Lighting the Patient Room of the Future: Evaluating Different Lighting Conditions from the Patient Perspective

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Abstract

Objective: This study explores whether “future” lighting systems that provide greater control and opportunity for circadian synchronization are acceptable to participants in the role of patients.

Background: Tunable, dimmable light emitting diode lighting systems provide multiple potential benefits for healthcare. They can provide significant energy savings, support circadian synchronization by varying the spectrum and intensity of light over the course of the day, address nighttime navigation needs, and provide user-friendly control. These trends have converged with an emerging understanding of the important effects of light; however, important questions remain about the experience and acceptability of the this “future” lighting if we are to adopt it broadly.

Methods: Volunteer participants (34) performed a series of tasks typical of patients, such as reading or watching a video, in a full-scale simulated inpatient room. Each participant conducted these tasks under 12 lighting conditions in a counterbalanced order that included varying illuminance levels, CCTs, and in a few conditions, saturated colors. The participants rated each lighting condition on comfort, intensity, appropriateness, and naturalness.

Results and Conclusions: The participants found that conditions with CCTs of 5000 K and higher were less comfortable and less natural than conditions with lower CCTs. Conditions with lighting distributed in multiple zones in the patient room were viewed more favorably than a traditional over-bed configuration. The participants in this simulated patient study reacted negatively to colored lighting on the footwall of the room but found a mixture of warmer and cooler luminaire CCTs acceptable.

Background

Tunable light emitting diode (LED) systems allow for control over the intensity of light and spectrum (color), providing multiple potential benefits for healthcare and other settings. These flexible systems can provide significant energy savings, support circadian synchronization by varying the spectrum and intensity of light over the course of the day, address nighttime navigation needs, and provide user-friendly control (Davis et al., 2016). The growth of LED systems has converged with an emerging understanding of the important effects of light on human visual and other biological responses (International Commission on Illumination, 2018; Berson et al., 2002; Brainard et al., 2001; Hattar et al., 2002; Lucas et al., 2014; Thapan et al., 2001).

The current understanding of using architectural lighting systems to support circadian synchronization indicates that bright, cool lighting during the day supports the suppression of melatonin, while dim, warm lighting in the evening can help minimize melatonin suppression before bedtime (Houser et al., 2021; Vetter et al., 2021). Specific recommendations that establish quantifiable definitions of appropriate intensities and spectral qualities have not been adopted by standards-setting organizations at the time of this paper, but the general guidelines are supported by prior publications (Lucas et al., 2014; International Commission on Illumination, 2018).

This new lighting potentially affects image-forming and non-image forming pathways that include visual performance, visual experience, visual comfort, circadian effects and acute effects of human functioning (de Kort, 2019). However, despite the potentially positive effects, it is unclear how everyday users of this "new" lighting experience the changes that are now possible, such as changes in color tones—and especially blue toned, but also other colors—and in variability within the room in the color and intensity of lighting.

These perceptions are important aspects of the visual experience and visual comfort of people in many settings that rely on electric lighting. Despite the likely positive benefits, it is important to understand the experience of new lighting to support adoption or improvement. Hospital rooms are of particular importance because of the importance of medical tasks and experience of patients, visitors and staff and because of the opportunity to introduce "new" lighting in both existing and new healthcare settings.

In this paper we address four specific hypotheses about this new lighting using a repeated measures experimental design: 1. Participant perceptions will change for different patient room lighting conditions that deliver varying levels of circadian stimulation; 2. Participant perceptions will vary based on differences in distribution of lighting in the room; 3. Participant perceptions will vary when colored light is introduced into the room; and 4. Participant perceptions will vary when there is a visible difference in luminaire CCTs.

Little research has explored user experience of tunable, dimmable LED lighting systems of these varied lighting designs (Perumal et al., 2021). Aires et al. applied tunable lighting in a controlled laboratory and a quasi-controlled field environment, finding inconsistent and inconclusive results between the two environments, with the authors suggesting testing lighting patterns in the field before implementing in a real environment (Aries et al., 2020). The acceptability of lighting technologies is contingent on user assessments of the light quality within specific environmental applications (*Assessment of solid-state lighting*, 2017). In an earlier paper (Graves et al., 2021) we reported the results of an experiment that explored how aspects of lighting in patient rooms were experienced and evaluated by nurses while performing simulated work in a mock-up patient room with tunable LED lighting. In this paper we explore the *patients'* perspective to see how those same conditions affect patient experiences.

Project overview

The experiment described in this paper is the second experiment in a research program aimed at exploring how various aspects of patient room lighting systems are experienced and evaluated by patients, visitors, and staff in inpatient hospital settings. While the first experiment studied nurses (Graves et al., 2021), this second experiment focused on understanding how people serving in the role of patients perceive lighting conditions in a patient room space, with specific interest in understanding patients' perceptions of bright cool-tone lighting that may help synchronize patient circadian rhythms, patients' perceptions of the various environments of care simulated with the lighting, and their perceptions of colored lighting introduced into the room.

To investigate these topics, a full-scale mock-up patient room was constructed at Georgia Tech in the SimTigrate Design Lab with a flexible LED lighting system that allowed tuning of white light, full dimming and introduction of a wide range of colored light. Participants in the study sat reclined in the patient bed and participated in a variety of activities similar to the types of activities typically available to patients in hospital patient rooms; these activities or tasks were completed under 12 lighting conditions. The various lighting conditions studied represented design strategies consistent with different environments of care that use the improved abilities to tune, dim and control lighting to support the experience and conduct of care: traditional, contemporary, and future (Davis et al., 2021). These design strategies relate to the sources used, intensity and spectrum control, and arrangements of luminaires into zones but are generally not specifically embodied in recommendations from organizations such as the Facilities Guidelines Institute and the Illuminating Engineering Society. In general, "traditional" was represented by static lighting designs with a single CCT and no dimming abilities; "contemporary" design having more flexibility with lighting zones and including dimming and "future" as including a wider range of flexibility with coloring tunability and control. After experiencing each condition, perceptions of each of the lighting conditions were documented by participants using a set of ratings scales.

Hypotheses

This experiment evaluated participants' impressions of lighting conditions from the perspective of a patient reclined in a hospital bed. The hypotheses and lighting conditions involved were:

1. Participant 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). Earlier work has suggested that bluer-toned lighting would be less positively viewed.
2. Participant perceptions will vary based on differences in distribution of lighting in the room, at different times of day, such as would occur with different environments of care. This was evaluated using daytime conditions 4 (D35/400 bed only) which represented a traditional lighting system, 5 (D35/400 bed and family) which represented a contemporary lighting system, and 6 (D35/400 bed, family, and wall) which represented a future lighting system. It is possible to distribute lighting with different areas of intensity and color-tone with "contemporary" and "future" lighting systems; an understanding of the experience these will allow lighting systems that provide better and more varied experience within a patient room.
3. Participant 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). The test room provided the opportunity to introduce saturated colors as well as tunable white. Understanding how users respond to these colors will help support a much wider range of lighting design choices.

4. Participant 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 5000 K in the family area). The goal of hospital room lighting has often been consistent color-tones throughout; but tunable white lights allow variations in color-tones within the room to increase interest or match outdoor lighting near windows.

Methods

Room layout

The experimental setup, shown in Figure 1, included a hospital patient room mock-up, located within a larger laboratory and office space, identical to the set up used in Graves et al. (2021). The room mock-up was approximately 4.37 m by 4.14 m (14.3 ft by 13.6 ft) with a ceiling height of 2.74 m (9 ft). A small entryway (2.16 m by 1.8 m (7 ft by 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 (6 ft by 4 ft) east-facing windows in the room were covered with blinds and blackout curtains to minimize light entry from outside to allow for better control of the experimental conditions.

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 (8 ft by 3.34 ft) hospital bed with one 56 cm by 56 cm by 91 cm (2 ft by 2 ft by 3 ft) tall table on the west side. The family area consisted of two 71 cm by 71 cm (2.33 ft by 2.33 ft) chairs as well as a 61 cm by 61 cm (2 ft by 2 ft) table that sat 43 cm (1.4 ft) tall (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.
The room shows 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 participants were instructed to sit or lay on the bed during the experiment. The wall-mounted monitor displayed a nature video that participants could watch as one of their optional activities.

Lighting equipment and layout

The lighting in the bed and family areas was provided by six recessed 61 cm by 61 cm (2 ft by 2 ft) LED luminaires from the Ledalite ArcForm family; the 3600-lumen option was provided (model number 3622-L-36) with 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 (4 ft by 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° and greater that satisfy discomfort glare criteria for common architectural spaces such as offices (Illuminating Engineering Society, 2020).

Lighting onto the footwall 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 21 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. A diagram of the location of the lighting fixtures is provided in Figure 2.

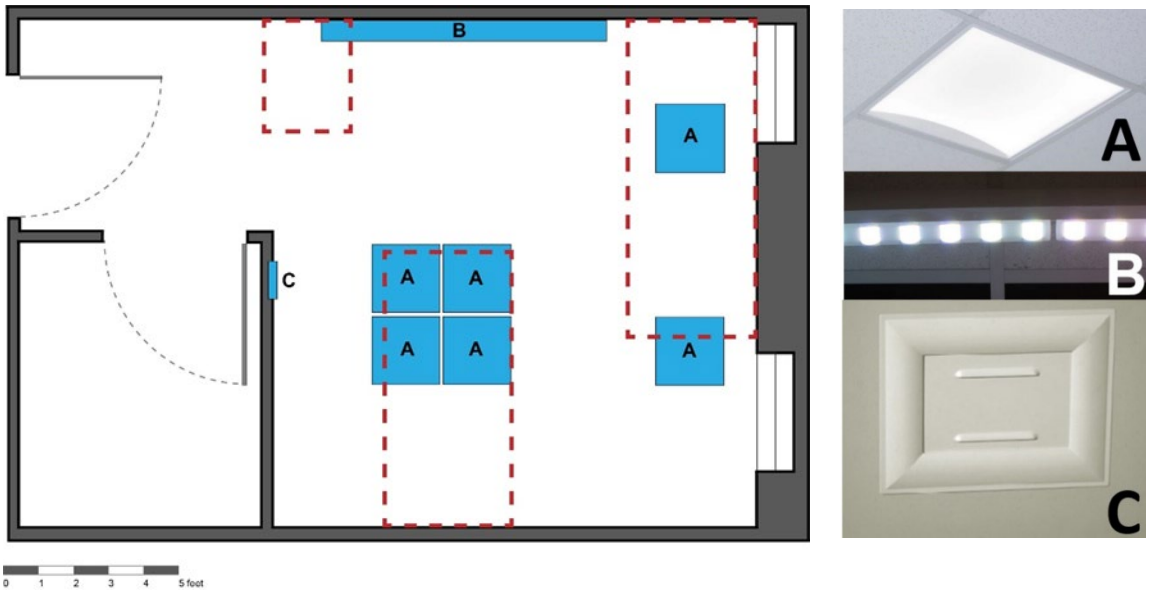

Figure 2. Reflected ceiling plan detailing the layout of luminaires.
The reflected ceiling plan (left) consists of four Ledalite tunable white ArcForm 2x2 luminaires over the bed and two in the family area (luminaire A), 8 ft of the Philips Color Kinetics PureStyle Intelligent Color Powercore RGBA linear 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 nurse work area in the footwall.

Activities

Participants were instructed to engage in any of four activities during each trial of their experimental session, while sitting or reclining on the bed—20 degrees from horizontal for Nighttime, and 60 degrees for Morning, Day, and Evening. The activities represented typical experiences a patient might have during an inpatient stay. To facilitate their engagement and comfort throughout the experimental session, participants were free to switch activities at any time. The activities were consistent across Morning, Day, and Evening conditions; however only rest was permitted as an activity for the Night condition:

1. read a printed article,
2. read an article on a digital notebook (iPad – simulating reading from a backlit screen),

3. watch a video of nature scenes on a tv, with sound muted and without any advertisements (simulating watching a backlit screen from afar), and
4. rest.

A printed list of these activities was placed on a bedside table and was available to the participant for reference at any time during the experiment. The printed article was entitled “How 'Eureka' Moments in Science Happen: From bathtubs to falling apples, find out what really drives some of the iconic tales of “light bulb” moments in science,” by Cathy Newman, and the digital notebook article was, “A Salute to the Wheel,” by Megan Gambino; both were chosen because they were brief (two pages), easy to read, and lacked polarizing themes. The nature scenes were of a tropical rainforest and were played from the beginning for each participant for the duration of the experiment.

Lighting conditions and measurements

Twelve lighting conditions were selected with a range of horizontal illuminances (5 to 1000 lux), CCTs (2700 to 6500 K), and lighting distribution patterns (Table 1). The 12 conditions were exactly the same as those tested by participants conducting nursing tasks in a previously published study (Graves et al., 2021). The nomenclature used to describe the conditions throughout this paper are defined in Table 1. Nine of these 12 conditions were developed to reflect multiple future morning, daytime, and nighttime lighting conditions with varying illuminance levels, CCT, and in a few cases, saturated lighting colors. Three traditional and contemporary comparison lighting conditions were also created. Both the daytime traditional and daytime contemporary lighting conditions had moderate illuminance (400 lux) and neutral CCT (3500 K) which are consistent with design practice for existing patient rooms (Illuminating Engineering Society, 2020). They differed in that the traditional condition (condition 4) only had two of the four overbed luminaires on to simulate conditions found in some older hospitals, whereas in the contemporary condition all four of the overbed luminaires were on plus the two luminaires in the family zone were illuminated. Conditions are defined by the target values; Table 2 shows the target and actual measured values for each condition.

LTG. COND.	DESIGNATION	DESCRIPTION	ENVIRON. OF CARE TYPE	TARGET ILLUMINANCE (lx)			TARGET CCT (K)		
				BED	FAM	WALL	BED	FAM	WALL
1	M65/1000	Morning, 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

LTG. COND.	DESIGNATION	DESCRIPTION	ENVIRON. OF CARE TYPE	TARGET ILLUMINANCE (lx)			TARGET CCT (K)		
				BED	FAM	WALL	BED	FAM	WALL
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

Table 1. Lighting condition designations and descriptions.
The designation scheme first indicates the time of day that was verbally provided to the participant for context (morning, day, evening, night), then the first two digits of the CCT / the target illuminance on the bed, with a B or R added when the wall light was blue or red, respectively. Variations in the lighting zones for conditions with similar designations are shown in the description and explained in the text.

		ACTUAL ILLUMINANCE (lx)			ACTUAL CCT (K)		
LTG. COND.	DESIGNATION	BED	FAM.	WALL	BED	FAM.	WALL
PRACTICE	NA	401	417	151	3095	3112	3062
1	M65/1000	1110	999	867	6340	6325	6448
2	M50/400	472	130	281	5022	4744	4755
3	M50/400	413	398	284	4669	4477	4657
4[a]	D35/400	413	155	116	3506	3475	3459
5	D35/400	433	434	159	3452	3454	3386
6	D35/400	462	478	357	3424	3413	3294
7	D35,50/400	450	446	361	3652	4342	3429
8	D35-50/400B	448	466	415	4058	6364	Blue
9	E27/100	97	57	56	2737	2732	2680
10	E27/100R	99	59	68	2622	2469	1984
11	N35/wall	28	43	211	3099	3171	3262
12	N27/5	5	5	4	3030[b]	3171[c]	Red

Table 2. Lighting conditions as applied.
Designations are explained in Table 1. Illuminance and spectrum measurements were taken 1m above the floor at 4-6 distributed points across each lighting zone.

[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 future 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. Although no standards have been established for MI levels, higher values indicate increased stimulation of the intrinsically photosensitive retinal ganglion cells (ipRGCs), which in turn may increase suppression of melatonin (Houser et al., 2021). Higher CS values also indicate higher expected levels of melatonin suppression, with a value of at least 0.3 recommended by Figueiro et al. (2016) during the early part of the day. The relative spectral power distributions (SPDs) are shown graphically in Figure 3.

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.

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 illuminance measures were also taken in the center of the pillow area, 0.76 m (2.5 ft) from the headwall and 0.85 m (2.8 ft) above the floor. Vertical illuminance and spectrum measurements were taken at a height of 1.3 m (4.3 ft) above the floor, with a Sekonic C-7000 meter positioned to measure the light reaching a patient's 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; see Table 4.

Participants

Thirty-four college students and community volunteers participated in the experiment. Participants included 17 males and 17 females, ranging between 18 to 71 years of age (mean age of 24). Students were recruited with flyers posted in various locations around campus as well as at an on-campus symposium, with online sign-up information for students and community volunteers. The use of contact lenses or eyeglasses did not prevent participation but was noted for all participants. One female and two male participants were excluded from analysis due to lighting software malfunctions during the experiment session and their data are not reported in this paper. Consequently, data from 31 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) showed that samples of 25-35 subjects provide sufficient statistical power to detect most large and medium effects in within-subjects experimental research, and in the prior experiment conducted by this team significant differences in perceptions of the participants were successfully revealed with 33 subjects (Graves et al., 2021).

Participant ratings

For each lighting condition, participants completed a paper response form consisting of four questions, each of which used a seven-point rating scale. Participants were asked to circle their chosen rating for each of the four questions. Each question focused on a different aspect of the lighting experienced by the participant *during the task*: comfort of the lighting, from extremely comfortable (1) to extremely uncomfortable (7); intensity of the lighting, from extremely too dim (1) to extremely too bright (7); appropriateness of the lighting color, from extremely appropriate (1) to extremely inappropriate (7); and, naturalness of the lighting, from extremely natural (1) to extremely unnatural (7).

At the conclusion of the experiment, the participants completed a verbal questionnaire with open-ended questions, in order to better understand their experience completing the activities under the various lighting conditions.

Pre-experiment preparation

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 Institute of Technology IRB*.) A participant was then directed into the experimental room, where the researcher explained the activities available in the room. The lighting had nominal settings of 400 lux, 3000 K in the bed and family areas during this introduction, as well as during the unannounced practice trial that preceded the 12 lighting conditions.

Experimental trials

For each trial, an individual participant entered the experimental room and was given the option of engaging in four activities for a total of one minute and 45 seconds. Participants then completed the paper rating response form while in the room. Upon completion the participant returned the form to the researcher and left the room, entering a designated waiting area where the illuminance varied between 143 and 529 lux with variations in daylight; these illuminances were within the range of illuminances experienced during the morning and daytime lighting conditions in the patient room. After the researcher changed the lighting condition and re-supplied the rating forms, participants were instructed to re-enter the room and repeat the process. During the entry instructions for each condition, participants were read a prompt noting the intended time of day that was established for each condition.

The order of the 12 experimental conditions, following the practice condition, were counterbalanced 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.

Results

The mean and standard deviation for each of the four rating questions for each of the 12 stimulus conditions are shown in Table 3. Overall, the mean ratings show that the lighting conditions were perceived as comfortable; mean ratings for the perceived comfort scale were greater than the neutral score of 4 (indicating less comfortable) for only two conditions (condition 1 with bright, cool-tone lighting and condition 8 with blue lighting on the wall). Condition 8 had the only score greater than 5 on the color appropriateness scale (more inappropriate) and had the highest mean score on the naturalness scale of 6.03 (more unnatural), with the mean score on the naturalness scale also exceeding 5 for condition 1.

	COMFORT		INTENSITY		COLOR APPROPRIATENESS		NATURALNESS	
LTG COND.	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV
1	4.71	1.32	5.84	0.82	3.84	1.53	5.13	1.65
2	3.42	1.39	4.13	0.85	3.45	1.39	4.10	1.60
3	3.58	1.39	4.65	0.80	3.48	1.59	4.10	1.58
4	4.00	1.77	4.23	1.41	3.52	1.67	4.19	1.80
5	2.87	1.18	3.97	0.60	2.58	1.09	3.81	1.40
6	2.77	1.15	4.32	0.65	2.71	1.24	3.26	1.57
7	2.81	1.28	4.29	0.59	2.71	1.10	3.29	1.30
8	5.10	1.42	4.71	1.04	5.48	1.39	6.03	1.20
9	2.84	1.75	2.77	0.96	3.68	1.66	3.90	1.70
10	3.16	1.53	2.90	1.01	4.39	1.75	4.55	1.65
11	3.19	1.60	5.03	0.95	3.52	1.77	4.10	1.42
12	2.87	1.78	4.26	1.03	2.61	1.52	3.19	1.72

Table 3. Summary of collected data.
Table 3 shows the mean and standard deviation for each rating question at each of the twelve stimulus conditions. Comfort ratings ranged from extremely comfortable (1) to extremely uncomfortable (7); intensity of the lighting, from extremely too dim (1) to extremely too bright (7); appropriateness of the lighting color, from extremely

appropriate (1) to extremely inappropriate (7); and, naturalness of the lighting, from extremely natural (1) to extremely unnatural (7).

Statistical analyses of the ratings data were performed 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. Because the specific contrasts being tested were pre-planned and limited, the significance values were not adjusted for multiple comparisons and the actual p values are reported (Armstrong 2014). All Friedman and Wilcoxon signed rank tests conducted were two-tailed tests.

Hypothesis 1: Participant perceptions will change for different patient room lighting conditions that deliver varying levels of circadian stimulation.

To test the hypothesis regarding perceptions of lighting conditions with different potential circadian impacts, participants' ratings of lighting conditions 1 (M65/1000), 3 (M50/400), 6 (D35/400) and 9 (E27/100) were compared. These conditions were compared because they represent the range of conditions that might be experienced in future patient rooms with a goal of supporting circadian synchronization, with bright, cool lighting in the morning (conditions 1 and 3) and dim, warm lighting in the evening (condition 9). Condition 6 represents a typical mid-day condition. Table 4 shows the MI and CS values for each of these lighting conditions; the full SPD data for the calculations were provided in an earlier paper (Graves et al., 2021). The relative SPDs are shown graphically in Figure 3. Figure 4 graphs the participants' mean perception ratings and shows that condition 1 was rated as the least comfortable, the least natural, and the least color appropriate, although the mean color appropriateness ratings for each of the four conditions were between neutral and extremely appropriate.

LTG. 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 4. Calculated circadian metrics at patient eye position and viewing direction when seated in bed.

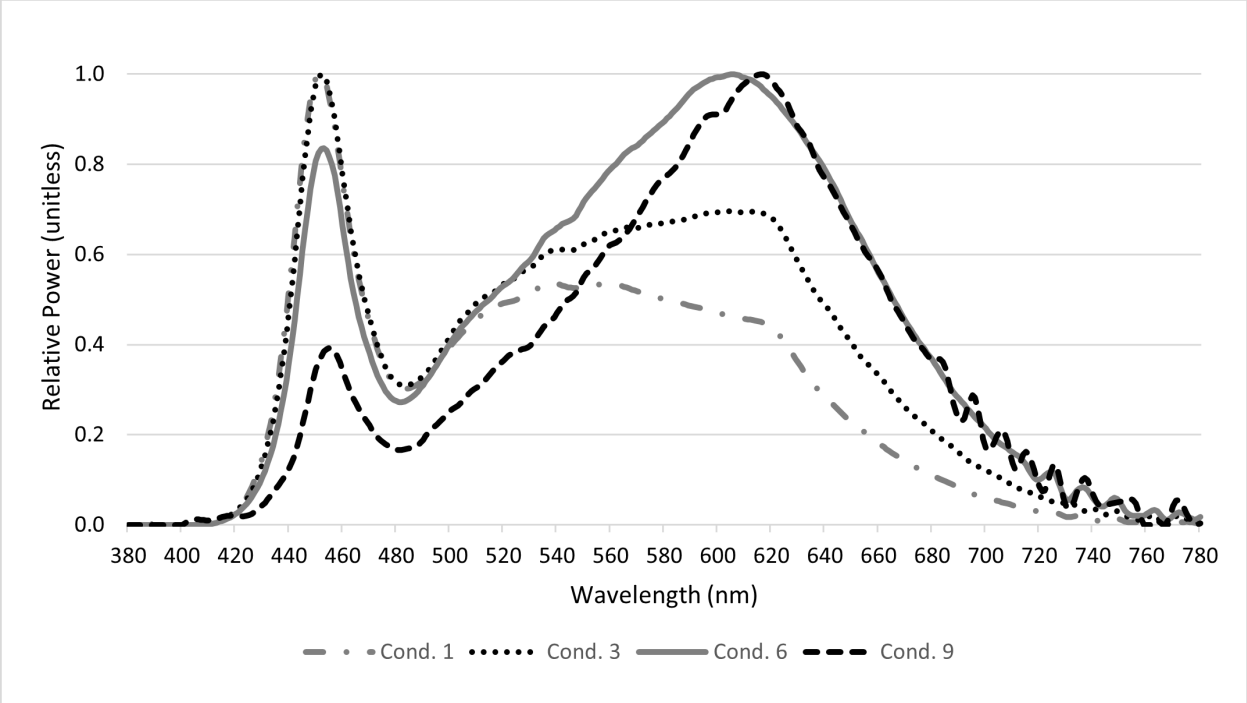

Figure 3. Plot of the relative spectral power distribution.
Specifically, for lighting conditions 1, 3, 6, and 9 measured at the task plane of the patient bed when completely flat. These measures capture the experience for patients resting while lying in bed and approximates the nurses' experience viewing 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.

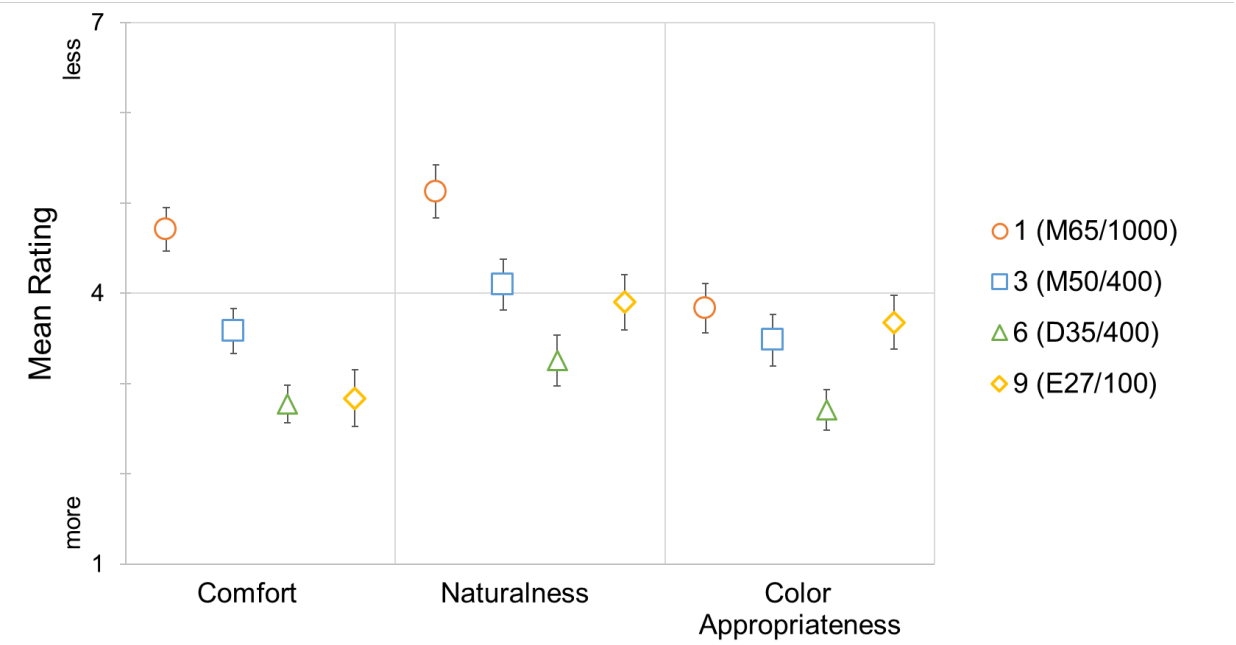

Figure 4. Comparison of participant ratings of comfort, naturalness, and color appropriateness.
Compares conditions with differing levels of circadian stimulus through variations in the CCT and illuminance. The shapes show the mean rating, with the error bars showing + standard error.

The Friedman tests showed that significant differences existed for the comfort, naturalness, and color appropriateness ratings. Condition 1, which was the brightest and coolest light condition, was rated as significantly less comfortable (C3, p=0.003; C6, p<0.001; C9, p=0.001) and significantly less natural (C3, p=0.009; C6, p=0.006; C9, p=0.024) than the other three conditions. While conditions 3 and 6 had the same intensity, condition 3 was set at a CCT of 5000 K compared with 3500 K for condition 6 and was rated as significantly less comfortable (p=0.005) and less natural (p=0.017) than condition 6. Condition 6 was rated as significantly more color appropriate than any of the other conditions (C1, p=0.021; C3, p=0.014; and C9, p=0.014). The ratings for intensity directly tracked with the illuminance levels of the conditions and no difference was reported between conditions 3 and 6, each of which had illuminance of 400 lux, but at different CCTs.

In sum, participants rated the high intensity, more blue-toned lighting as less comfortable and less natural than the warmer-toned lighting.

Hypothesis 2: Participant perceptions will vary based on differences in distribution of lighting in the room.

Several conditions were established to compare patient room lighting with characteristics typical of traditional, contemporary, and future lighting systems. For daytime comparisons, traditional lighting condition 4 (D35/400 bed only), contemporary lighting condition 5 (D35/400 bed and family), and future lighting condition 6 (D35/400 bed, family, and wall) were evaluated. Friedman tests reported significant differences in comfort, naturalness, and color appropriateness ratings, as shown graphically in Figure 5. Wilcoxon Signed-Ranks tests indicated that traditional condition 4 was rated as significantly less comfortable than both the contemporary and future conditions (C5, p=0.002; C6, p=0.001). The traditional condition 4 was also rated as significantly less color appropriate than either the contemporary or future settings (C5, p=0.005; C6, p=0.03); condition 4 was also rated as significantly less natural than condition 6 (p=0.013). The contemporary and future conditions (C5 and C6, respectively) were not rated as significantly different from each other for any of the measures.

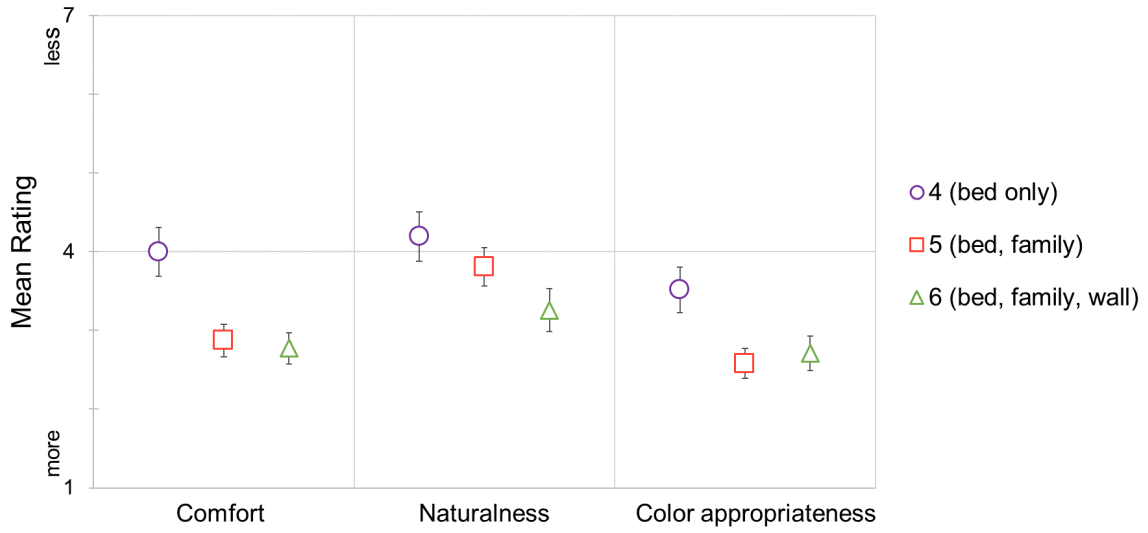

Figure 5. Comparison of participant ratings of comfort, naturalness, and color appropriateness.
Compares lighting conditions which differed based on the design standards of typical environments of care – traditional (condition 4), contemporary (condition 5), and future (condition 6). The shapes show the mean rating, with the error bars showing ± standard error.

Hypothesis 3: Participant perceptions will vary when colored light is introduced into the room.

Two pairs of conditions provide insight into participants' perceptions about the use of colored lighting on the wall, with the sole difference between each being the presence of blue or red light instead of white light on the footwall opposite the bed. 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 (see Figure 6, $p < 0.0001$ in all cases). However, the two evening conditions were rated significantly different for color appropriateness ($p=0.020$) and naturalness ($p=0.023$), but not for perceived comfort ($p=0.159$). In this case, the condition with the red lighting on the wall (condition 10) was less favorably rated as shown in Figure 7.

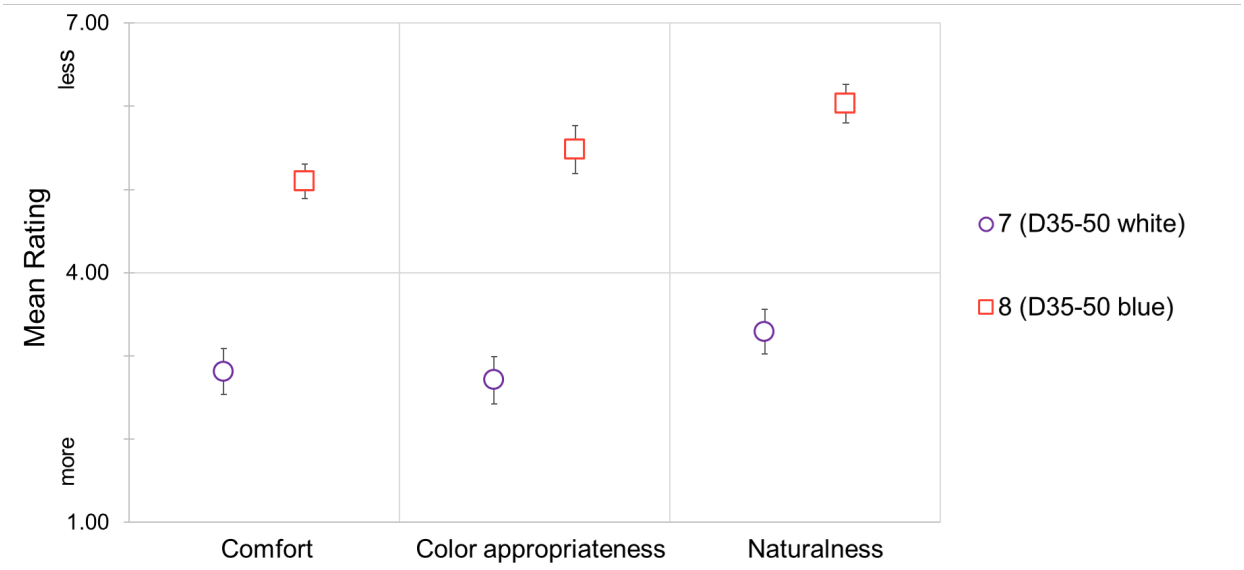

Figure 6. Comparison of participant ratings of comfort, naturalness, and color appropriateness.
Compares lighting conditions which differed based on the use of colored wall lighting, comparing condition 7 with condition 8. The shapes show the mean rating, with the error bars showing ± standard error.

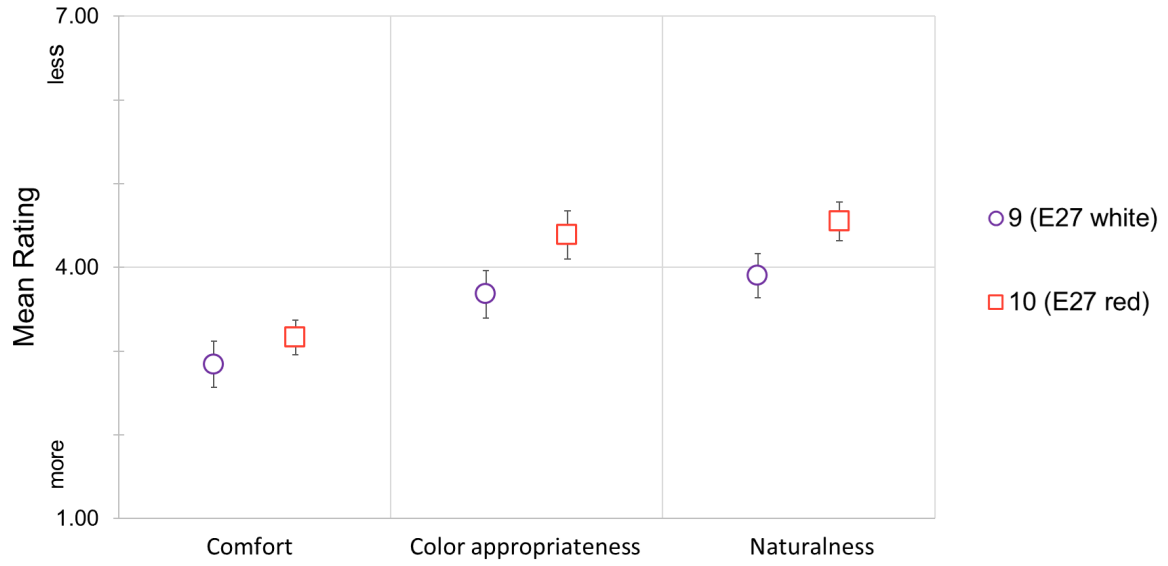

Figure 7. Comparison of participant ratings of comfort, naturalness, and color appropriateness.
Compares lighting conditions which differed based on the use of colored wall lighting, comparing condition 9 with condition 10. The shapes show the mean rating, with the error bars showing ± standard error.

Hypothesis 4: Participant perceptions will vary when there is a visible difference in luminaire CCTs.

Comparing two conditions with the same CCT (3500 K) for the patient bed and wall wash luminaires, but where condition 7 had a different CCT (5000 K) over the family zone (compared to 3500 K for condition 6) allowed for testing participants' reactions to having varying CCTs concurrently in different areas of the mock patient room. As shown in Table 3, the mean ratings for these two conditions were very similar for all four lighting aspects. The presence of luminaires of a different CCT in one of the zones in the room in condition 7 had no significant effect on participant judgements compared to condition 6.

Discussion

Lighting to support circadian synchronization

Lighting conditions 1 (M65/1000) and 3 (M50/400) represented two possible morning conditions for future patient room lighting, with condition 1 providing a combination of high intensity and high CCT that participants found least acceptable overall, while condition 3 provided a more moderate combination of intensity and CCT. As described in Hypothesis 1, these two systems were compared to conditions 6 (D35/400, representing typical patient room daytime lighting) and 9 (E27/100, representing a possible future evening condition of warm, dim lighting).

Patients perceived the condition with the highest intensity, and coolest CCT as significantly less comfortable and less natural than the other three conditions and further, reported that even the condition with the lowest effective circadian stimulus (condition 3) was significantly less comfortable and less natural than condition 6 which had a comparable intensity, but significantly warmer CCT. In other words, compared to what can be considered a normal daytime lighting condition, patients had negative perceptions of the morning conditions that may support circadian synchronization based on the MI and CS reported in Table 4. This is consistent with findings from other studies (Aryani &

Suryabrata, 2020). For patients, the comfort with the lighting increased as the illuminance and CCT decreased between conditions 1 and 3. The higher comfort rating for condition 6 versus condition 3 suggests that CCT had a stronger influence on comfort than illuminance, since those conditions had the same illuminance but condition 6 had lower CCT (3500 K vs. 5000 K).

Participants in this study were positioned directly under the luminaires and responded negatively to the higher CCT conditions. As one of the participants noted that they "Didn't like them [the brightest lights in condition 1] because it was too harsh and I feel like the only thing I could do is read," noting that resting would be too difficult under those conditions.

The importance of the distribution of light and the use of lighting zones

The three environments of care that informed the lighting conditions used varied in the use of different lighting zones within the patient room, resulting in a varying distribution of light throughout the patient room. These environments of care were examined by comparing traditional condition 4 (D35/400 with a nominal 2 ft by 4 ft luminaire area above the bed), contemporary condition 5 (D35/400 with a nominal 4ft by 4 ft luminaire above the bed and a separate lighting zone in the guest area), and future condition 6 (D35/400 similar to condition 5 with the addition of a wall lighting zone).

The participants found the traditional condition 4 to be significantly less satisfactory on comfort, naturalness and color appropriateness compared with the contemporary and future settings where light was provided in more zones across the room. This finding raises interesting questions about the possible role of lighting distribution in a room affecting color perception. For all three of the lighting conditions, the activated luminaires were set at 3500 K CCT. But for condition 4, the lighting was limited to the patient bed zone, while conditions 5 and 6 added additional lighting zones in the space. The relative dimness of these other zones in condition 4 may have resulted in colors seeming less saturated due to the Hunt effect (Hunt, R. W. G., 1952), which could have influenced the color appropriateness ratings. If further research evidence supports this finding, it may provide additional support for the ongoing implementation of patient room lighting systems that provide broader distribution of light throughout different lighting zones within the patient room.

The lighting attributes of contemporary and future patient room lighting conditions that were included in this experiment (i.e., broad distribution of light throughout the room and multiple lighting zones) produced more positive perceptions from participants than the traditional lighting condition.

Perceptions of light and color: Differing luminaire CCTs and the use of colored wall light

The ability to vary the spectrum of light with a tunable LED lighting system presents opportunities to alter the patient room environment in new ways. For example, while lighting condition 6 in these experiments had uniform 3500 K luminaires throughout the patient room, lighting condition 7 kept 3500 K for the bed and wall luminaires, but altered the guest zone luminaires to 5000 K. The mean perception ratings for comfort, naturalness, and color appropriateness were very similar for these two conditions, with no significant differences found. Participants found the room with differing luminaire CCTs in different zones to be acceptable. While this goes against lighting design conventions that typically require all luminaire CCTs to be the same within a room it might be a desirable strategy to further define the zones visually, or to have the guest luminaires near a window better match the spectrum of the incoming daylight, or to accommodate different activities/preferences of guests versus visitors.

The use of colored lighting on the wall, however, did produce significant differences in perceptions. The luminaire used for the wall lighting was a tunable LED lighting product that utilizes a combination of

narrow-band LEDs such as red-green-blue (RGB) capable of producing different CCTs of white light, as well as different hues of colored light. Colored lighting can be used as an architectural accent or may serve as an element of positive distraction for a patient (Illuminating Engineering Society, 2020).

Participants in the experiment perceived condition 8 with blue lighting on the wall as significantly less comfortable, natural, and color appropriate than the similar room lighting condition with white lighting on the wall. Several participants called out this condition as their least favorite: “The brightest in my opinion was the blue light and that was pretty glary.” Another participant said, “the purple one hurt my eyes,” a third said, “I would never recommend the violet blue lighting,” and yet another stated the “blue/violet was horrible”.

However, the use of red lighting on the wall (Condition 10) was not perceived as negatively. Relative to the paired condition with all luminaires in the room set to 2700 K CCT, the condition with the wall luminaire producing red light onto the wall had no significant difference in perceived comfort for participants. Despite the negative responses to the blue lighting, many of the participants commented that they would like to have colored lighting available, provided they could control it themselves.

Limitations and further research

This study evaluated a series of lighting conditions that may be found in hospital patient rooms, yet the experimental room was different than actual patient rooms in several key ways. While the tunable lighting system was used to simulate traditional and contemporary conditions, the room furnishings and the lighting system were all new, whereas in actual traditional facilities the environments usually reflect the age of the facility. The experimental room purposely did not incorporate any daylighting, while most actual patient rooms have at least one window. The amount of time and activities while in the patient room was also very limited. These factors resulted in participants not experiencing the dynamic nature of light that occurs over time with daylighting and with some automated tunable lighting systems. Additionally, the participant age did not align with the typical ages of hospital patients, with a mean age of 24 and only three participants over 30 years of age, and unlike actual patients these participants were healthy.

Participants were not allowed to change the lighting in the room, so they did not experience the benefit of direct user control. This limitation may be especially relevant for the findings about implementing colored lighting into patient rooms. The use of colored lighting may provide a distracting element in hospital care; this type of positive distraction is likely to be most potent if the patient can dynamically change the color of lighting being used for the accented area. Controllable colored lighting has the potential to serve as a positive distraction improving the experience of hospitalized patients, but this experiment did not investigate controllability of lighting. Further research that specifically explores the use of dynamic control of patient room lighting (colored or white) as a possible element for positive distraction is needed to fully understand the potential drawbacks and advantages to this design strategy.

Furthermore, the findings regarding the colored wall wash are difficult to interpret because of the study design. Because blue colored light was tested during a daytime condition and the red colored light was tested during a nighttime lighting condition, it is possible that some of the reactions were impacted by contrast with the rest of the room as opposed to purely regarding the colored lighting. To clarify whether the response to the colors varies by color or by the ambient lighting conditions in room, additional studies will need to be conducted.

Negative perceptions towards high CCT lighting shown in this experiment may reflect the state of the common LED technology in use at the time of this study, but the perceptions are most likely based on

specific aspects of the lighting spectrum and not necessarily the CCT itself. Daylight during the middle of the day, is much more intense and has a higher CCT than electric lighting, yet it is widely preferred to electric lighting suggesting that a high CCT is not necessarily undesirable (Knoop et al., 2020). Emerging technologies using advanced spectral engineering techniques may enable lighting systems that are optimized for desired circadian (e.g. provide sufficient stimulus to suppress melatonin) and other biological effects with more pleasing light and color quality than current high CCT systems. These technologies could be incorporated into future studies for evaluation.

Extending these simulation studies into patient rooms within hospitals would allow the exploration of other research questions that were not included in these initial experiments. These questions include such topics as perceptions of lighting in different environments of care during extended time periods, responses to a variety of user control interfaces for lighting, and the ability to compare physiological and medical outcomes to patient and nurse perceptions for general care and various types of specialized care would all be valuable topics for future exploration.

Conclusions

The overall implications for this study are that there is great possibility to utilize the expanded capabilities of lighting to improve the experience in patient rooms, but there is more work that needs to be done to improve the acceptability of lighting solutions that deliver circadian benefits. While there is growing evidence that light of a certain quality (high circadian stimulus or melanopic irradiance) can help entrain the human circadian rhythm when applied during the early part of the day, when the LED lights tested in this study where set to an efficacious level, participants did not find the light conditions acceptable in terms of comfort and naturalness. Given that sleep is so important for hospitalized patients, and light has such strong potential to improve patient sleep, there is strong motivation to develop lighting technologies and design strategies that can deliver a sufficient dose of light in a way that is pleasant to patients.

Participants showed a strong preference for the future environments of care lighting conditions where light was applied in multiple zones across the room. Designers of patient rooms should take ample advantage of current and emerging lighting technologies that allow for layers of light throughout the space. The fact that participants did not object to having visibly different CCTs of light illuminated simultaneously in different zones of the room, gives designers more leeway to creatively apply different lighting elements. This finding opens up the potential for having lighting in the nursing task area that might be stimulating in the evening, while the patient area has a warmer color of light.

Ongoing innovation in lighting technologies will allow for greatly improved patient room applications and this research provides some input into the intensity, color and distributions of light that support nurses in their work and are agreeable to patients.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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