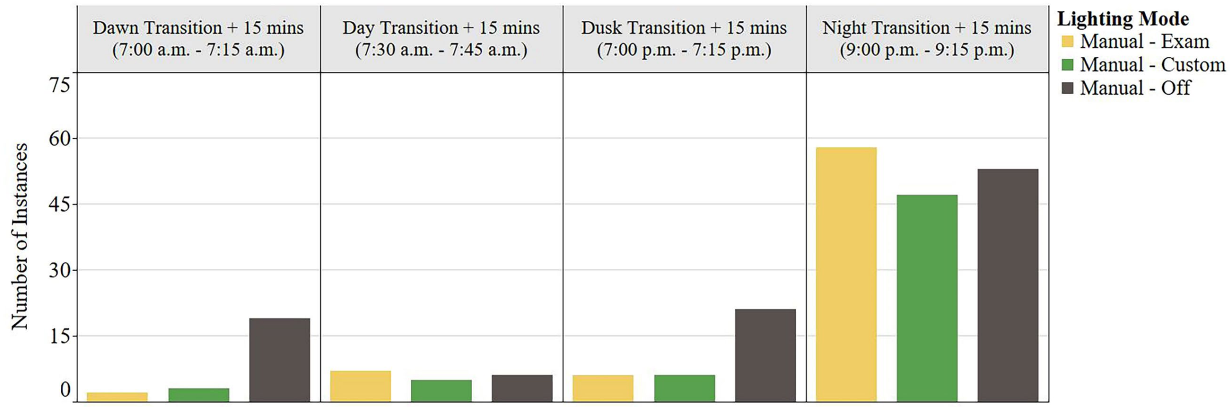



**Figure 8.** Manual Modes Use within 15 minutes of a CLP Transition. Instances are recorded for the timeframe in which the Manual mode was initiated within 15 minutes of the CLP Dawn, Day, Dusk, and Night mode transitions.

It is worth noting that the infrequent use of Manual modes in response to the morning transitions is in part due to the scheduled CLP Dawn and Day transitions not occurring. As shown in Fig. 9, the LCS was often in a Manual mode at 7:00 a.m. and was thereafter switched to the CLP mode. The scheduled transitions only occurred if the lighting system was in the CLP mode, and use of Exam, Custom, or Manual Off modes overrode the CLP. The patient rooms were only in the program mode 32% of the time when the Dawn transition was scheduled. While the lighting system did not automatically transition in these instances, the captured controls data suggests the nursing staff manually reverted the lighting systems to the CLP within 5-10 minutes of the programmed Dawn transition. This can be seen by the clear increase (32-47%) from Manual modes to the CLP dawn mode between 6:55 a.m. and 7:10 a.m. The increase in the CLP mode continues throughout the morning until about 9:30 a.m., when over 70% of the data indicates the rooms are in a CLP mode.

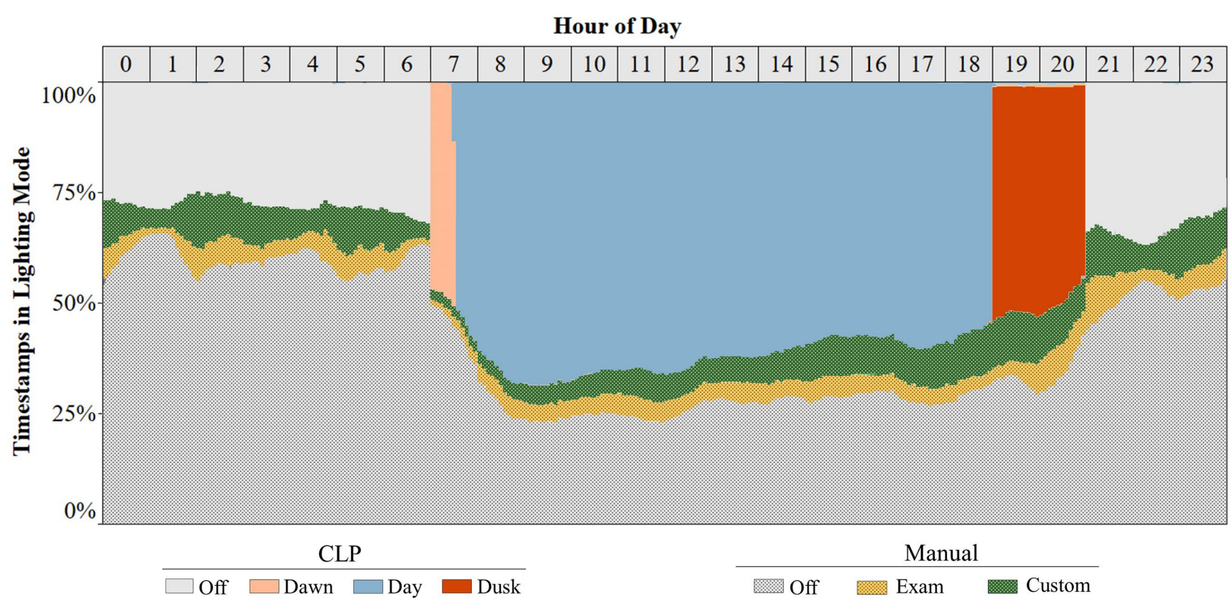



**Figure 9.** Use of All Modes throughout the 24-hour Day. The mode at every 5-minute interval is plotted for the duration of the 24-hour day for all five patient rooms for the entire 25-week monitoring period. This summary includes the 14 days (out of 875 days) that it is assumed the rooms were unoccupied, based on less than 3 button presses in a 24-hr period (midnight to midnight).

## 4.4 Downlights at Nighttime

For the nurses entering the patient room during the nighttime, the only options for turning lights on in the patient room were Exam mode or some combination of downlights. The Custom mode was expected to be used during the nighttime to provide a low level of light for navigation as well as to allow the nurse to see the patient without needing to use Exam mode (the linear luminaire would only turn on in Exam mode during the nighttime). Figure 10 plots each instance of the use of the downlights between 9 p.m. and 6:59 a.m. across all five patient rooms during the monitoring period. The LCS is not programmed based on illuminance values, but rather on control signals that are a rough approximation of the luminaire output.

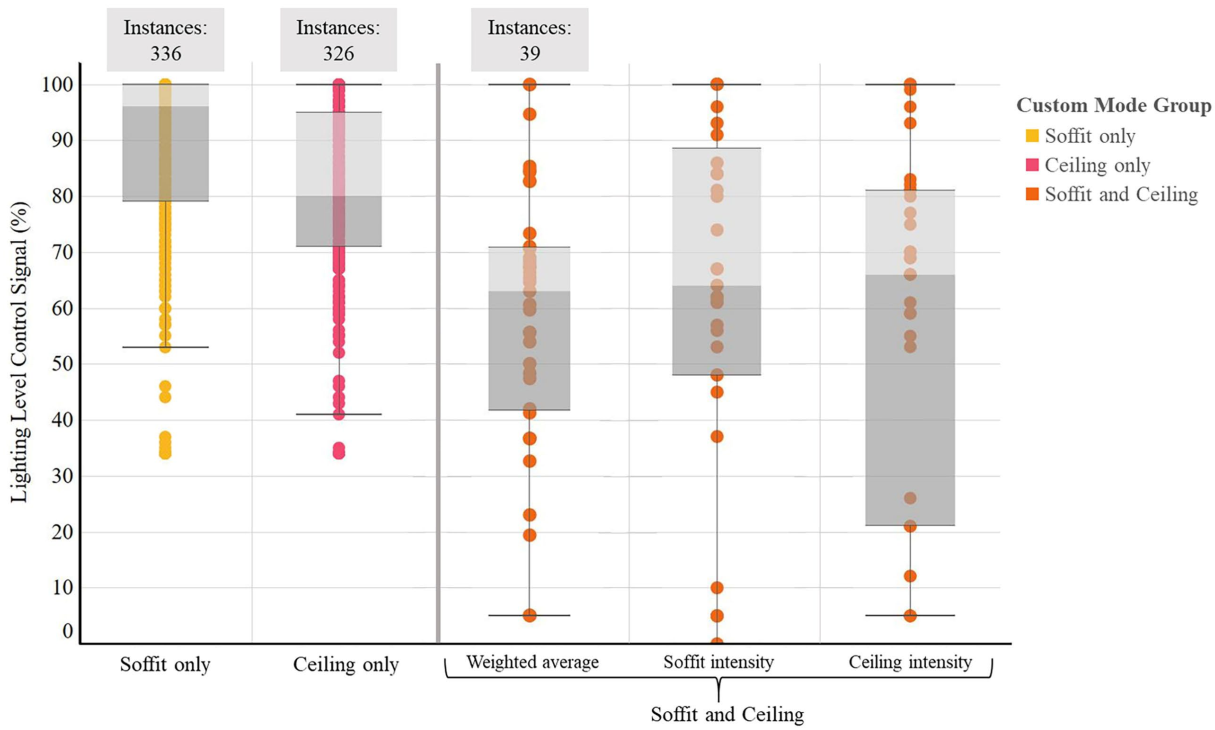



**Figure 10.** Nighttime Downlight Control Settings. Plotted are the control signals for each instance of downlight use during the nighttime (9:00 p.m. to 6:59 a.m.) for all five patient rooms across the monitoring period. The center line of each box corresponds to the median value, with the extents of the box corresponding to the upper and lower quartiles. The whiskers indicate the data points that are within 1.5 times the interquartile range, with outliers displayed outside of these whiskers.

When the occupant selected the two soffit downlights or the four ceiling downlights, they turned on at a control signal of 34%. For 100% of instances, the nurses increased the light level beyond the initial setting, revealing that the default light level at night was not enough for the nurses to complete their checks and procedures. Three-quarters of control signal values lie above 71% and 79% when the ceiling downlights or soffit downlights are turned on, respectively. Additionally, half of the instances are above a control signal of 96% when only the soffit downlights are used and 80% when only the ceiling downlights are used. This clearly indicates that a higher control signal is preferred.

When the nurses selected both the soffit and ceiling downlights during the nighttime, the occupants preferred lighting level control signals that ranged from 5-100%. For half of the instances, the nurses selected a control signal of 63% or less. It is likely that the difference in preference between one group of downlights and both groups of downlights is related to the quantity of downlights. As expected, a control signal of 34% for the combined soffit and ceiling downlights results in a higher illuminance at the infant bed. Another considerable difference is that nurses were much more likely to turn on the ceiling or soffit downlights, with over 650 instances, compared to the 39 instances where both the soffit and ceiling downlights were selected. Additionally, if the nurses wanted both the soffit and ceiling downlights on, it would be easier to hit one button, Exam, rather than select the button for the soffit and then for the ceiling, and then adjust the brightness for both groups.

### 4.5 Observations and Conversation with Nurses

Verbal feedback from the UK NICU nursing staff, combined with an onsite assessment by the authors, confirmed that the lighting design and sequence of operations were implemented as intended throughout the facility. For multiple rooms across the unit, the color temperatures, lumen output, and fade rates of the patient room luminaires matched the specified light scenes and transitions. The onsite assessment of the facility was also used to confirm that the data collected from the lighting control system was accurately reporting information about the luminaires and could be used for analysis.

While the research team was on-site observing the operation of the lighting system, there was a happenstance opportunity to have a casual discussion about the lighting with a small group of nurses who regularly met to discuss ways to improve care. It was clear from conversation that part of the benefit for the nurses was the cueing that occurred. The automatic transition of the lighting system communicated with the parents and visitors on the unit, reducing the need for the nurses to do so. The automatic turning on that occurred as part of the Dawn transition helped any parents who spent the night to wake up without the nurses or other staff waking them up. This was particularly helpful because there were no exterior windows in the patient room. The scheduled lighting transitions also helped facilitate evening unit transitions, with the transition to CLP Dusk mode aligning with the start of visiting hours on the unit. After 2 hours, the lights slowly faded to off as part of the CLP Off mode, signaling to visitors that it was time to leave. While the transition to CLP Off mode was seen as beneficial by the nurses in this group, the control data indicates that there is still opportunity to decrease the number of overrides that happen during the Night transition.

The nurses also commented that compared to the older unit, they noticed fewer parents complaining about babies' sleep schedules being out of sync with typical day-night schedules. There was no documentation of who occupied the patient rooms throughout the 25-week monitoring period; however, more context was provided during the conversation with the nurses. Families tended to visit at night, and it was also common for families to not live near the NICU, making it more difficult for them to be present. Additionally, the nurses noted that there was a parent with post-traumatic stress disorder who had figured out how to set the downlights to 3000 K during the day by hitting the dimming arrow instead of the "On" button. The nurses were also able to adjust the lighting for parents as a gesture of support. It is clear from both the subjective and objective feedback that the nurses found the flexibility of the tunable lighting system valuable, with the subjective feedback specifically highlighting how the lighting was also used to support the parents.

## 5. Lighting System Data: Opportunities for Design and Operation

Historically, the focus of lighting design has been to meet visual task needs, aesthetic goals, and occupant preference, with the use of controls encouraged to provide more flexibility and energy savings. Selection of the light level for a given task and application is typically based on Illuminating Engineering Society recommendations, as determined from the collective knowledge of industry experts. Architects, clients, and lighting designers/specifiers often work together to finalize the overall design of a space or building, while the design is installed and commissioned by a construction team. The lighting designer/specifier typically has little, if any, involvement in the implementation of the lighting system and rarely returns to a project to examine the design after commissioning because these steps are not prioritized in most construction budgets. The relative success of a project is often based on generally subjective measures, such as an email from a facilities manager confirming the lighting is working. These measures are sometimes not even related to the occupant of the space, despite this being the primary focus of the design.

As new technology and lighting design techniques are incorporated into patient rooms, it is also important to understand the user response to the technology. Recommendations and best practices frequently rely on collective experience; however, with tunable lighting, this collective experience remains limited by the sparse number of installations of this new technology. There have been several studies pointing to the desire for control in the patient room environment, with McCunn et al. (2020) finding that nurses across multiple hospitals desire more control over the fluorescent lighting in the patient rooms where they work. Similarly, a survey of nearly 400 medical-surgical nurses across the United States found a significant relationship between nurse satisfaction with the lighting and access to controls (switches and dimmers) (Hadi et al. 2016), and the authors also interviewed a subset of nurses, finding that commonly switching the lights from a day setting to a night setting tends to fall to nurses who feel overloaded, and consequently gets overlooked.

Additionally, Engwall and colleagues (2015) compared standard lighting in an ICU patient room to tunable lighting, noting as one of their implications for practice that lighting experiences are highly individual, with light at night disturbing for some while providing a feeling of security for others based on patient surveys and interviews with patients. Understanding how occupants interact with a programmed tunable lighting system is important for creating an environment that supports sleep and patient health while also addressing the other needs and preferences of the patients and the hospital staff.

## 5.1 Improving Operation Based on Occupant Use of System

As the availability of lighting system data increases, there is a considerable opportunity to improve the operation of lighting systems to increase efficiency and better meet the needs and preferences of occupants. This is particularly important as lighting systems and recommendations begin to change in response to new technology and new research. For example, there is increasing awareness of the need to minimize light at night for improving sleep. Setting the default for the downlights in the UK NICU to a low light level makes sense from this perspective, with the goal to minimize disruption to infants and visiting family, but looking at the data provides a different perspective.

From the UK control data it is clear that when only the ceiling or the soffit downlights are turned on, the nurses are regularly increasing the light level in order to complete their tasks. The nurses may even be using the Exam mode more because it provides a high light level with one button press instead of turning the downlights on and pressing the arrow button multiple times to reach the light level desired. The results from the downlight analysis could be used to adjust the default from the control signal of 34% to a slightly higher control signal to see if the nurses find that light level more satisfactory. If a majority of nurses still are increasing the light level, then it could always be raised further. This may initially seem to require more energy, but it could be that the nurses have been using Exam mode because it is more convenient to get enough light, and that once this adjustment is made, the use of the more energy-intensive Exam mode will decrease.

In the future, these types of optimizations could be identified by the control system software or a BAS through automated analytical models and implemented by the facility manager in coordination with the unit. Data analysis methods like machine learning could allow the system to learn nurse preferences, such as light level. These preferences could be used to develop individual presets for the nurses, supplemented by information (like shift schedule) that is already contained in an electronic medical record system. The LCS could make the presets readily available for nurses working in a particular patient room for the duration of their shift.

### 5.2 How Data Shifts the Design Process

Lighting system control data can provide an additional reason to shift where time is spent as part of the design process. Typically, a significant amount of time is spent during the design and construction process predicting the performance of the lighting system and then optimizing based on the predicted performance. For lighting systems, often the control system and luminaires initially selected by the designer/specifier are different than what actually gets installed, yet as the design process currently stands, a disproportionate amount of time is spent optimizing the prediction and not the actual installation. When lighting control systems are installed, there is typically a commissioning professional that makes sure the lighting system is operating as specified; however, the commissioning professional rarely interacts with the designer/specifier and does not have access to the broader design goals.

Even with full-scale mock-ups during the design process, it is difficult to understand how a lighting system will be used. Without a way to characterize the actual operation of a lighting system, too often price and other factors become the measure of success instead of how the design meets the needs of occupants. Control data can serve as a feedback mechanism for lighting designers/specifiers to determine whether the decisions that were made during design through commissioning suit the ongoing needs of occupants after installation; currently, there is no feedback loop for lighting designers/specifiers to determine this. These reviews could be a way to engage occupants and make them to feel more connected to their environment.

## 6. Quantification for Research and Energy Codes

Control data can also be helpful for researchers who are trying to quantify light exposure as part of a broader experiment. For example, in a hospital environment where the room layout is very similar between rooms and daylight is limited, estimation of the stimulus for all rooms can be based on physical measurements from a small subset that have been extrapolated based on LCS data. This is less cumbersome than installing light sensors.

The control data may also be useful to meet future energy codes that are not primarily based on the maximum wattage of all installed luminaires and instead begin to account for the time component. When analyzing this data for energy considerations, Safranek et al. (2021) found that there was a minimal increase in energy use compared to the baseline of the CLP, yet the additional downlights provided the occupants with valuable flexibility.

## 7. Limitations

While the data collected from the control system provides valuable insight into how the lighting system was being used by occupants, there are several noteworthy limitations to the dataset. Information related to room occupancy was not recorded over the monitoring period. It is possible to assume periods of vacancy, for example, if the lighting mode did not change over one or more days; however, there were no occupancy sensors, as is the case for most U.S. patient rooms.

Control signal information was also not collected for the guest recessed luminaire behind the visitor seating area or for the sink downlight. The sink downlight was continuously on, but only had a 2-inch aperture with minimal light output, so it is unlikely it affected how the general lighting was used. The slot luminaire had a potentially greater contribution to illuminance levels in the patient room, although it was less likely to be used because the control station was on the back wall of the patient room. The lighting conditions were also sampled every 5 minutes instead of recording each time the lighting changed, so if multiple lighting modes were used within a 5-minute period this nuance was not captured as only one mode would be recorded.

# 8. Conclusion

The advancement of SSL and controls technology, computing capacity, and software provides new opportunities for researchers and designers to work together to further optimize spaces for occupant benefit and energy savings, informing lighting recommendations and best practice. Rarely does a specifier, manufacturer, or other interested party, such as a facilities manager, know how well the lighting system is working for the occupants, despite this being a primary goal of lighting system design. The analysis of the control data highlights the opportunities provided by advanced lighting systems for optimization after installation using objective data that details how the lighting system is used by the actual occupants of spaces. The collection of the data did not require any additional hardware or software. As collection and analysis of control data becomes more common, the more robust and valuable this data will become for improving the lighted built environment.

# Acknowledgments:

The authors acknowledge Craig Casey with Lutron and Bobbie Tincher with the University of Kentucky for their assistance with this research.

# Disclosure Statement:

The authors have no financial interests to declare.

# Funding:

This work was supported by the U.S. Department of Energy's Solid-State Lighting Program, part of the Building Technologies Office within the Office of Energy Efficiency and Renewable Energy (EERE).

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