Patient room lighting influences on sleep, appraisal and mood in hospitalized people

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Keywords
circadian medicine, dynamic lighting, healing environments, length of stay, nursing, sleep-onset latency

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Accepted in revised form 27 September 2016; received 5 March 2016
DOI: 10.1111/jsr.12470

INTRODUCTION

Impaired sleep is a known hospital stressor, and hospitalized patients struggle to get sufficient sleep at night due to factors like discomfort, worries, noise, inappropriate light exposure and pain (Manian and Manian, 2015; Pisani et al., 2015; Redeker and Hedges, 2002; Volier and Bohannon, 1975). Sleep is an important factor to promote the wellbeing and recovery of patients. The human sleep–wake pattern is strongly regulated by the central circadian pacemaker residing in the suprachiasmatic nuclei within the hypothalamus. This pacemaker uses light–dark information to initiate and control the timing, alignment and stability of the endogenous 24 h patterns in our sleep, physiology, alertness and mood. Proper timing of the light exposure is critical: brighter daytime light conditions are associated with better mood and sleep quality (Ancoli-Israel et al., 2003; Boukhoum et al., 2014; Harrison, 2004; Lambert et al., 2002; Mishima et al., 2001; Riemersma-Van Der Lek et al., 2008; White et al., 2013), while excessive light exposure during
the evening or night-time has an acute disruptive influence on sleep (Czeisler, 2013; Santhi et al., 2011; White et al., 2013). The blue-light-sensitive photoreceptor pigment melanopsin (Lucas et al., 2014) is an important mediator for the effects of light on our sleep–wake behaviour (Hughes et al., 2015). In many healthcare facilities access to (blue-rich) daylight is limited, and current standards and guidelines for lighting systems within normal patient rooms specify horizontal illuminance thresholds in the range of 100–300 lux (CEN, 2011; IES, 2011). Consequently, the typical daytime illuminance indoors is insufficient to generate the same benefits as the outdoor illuminance (2000–100 000 lux of blue-rich light) under which we have evolved. Daytime exposure to high illuminances, from either sunlight or a few hours of bright-light therapy, is known to have beneficial effects on clinical parameters such as recovery, length of stay (LOS), delirium, depression, anxiety and use of pain medication (Beauchemin and Hays, 1998; Benedetti et al., 2001; Bernhofer et al., 2014; Taguchi et al., 2007; Tuunainen et al., 2004; Walch et al., 2005; Youngstedt and Kripke, 2007). Moreover, in neonatal intensive care units cycled lighting has a favourable influence on many outcomes as compared to 2 h dimmed light or continuous light (Morag and Ohlsson, 2013). In people with dementia, night-time sleep increased significantly after 3 weeks of exposure to either morning or all-day bright light (Sloane et al., 2007). Moreover, a single 2-h bright-light pulse in the morning advances the circadian rhythm (Minors et al., 1991) and can help prevent sleep-compromising delays of the body clock.

Cardiovascular disease continues to be a major burden for healthcare in Europe, with close to 2500 annual hospital discharges per 100 000 inhabitants, costing €106 billion annually, of which 49% is for inpatient hospital care (Nichols et al., 2012). The optimization of patient room lighting conditions can help to alleviate this burden. Therefore, we examined the effects of a dynamic patient room lighting cycle on sleep, appraisal and mood during hospitalization on a cardiology ward. Patients either stayed in control rooms with standard lighting or in intervention rooms equipped with a new dynamic lighting system. The light intensity and spectral composition in the intervention rooms are automatically tuned to generate a dynamic 24 h lighting rhythm with two late-morning hours of bright, blue-enriched white light, and low light exposure during evenings and at night-time. Wrist actigraphy was used to assess total sleep duration (TSD) and sleep-onset latency (SOL). Subjective ratings were used to evaluate sleepiness, sleep quality, headache, eye-strain, depression, anxiety, and lighting appraisal.

MATERIALS AND METHODS

Study design

From the 15th of December 2009 until the 15th of September 2010, 196 patients of the cardiology ward of the Maastricht University Medical Center (MUMC) in the Netherlands participated in the study. All study participants gave written informed consent, and the protocol was approved by the local Medical Ethics Committee of the Maastricht University Medical Center. Patients were assigned to either a control room with standard (fluorescent) lighting conditions or to an intervention room in which the fluorescent general lighting had automated gradual changes in illuminance and correlated colour temperature (3000–6500 K) across the day, offering a dynamic 24 h light/dark cycle with low nocturnal light exposure, bright, blue-enriched white light (1750 lux, 6500 K) between 10:30 and 12:30 hours, and a 45-min post-lunch illuminance of 100 lux (3000 K) on the bed. Details of the lighting conditions are given in Fig. 1 and in Data S1.

The study was initiated as a fully randomized controlled clinical trial. However, the high occupancy of the ward forced us to abandon randomization. It appeared impossible to secure the simultaneous availability of one empty bed in both the intervention- and control-condition on sufficient inclusion moments. Instead, room assignments were done by regular hospital staff, based on room availability and routinely used hospital procedures, irrespectively of health status and fully out of reach of the investigators. The cardiologist and the resident-cardiologist supervising the ward determined the discharge date of a patient. The staff were not aware of the study assessments and acted fully independently, without any relation to the study; neither in the preparation, nor in the execution, nor in the analysis.

Figure 1. Schematic representation of the typical 24 h profile in general lighting within intervention rooms (solid line) and control rooms (dashed). The y-axis gives the horizontal illuminance on the bed, and the corresponding correlated colour temperatures (CCT) are indicated in the figure. The grey area indicates the evening and night-time hours with manual (de)activation of the general lighting and reading light usage. The reading light in control rooms is undimmable and delivers 300 lux horizontal illuminance on the bed. Intervention rooms have a dimmable reading light, with a maximum illuminance of 300 lux. Between 23 h and 7 h, the general lighting within intervention rooms, when activated, delivers 50 lux on the bed with a CCT of 3000 K. The general lighting in control rooms, when activated, always delivers 100 lux on the bed with a CCT of 3000 K.


Study assessments

The study probed patient expectations at intake, and made daily assessments of actigraphic sleep, Hospital Anxiety and Depression Scale (HADS), Karolinska Sleepiness Scale (KSS), Headache and Eye-Strain (HES) symptoms. The Pittsburgh Sleep Quality Index (PSQI) was completed at study intake and discharge, modifying all “During the past month…” questions into “During the past days…”. Lighting appraisal was probed using a seven-point Likert scale (0 = very unsatisfied, 3 = neutral, 6 = very satisfied) to answer “How satisfied are you with the lighting system in the patient rooms?”. Table 1 and the Data S1 provide more details about these assessments.

Analysis

Between-group differences in gender, smoking, intake in autumn/winter, hypertension, diabetes, depression history and discharge diagnosis were tested by means of a Chi-squared test. A Mann–Whitney test was used to assess between-group differences in expectation, appraisal and LOS. An independent, two-sided Student’s t-test was used to assess between-group differences in age, body mass index, heart rate, blood pressure and PSQI. The multilevel regression model is described by Eq. (1).

\[
\text{Outcome}_{ij} = \beta_0 + \beta_1 \times \text{HospitalDay}_{ij} + \beta_2 \times \text{Intervention}_{ij} + \beta_3 \times (\text{Intervention} \times \text{HospitalDay})_{ij} + \alpha_j + \epsilon_{ij} \tag{1}
\]

The time axis is represented by HospitalDay_{ij}, which indicates the number of days a patient (j) has spent at the hospital at any moment (i, expressed in days) that the Outcome_{ij} is measured. On the hospital intake day, HospitalDay equals one. The parameter Intervention_{ij} indicates the lighting condition of a given patient j. It equals 0 for control patients and 1 for intervention patients. The intercept of the model represents the Outcome parameter at baseline (i.e. for HospitalDay = 0, this is the last night before hospitalization), and is defined by \(\beta_0\) and \(\beta_2\). Within control patients the time dependency of Outcome_{ij} is described by \(\beta_1\), and in intervention patients by \(\beta_1 + \beta_3\), where \(\beta_3\) represents the intervention \times time interaction. In Eq. (1), \(\alpha_j\) represents the patient-dependent (random) part of the intercept, and \(\epsilon_{ij}\) represents the error term.

The model parameters were assessed for two cases. The first case used all available data. The second case only used the data collected during the first 5 days (and 5 nights) of the hospitalization period (i.e. HospitalDay \leq 5). This allows to evaluate the robustness of the model and its effect sizes when the follow-up time is restricted to the median LOS of 5 days. Simultaneously, it provides extra information on how the effect-estimates develop over time. Regression coefficients were tested for significance (\(P < 0.05\)) with the Wald test. The \(P\)-values are two-tailed.

RESULTS

In total, 580 cardiology ward patients were considered for inclusion in the study. At study closure 196 participants (mean age 66.5 ± 13.1 years SD) were enrolled (Fig. 2). Table 2 provides more information on the characteristics of the study participants. Two intervention patients discontinued their participation: one due to migraine complaints induced by the interventional lighting; and one due to actiwatch-induced skin irritation. No patient dropped out of the study due to death. The analyses were done within a homogeneous patient population, excluding all patients for which the discharge diagnosis differed from coronary artery disease or heart failure and those patients that only stayed for one night. More details on the characteristics of the various sub-samples within this study are provided in the Data S2.

At study intake, patient expectations regarding effects of the lighting system on visual comfort, mood, performance, alertness, vitality, concentration and sleep quality did not differ between control and intervention patients (\(P > 0.14\)).

Length of stay

The median LOS [± interquartile range (IQR)] was 4.5 (± 3) days in control patients and 5 (± 5) days in intervention patients, without a between-group difference (\(z = -0.23, P = 0.82\)). The largest LOS was 19 days.

Lighting appraisal

Scores on satisfaction with the lighting were analysed for 90 patients and 36 nursing-staff members. Median satisfaction
Figure 2. Flow of participants included in the study.

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The vast majority of patients were included in the study shortly after admission from home. The number of patients coming from intensive care is expected to be very low; however, we did not record these data. Patients were bedridden, and in general had no surgery or anaesthesia (post-operative patients in principle were admitted on a different ward). Moreover, we believe that the analysis sample represents the less ill patient group. The study included a relatively large number of questionnaires, which is difficult to comply with for very ill patients. Severely ill patients were less likely to consent to the study.

### Table 2 Characteristics of the study intake population in the control and intervention groups

|                          | Intervention group (n = 100) | Control group (n = 96) | P-value |
|--------------------------|-----------------------------|------------------------|---------|
| Age (years), mean ± SD   | 68.1 ± 12.2 (n = 100)       | 64.9 ± 13.9 (n = 96)   | 0.09    |
| Female                   | 34 (n = 100)                | 27 (n = 96)            | 0.38    |
| Body mass index (kg m\(^{-2}\)), mean ± SD | 27.6 ± 5.5 (n = 98) | 27.5 ± 5.6 (n = 95) | 0.95    |
| Heart rate (bpm), mean ± SD | 75.5 ± 16.2 (n = 58)   | 79.3 ± 26.2 (n = 56)   | 0.36    |
| Blood pressure diastolic (mmHg), mean ± SD | 75.6 ± 12.5 (n = 80) | 72.6 ± 14.0 (n = 82) | 0.14    |
| Blood pressure systolic (mmHg), mean ± SD | 129.9 ± 18.9 (n = 80) | 122.3 ± 18.1 (n = 82) | 0.01    |
| Active smoking           | 11 (n = 98)                 | 20 (n = 92)            | 0.05    |
| Diabetes                 | 28 (n = 96)                 | 17 (n = 91)            | 0.09    |
| Hypertension             | 46 (n = 95)                 | 43 (n = 94)            | 0.71    |
| Depression history       | 28 (n = 98)                 | 37 (n = 92)            | 0.09    |
| Hospital admission in autumn/winter (Sept. 21st - March 21st) | 68 (n = 100) | 69 (n = 96) | 0.55    |
| Coronary artery disease discharge diagnosis | 41 (n = 96) | 46 (n = 94) | 0.39    |
| Heart failure discharge diagnosis | 35 (n = 96) | 28 (n = 94) | 0.33    |

The number of observations is given between brackets. The table gives the P-values (of the Student’s t-tests or the Chi-squared test) that result when testing for differences between the groups.

### Table 3 Mean subjective sleep scores and 95% confidence interval (95% CI) within control and intervention patients at study intake and hospital discharge, as evaluated by the Pittsburg Sleep Quality Index (PSQI) global score

|                          | Intake | Discharge | Delta = discharge – intake |
|--------------------------|--------|-----------|---------------------------|
|                          | Control | Intervention | Control | Intervention | Control | Intervention |
| Subjects per group       | 44     | 48        | 37            | 43          | 37      | 43          |
| Global PSQI              | 7.32   | 8.54      | 7.62          | 8.16        | 0.27    | -0.88       |
| (95% CI)                 | (5.93–8.71) | (7.21–9.87) | (6.34–8.9) | (6.97–9.35) | (-1.00 to 1.54) | (-2.06 to 0.30) |

The delta column gives the mean of the discharge – intake PSQI score of individual patients for both groups. The global PSQI score ranges from 0 to 21, a lower score indicates a better sleep quality.

Subjective sleep: PSQI scores

The global PSQI scores at intake and discharge are given in Table 3, along with the within-subject discharge minus intake score (delta) for both groups. There were no significant differences between the groups. However, subjective sleep, as judged from the delta global PSQI value, tended to improve within intervention rooms. The detailed PSQI results are presented in the Data S2.

Objective sleep: actigraphy

Table 4 summarizes the regression results for actigraphic TSD and SOL. Figure 3 displays the raw TSD data and regression lines for the individual control- and intervention-patients. There were no significant interventional effects on the actigraphy baseline effect estimates (β0) of the regression models in Table 4. The TSD data yielded a significant interaction effect (β2) between HospitalDay and the intervention in the 20-day period.

Multilevel linear regression analyses

We evaluated several regression model extensions of Eq. (1), including a random intercept on the room level and random slopes (see Data S2). In each case where Eq. (1) yielded a significant interventional effect, we concluded that Eq. (1) provides a reasonable model for the interventional effect estimation, obviating the need for these extensions.

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analysis; for every single day that a patient stays in the intervention room as compared to staying in the control room, TSD increases by an extra 5.9 min per hospital day ($P = 0.03$).

When the regression analysis is restricted to the first five hospitalization days, TSD in intervention patients tends to increase by an extra 14.5 min per day ($P = 0.00503$) as compared to control patients. In the 5-day case, SOL in intervention patients decreases by an extra 4.3 min per day ($P = 0.02$) as compared to patients in the control group. Figure 4 shows how the between-group differences as predicted by the Table 4 regression models develop over time.

There were no significant interventional effects within the actigraphic sleep efficiency regression coefficients, neither for the 20-day nor for the 5-day case (see Data S2).

### Sleepiness and mood symptoms

There were no significant interventional effects within the regression coefficients of the KSS and HADS data, neither for the 20-day nor for the 5-day models. The data are presented in the Data S2.

### Headache and eye-strain

The HES questionnaire probes eight items, each on a discrete four-point scale (0 = absent, 1 = slight, 2 = moderate, 3 = severe). Four items had significant interventional effects in the 20-day and 5-day regression analyses. Table 5 shows the regression effect estimates for these four items. In the 20-day analysis, the HES-items ‘eye-strain’ and ‘eye-fatigue’ had a significantly higher baseline score (i.e. more symptoms) in intervention patients as compared to control patients (the corresponding $\beta_3$ and $P$-values are shown in Table 5). Moreover, intervention patients developed slightly more ‘difficulties concentrating’ over time than control patients: in Table 5 the intervention $\times$ time effect was small but significant ($\beta_3 = 0.032; P = 0.034$). In the 5-day model, the interaction effect for ‘difficulties concentrating’ was no

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**Table 4** Effect estimates of the multilevel linear regression model (Eq. 1) for the actigraphic outcomes TSD and SOL as obtained for the overall analysis (up to 20 days of hospitalization) and for the restricted analysis (up to the first 5 days of hospitalization)

|                        | Overall analysis | First 5 days analysis |
|------------------------|------------------|-----------------------|
|                        | TSD (95% CI)     | SOL (95% CI)          | TSD (95% CI)     | SOL (95% CI)          |
| Baseline control group ($\beta_0$) | 402.3 min (375.6-428.9) | 17.9 min (11.7-24.1) | 406.8 min (367.6-446.0) | 12.4 min (3.1-21.7) |
| Baseline intervention group ($\beta_0 + \beta_2$) | 401.0 min (374.7-427.4) | 15.7 min (9.6-21.9) | 378.0 min (338.5-417.6) | 22.4 min (12.9-31.9) |
| Control group change over time ($\beta_1$) | $-1.3$ min day$^{-1}$ (9.5-2.5) | 0.2 min day$^{-1}$ (-0.8 to 1.1) | $-3.2$ min day$^{-1}$ (-13.5 to 7.0) | 1.5 min day$^{-1}$ (-1.1 to 4.1) |
| Intervention group change over time ($\beta_1 + \beta_3$) | 4.5 min day$^{-1}$ (0.8-6.2) | $-0.7$ min day$^{-1}$ (-1.6 to 0.3) | 11.3 min day$^{-1}$ (1.0-21.6) | $-2.8$ min day$^{-1}$ (-5.4 to -0.2) |
| Intervention effect on baseline ($\beta_2$) | $-1.2$ min (-38.7 to 36.2) | $-2.1$ min (-10.8 to 6.6) | $-28.8$ min (-84.5 to 26.9) | 10.0 min (-3.3 to 23.3) |
| Intervention effect on change over time ($\beta_3$) | 5.9 min day$^{-1}$ (0.6-11.2) | $-0.8$ min day$^{-1}$ (-2.2 to 0.6) | 14.5 min day$^{-1}$ (0.0-29.1) | $-4.3$ min day$^{-1}$ (-8.0 to -0.6) |
| Intervention-control, 5th hospital night ($\beta_2 + 5 \beta_3$) | 28.2 min (-3.0 to 58.3) | $-6.2$ min (-12.6 to 0.1) | 43.9 min (2.7-85.0) | $-11.6$ min (-20.8 to -2.3) |
| Standard deviation of $\sigma_j$ | 57.5 | 10.9 | 58.5 | 10.2 |
| Standard deviation of $\sigma_k$ | 70.9 | 18.9 | 70.4 | 18.3 |

The 95% confidence interval (95% CI) is given in brackets. For the interventional effect estimates $\beta_2$ and $\beta_3$, the two-sided $P$-values are also given, and an asterisk (*) denotes a significant effect ($P < 0.05$).

The baseline value is the regression model estimation (Eq. 1) for the night before hospitalization (i.e. for HospitalDay = 0).

$\sigma_j$ represents the patient-dependent (random) part of the intercept of Eq. (1), and $\sigma_k$ represents the error term.

Note that the slope of the Eq. (1) regression model within control patients equals $\beta_1$, and in intervention patients it equals $\beta_1 + \beta_3$. These coefficients are constant and do not vary among individual patients, only the intercept of the regression line depends on the individual patient.

After 5 nights of hospitalization, the TSD and SOL change with respect to baseline equals $5 \times \beta_1$ for control patients, and $5 \times \beta_1 + 5 \times \beta_3$ for intervention patients, see Eq. (1). For this change the between-group difference hence equals $5 \times \beta_3$. In the overall TSD case this corresponds to 29 min.

After model adjustment, some of the patient characteristics from Table 2 influenced the coefficients of the TSD and SOL regression models, see Supporting Information Data S2. However, those characteristics did not have a significant unbalance ($P < 0.05$) between the control and intervention sample used. Therefore, the unadjusted basis model of Eq. (1) was used to estimate effect sizes.

SOL, sleep-onset latency; TSD, total sleep duration.

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Figure 3. The actigraphic total sleep duration (TSD, in min) data-points and the corresponding regression model lines (see Eq. 1 and Table 4) of each individual patient (denoted by the number above each panel), for the overall (20-day) analysis (black), and when restricting the analysis to the data of the first five hospitalization nights only (grey). Each panel represents a patient: (a) all control patients, CP (01-39); (b) all intervention patients, IP (40-78).
longer significant ($P = 0.56$), but here intervention patients had an extra increase over time as compared with control patients for the items ‘headache’ and ‘eye-fatigue’, the extra increases being 0.17 and 0.13 points per day, respectively. Moreover, in the 5-day model, intervention patients had a significantly lower baseline score for ‘headache’ as compared with control patients ($\beta_2 = -0.677; P = 0.008$).

**DISCUSSION**

The overall (20-day) regression model for actigraphic sleep showed a significant TSD increase by 5.9 min per hospitalization day with the new lighting system instead of standard lighting. In the 5-day regression, i.e. when only analysing data of the first five hospitalization nights, TSD increased by 14.5 min per intervention day with a $P$-value on the verge of significance. The confidence intervals of the model parameters for both regressions are largely overlapping. In the 20-day regression the standard error in $\beta_3$ is smaller as compared to the 5-day regression. This is likely due to the larger range in the explanatory variable ‘HospitalDay’ for the 20-day regression. Non-linearity of the changes over time can also contribute to the difference in $\beta_3$ between the 5- and 20-day regression: in the early days of hospitalization, the changes over time are expected to be larger as compared with later days where effect sizes tend to saturate. Moreover, patients with a shorter LOS might have better (health) characteristics than patients with a longer LOS, with fewer sleep-compromising medical factors, and a better ability to respond to the intervention (at least initially). Hence, a higher TSD increase per intervention day ($\beta_4$) is expected for the 5-day regression than for the 20-day regression, as is indeed observed. With the same argumentation a larger decrease in SOL per intervention day is expected for the 5-day regression than for the 20-day regression. For SOL the $\beta_3$ value differed significantly from zero only in the 5-day regression. These findings suggest that the new lighting system is supportive for a shorter SOL. Moreover, the global PSQI score tended to improve under the new lighting system. We were unable to assess effects of the lighting intervention on daytime sleep, as many patients did not wear the actiwatch during daytime.

Regular 24 h light/dark patterns with sufficient daytime brightness, and night-time darkness (or dim light), can help health- and elderly-care residents to maintain their circadian rhythm (Beauchemin and Hays, 1998; Campbell et al., 1986; Morag and Ohlsson, 2013; Ritchie et al., 2015; White et al., 2013; Wirz-Justice, 2007). Moreover, evening/night-time light exposure acutely suppresses melatonin production. This sleep-disruptive effect can be reduced by lowering light intensity (Brainard et al., 2015; Santhi et al., 2011), or by offering a preceding (daytime) exposure to bright light (Hebert et al., 2002). Furthermore, 4 weeks of midday bright light are known to increase nocturnal melatonin levels in elderly insomniacs (Mishima et al., 2001). In white-collar office workers, the quality of subjective nocturnal sleep was found to improve under a 4-week exposure to blue-enriched white light during daytime workhours (Viola et al., 2008). As the current lighting intervention combines a low evening/night-time light exposure with two late-morning hours of bright, blue-enriched light, similar effects and mechanisms could contribute to the modest favourable influence of the current lighting intervention on sleep duration during hospitalization.

Two large-scale investigations (Choi et al., 2012; Joarder and Price, 2013) found an association between brighter daytime light conditions and shorter LOS of patients. In our study we found no difference in LOS between intervention and control patients. Study participants had a mean baseline sleep duration of 401.6 min, quite similar to the 424.5 min reported by Redeker et al. (1998). An exploratory analysis within the current population sample indicated that a longer baseline sleep duration can act as a significant predictor for a shorter LOS (see Data S3).

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Table 5 Effect estimates of the linear multilevel regression model for the four HES items that had significant interventional effects in the 20-day and 5-day analyses

| Overall analysis |
|------------------|
|                  | HES eye-strain (95% CI) | HES eye-fatigue (95% CI) | HES difficulty concentrating (95% CI) | HES headache (95% CI) |
| Baseline control group ($\beta_0$) | 0.239 (0.060–0.418) | 0.421 (0.215–0.626) | 0.523 (0.332–0.714) | 0.472 (0.301–0.643) |
| Baseline intervention group ($\beta_0 + \beta_1$) | 0.528 (0.353–0.702) | 0.757 (0.557–0.957) | 0.522 (0.335–0.708) | 0.399 (0.222–0.556) |
| Control group change over time ($\beta_1$) | 0.004 (−0.013 to 0.022) | −0.014 (−0.034 to 0.006) | −0.029 (−0.050 to −0.008) | −0.022 (−0.042 to −0.002) |
| Intervention group change over time ($\beta_1 + \beta_2$) | −0.010 (−0.027 to 0.007) | −0.018 (−0.038 to 0.002) | −0.029 (−0.018 to 0.024) | −0.009 (−0.028 to 0.011) |
| Intervention effect on baseline ($\beta_2$) | 0.289 (0.038–0.539) | 0.336 (0.050–0.623) | −0.002 (−0.268 to 0.265) | −0.083 (−0.323 to 0.156) |
| Intervention effect on change over time ($\beta_3$) | −0.014 (−0.039 to 0.010) | −0.004 (−0.032 to 0.025) | 0.032 (0.002–0.062) | 0.013 (0.015 to 0.041) |
| Intervention-control, night ($\beta_2 + \beta_3$) | 0.218 (−0.001 to 0.437) | 0.317 (0.067–0.567) | 0.785 (−0.064 to 0.381) | 0.367 (−0.213 to 0.175) |
| Standard deviation of $\pi$ | 0.514 | 0.584 | 0.507 | 0.435 |
| Standard deviation of $\epsilon$ | 0.346 | 0.404 | 0.424 | 0.403 |

The 95% confidence interval (95% CI) is given in brackets. For the interventional effect estimates ($\beta_2$ and $\beta_3$), two-sided P-values are given below the 95% CI, an asterisk (*) denotes that the parameter differs significantly (P < 0.05) from zero.

The HES questionnaire uses a discrete four-point scale (0 = absent, 1 = slight, 2 = moderate, 3 = severe) for eight items: irritability, headache, eye-strain, general eye-discomfort, eye-fatigue, difficulty focusing, difficulty concentrating, and blurred vision.

The baseline value is the regression model estimation for the variable in the night before hospitalization (i.e. for HospitalDay = 0).

The HES, Headache and Eye-Strain questionnaire.

Multilevel linear regression models tend to overestimate the significance of effects on outcomes that are highly discrete in nature, like the HES. Nonetheless, the findings suggest that the intervention slightly affects some HES items. More studies are needed to assess the influence of lighting conditions on headache and eye-strain complaints in hospital patients.

The HADS scores in this study were close to 5 (see Data S2) and classified as ‘normal’, leaving little opportunity for improvements. Additional studies need to clarify whether the intervention can treat depressive patients.

Two limitations of this study are worth noting. During the study the hospital changed from paper-based to electronic registration of medication prescriptions, and prescription data could not be retrieved for nearly 20% of the patients. Prescription evaluation classified patients as users or non-users for: (1) aspirin/oral anti-coagulation; (2) anti-arrhythmic drugs; (3) psychopharmaca; (4) AT2-antagonists; (5) calcium-antagonists; (6) diuretics; (7) nitrates; (8) ACE-inhibitors; (9) beta-blocking agents. Hypnotics were used very restrictively. The two intake groups in this study as shown in Table 2 only differed significantly for beta-blockers (P = 0.04), these were used more frequently in intervention patients. Beta-blockers are known to negatively impact sleep (Yamada et al., 1995) and might affect the ability of a patient to respond to the intervention. Sleep in patients on beta-blockers improves under nightly melatonin administration (Scheer et al., 2012). The lighting intervention could induce similar effects within patients on beta-blockers (increasing their endogenous night-time melatonin production). However, a beta-blocker-adjusted analysis for TSD (20-day case) suggests that beta-blocker users might be less responsive to the lighting intervention than beta-blocker non-users (see Data S2). This topic merits further study.

Patient inclusion in this study proceeded much slower than expected, and time and budget restrictions enforced study closure without reaching the targeted sample size. The current analysis was based on a relatively modest and incomplete dataset.

In summary, standardly-lit patient rooms did not differ in LOS as compared to patient rooms with a dynamic lighting system that provided bright daytime, and low nocturnal light exposure.
Also, subjective sleep (PSQI), and anxiety and depression scores (HADS) were not different between the conditions. The lighting intervention resulted in some improvements in objective (actigraphic) sleep and lighting appraisal within hospitalized patients. Concurrently, the subjective sleep of intervention patients, as judged from the global PSQI scores, had a tendency to improve during hospitalization. The application of lighting conditions to shape healthcare facilities that support health and wellbeing, both for patients and staff, merits further research, thus developing lighting strategies that enable hospital environments to become less disruptive for sleep, mood and circadian rhythms.

ACKNOWLEDGEMENTS

The authors thank P. Heijmans, J. van Stiphout (†), T. Becker, T. Tsoneva (all Philips), T. Kleijnen, C. de Bont, J. Huismann (all CTCM) and M. van IJsselstein (MUMC) for their support during the project. The authors thank Prof. E. van Someren for his advice and practical help while starting the regression analyses.

AUTHOR CONTRIBUTIONS

LMG, MV, PL, GJBMM, HH and LJMS defined the study. LMG and MV carried out data collection. MCG, LMG, MV, PL, Bdr, JWB, PMJCK and LJMS conducted the data analysis and interpretation. MCG, LMG, MV, HH, JWB and LJMS prepared the manuscript.

CONFLICT OF INTEREST

Philips funded the study; MV, PL and PMJCK declare no further conflicts of interest; JWB received consulting fees from Philips; MCG, LMG, GJBMM, HH and LJMS are employees of Philips.

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