Lighting the Patient Room of the Future: Evaluating Different Lighting Conditions for Performing Typical Nursing Tasks

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Abstract

Purpose: This study explores how aspects of lighting in patient rooms are experienced and evaluated by nurses while performing simulated work under various lighting conditions. The lighting conditions studied represent design standards consistent with different environments of care—traditional, contemporary, and future.

Background: Recent advances in lighting research and technology create opportunities to use lighting in hospital rooms to improve everyday experience and provide researchers with opportunities to explore a new set of research questions about the effects of lighting on patients, guests, and staff. This study focuses on the experience of nurses delivering simulated patient care.

Method: Perceptions of each of the 13 lighting conditions were evaluated by nurses using rating scales for difficulty of task completion, comfort, intensity, appropriateness of the lighting color, and naturalness of the lighting during the task. The nurses' ratings were analyzed alongside qualitative reflections to provide insight into their responses.

Results: Significant differences were found for several a priori hypotheses. Interesting findings provide insight into lighting to support circadian synchronization, lighting at night, the distribution of light in the patient room and the use of multiple lighting zones, and the use of colored lighting.

Conclusion: The results of this study provide insight into potential benefits and concerns of these new features for patient room lighting systems and reveal gaps in the existing evidence base that can inform future investigations.

Background

Recent advances in lighting technology and control systems create opportunities to use lighting in hospital rooms to improve everyday experiences for patients, visitors, and staff. Developments in tunable LED lighting systems provide the ability to vary the spectrum and intensity of light separately for different lighting zones and luminaires, over the course of the day and night. Additionally, the high efficiency of these systems provides the opportunity for significant energy savings, enabling the introduction of innovative lighting solutions in cost-conscious domains such as healthcare. These solutions can make it easier to support circadian synchronization, address nighttime navigation needs, enable more user-friendly control, and provide opportunities to explore a new set of research questions about the effects on, and evaluation of, lighting by patients, guests, and staff. This study focuses on the evaluation of tunable, dimmable lighting by nurses and those executing nursing tasks.

The availability of these new lighting systems coincides with emerging research demonstrating that the spectrum, intensity, distribution, timing, and duration of light can affect task performance, alertness, and sleep patterns (Figueiro et al. 2016, Giménez et al. 2016, Rahman 2017, Smith et al. 2009), and that these effects can be important for healthcare patients (Hadi et al. 2019). The intrinsically photosensitive retinal ganglion cells (ipRGCs), with peak sensitivity to short-wavelength light of around 480 nm, help synchronize circadian rhythms and can separately produce short-term alerting effects (Brainard et al. 2001, Thapan et al. 2001, Berson et al. 2002, Hattar et al. 2002, Lucas mc. 2014). Electric lighting may be needed for these effects as simulations have shown that, depending on the size of windows and the geographic location, patients in hospital rooms may not get sufficient lighting stimulus at the eye from daylighting to synchronize their circadian rhythms (Acosta et al. 2017).

In healthcare design, the term environment of care refers to "those physical environment features in a health care facility that are created, structured, and maintained to support and enhance the delivery of health care" (Facilities Guidelines Institute [FGI], 2018). In many existing hospital patient rooms, especially those built several decades ago, the environment of care reflects a focus on maximizing the efficiency of delivering medical care, sometimes without ample attention to the impact of design on the patient and guest experience (Bates, 2018). Hospitals from this era are characterized herein as having a traditional environment of care (TEC).

In the mid-1980s, hospital design began to transition into a contemporary environment of care (CEC) with a recognition that the physical settings in a hospital must not only support the effective delivery of care; they are in and of themselves tools in the healing process, supporting wellness through psycho-physiological effects (Nesmith, 1995). Today, a convergence of evolving research in patient-centered, evidence-based design and new technologies has enabled a transition into what may be considered the future environment of care (FEC). FEC is defined by a deeper focus on the experiences of patients, visitors, and staff, centered on the potential therapeutic and safety effects of hospital design.

Table 1 summarizes the differences between the lighting systems that typify the TEC, CEC, and FEC design practices. These practices that relate to the sources used, intensity and spectrum control, and arrangements of luminaires into zones are generally not embodied in recommendations from organizations such as the Facilities Guidelines Institute and the Illuminating Engineering Society; those recommendations have typically focused on establishing target illuminance levels (FGI, 2018). While the ability of FEC lighting systems to adjust the spectrum of light based on circadian and other physiological needs is exciting, the relationship between those lighting variables and patient and staff outcomes in realistic settings needs to be documented, along with an understanding of how those variations may affect other environmental perceptions.

Table 1. Descriptions of lighting systems for different environments of care.

ENVIRONMENT OF CARE*	DATES	DESIGN FOCUS	LIGHT SOURCES	LIGHTING ZONES?	INTENSITY CONTROL?	SPECTRUM CONTROL?	NIGHT NAV?
Traditional (TEC)	1945–1985	Efficiency, Technology	Incandescent, Fluorescent	No	On / Off	No	No
Contemporary (CEC)	1985–2020	Patient, Residential	Daylight, Fluorescent, LED	Yes	On / Off with some dimming	No	Not always
Future (FEC)	2020–??	Holistic health, Adaptable	Daylight, LED	Yes	Full dimming	Yes	Yes

Notes: Health care facilities built within the range of dates shown are likely to have the characteristics shown, although the transitions between categories are gradual and facility upgrades can change the characteristics of the lighting. "Design focus" refers to the general principles driving health care design during the related time period. "Zones" refer to whether different areas within the patient room are identified for specific lighting, such as the patient bed, family area, nurse station, etc. "Intensity control" refers to the method of control used to alter the intensity of light. "Spectrum control" refers to the ability to dynamically alter the spectrum of light. "Night nav" refers to the provision of separate lighting to enable patient and staff navigation within the room at night without needing to turn on the general room lighting or use supplemental lighting.

Experiment Overview

The experiment described in this paper is part of a larger research program exploring how various aspects of lighting are experienced and evaluated by patients, visitors and staff in inpatient hospital settings. This experiment studies how nurses perceive different lighting conditions in a patient room while performing work tasks, with specific interests in understanding nurses' perceptions of 1) bright cool-tone lighting that may help to properly synchronize patient circadian rhythms, 2) lighting that represents the different environments of care, and 3) colored lighting introduced into the room. These perceptions are important aspects of the visual experience and visual comfort of nurses when working in patient rooms and fit into a broader theoretical construct of human psychological functioning as explained in de Kort (2019).

To investigate these topics, a full-scale mock-up patient room with a tunable LED lighting system was constructed at SimTigrate Design Lab at the Georgia Institute of Technology in Atlanta, GA. Participants in the study completed three tasks developed to mimic the types of tasks that nurses perform in patient rooms under 13 different lighting conditions. After completing the tasks, perceptions of each of the lighting conditions were measured using a set of ratings scales.

Methods

Room Layout

The experimental setup included a hospital patient room mock-up, located within a larger laboratory and office space. The room mock-up was approximately 4.37 m by 4.14 m (14.3 ft x 13.6 ft) with a ceiling height of 2.74 m (9 ft). The room consisted of two permanent walls (east and north walls), and two temporary walls (south and west walls). A small entryway (2.16 m or 7 ft by 1.8 m or 6 ft) led to the patient room doorway in the northwest corner. A full-length blackout curtain was used in the doorway to minimize light from adjacent office and lab spaces. The two 1.73 m by 1.04 m (6ft x 4 ft) east-facing windows in the room were covered with blinds and blackout curtains to minimize light entry from outside.

For purposes of defining the task areas, three areas were defined within the room. The bed area consisted of a 2.31 m by 1.02 m (8ft x 3.34 ft) hospital bed with one 56 cm by 56 cm by 91 cm (2ft x 2ft x

3ft) tall table on the west side. The family area consisted of two 71 cm by 71 cm (2.33 ft x 2.33 ft) chairs as well as a 61 cm by 61 cm (2ft x 2 ft) table that sat 43 cm (1.4 ft) tall. The nurse work area consisted of a table identical to the bedside table, which sat beside a non-functioning model sink, along the north wall of the room (Figure 1). A small control room for the experiment was located within the space that would normally be the patient bathroom. The door to this room remained closed when participants were in the patient room.

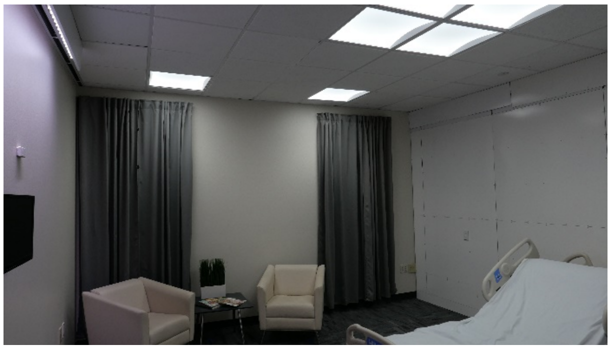

Figure 1. The hospital patient room mock-up, showing the four recessed luminaires over the bed, the two recessed luminaires over the family area, and the wall wash luminaire. The photo on the left shows the room in a bright white lighting mode (experimental condition 1) while the photo on the right shows some other capabilities of the tunable lighting system, with the luminaires in the bed area set to a different light level to those in the family area, and with the wall luminaire producing colored light (experimental condition 10). The wall-mounted monitor shown was removed during the experiment; in that area of the room a nurse work area was placed near the wall, including a mobile table which sat beside a non-functioning model sink. This was used during the experiment for simulated medication identification.

Lighting Equipment and Layout

The lighting in the bed and family areas was provided by six recessed 61 cm by 61 cm (2 ft x 2 ft) LED luminaires from the Ledalite ArcForm family; the 3600-lumen option was provided (model number 3622-L-36) which has a rated power draw of 35 W. These luminaires had two-channel tunable white technology with dimming control settings from 1% to 100% and a CCT range from 2700 K to 6500 K. Four of these luminaires were located above the bed in a 122 cm by 122 cm (4ft x 4 ft) configuration, and two were located above the family area with 1.83 m (6 ft) center-to-center spacing. These luminaires have published luminous intensity values at vertical angles of 65^{o} and greater that satisfy discomfort glare criteria for common architectural spaces (ANSI/IES 2018).

Lighting onto the north wall was delivered by eight 30.5 cm (1 ft) strip Philips Color Kinetics PureStyle Intelligent Color Powercore RGBA linear LED luminaires mounted continuously on the ceiling, 15 cm (0.5 ft) from the wall and hidden from normal viewing angles by a 20 cm (0.7 ft) tall fascia board. This was a color-tunable luminaire, able to deliver white hues as well as saturated color hues. Nighttime navigation lighting was provided by amber LEDs in a 20 cm (0.7 ft) wide and 15 cm (0.5 ft) high Chloride SoftGlo LED luminaire, recessed into the west wall approximately 3.7 m (12 ft) from the corner of the entry hallway and 30.5 cm (1 ft) above the floor (Figure 2).

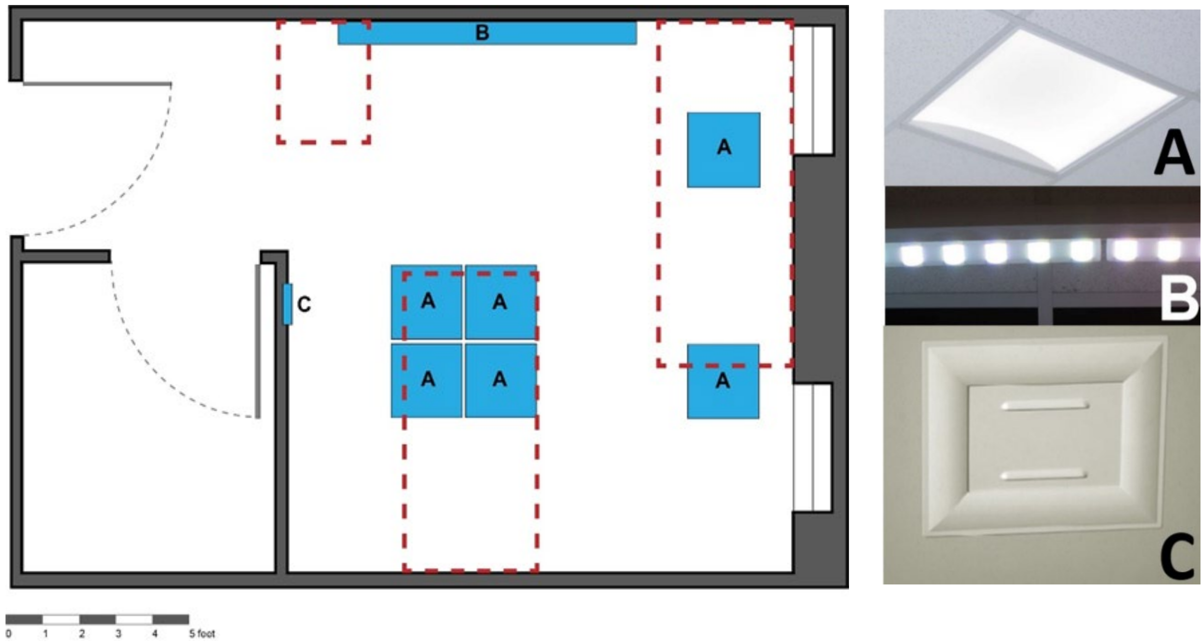

Figure 2. Reflected ceiling plan detailing the layout of luminaires. The reflected ceiling plan (left) consists of four Ledalite tunable white ArcForm 2x2 luminaires over the bed and two in the family area (luminaire A), 8 ft of the Philips Color Kinetics PureStyle Intelligent Color Powercore RGBA linear LED luminaire in a soffit on the opposite wall (luminaire B), and a Chloride SoftGlo recessed amber pathlight to provide night lighting (luminaire C). The red dotted lines indicate the measurement areas designated as bed, family, and wall.

Tasks

Three tasks were created based on the visual needs of nurses during routine patient evaluation procedures, as detailed in an interview by the research team with a nurse educator from Nationwide Children's Hospital. These tasks were developed to engage participants with each lighting condition. A task sheet with prompts for the participants was placed in the nurse's work area at the start of each lighting condition and participants recorded responses for two of the tasks on this sheet. The following task ordering was consistent for each condition throughout all participants:

1. Patient-Medicine Identification: Participants were asked to find a particular patient's pill bottle among a total of thirteen bottles by reading the labels, then place the bottle on the bedside table. The specific patient name was randomized throughout the experiment for each participant. This task was informed by nurse charting and medicine distribution procedures.
2. Color-Word Identification: A 21.6 cm by 27.9 cm (0.7 ft x 0.9 ft) card was placed underneath the bed sheet near the foot of the patient bed with a list of words; each word was in a distinctly different color. Participants were told to identify the color of a certain word, then participants needed to lift the sheet to perform the task and record their response on the task sheet at the nurse work area. This task was informed by typical wound care procedures involving obstructed light.
3. Letter/Number-Color Identification: Participants were asked to identify the letter or number of a designated color along a vertical rope hanging next to the head of the bed. Participants then wrote the letter or number on the task sheet located at the nurse work area. This task was informed by IV procedures and visual scanning.

Lighting Conditions and Measurements

Thirteen lighting conditions were selected with a range of horizontal illuminances (5 to 1000 lx), CCTs (2700 to 6500 K), and lighting distribution patterns (Table 2). The nomenclature used to describe the conditions throughout this paper is also described in Table 2. Ten of these 13 conditions were developed to reflect multiple FEC lighting conditions and the other three represented TEC and CEC lighting conditions. The TEC and CEC conditions both had moderate illuminance (400 lx) and neutral CCT (3500 K) which are consistent with design standards for existing patient rooms, but the TEC lighting condition (4) only had two of the overbed luminaires on to simulate conditions found in some older hospitals. Conditions are defined by the target values; Table 3 shows the target and actual measured values for each condition.

Table 2. Lighting condition designations and descriptions.

LTG. CONDITION	DESIGNATION	DESCRIPTION	ENVIRON. OF CARE TYPE	TARGET ILLUMINANCE (lx)			TARGET CCT (K)		
				BED	FAMILY	WALL	BED	FAMILY	WALL
1	M65/1000	Morning, very high CCT, high illuminance	FEC	1000	1000	1000	6500	6500	6500
2	M50/400	Morning, high CCT, normal illuminance	FEC	400	OFF	400	5000	OFF	5000
3	M50/400	Morning, high CCT, normal illuminance	FEC	400	400	400	5000	5000	5000
4	D35/400	Day, bed only, 2 of 4 luminaires	TEC	400*	OFF	OFF	3500	OFF	OFF
5	D35/400	Day, bed and family	CEC	400	400	OFF	3500	3500	OFF
6	D35/400	Day, bed, family and wall	FEC	400	400	400	3500	3500	3500
7	D35,50/400	Day, mixed CCT	FEC	400	400	400	3500	5000	3500
8	D35-50/400B	Day, mixed CCT, blue wall light	FEC	400	400	NA	3500	5000	blue
9	E27/100	Evening, low CCT & illuminance	FEC	100	50	50	2700	2700	2700
10	E27/100R	Evening, low CCT & illum., red wall light	FEC	100	50	NA	2700	2700	red
11	N35/wall	Night, wall only	FEC	OFF	OFF	400	OFF	OFF	3500
12	N27/5	Night, bed only, dim	CEC	5	OFF	OFF	2700	OFF	OFF
13	N NL	Night, night light only	TEC	OFF	OFF	OFF	OFF	OFF	OFF

The designation scheme first indicates the time of day that was provided to the participant for context (morning, day, evening, night), then the first two digits of the CCT / the target illuminance on the bed. Variations in the lighting zones for conditions with similar designations are shown in the description and explained in the text. See Table 1 for explanations of the environment of care types.

Table 3. Lighting conditions as applied.

LTG. COND.	ACTUAL ILLUMINANCE (lx)			ACTUAL CCT (K)		
	BED	FAMILY	WALL	BED	FAMILY	WALL
PRACTICE	401	417	151	3095	3112	3062
1	1110	999	867	6340	6325	6448
2	472	130	281	5022	4744	4755
3	413	398	284	4669	4477	4657
4[a]	413	155	116	3506	3475	3459
5	433	434	159	3452	3454	3386
6	462	478	357	3424	3413	3294
7	450	446	361	3652	4342	3429
8	448	466	415	4058	6364	Blue
9	97	57	56	2737	2732	2680
10	99	59	68	2622	2469	1984
11	28	43	211	3099	3171	3262
12	5	5	4	3030[b]	3171[c]	Red
13	--	3	--	--	--	--

Illuminance and spectrum measurements were taken 1m above the floor at 4–6 distributed points across each lighting zone. Blank cells for condition 13 indicate that all measured values were under the meter's threshold.
[a] Only two of the four luminaires over the bed were turned on for condition 4, to mimic a traditional lighting system.
[b] Average of five of the six measurement points; the value at remaining point was less than the meter's threshold.
[c] Average of two of the six measurement points; the values at remaining points were less than the meter's threshold.

The FEC conditions had varying illuminance levels, CCTs, and in a few conditions, saturated colors. These conditions were established to represent the range of lighting settings that can be achieved by tunable LED lighting systems that are likely to be used in future patient rooms. For example, conditions 1–3 use higher CCTs than typical and normal or higher illuminance in order to produce elevated levels of stimulation for the circadian system in the mornings. Conditions 6–8 represent daytime conditions with variations in luminaire CCTs in different zones and the use of colored lighting on the wall in order to test specific hypotheses. Conditions 9–10 use lower CCTs and lower illuminances to avoid high circadian stimulation in the evening and introduce colored wall lighting to test a related hypothesis. The market pressure to introduce these tunable lighting systems into patient rooms primarily focuses on patient responses; this experiment documented nurses' perceptions of the patient room with these different conditions.

Horizontal illuminance measurements were taken 1 m (3.28 ft) above the floor at four to six measurement points distributed uniformly within each lighting area. Horizontal patient experience illuminance measures were also taken in the center of the pillow area, 0.76 m (2.5 ft) from the wall behind the bed and 0.85 m (2.8 ft) above the floor (Figure 3). Vertical illuminance and spectrum measurements were taken at a height of 1.3 m (4.3 ft) above the floor, with the meter positioned to measure the light reaching a patients' eyes when seated in the bed; the data were used for calculations of lighting metrics related to non-visual effects of light such as effects on circadian physiology.

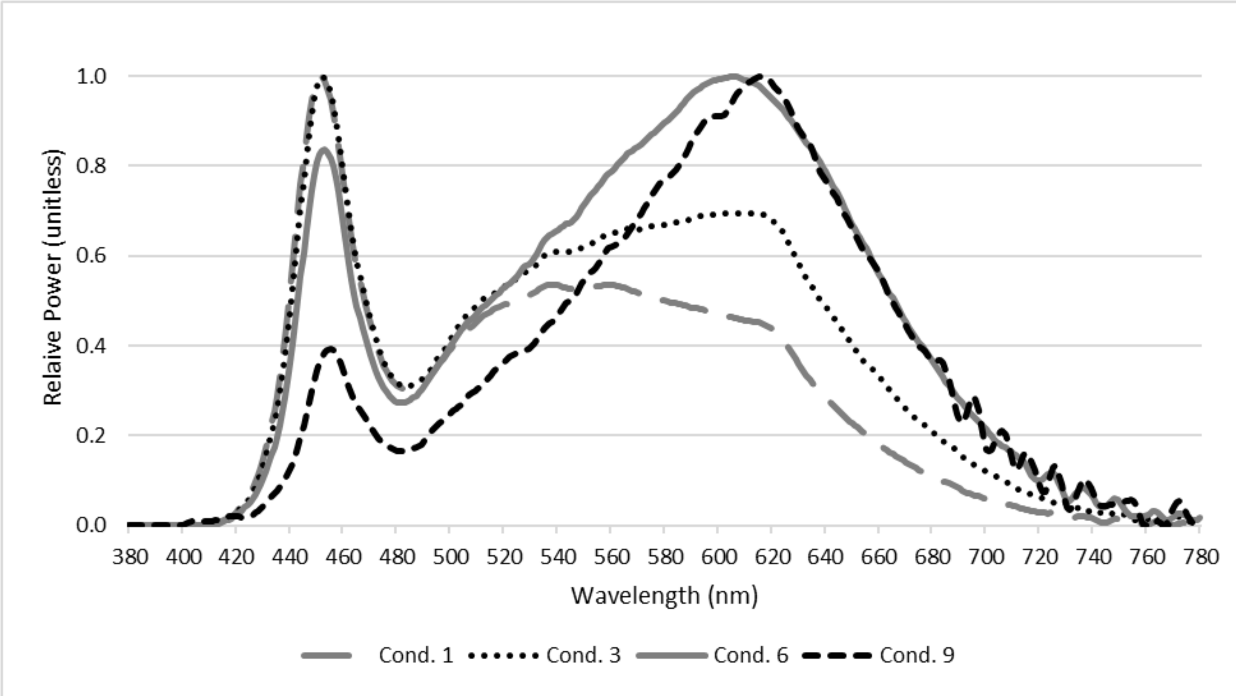

Figure 3. Plot of the relative spectral power distribution for lighting conditions 1, 3, 6, and 9 measured at the task plane of the patient bed when completely flat. These measures capture the experience for patients resting while lying in bed and approximates the nurses' experience viewing the patient at the bedside. These measures were taken on the horizontal plane of the bed in the center of the pillow area, 0.76 m (2.5 ft) from the wall behind the bed and 0.85 m (2.8 ft) above the floor.

Participants

A group of 35 nurses and college-level students participated in the experiment, including 20 nurses and 15 students. Participants included 8 males and 27 females, ranging between 20 to 53 year of age (mean of 25). In order to recruit bedside healthcare nurses, recruitment flyers with online sign-up information were posted at Emory University Hospital Midtown in Atlanta and Children's Healthcare of Atlanta Hospital. Similar flyers were posted around the Georgia Tech campus to recruit students. The use of contact lenses or glasses was noted for all participants. Two female student participants were excluded from analysis due to lighting software malfunctions during the experimental sessions, their data are not reported in this paper. Consequently, data from 33 participants were analyzed. This sample size was determined based on expectations that it would provide sufficient power for the types of statistical analyses planned to evaluate the participants' results. Uttley (2019) shows that samples of 25–35 subjects provide sufficient statistical power to detect most large and medium effects in within-subjects experimental research.

Participant Ratings

For each lighting condition, participants completed a paper response form consisting of five questions and were asked to circle their rating on a seven-point scale for each question. Each question focused on a different perception of a lighting characteristic or aspect of the task: difficulty of task completion, with choices from extremely easy (1) to extremely difficult (7); comfort of the lighting during the task, extremely comfortable (1) to extremely uncomfortable (7); intensity of the lighting during the task, extremely too dim (1) to extremely too bright (7); appropriateness of the lighting color for the task, extremely appropriate (1) to extremely inappropriate (7); and naturalness of the lighting during task completion, extremely natural (1) to extremely unnatural (7). At the conclusion of the experiment, the participants gave verbal responses to open-ended questions describing their experience.

A Mann-Whitney U test was used to check the rating scale results of the nurses against the students, looking for significant differences between results of the two samples across each question and condition. Of the 65 comparisons made (5 rating scales for 13 lighting conditions), significant differences were found in three instances: in comfort and color appropriateness for condition 13 (night light only) and in naturalness for condition 4. This indicated that nurses and students had similar views of the lighting environment overall; therefore, the combined student and nurse data were used in the full analyses, with a plan to further explore the three cases where significant differences occurred if necessary. When a significant result occurred that involved one of those three circumstances, the nurse and the student results were tested separately and in all cases the finding of significance occurred for both groups. Consequently, the combined data were used for all analyses and discussion.

Pre-Experiment Preparation

Each experimental session had a single participant. Upon arrival, participants were met by a researcher who asked them to review and sign an informed consent form as well as complete the demographics form. This study was approved by the Georgia Tech IRB under research protocol number H18214. Participants were then directed into the experimental room, where they were shown the three tasks that were to be performed during each lighting condition. The lighting had nominal settings of 400 lx, 3000 K in the bed and family areas during this introduction, as well as during the unannounced practice trial that preceded the 13 lighting conditions.

Experimental Trials

For each trial, a researcher read a prompt to the participant noting the time of day that was represented by each condition. The participant then entered the experimental room, moved about the room while completing the three provided tasks, and completed the paper rating response form while standing in the room with freedom to look about the room; this process required 3–5 minutes for each trial. Upon completion, participants turned in the forms to the researcher and left the room, waiting in a designated area. The illuminance in the waiting area was within the range of illuminances experienced during the morning and daytime lighting conditions (measured between 143 and 529 lx), and consistent with the variations that nurses experience transitioning between corridors and patient rooms.

After the researcher changed the lighting condition and re-supplied the task objects and rating forms, participants re-entered the room and repeated the process. The order of the 13 experimental conditions, following the practice condition, were counterbalanced among participants to account for order effects as recommended by Veitch et al (2019) for studies comparing many lighting conditions. Participants spent a total of about 60 minutes completing all trials.

Hypotheses

Several a priori hypotheses were developed that informed the lighting conditions and dependent ratings used in the experiment. The hypotheses and lighting conditions involved were as follows:

First, nurse perceptions will change for different patient room lighting conditions that deliver varying levels of circadian stimulation throughout the day, as measured by melanopic irradiance (MI, CIE 2018) and circadian stimulus (CS, Figueiro et al. 2016a). This was evaluated using lighting conditions 1 (M65/1000), 3 (M50/400), 6 (D35/400) and 9 (E27/100). Second, nurse perceptions will vary based on differences in distribution of lighting in the room, at different times of day, such as would occur with differences in the environment of care. This was evaluated using daytime conditions 4 (D35/400 bed only) which represented a TEC lighting system, 5 (D35/400 without wall lighting) which represented a CEC lighting system, and 6 (D35/400 with wall lighting) which represented an FEC lighting system. Alternative distributions of nighttime lighting were also evaluated by comparing FEC conditions 11 (N35/wall only) and 12 (N27/5 bed only) and TEC condition 13 (night light only). Also, nurse perceptions will vary when colored light is introduced into the room. This was evaluated by comparing conditions 7 (D35-50/400) and 8 (D35-50/400 with blue wall light), and by comparing conditions 9 (E27/100) and 10 (E27/100 with red wall light). Finally, nurse perceptions will vary when there is a visible difference in luminaire CCTs. This was evaluated by comparing conditions 6 (D35/400) and 7 (D35-50/400 with 5000K in the family area).

Results

The mean and standard deviation for each of the five rating questions for each of the 13 stimulus conditions are shown in Table 4. Overall, the mean ratings show that the lighting conditions were perceived favorably. For example, 11 of the 13 conditions had a mean task difficulty rating of less than 3 (with a rating of 1 being "extremely easy"); these same 11 conditions had mean perceived intensity ratings between 3 and 5. The only exceptions were two of the dim nighttime conditions, 12 and 13. Participants also found the lighting conditions to be comfortable overall; mean ratings for the perceived comfort scale were greater than the neutral score of 4 for only three conditions (the nighttime conditions 12 and 13 and condition 8 with blue lighting on the wall).

Table 4. Summary of collected data, showing the mean and standard deviation for each rating question at each of the 13 stimulus conditions.

LTG COND.	DIFFICULTY		COMFORT		INTENSITY		COLOR APPROPRIATENESS		NATURALNESS	
	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV
1	1.29	0.461	2.94	1.825	5.00	1.065	2.52	1.61	4.55	1.748
2	1.42	0.765	2.42	1.628	4.03	0.875	2.23	1.407	3.71	1.575
3	1.58	1.025	2.42	1.628	4.26	0.815	2.23	1.454	3.42	1.766
4	1.87	1.258	2.61	1.585	3.65	1.142	3.06	1.526	3.13	1.628
5	1.48	0.89	2.06	1.181	4.10	0.597	2.10	1.326	3.26	1.653
6	1.42	0.886	2.16	1.463	4.03	0.706	2.23	1.454	2.84	1.551
7	1.39	0.667	1.84	1.267	4.06	0.772	1.84	1.241	3.13	1.765
8	2.55	1.502	4.71	2.116	4.52	1.208	5.00	1.506	6.06	1.315
9	2.45	1.524	2.97	1.958	3.00	0.931	3.35	1.959	3.61	1.745
10	2.48	1.503	3.71	1.736	3.10	0.831	4.19	1.558	5.00	1.39
11	2.00	1.095	2.1	1.35	3.65	0.661	2.39	1.407	2.87	1.50
12	4.26	2.016	4.03	1.958	2.32	0.871	4.61	1.667	3.84	1.715
13	6.84	0.374	6.23	1.309	1.06	0.25	6.23	1.454	4.19	2.136

Statistical Analyses

Statistical analyses of the ratings data were carried out using SPSS software version 24. Nonparametric tests were used based on a finding of non-normality using Kolmogorov-Smirnov tests. Differences in rank positions of the ratings with groups of more than two conditions were tested using Friedman tests;

if results of a Friedman test showed a significant difference among a group, individual pairs were tested using the Wilcoxon signed rank test. In comparing study variables, p values < 0.05 were considered statistically significant. All Friedman and Wilcoxon signed rank tests conducted were two-tailed tests.

Hypothesis 1: FEC Lighting Systems with Varying Levels of Circadian Stimulation. To test the hypothesis regarding perceptions of lighting conditions with different potential circadian impacts, participants' perceptions of lighting conditions 1, 3, 6 and 9 were compared. Table 5 shows the MI and CS values for each of these lighting conditions while Table 6 provides the raw data for that calculation; Figure 4 shows the participants' perceptions and Figure 5 provides context to the comparison by showing SPDs of the four conditions. The daytime condition 6 (D35/400) was rated as the most comfortable and the most natural, while condition 1 (M65/1000) was the least comfortable and the least natural. The differences in the comfort ratings were not significant ($p = 0.06$), while condition 1 was rated as significantly less natural than condition 6 ($p < 0.0001$). Condition 9 (E27/100) was rated as the least color appropriate and this difference was significant ($p = 0.007$). There were no significant differences in rated difficulty.

Table 5. Calculated circadian metrics at patient eye position and viewing direction when seated in bed.

LIGHTING CONDITION	CIRCADIAN STIMULUS	MELANOPIC IRRADIANCE (µW/cm²)	ILLUMINANCE (lx)	CCT (K)
1	0.556	103.3	859	6311
3	0.334	33.8	339	4655
6	0.245	29.1	376	3409
9	0.105	4.8	83.2	2735

Table 6. Raw spectral power distribution data used to calculate the circadian metrics in Table 5. Measurements were taken at the patient eye position when laying slightly upright in bed for lighting conditions 1, 3, 6, and 9.

Wavelength (nm)	Spectral Irradiance (W/m²)			
	Cond. 1	Cond. 3	Cond. 6	Cond. 9
380	0.00000	0.00000	0.00000	0.00001
385	0.00000	0.00000	0.00000	0.00006
390	0.00000	0.00000	0.00001	0.00008
395	0.00000	0.00000	0.00000	0.00004
400	0.00000	0.00000	0.00000	0.00002
405	0.00000	0.00001	0.00002	0.00003
410	0.00005	0.00006	0.00008	0.00003
415	0.00023	0.00013	0.00013	0.00004
420	0.00070	0.00024	0.00021	0.00006
425	0.00170	0.00049	0.00039	0.00009
430	0.00356	0.00103	0.00074	0.00013
435	0.00693	0.00200	0.00139	0.00018
440	0.01247	0.00361	0.00250	0.00028
445	0.01910	0.00570	0.00401	0.00045
450	0.02327	0.00722	0.00524	0.00064

Wavelength (nm)	Spectral Irradiance (W/m²)			
	Cond. 1	Cond. 3	Cond. 6	Cond. 9
455	0.02273	0.00722	0.00545	0.00075
460	0.01894	0.00600	0.00469	0.00070
465	0.01499	0.00470	0.00377	0.00057
470	0.01207	0.00375	0.00307	0.00045
475	0.00979	0.00302	0.00252	0.00037
480	0.00841	0.00260	0.00220	0.00036
485	0.00797	0.00252	0.00211	0.00036
490	0.00817	0.00264	0.00222	0.00037
495	0.00882	0.00289	0.00247	0.00039
500	0.00971	0.00322	0.00281	0.00047
505	0.01053	0.00354	0.00314	0.00056
510	0.01125	0.00381	0.00345	0.00062
515	0.01184	0.00399	0.00372	0.00064
520	0.01223	0.00415	0.00395	0.00070
525	0.01247	0.00429	0.00412	0.00076
530	0.01277	0.00446	0.00431	0.00081
535	0.01308	0.00466	0.00453	0.00088
540	0.01307	0.00474	0.00466	0.00093
545	0.01288	0.00472	0.00473	0.00095
550	0.01286	0.00477	0.00489	0.00100
555	0.01292	0.00490	0.00512	0.00107
560	0.01289	0.00498	0.00532	0.00115
565	0.01274	0.00502	0.00550	0.00121
570	0.01246	0.00503	0.00564	0.00128
575	0.01222	0.00508	0.00580	0.00135
580	0.01200	0.00510	0.00598	0.00140
585	0.01184	0.00515	0.00618	0.00149
590	0.01169	0.00521	0.00638	0.00158
595	0.01153	0.00524	0.00656	0.00164
600	0.01137	0.00526	0.00676	0.00169
605	0.01128	0.00531	0.00701	0.00175
610	0.01128	0.00537	0.00728	0.00182
615	0.01134	0.00544	0.00756	0.00188
620	0.01117	0.00538	0.00761	0.00188
625	0.01041	0.00507	0.00724	0.00180
630	0.00914	0.00459	0.00652	0.00167

Wavelength (nm)	Spectral Irradiance (W/m²)			
	Cond. 1	Cond. 3	Cond. 6	Cond. 9
635	0.00789	0.00408	0.00579	0.00154
640	0.00688	0.00369	0.00523	0.00143
645	0.00608	0.00332	0.00472	0.00131
650	0.00542	0.00299	0.00430	0.00118
655	0.00479	0.00273	0.00393	0.00110
660	0.00425	0.00245	0.00357	0.00102
665	0.00375	0.00220	0.00322	0.00090
670	0.00328	0.00195	0.00288	0.00079
675	0.00289	0.00171	0.00258	0.00073
680	0.00257	0.00156	0.00232	0.00068
685	0.00224	0.00141	0.00208	0.00059
690	0.00190	0.00119	0.00178	0.00050
695	0.00160	0.00101	0.00154	0.00044
700	0.00139	0.00091	0.00137	0.00041
705	0.00121	0.00079	0.00119	0.00038
710	0.00103	0.00066	0.00103	0.00026
715	0.00084	0.00057	0.00087	0.00023
720	0.00072	0.00048	0.00073	0.00026
725	0.00063	0.00041	0.00065	0.00014
730	0.00045	0.00033	0.00057	0.00021
735	0.00046	0.00034	0.00046	0.00013
740	0.00033	0.00022	0.00041	0.00015
745	0.00023	0.00024	0.00030	0.00010
750	0.00029	0.00019	0.00030	0.00008
755	0.00019	0.00010	0.00025	0.00009
760	0.00009	0.00015	0.00021	0.00006
765	0.00015	0.00009	0.00018	0.00004
770	0.00011	0.00009	0.00018	0.00006
775	0.00014	0.00014	0.00019	0.00006
780	0.00008	0.00008	0.00014	0.00004

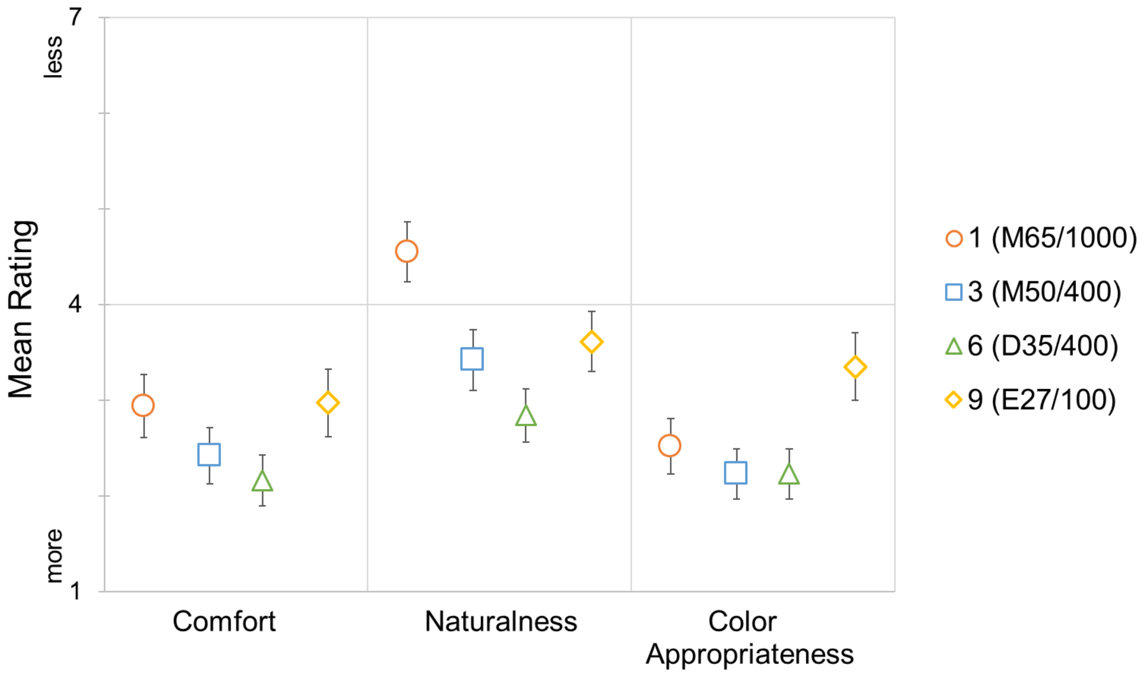

Figure 4. Comparison of participant ratings of comfort, naturalness, and color appropriateness for conditions with differing levels of circadian stimulus through variations in the CCT and illuminance. The shapes show the mean rating, with the error bars showing + standard error.

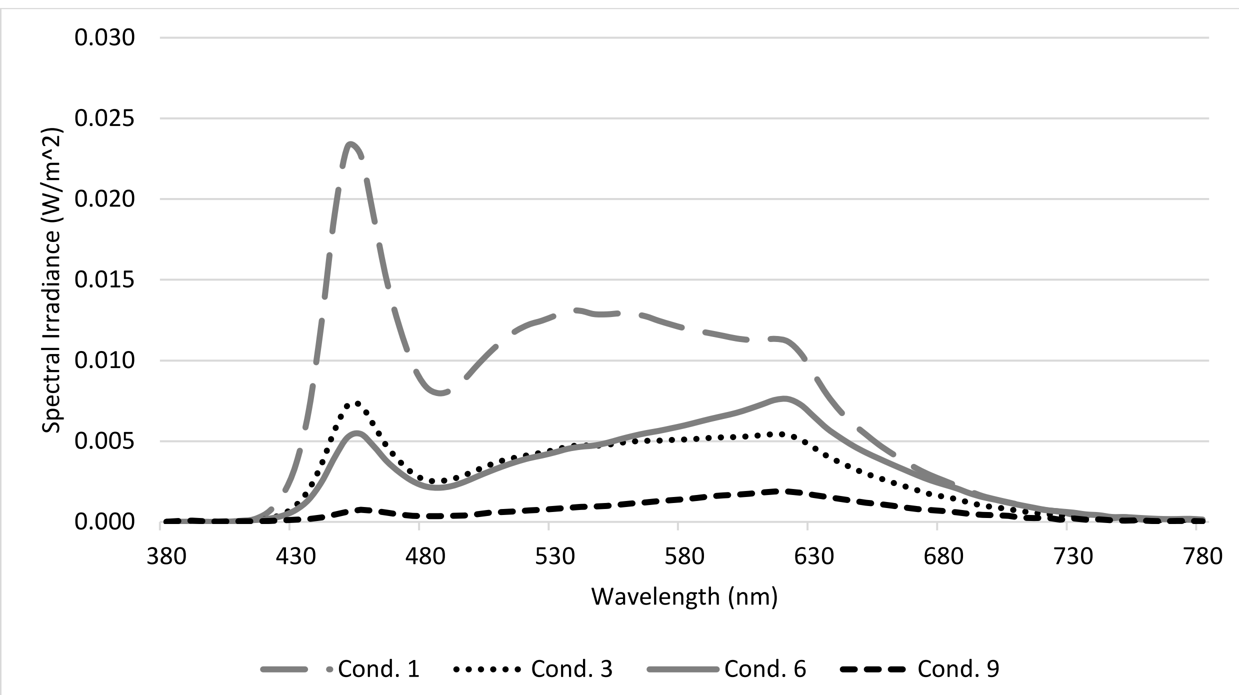

Figure 5. Plot of the spectral power distribution measured at the patient eye position when laying slightly upright in bed for lighting conditions 1, 3, 6, and 9.

A second aspect of this analysis was to evaluate the acceptability of high CCT conditions at different illuminances; conditions 1 (M65/1000) and 3 (M50/400) were compared. A Wilcoxon Signed-Ranks test indicated that condition 1 was rated as significantly less natural than condition 3 ($Z = -2.804$, $p = 0.005$), though no significant differences were found in ratings of difficulty, comfort, or color appropriateness.

Hypothesis 2: Lighting Distributions for Different Environments of Care. Several conditions were established to compare patient room lighting with characteristics typical of TEC, CEC, and FEC lighting systems. For daytime comparisons, TEC lighting condition 4 (D35/400 bed only), CEC lighting condition 5 (D35/400 without wall lighting), and FEC lighting condition 6 (D35/400 with wall lighting) were evaluated; Figure 6 shows the results. Following a Friedman test reporting significant differences in color appropriateness, a Wilcoxon Signed-Ranks test indicated that significant differences existed for CEC lighting condition 5 and FEC lighting condition 6; both were rated as more appropriate in lighting color than TEC lighting condition 4 ($Z = -2.796$, $p = 0.005$ and $Z = -2.327$, $p = 0.02$ respectively). Conditions 5 and 6 were not rated as significantly different in color appropriateness ($Z = -0.444$, $p = 0.657$). No significant differences were found in comfort ($p = 0.077$) or naturalness ($p = 0.812$) among the three conditions.

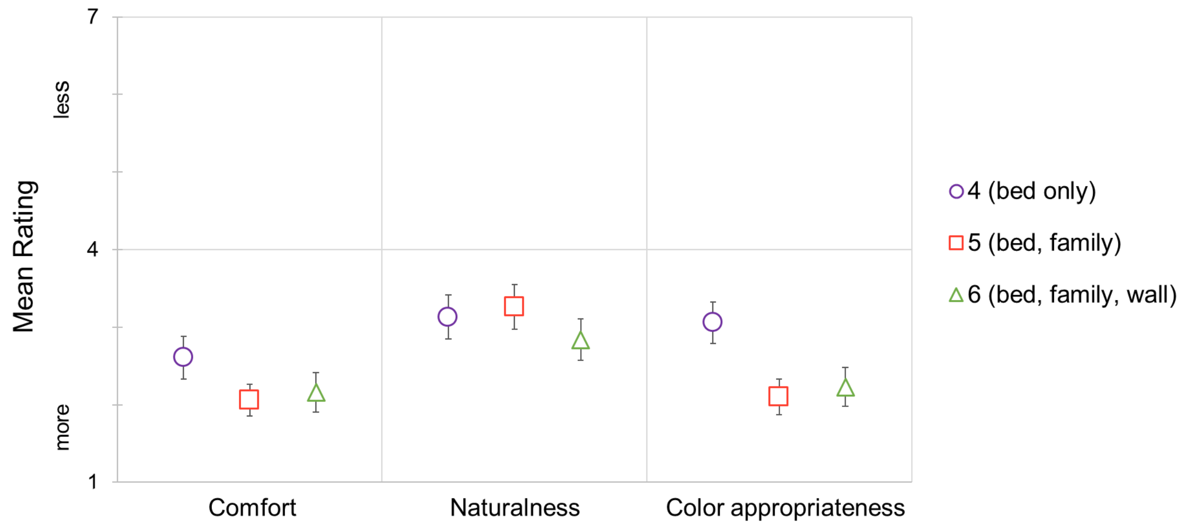

Figure 6. Comparison of participant ratings of comfort, naturalness, and color appropriateness for conditions representing the three daytime lighting conditions differentiated by the environment of care, with similar CCTs and illuminances. The shapes show the mean rating, with the error bars showing ± standard error. Condition 4 represented a TEC with just two luminaires on over the bed, condition 5 a CEC with four luminaires on over the bed and the family area luminaires on, and condition 6 a FEC similar to condition 5 with wall lighting added.

For nighttime comparisons, FEC lighting condition 11 (N35/400 wall only), FEC lighting condition 12 (N27/5 bed dim), and TEC lighting condition 13 (night light only) were evaluated; see Figure 7. A Friedman test reported significant differences in difficulty ($p = 0.0001$) within the group. A Wilcoxon Signed-Ranks test indicated that conditions 11 and 12 were rated as significantly less difficult than condition 13 ($Z = -4.916$ and -4.574, $p < 0.0001$ for both), and that condition 11 was significantly less difficult than Condition 12 ($Z = -4.532$, $p < 0.0001$).

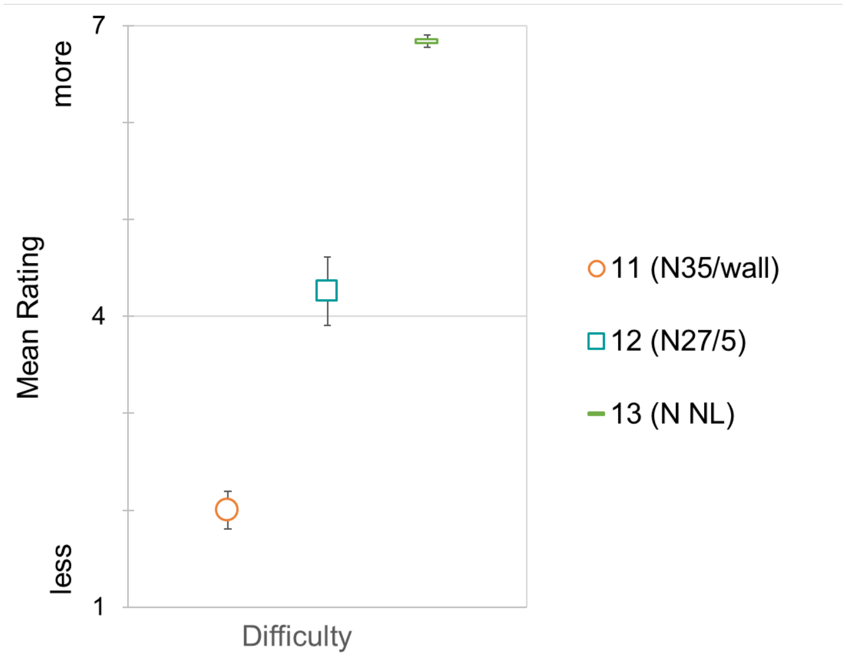

Figure 7. Comparison of participant ratings of task difficulty for conditions representing the three nighttime lighting conditions differentiated by the environment of care. The shapes show the mean rating, with the error bars showing + standard error. Condition 11 represented an FEC with dim wall lighting, condition 12 a CEC with dimmed overhead lighting above the bed, and condition 13 a TEC with no room lighting except the night lights.

Hypothesis 3: The Use of Colored Wall Lighting. One variable of interest between conditions was the presence of distinctive colored light, instead of white light, within the room. Two pairs of conditions provide insight into this research question, with the sole difference between each being the presence of blue or red light instead of white light on the north wall of the room. A Wilcoxon Signed-Ranks test was used to test for meaningful differences between the paired conditions, condition 7 (D35-50/400 with white lighting on the wall) compared to condition 8 (D35-50/400 with blue lighting on the wall), and condition 9 (E27/100 with white lighting on the wall) compared to condition 10 (E27/100 with red lighting on the wall).

Participants rated the presence of blue colored light on the wall (condition 8) as significantly less comfortable, less natural, and less color appropriate than the corresponding condition (7) with white light on the wall ($p < 0.0001$ in all cases). While the evening condition with white lighting on the wall (9) was rated as significantly more natural ($Z = -3.409$, $p = 0.001$) than the corresponding condition with red lighting on the wall (10), these two conditions were not rated as significantly different in comfort ($Z = -2.036$, $p = 0.042$) or color appropriateness ($Z = -2.173$, $p = 0.03$), with a Bonferroni correction reducing the criterion p-value for the three tests.

Hypothesis 4: The Use of Different Luminaire CCTs. Comparing two conditions with the same CCT (3500K) for the patient bed and wall wash luminaires, but where one of the conditions had a different CCT (5000K) over the family zone (condition 6 vs. condition 7) allowed for testing participants' reactions to having varying CCTs concurrently in different areas of the mock patient room. Table 4 shows that the mean ratings between these two conditions were very similar, and a Wilcoxon Signed-Ranks test indicated that there was not a significant difference between rated comfort ($Z = -1.596$, $p = 0.11$), naturalness ($Z = -0.965$, $p = 0.334$), or color appropriateness ($Z = -1.809$, $p = 0.071$).

Discussion: Patient Room Lighting for FEC Facilities

The purpose of this project was to examine how aspects of lighting in patient rooms were experienced and evaluated by participants completing simulated clinical nursing tasks in a mock patient room. Advanced LED lighting systems provide new opportunities to support the type of adaptable environments that are likely to typify FEC hospitals. This experiment provides insight into several features of tunable LED lighting for FEC hospitals, as discussed below.

Lighting to Support Circadian Synchronization

As mentioned previously, hospitals with TEC and CEC lighting do not have the opportunity to vary the spectrum of light and have little to no opportunity to vary the intensity of light (other than on / off control); these variations are now understood to be important for supporting healthy circadian synchronization of patients. Table 5 shows the wide range of circadian metric values achieved with the tunable LED lighting system in this experiment, documenting that both of the morning conditions (1, M65/1000 and 3, M50/400) had high MI values and exceeded the recommended minimum of 0.3 CS for mornings, while the evening condition (9, E27/100) had very low MI and was consistent with the recommended maximum of 0.1 CS for evenings (Figueiro and others, 2016a). These metrics were calculated based on measurements of the spectrum and intensity of light at the patient's eye position while seated in bed since they spend all of their time in the room and are more susceptible to circadian disruption than the nurses who have more freedom of movement.

This experiment addressed the question of how nurses' perceptions of lighting might be affected by these different lighting conditions which they may not have previously experienced. Nurse ratings for the four conditions (Figure 4) revealed that condition 6 (D35/400) was rated as the most comfortable and most natural of the four; this condition typifies common conditions with TEC and CEC systems. Condition 1 (M65/1000) provided the highest values of the circadian metrics for patients but was rated as less comfortable and natural than conditions 3 (M50/400) or 6 (D35/400); the difference in naturalness was significant. Condition 3 also provided high values of the circadian metrics and was rated more favorably than condition 1.

In terms of perceived intensity, condition 1 (M65/1000) had the highest mean intensity rating of the 13 conditions. The high-CCT, high-intensity conditions in the room elicited open-ended comments such as, "It was uncomfortable, I almost had to squint," and "Unrealistic, way too bright, it hurt my eyes. It lit the room up but was way too bright." Even so, it was interesting to note that the mean rating for intensity of this condition was only 5 on the 7-point scale, with only 2 people selecting 7 for "extremely too bright" and 3 people actually rating it at 3 or "slightly too dim." This finding likely demonstrates that some participants are more sensitive to the high levels of intensity and CCT than others, that there may be more tolerance for this level of lighting than commonly presumed, and support for the idea raised by Kakitsuba (2020) that the spectral composition of LED lights may change the range of comfort.

Condition 9 (E27/100), which provided the low levels of the circadian metrics desired in the evening, was rated as significantly less color appropriate than conditions 1, 3, and 6, even though its color properties were within the range of typical interior lighting. This finding may indicate that the low intensity of light with condition 9 contributed to the color appropriateness rating; the Hunt effect (Hunt 1952) shows that colors are perceived as less saturated under low intensity levels, which may explain the color appropriateness ratings.

The Challenges of Lighting Patient Rooms at Night

Nighttime in a hospital patient room provides a difficult situation for nurses, who often need to perform visual tasks in the room while understanding the importance of sleep to the patient's healing process. Many TEC and some CEC patient room lighting systems force the nurse to choose between turning on bright, overhead lighting or attempting to perform their tasks without this lighting. In some cases, nurses rely on bringing their own supplemental lighting device (such as a flashlight or smartphone) to avoid disrupting the patient's sleep (McCunn et al. 2020*).*

This experiment demonstrated the potential benefits of FEC lighting systems for the nighttime conditions. Condition 13 (N NL) represented a TEC patient room with night lighting, and the nurse participants were not permitted to use any supplemental lighting. Conditions 11 (N35/wall) and 12 (N27/5) represented possible FEC lighting scenarios, one with lighting on the wall remote from the head of the bed, and one which provided dim overhead lighting from a low CCT source. Nurses rated their perceived difficulty in performing the tasks as significantly more difficult for condition 13 than for either condition 11 or 12, and rated condition 13 as less comfortable than conditions 11 or 12. Condition 11, which provided 28 lux on the bed from the wall lighting, was rated as less difficult and more comfortable than condition 12, which provided 5 lux on the bed from the overhead luminaires.

The Importance of the Distribution of Light and the Use of Lighting Zones

TEC lighting systems typically use few luminaires and have limited (if any) options for differentially illuminating portions of the patient room. For example, a common TEC approach used a single recessed multi-functional luminaire over the patient's bed. Condition 4 (D35/400) represented this TEC condition, with only a 0.6 m by 1.2 m (2 ft x 4 ft) luminaire area used over the bed. CEC systems often use more luminaires to illuminate different zones of the patient room, such as condition 5 which illuminated the family area separately from the bed. Condition 6 (D35/400) represented a FEC lighting solution, by adding separate wall lighting.

As shown in Figure 6, condition 4 was rated as significantly less color appropriate than conditions 5 or 6; it also had a mean rating for comfort indicating a perception that it was less comfortable. Table 4 further shows that the mean rating of perceived intensity was lower for condition 4 than for condition 5 or 6; in fact, of the conditions with a target bed illuminance of 400 lux (conditions 2–8), condition 4 was the only one with a mean perceived intensity level of less than 4. These findings of more favorable perceptions are consistent with some of the expected benefits of lighting systems with multiple zones and broader distribution of light. The differences in ratings were relatively small between conditions 4, 5, and 6, perhaps in part because the rest of the room environment did not necessarily match the expectation of a TEC patient room. This idea is discussed further in the limitations section below.

Another aspect of a lighting system that provides differential control over multiple zones of luminaires is the opportunity to have the color quality of the lighting in different zones vary at any time. For example, a family area that is near a window could have luminaire CCTs that are higher than the rest of the room, better matching the incoming daylight in that area. Or a guest in the family area might desire a lower CCT than the patient during certain times. With TEC and CEC lighting systems, these variations were both difficult to achieve technologically and viewed as undesirable by many design and facility staff, since CCT differences within a room usually indicated a maintenance issue with TEC lighting products.

This experiment examined participant response to luminaires with different CCTs in different areas of the patient room, finding a lack of significant difference between conditions 6 (with 3500K luminaires in all areas) and 7 (with 3500K luminaires over the bed and on the wall and 5000K luminaires in the family area). **This may provide evidence that visible differences in CCT between luminaires in different zones**

of the same room are acceptable. Further study in this area is needed, as this experiment only looked at increasing the CCT of family area luminaires adjacent to the windows.

Tunable LED systems with multiple zones of luminaires also provide the opportunity to introduce colored light into the patient room. In this experiment, the perceptions of nurses to the presence of static colored light on one wall in the room were assessed. Overall, the conditions with colored wall lighting were viewed by the nurses as being less natural: the only conditions with naturalness mean ratings of 5 or greater (with 7 being "extremely unnatural") were the two with colored wall lighting. The two conditions with colored wall lighting also had mean appropriateness ratings greater than 4 (i.e., tending towards "inappropriate lighting color"); the only other conditions with a mean appropriateness rating of greater than 4 were two of the night conditions with very dim lighting. For the participants in this experiment, who were focused solely on performing typical nursing tasks, the presence of colored wall lighting was viewed negatively. The possible benefits of dynamic colored lighting for patient control and patient distraction (see Ulrich, 1999) was not addressed in this experiment but needs to be explored through other studies as explained below.

Limitations and Further Research

This study evaluated a series of lighting conditions that represented settings that may be found in patient rooms from TEC, CEC and FEC hospital facilities. While the experimental setup enabled the collection of participants' perceptions of 13 different conditions, the study was not designed to allow participants to experience dynamic changes in the lighting, to experience the lighting for more than a five-minute period, or to personally control the tunable lighting. Results are therefore limited to perceptions of the environment based on short-term exposure to specific settings of a tunable lighting system. **Further explorations of the perceived advantages of dynamic changes to lighting are needed, especially studies that deliberately explore the possible benefits of personal control of lighting and the positive distraction possibilities with dynamic lighting.** Considerations of dynamic changes to lighting in patient rooms in future studies can also address important questions related to windows and daylighting and their integration and interaction with the electric lighting systems used. These questions are better explored over longer time periods in a hospital setting, rather than through short-duration laboratory experiments such as this study.

While some of the lighting conditions studied were designed to simulate patterns of light typically found in TEC and CEC facilities, the lighting equipment itself was all new and the room furnishings and décor were modern. The practicality of conducting the study in a single room meant that other elements of the physical environment were not consistent with those of a TEC facility, and these elements may influence the overall subjective response as much as or more than lighting. This fact may explain the overall positive nature of the ratings for all conditions, especially given the more negative reactions to lighting systems in TEC facilities reported in several surveys of nurses working directly in these facilities (McCunn et al. 2020; Hadi et al. 2016). Additional research that compares nurse and patient responses to different environment of care settings in real hospitals would better document the responses from the full range of existing environments.

Participants in this study performed tasks designed to simulate realistic nursing tasks and rated the environments based on their experience performing those tasks in the patient room. Data analysis from a second experiment exploring the perceptions from the patients' viewpoint to these lighting conditions is underway, to provide a broader view of responses from different sets of users. Participants were not given any information about how lighting variations might affect responses such as circadian synchronization, positive distraction, and other potential benefits to patients and families.

Some of the results from the color appropriateness item did not seem to relate directly to the color properties of the lighting condition. As discussed above, this may be the result of differences in the distribution of light or the intensity of light producing differences in ratings of color appropriateness, similar to the findings by Yu et al (2019) that the brightness ratings for light were varied by CCT even when the illuminance was held constant. However, it is also possible that participants used this rating scale to report an overall perception of appropriateness of lighting, not just color appropriateness.

The findings of this experiment demonstrate that the ratings of perceived comfort, naturalness, difficulty of performing tasks, and color appropriateness were sufficiently distinct to serve as meaningful evaluation parameters for patient room lighting. It is not clear, though, how participants value these parameters and which might have the most influence on their overall preferences. For nurses, the difficulty of performing tasks under given lighting conditions should be given priority in hospital settings, and in this experiment, most conditions were rated favorably in this regard; the only conditions where difficulty was markedly higher than the others were in the two dimmest nighttime settings. Relationships between these individual constructs and overall environmental preference should be explored in future research.

Conclusion

Recent research highlights an emerging evidence base about the holistic effects of light on human physiology. At the same time, newly available tunable LED lighting systems not only provide the opportunity for significant energy savings in hospitals, but they also can make it easier to support circadian synchronization, achieve positive perceptions, address nighttime navigation needs, enable more user-friendly control, and better satisfy these holistic needs of patients, guests, and staff in healthcare applications. This study explored nurses' perceptions of patient room lighting conditions representing a variety of aspects of lighting in traditional, contemporary, and future patient rooms. Key findings include the following concepts: the condition providing the highest values of circadian lighting metrics received significantly lower scores in naturalness; performing tasks with nighttime lighting conditions was significantly less difficult with low levels of wall lighting or overhead lighting than with only nighttime navigation lighting; lighting systems with multiple zones of luminaires and broader distribution of light were rated more favorably than a single luminaire over the bed; having visibly different CCTs in luminaires in different zones of the patient room did not affect perceptions, and the introduction of colored lighting on the wall resulted in less favorable ratings than white lighting.

Results of this study provide insight into potential benefits and concerns of these new features for patient room lighting systems and reveal gaps in the existing evidence base that can inform future investigations.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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