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Sound and light levels in intensive care units in a large urban hospital in the United States

Michael J Leone[1,2], **Hassan S Dashti**[3,4,5,6], **Brian Coughlin**[1], **Ryan A Tesh**[1,2], **Syed A Quadri**[1,2], **Abigail A Bucklin**[1,2], **Noor Adra**[1,2], **Parimala Velpula Krishnamurthy**[1,2], **Elissa M Ye**[1,2], **Aashritha Hemmige**[1,2], **Subapriya Rajan**[1,2], **Ezhil Panneerselvam**[1,2], **Jasmine Higgins**[1,2], **Muhammad Abubakar Ayub**[1,2,7], **Wolfgang Ganglberger**[1,2,8,9], **Luis Paixao**[1,2,10], **Timothy T Houle**[8,11], **B Taylor Thompson**[7], **Oluwaseun Johnson-Akeju**[4], **Richa Saxena**[3,4,5,6], **Eyal Kimchi**[1], **Sydney S Cash**[1,2], **Robert J Thomas**[2,12], **M Brandon Westover**[1,2,11]

[1]Department of Neurology, Massachusetts General Hospital, Boston, Massachusetts, USA

[2]Clinical Data Animation Center, Massachusetts General Hospital, Boston, Massachusetts, USA

[3]Center for Genomic Medicine, Massachusetts General Hospital, Boston, Massachusetts, USA

[4]Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Boston, Massachusetts, USA

[5]Brain Data Science Platform, Broad Institute, Cambridge, Massachusetts, USA

[6]Division of Sleep Medicine, Harvard Medical School, Boston, Massachusetts, USA

[7]Division of Pulmonary and Critical Care, Department of Medicine, Massachusetts General Hospital, and Harvard Medical School, Boston, Massachusetts, USA

[8]Sleep & Health Zurich, University of Zurich, Zurich, Switzerland

[9]Henry and Allison McCance Center for Brain Health, Massachusetts General Hospital, Boston, Massachusetts, USA

[10]Department of Neurology, Washington University School of Medicine in St. Louis, St. Louis, Missouri, USA

[11]Department of Medicine, Massachusetts General Hospital, Boston, Massachusetts, USA

Corresponding author: M. Brandon Westover, M.D., Ph.D, Department of Neurology, Massachusetts General Hospital, Boston, MA, Massachusetts General Hospital, Boston, MA. mwestove@bidmc.harvard.edu.

[*]Equal contribution, co-first authors.

[†]Co-senior authors

Authors' contributions

The authors' contributions were as follows: MJL, BC, RAT, SQ, OJA, SSC, RJT, and MBW: designed the study; MJL, HSD, BC, RAT, SQ, AAB, NA, PVK, WMT, AH, SR, EP, JH, MAA, WG, LP, SSC, TTH, TT, OJA, RS, SSC, RJT, and MBW conducted research and contributed to statistical analyses; MJL, HSD, BC, RAT, SQ, AAB, NA, SSC, RJT, and MBW interpreted data; MJL, HSD, BC, RAT, SQ, and MBW wrote the manuscript; and all authors: read and approved the final version of the manuscript.

Ethics approval and consent to participate

All recruited patients provided written consent upon enrollment. The present study protocol was approved by the MGB Institutional Review Board #2017P000090).

Consent for publication

Not applicable

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[12]Department of Medicine, Division of Pulmonary, Critical Care & Sleep, Beth Israel Deaconess Medical Center, Boston, Massachusetts, USA

Abstract

Background: Intensive care units (ICUs) may disrupt sleep. Quantitative ICU studies of concurrent and continuous sound and light levels and timings remain sparse in part due to the lack of ICU equipment that monitors sound and light. Here, we describe sound and light levels across three adult ICUs in a large urban United States tertiary care hospital using a novel sensor.

Methods: The novel sound and light sensor is composed of a Gravity Sound Level Meter for sound level measurements and an Adafruit TSL2561 digital luminosity sensor for light levels. Sound and light levels were continuously monitored in the room of 136 patients (mean age =67.0 (8.7) years, 44.9% female) enrolled in the Investigation of Sleep in the Intensive Care Unit study (ICU-SLEEP; Clinicaltrials.gov: #NCT03355053), at the Massachusetts General Hospital.

Results: The hours of available sound and light data ranged from 24.0 to 72.2 hours. Average sound and light levels oscillated throughout the day and night. On average, the loudest hour was 17:00 and the quietest hour was 02:00. Average light levels were brightest at 09:00 and dimmest at 04:00. For all participants, average nightly sound levels exceeded the WHO guideline of <35 decibels. Similarly, mean nightly light levels varied across participants (minimum: 1.00 lux, maximum: 577.05 lux). Sound and light events were more frequent between 08:00 and 20:00 than between 20:00 and 08:00 and were largely similar on weekdays and weekend days. Peaks in distinct alarm frequencies (Alarm 1) occurred at 01:00, 06:00, and at 20:00. Alarms at other frequencies (Alarm 2) were relatively consistent throughout the day and night, with a small peak at 20:00.

Conclusions: In conclusion, we present a sound and light data collection method and results from a cohort of critically ill patients, demonstrating excess sound and light levels across multiple ICUs in a large tertiary care hospital in the United States.

Registration: ClinicalTrials.gov, #NCT03355053. Registered 28 November 2017, https://clinicaltrials.gov/ct2/show/NCT03355053

Keywords

Intensive care units; sound; light; devices; critical illness; urban hospitals

Introduction

Sleep is sensitive to sound-induced disruption [1–5] and light [6–10]. There is a substantial literature describing the adverse effect of environmental sound on sleep, with an overall effect of shorter, lighter, and fragmented sleep [3, 11–13]. In addition, lights-on sleep is associated with increased stage 1 sleep (N1), decreased slow-wave sleep (SWS), and an increased arousal index. In an experimental lights-on sleep condition, spectral analysis shows that theta power (4-8 Hz) during REM sleep and slow oscillation (< 1 Hz), delta (1-4 Hz), and spindle (10-16 Hz) power during NREM sleep are decreased [10].

One area of medical care where excess sound and light are ubiquitous is intensive care units (ICUs) [14–16]. The World Health Organization (WHO) recommends that average hospital sound levels remain below 35 decibels (dB) at night, as a vital part of recovery from critical illness [17]. Recent studies have also recommended reducing light pollution to promote sleep and recovery in ICUs [18]. These recommendations are particularly important considering that sleep is generally poor among adult ICU patients, with reports indicating that up to 61% of patients experience frequent sleep disruptions and inadequate sleep duration [19, 20]. Ambient sound and light are also important environmental cues affecting the circadian clock, thus monitoring the exposure of ICU patients to these factors is necessary [18].

Characterizing and quantifying 24-hour sound and light levels in ICUs can determine the magnitude of future sound and light interventions[21]. Quantitative studies of concurrent and continuous sound and light levels and timings in the ICU remain limited. The absence of data is in part due to the lack of ICU equipment that systematically monitors sound and light. To address this gap, we developed a novel, an inexpensive sound and light sensor to characterize concurrent 24-hour sound and light levels in a large number of ICU patients. Here, we describe sound and light levels across three adult ICUs in a large urban United States tertiary care hospital using a novel sensor.

Methods

Sound and light sensor assembly

The core of the sound and light sensor is an Arduino Uno embedded computing system (Arduino.cc) with an Adafruit data logging shield for writing timestamped sensor measurements to .csv files on an SD card. For sound level measurements we used a Gravity Sound Level Meter with a measuring range of 30–130dBA, A-weighted frequency weighting, and a sampling rate of 3.33 Hz. Light levels were measured with an Adafruit TSL2561 digital luminosity sensor (Adafruit.com) and data were recorded as lux values. These sensors have a range of 0.1 to 40,000 lux and were set to medium gain for best performance in both bright and dim light conditions. Integration time was set to 100ms to balance speed of sampling and resolution of lux sensor output. To protect the device, we designed a 3D-printed enclosure to hold the Arduino, SD shield, and both sensors. Ports for the sensor components as well as the SD card and power/USB ports on the Arduino allow for data collection without any need for disassembly. Details on the design and instructions to build the sensor are included in the Supplemental Material.

Study Population and Setting

The sound and light sensors were used in the Investigation of Sleep in the Intensive Care Unit study (ICU-SLEEP; Clinicaltrials.gov: #NCT03355053), at the Massachusetts General Hospital (MGH), a large urban tertiary care academic teaching hospital in Boston, MA. The study was carried out in the three Intensive Care Units (ICUs) at MGH, an 18-bed Medical Intensive Care Unit (MICU), 20-bed Surgical Intensive Care Unit (SICU) and 18-bed mixed ICU medical and surgical ICU. The aim of the ICU-SLEEP randomized clinical trial is to determine whether dexmedetomidine reduces delirium by improving sleep in critically ill ICU patients. Trial inclusion and exclusion criteria and procedures are provided in the supplemental material.

ICU-SLEEP enrollment and data collection

We analyzed available sound and light level data in secondary analysis of data collected from patients enrolled between January through November 2019. Sound and light levels were continuously monitored in each patient's room throughout their study enrollment period. For each patient, recordings began the evening of study enrollment and continued until ICU discharge. All study participants provided informed consent prior to the start of study procedures. The study protocol was approved by the Mass General Brigham Institutional Review Board (protocol # 2017P000090).

Upon enrollment, the sound and light sensor was placed near the patient's bed up to 5 feet from the patient: either on a nearby device rack, on a counter by a window, or on a table next to the bed. The sound and light sensors were positioned upwards. A musical tuner was used to mark the start time of the recording to the nearest second by creating a notable square wave visually identifiable in the sound signal. The sensor remained in the room throughout the ICU admission. Following ICU discharge, the sensor was retrieved, and data were downloaded.

Sound and light sensor data processing

Sound data were visualized in MATLAB. The pulse from the musical tuner was first identified and the recorded time was used as the reference point to generate a timestamp for each signal sample in the file based on the 5 Hz sampling rate of the device. Data files without a visually identifiable pulse were excluded.

Average sound and light levels for each patient per hour was computed by binning each hour of signal into mutually exclusive segments, consistent with the change in clock hour (i.e., [0:00:00.00 - 0:59:59.99], [1:00:00.00 - 1:59:59.99], etc.). In addition, we computed hourly sound and light levels for all patients in aggregate.

A sound event was defined as a discrete period starting when the sound level first exceeds 80 dB and ending when the sound falls below 80 dB for at least three seconds. A series of noisy periods exceeding 80 dB occurring within three seconds of each other were considered as a single event.

To identify signatures of ICU alarms, we first automatically detected candidate alarms by computing the spectral power of the signal and identifying candidate segments with frequencies that match the alarms. To do so, we first smoothed the signal using a sixth-order Butterworth low-pass filter with upper frequency cutoff of 2 Hz. Next, we calculated the signal spectrogram with a segment length of 20 seconds and overlap of five seconds, returning a time series of power spectral densities with magnitude dB/Hz. Based on prior visual inspection of alarm signals, we determined that the characteristic frequency of Alarm 1 is exactly 0.2 Hz, and the frequency of Alarm 2 is 0.5 Hz. We determined that an appropriate spectral density threshold was 150 dB/Hz for Alarm 1, and 125 dB/Hz for Alarm 2. Using these thresholds, we identified candidate segments of possible alarms.

Next, we used a graphical user interface to display each candidate alarm and surrounding signal [size of time window], and these were confirmed or rejected as alarms based on visual inspection of waveform shape and the signal strength compared to background sound.

Light measures were smoothed with a one-second moving average. Following smoothing, we identified light events based on a relative change. For time t_i, we calculated the relative change in light signal L at t_i and L a distance Δt away, and compared this to a pre-determined threshold T:

$$|L(t_i + \Delta t) - L(t_i)| / (\min(L(t_i + \Delta t), L(t_i)) + 1) < T,$$

where |•| is absolute value and min(•) + 1 takes the minimum value of the signals, with an extra additive term to prevent unstable division by very small values. Thus, for each period Δt, we examined for a significant relative change (increase or decrease) in the light signal that occurred within the period that exceeded the relative threshold T. This approach identifies abrupt changes in light levels occurring within Δt, such as a light being turned on or off. The thresholding of relative changes in light level rather than absolute change is based on Weber's Law of human perception, where the minimum change in a signal that will cause a change in perception is proportional to the baseline level of the stimulus.

We set $\Delta t = 5$ seconds, $T = 0.5$, and only counted light events if at least one of $L(t_i)$ and $L(t_i + \Delta t)$ exceeded 10 flux, i.e. we did not count large relative changes in light as an event if the overall light level was consistently very low.

Sound and light sensor validation

To validate the performance of our sensor assembly in recording sound levels, recorded dB levels were compared between our sensor and a REED R8050 sound level meter. The Reed was set to A-weighted dB curve and fast sampling. Recordings of ambient sound levels were taken at 3 locations with different environmental sound levels. These were taken simultaneously, with devices placed next to one another to best accommodate changes in background sound. The sensors were powered on, and samples from the Reed meter were collected at 3 points during the recordings. The mean and standard deviation for the Reed sensor samples were calculated for each location. For all device recordings, 500 samples were used to calculate the mean and standard deviation of dB levels in each location. To test differences in frequency response, we also recorded sound levels from speakers generating a pure sine wave tone at 5 different frequencies within the human hearing spectrum (250, 500, 1000, 2000, 4000, and 8000 Hz). Sine wave tones were generated using an online tone generator (https://www.szynalski.com/tone-generator/) and constant gain on our speakers (Logitech Z130). Three samples were taken with the Reed meter at each frequency and averaged. Three windows of 16 samples were taken for the device recordings at each frequency and averaged. The mean and SD of the Reed meter and the mean of the window averages were calculated at each frequency.

To validate the lux data recorded by our sensors, readings were compared to data from an Extech Instruments LED Light Meter. The multiplication factor for our user calibration was set to 1x. The sensor enclosure and the sensor dome for the Extech were placed side by side in 3 different lighting conditions. To synchronize the devices, the lux sensor on the sensor was covered to “zero” the start time between sensors. The average mode on the Extech sensor was enabled and collected samples for 30 seconds. The displayed value was recorded, and the sensor data was downloaded to a computer via SD card reader for averaging over the same period. The start of the period was defined as the first value after removal of the finger and the mean of the 100 subsequent lux samples were taken to get a 30 second average. This process was repeated five times for each device under each lighting condition. Mean and SD of the averages are reported for 2 devices and the Extech for each condition.

Statistical Analysis

Patients with multiple days and nights available for the same hour contributed more to the hourly average, proportional to the number of signals available for that hour, allowing for maximal use of all available data. In addition, sound and light levels at night, between the hours of 20:00 to 08:00, were examined. To determine whether sound and light levels were related, we examined correlations between the sound and light data. Similarly, for patients with multiple days of sound and light events and for ICU alarms data, values were averaged across the number of days with available data. In sensitivity analyses, sound and light events from weekdays and weekend days were analyzed separately. Population-level summary statistics of these variables are presented as mean (SD). Analyses were conducted using MATLAB R2018a and Python 3.6.7.

Results

Subject characteristics

A total of 165 patients were enrolled between January and November 2019 across 3 adult ICUs (Figure 1). Of these, sound data were available for 136 participants, of which 127 had available light data (Table 1). The patients spanned 3 ICUs. Mean age was 67.0 (8.7) years, 44.9% of participants were female, 85.3% were White, and 92.6% were non-Hispanic. The median ICU and hospital length-of-stay were 5.0 and 11.0 days, respectively. The hours of available sound and light data ranged from 24.0 to 72.2 hours per participant. In aggregate, there were 458 days of sound recording (weekday/weekend days = 405/53) and 378 days of light recording (weekday/weekend days = 329/49).

Sound and light levels

Hourly sound and light levels across 24 hours are presented in Figure 1. Average sound and light levels oscillated throughout the day and night. On average, the loudest hour was 17:00 and the quietest hour was 02:00. Average light levels were brightest at 09:00 and dimmest at 04:00. ICUs were generally quieter and dimmer between 20:00 and 08:00, and louder and brighter between 08:00 to 20:00. Average hourly sound levels were consistently above 50 dB throughout the day. Light levels were below 10 lux between midnight and 4:00.

Sound levels at night (i.e., 20:00 to 08:00) varied across participants (Figure 2): the quietest hospital night was on average 42.67 dB while the loudest hospital stay was on average 62.79 dB. For all participants, average nightly sound levels exceeded the WHO guideline of <35 dB. Similarly, mean nightly light levels varied across participants (minimum: 1.00

lux, maximum: 577.05 lux). We found no significant correlations between nightly sound and light averages (Pearson correlation = −0.13; p = 0.12).

Alarms

We computed the hourly frequency of alarms throughout a 24-hour period (Figure 3). On average, there were fewer than one alarm per hour across all hours. Peaks in distinct alarm frequencies (Alarm 1) occurred at 01:00, 06:00, and at 20:00. Alarms at other frequencies (Alarm 2) were relatively consistent throughout the day and night, with a small peak at 20:00.

Sound and light events

We calculated the hourly frequency of sound and light events (Figure 4). Sound and light events were more frequent between 08:00 and 20:00 than between 20:00 and 08:00. On average, there were more than one sound and light event per hour at every hour of the day. The frequency of events was highest at 17:00 and 15:00 for sound and light, respectively. Whereas the patterns of sound and light events were similar on weekdays and weekend days, events were generally fewer on weekend days compared to weekdays (Figure 4).

Validation of sound and light sensors

Our validation tests showed our devices can reliably record ambient dB levels in multiple environments (Table 2). Sine wave tests showed a discrepancy in power at specific frequencies, either due to a difference in the A-weighting of the sensor or frequency-specific filtering of the enclosure. Broadband recordings - the devices' intended use – were accurate. Lux sensors showed less-reliable absolute values when compared to commercial sensors (Table 3). Values were consistent between sensors; therefore, the dynamics of the light levels are still reflected in these data and can be compared between sound and light sensors.

Discussion

Our study characterizes patterns of sound and light variations across three ICUs in a large tertiary care hospital. Sound and light levels showed systematic patterns of variation according to time of day, varied from patient to patient, but were not strongly correlated. Sound levels consistently exceeded recommended sound thresholds established by the WHO. Light levels showed a relatively clear but shortened scotoperiod and thus an elevated photoperiod. Light and sound events with disruptive potential were frequent.

We found that sound and light levels indicated that disturbances from environmental disruptors occurs at all hours in the ICU. Generally, daytime hours between 08:00 and 20:00 were louder and brighter than nighttime hours between 20:00 and 08:00. Sound levels were on average 15 dB higher than the threshold established by the WHO throughout the day and night. The loudest detected hour of 17:00 coincides with a known time of day of increased clinical activities, including shift changes and ICU discharge. Light levels in the ICU were brightest at 09:00, at a time when likely both natural and artificial light exposure may peak. The weak correlations between sound and light levels suggest that the sources of sound and light disruptors are unrelated.

Two distinct alarm signatures, based on volume and frequency, were detected in the ICUs. Alarm 1, which peaked at 01:00, 06:00, and 20:00, coincided with the times of study-related drug administration. Alarm 2, which was generally evenly distributed throughout all hours of the day and night, may be related to sound emitted from medications, pressors, and antibiotics on pumps, alarms outside the room, alarm signals resulting from cardiac arrythmias or other irregularities in vital signs. Closer analysis of ICU alarm data may provide insights into alarm management solutions that may reduce the frequency and duration of sound disruptors throughout the ICU [22].

While trends in sound and light levels were generally comparable across patients, the magnitude of the exposure to these environmental disruptors varied from patient to patient. Variability in exposure may be related to the relative location of the room within the ICU, for example proximity to the ICU entrance (relevant for ICU admissions and discharges), other patient rooms, or nurse station, the design and size of the ICU room, for example number and placement of windows, the placement of the sound and light sensor within the room, which varied across patients, or the severity of patient illness which would directly impact the number of medical devices supporting the patient and the frequency of patient contact by the medical team. The contribution of each of these factors impacting sound and light variability in patient rooms cannot be elucidated from this study. Careful future examination of these factors may help disentangle their relative contribution to sound and light.

Excess sound or light in the ICU is known to affect sleep quality in critically ill patients. Up to 61% of adults in the ICU experience a lack of sleep or sleep disruptions [20]. Sleep disturbance is particularly common after surgery [23], as well as in critically ill patients on mechanical ventilation [19]. Preliminary evidence suggests that prioritizing sleep in the ICU may improve delirium-related outcomes, which could reduce ICU length-of-stay [24]. Impaired circadian rhythms have also been reported in ICU patients and may be due to exposure to consistently low lighting during the day and bright light at night [25]. Thus, the 24-hour consideration of both sound and light levels, and not only nighttime, is necessary for critically ill patients.

Modern ICU environments and operations remains suboptimal to support good quality sleep. Several simple and practical steps may be employed to limit environmental sound and light disruptors. Interventions, such as the application of earplugs or eye masks together with relaxing music have been reported to promote sleep in a cardiac surgical ICU patient population [26]. Similarly, the use of self-initiated patient-directed music or noise-cancelling headphones in critically ill patients receiving ventilatory support reduced anxiety and sedation intensity compared with usual care[27]. Limiting patient disturbances during the night, whenever possible, or the strategic placement of patients in certain ICU rooms based on traffic, may also provide additional opportunities for controlling overall sound and light exposure [28]. Upgrading room and bed lightening, orienting patients towards or away from windows, and utilizing solar shades can also provide contrast between bright daytime lighting and dim nighttime light levels, which may promote robust circadian rhythms [29, 30]. Although many patients in the ICU may have their eyes closed, bright light can still be a potent entrainer of circadian rhythms [18]. Reducing overall noise in the ICU may also limit stress levels and improve well-being among staff members.

A strength of this study is the multiple-day concurrent assessment of sound and light in a large, heterogeneous critically ill patient cohort across several ICUs in a large urban hospital in the United States. However, important limitations should be considered. The placement of the sensors varied across patients, thus the measured ambient sound and light may not reflect the exact levels perceived by the patients, especially in special circumstances when patients temporarily leave the room, for example for radiology. As the present study focuses on characterizing sound and light levels in the ICU, their impact on clinically relevant outcomes, such as risk of delirium, and patients' perception of the sound and light levels, including possible annoyance and intolerance, in this cohort remains unknown. In addition, the source of the sound and light exposures such as events and alarms cannot be elucidated. Thus, it remains unclear what efforts are necessary to mitigate environmental disruptors in large urban hospital ICUs. Alarm determination from careful visual inspection of waveform shape and the signal strength is prone to various errors, and thus results pertaining to the alarms should be interpreted cautiously. Lastly, as the study focused on a single large urban hospital in the United States, similar characterization of sound and light levels in other hospitals is necessary for external validity of these findings.

Conclusion

In summary, we present a light and sound data collection method and results from a cohort of critically ill patients, demonstrating likely excessive sound and light levels across multiple ICUs in a large tertiary care hospital in the United States. Continued efforts to mitigate environmental disruptors, including sound and light, in clinical settings are necessary.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Availability of data and materials

Data are available from the Mass General Brigham Human Research Office/Institutional Review Board at Mass General Brigham (contact located at https://www.partners.org/Medical-Research/Support-Offices/Human-Research-Committee-IRB/Default.aspx) for researchers who meet the criteria for access to confidential data.

Reference

1. Coborn JE, Lessie RE, Sinton CM, Rance NE, Perez-Leighton CE, Teske JA. Noise-induced sleep disruption increases weight gain and decreases energy metabolism in female rats. Int J Obes (Lond). 2019;43:1759–68. doi:10.1038/S41366-018-0293-9. [PubMed: 30568267]
2. Fidell S, Tabachnick B, Pearsons K. The state of the art of predicting noise-induced sleep disturbance in field settings. Noise Health. 2010;12:77–87. doi:10.4103/1463-1741.63207. [PubMed: 20472953]
3. Lechat B, Scott H, Decup F, Hansen KL, Micic G, Dunbar C, et al. Environmental noise-induced cardiovascular responses during sleep. Sleep. 2022;45. doi:10.1093/SLEEP/ZSAB302.
4. Saletu B, Grunberger J. Traffic noise-induced sleep disturbances and their correction by an anxiolytic sedative, OX-373. Neuropsychobiology. 1981;7:302–14. doi:10.1159/000117865. [PubMed: 6118840]
5. Sanok S, Berger M, Müller U, Schmid M, Weidenfeld S, Elmenhorst EM, et al. Road traffic noise impacts sleep continuity in suburban residents: Exposure-response quantification of noise-induced awakenings from vehicle pass-bys at night. Sci Total Environ. 2022;817. doi:10.1016/J.SCITOTENV.2021.152594.
6. Daurat A, Aguirre A, Foret J, Benoit O. Circadian Rhythms Disruption of Sleep Recovery After 36 Hours of Exposure to Moderately Bright Light. Sleep. 1997;20:352–8. https://academic.oup.com/sleep/article/20/5/352/2732126. Accessed 13 Apr 2022. [PubMed: 9381057]
7. Raap T, Pinxten R, Eens M. Light pollution disrupts sleep in free-living animals. Sci Rep. 2015;5. doi:10.1038/SREP13557.
8. Mason IC, Grimaldi D, Reid KJ, Warlick CD, Malkani RG, Abbott SM, et al. Light exposure during sleep impairs cardiometabolic function. Proc Natl Acad Sci U S A. 2022;119. doi:10.1073/PNAS.2113290119.
9. Ohayon MM, Milesi C. Artificial Outdoor Nighttime Lights Associate with Altered Sleep Behavior in the American General Population. Sleep. 2016;39:1311–20. doi:10.5665/SLEEP.5860. [PubMed: 27091523]
10. Cho JR, Joo EY, Koo DL, Hong SB. Let there be no light: the effect of bedside light on sleep quality and background electroencephalographic rhythms. Sleep Med. 2013;14:1422–5. doi:10.1016/J.SLEEP.2013.09.007. [PubMed: 24210607]
11. Fidell S Brief on noise-induced sleep disturbance. Noise Health. 2010;12:59–60. doi:10.4103/1463-1741.63203. [PubMed: 20472949]
12. Michaud DS, Fidell S, Pearsons K, Campbell KC, Keith SE. Review of field studies of aircraft noise-induced sleep disturbance. J Acoust Soc Am. 2007;121:32–41. doi:10.1121/1.2400613. [PubMed: 17297758]
13. Rojek M, Wojciechowska W, Januszewicz A, Czarnecka D, Skalski P, Rajzer M. The relation of nocturnal exposure to aircraft noise and aircraft noise-induced insomnia with blood pressure. Polish Arch Intern Med. 2021;131:33–41. doi:10.20452/PAMW.15716.
14. Aaron JN, Carlisle CC, Carskadon MA, Meyer TJ, Hill NS, Millman RP. Environmental noise as a cause of sleep disruption in an intermediate respiratory care unit. Sleep. 1996;19:707–10. doi:10.1093/SLEEP/19.9.707. [PubMed: 9122557]
15. Freedman NS, Gazendam J, Levan L, Pack AI, Schwab RJ. Abnormal sleep/wake cycles and the effect of environmental noise on sleep disruption in the intensive care unit. Am J Respir Crit Care Med. 2001;163:451–7. doi:10.1164/AJRCCM.163.2.9912128. [PubMed: 11179121]
16. Horsten S, Reinke L, Absalom AR, Tulleken JE. Systematic review of the effects of intensive-care-unit noise on sleep of healthy subjects and the critically ill. Br J Anaesth. 2018;120:443–52. doi:10.1016/J.BJA.2017.09.006. [PubMed: 29452801]
17. Berglund B, Lindvall T, Schwela DH. Guidelines For Community Noise. 1999. https://www.who.int/docstore/peh/noise/Comnoise-1.pdf. Accessed 29 Jun 2021.
18. Durrington HJ, Clark R, Greer R, Martial FP, Blaikley J, Dark P, et al. ‘In a dark place, we find ourselves’: light intensity in critical care units. Intensive Care Med Exp. 2017;5. doi:10.1186/s40635-017-0122-9. [PubMed: 28105603]

19. Cooper AB, Thornley KS, Young GB, Slutsky AS, Stewart TE, Hanly PJ. Sleep in critically ill patients requiring mechanical ventilation. Chest. 2000;117:809–18. doi:10.1378/CHEST.117.3.809. [PubMed: 10713011]
20. Gabor JY, Cooper AB, Crombach SA, Lee B, Kadikar N, Bettger HE, et al. Contribution of the intensive care unit environment to sleep disruption in mechanically ventilated patients and healthy subjects. Am J Respir Crit Care Med. 2003;167:708–15. doi:10.1164/rccm.2201090. [PubMed: 12598213]
21. Elliott RM, Mckinley SM, Eager D. A pilot study of sound levels in an Australian adult general intensive care unit. Noise Health. 2010;12:26–36. doi:10.4103/1463-1741.59997. [PubMed: 20160388]
22. Poncette AS, Wunderlich MM, Spies C, Heeren P, Vorderwülbecke G, Salgado E, et al. Patient Monitoring Alarms in an Intensive Care Unit: Observational Study With Do-It-Yourself Instructions. J Med Internet Res. 2021;23. doi:10.2196/26494.
23. Redeker NS, Hedges C. Sleep during hospitalization and recovery after cardiac surgery. J Cardiovasc Nurs. 2002;17:56–68; quiz 82–3. http://www.ncbi.nlm.nih.gov/pubmed/12358093. Accessed 8 Oct 2019. [PubMed: 12358093]
24. Flannery AH, Oyler DR, Weinhouse GL. The Impact of Interventions to Improve Sleep on Delirium in the ICU: A Systematic Review and Research Framework. Crit Care Med. 2016;44:2231–40. doi:10.1097/CCM.0000000000001952. [PubMed: 27509391]
25. Fan EP, Abbott SM, Reid KJ, Zee PC, Maas MB. Abnormal environmental light exposure in the intensive care environment. J Crit Care. 2017;40:11–4. doi:10.1016/j.jcrc.2017.03.002. [PubMed: 28292665]
26. Hu R-F, Jiang X-Y, Hegadoren KM, Zhang Y-H. Effects of earplugs and eye masks combined with relaxing music on sleep, melatonin and cortisol levels in ICU patients: a randomized controlled trial. Crit Care. 2015;19:115. doi:10.1186/s13054-015-0855-3. [PubMed: 25881268]
27. Chlan LL, Weinert CR, Heiderscheit A, Tracy MF, Skaar DJ, Guttormson JL, et al. Effects of patient-directed music intervention on anxiety and sedative exposure in critically ill patients receiving mechanical ventilatory support: a randomized clinical trial. JAMA. 2013;309:2335–44. doi:10.1001/JAMA.2013.5670. [PubMed: 23689789]
28. Tamburri LM, DiBrienza R, Zozula R, Redeker NS. Nocturnal Care Interactions with Patients in Critical Care Units. Am J Crit Care. 2004;13:102–13. doi:10.4037/AJCC2004.13.2.102. [PubMed: 15043238]
29. Madrid-Navarro C, Sanchez-Galvez R, Martinez-Nicolas A, Marina R, Garcia J, Madrid J, et al. Disruption of Circadian Rhythms and Delirium, Sleep Impairment and Sepsis in Critically ill Patients. Potential Therapeutic Implications for Increased Light-Dark Contrast and Melatonin Therapy in an ICU Environment. Curr Pharm Des. 2015;21:3453–68. doi:10.2174/1381612821666150706105602. [PubMed: 26144941]
30. Engwall M, Fridh I, Johansson L, Bergbom I, Lindahl B. Lighting, sleep and circadian rhythm: An intervention study in the intensive care unit. Intensive Crit care Nurs. 2015;31:325–35. doi:10.1016/J.ICCN.2015.07.001. [PubMed: 26215384]

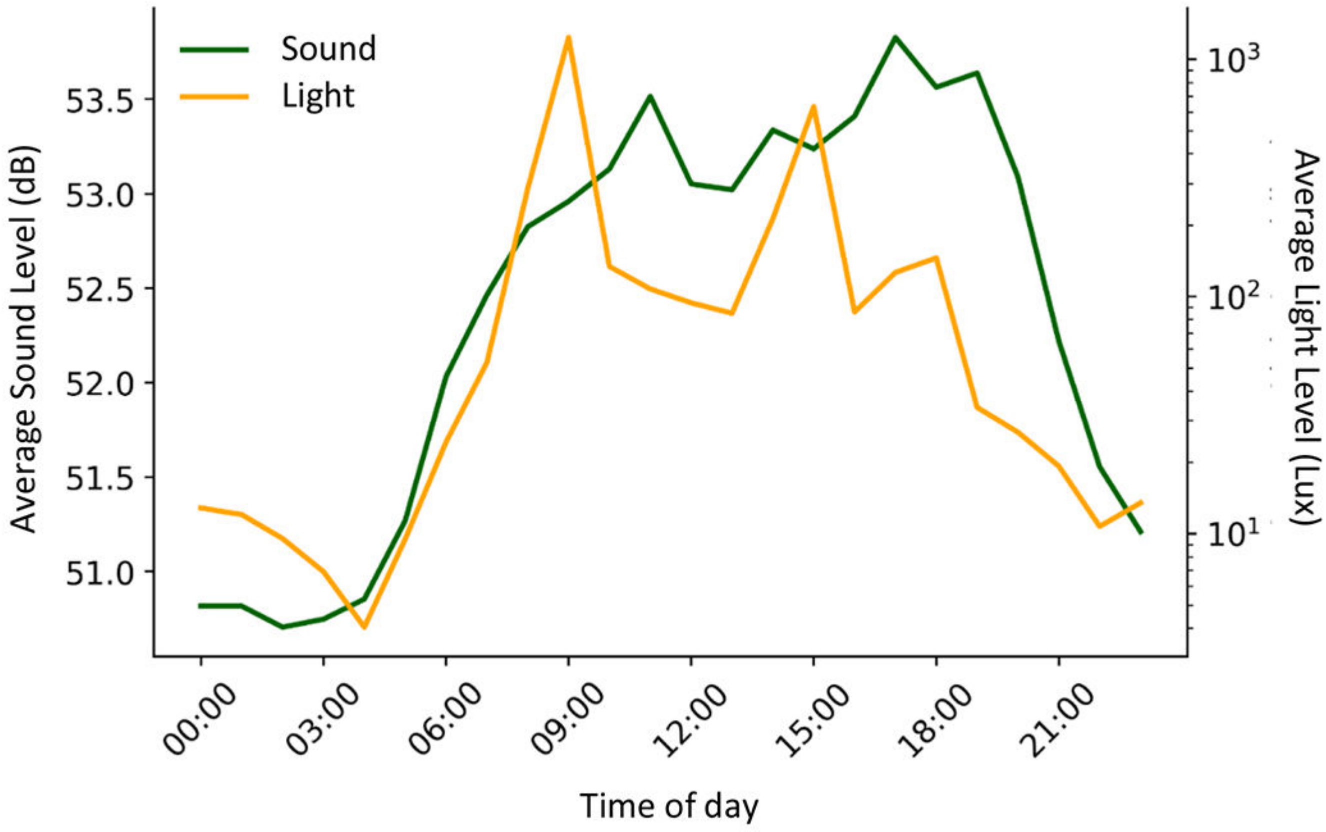

Figure 1:

Hourly averages of sound and light levels across 24 hours in three adult ICUs.

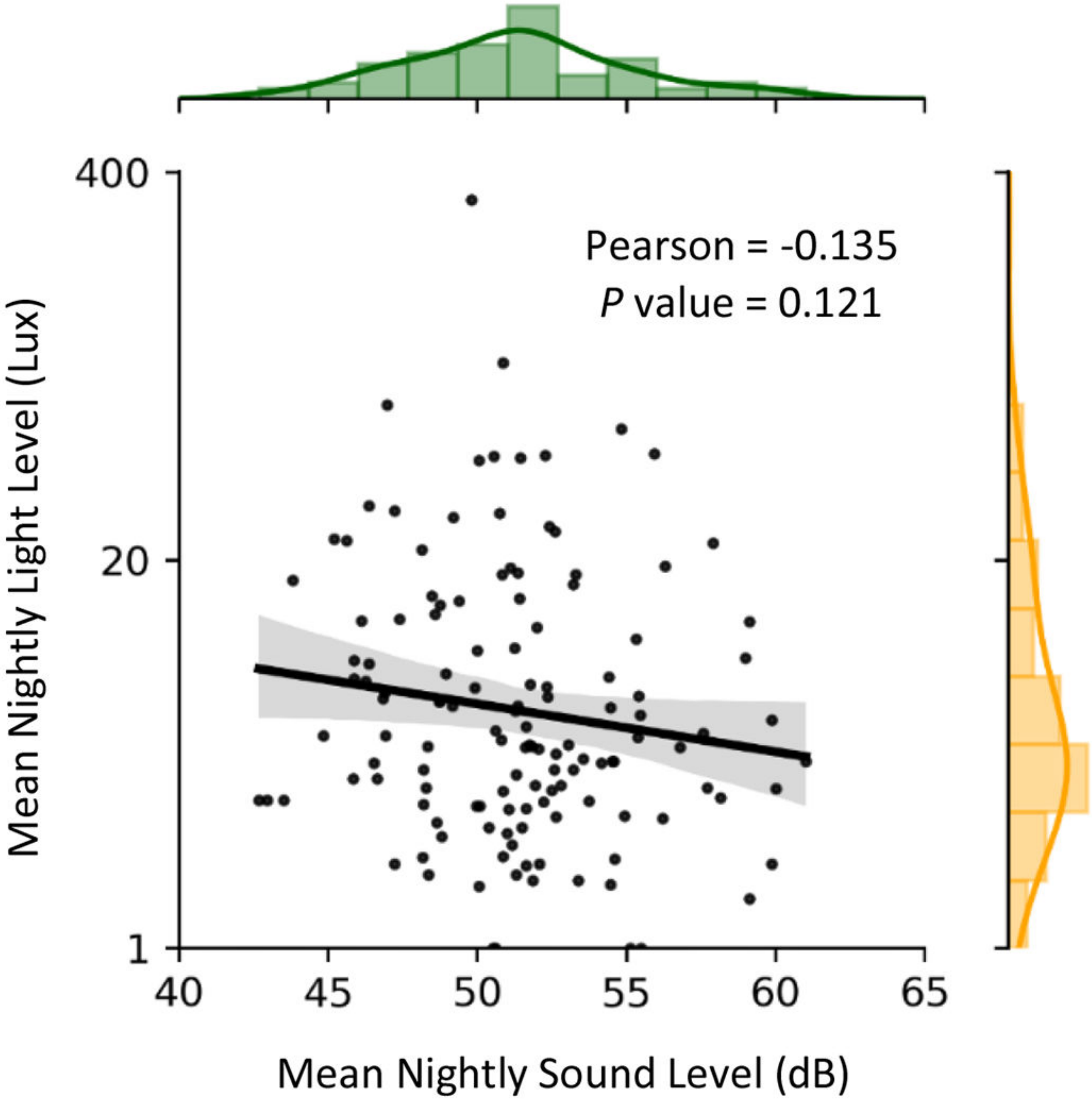

Figure 2:

Distribution of average night (i.e., 20:00 to 08:00) sound against light levels in three adult ICUs. Scatterplot and regression line show the linear correlations between nightly sound and light levels by participant. Green and yellow histograms show nightly sound and light levels by participant, respectively.

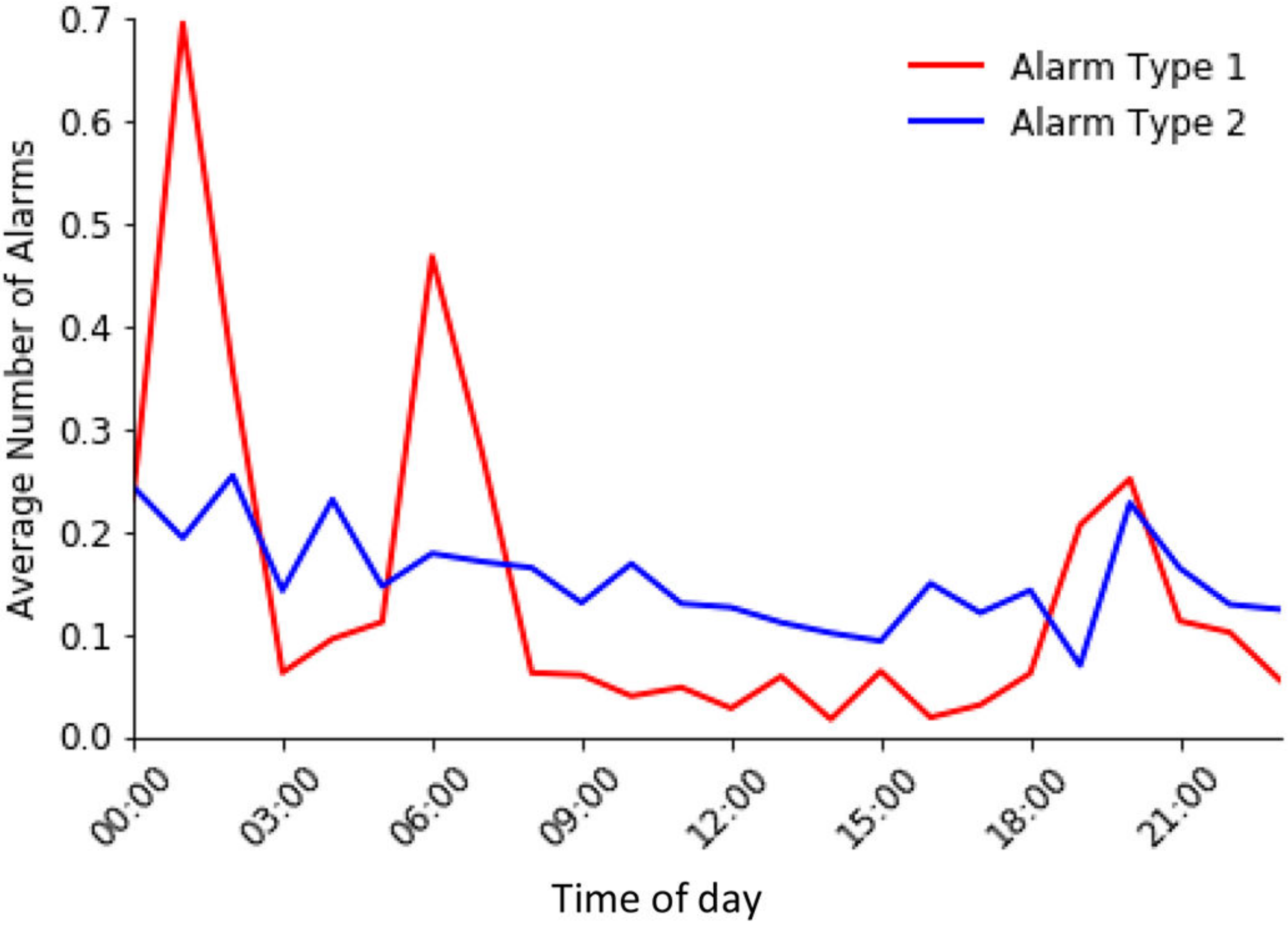

Figure 3:

Hourly averages of two alarm types across 24 hours in three adult ICUs.

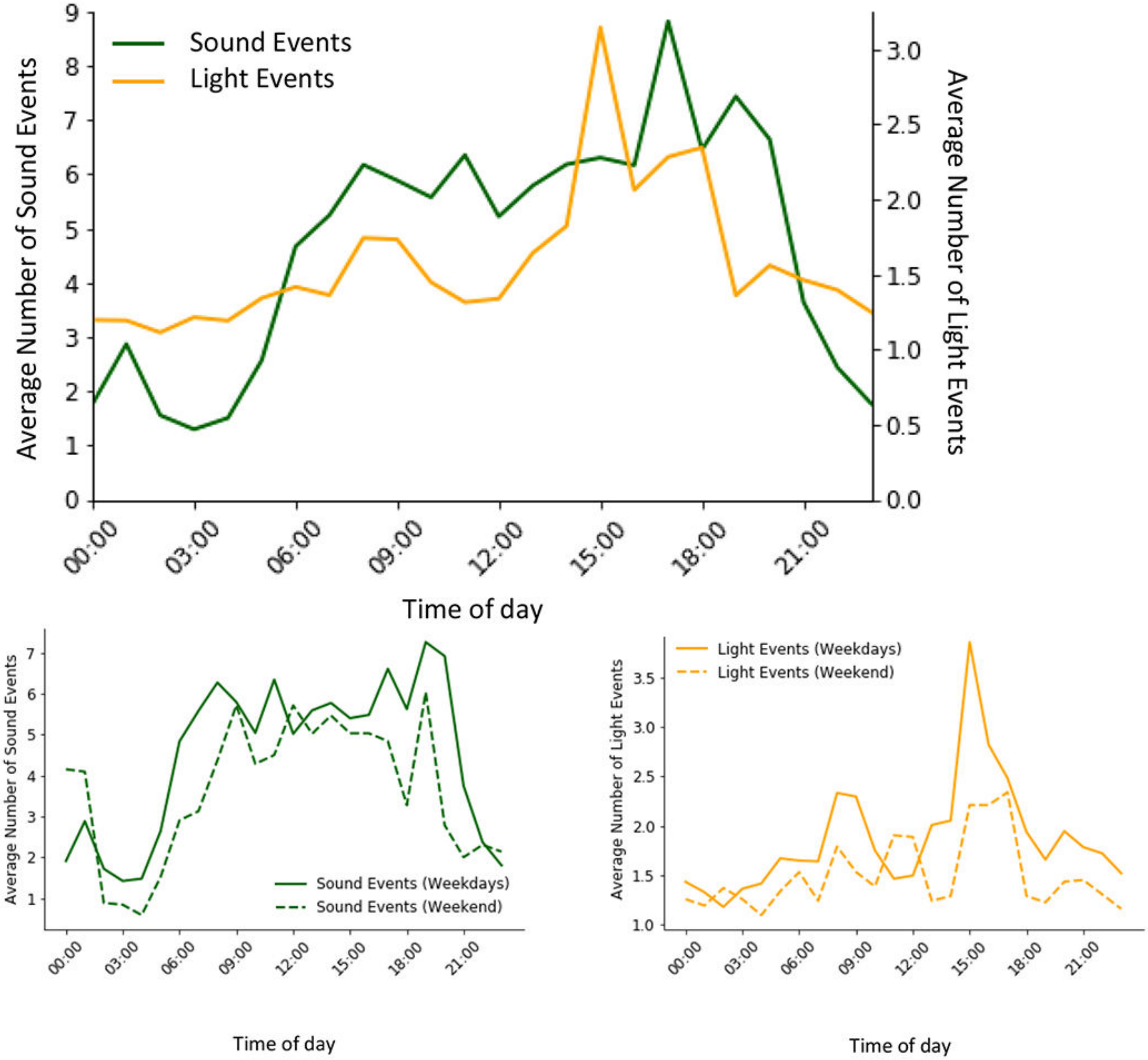

Figure 4:

Hourly averages of sound and light events across 24 hours in three adult ICUs and stratified by weekdays and weekend days.

Table 1:

Characteristics of patients enrolled in the ICU-SLEEP study.

	Overall
n	136
Age, mean (SD)	67.0 (8.7)
Gender, n (%)	
Female	61 (44.9)
Male	75 (55.1)
Hispanic, n (%)	
Unknown	3 (2.2)
No	126 (92.6)
Yes	7 (5.1)
Race, n (%)	
Asian	4 (2.9)
Black	5 (3.7)
Unknown	9 (6.6)
Other	2 (1.5)
White	116 (85.3)
ICU Site, n (%)	
Blake 12	57 (41.9)
Blake 7	30 (22.1)
Ellison 4	49 (36.0)
ICU length-of-stay, median (IQR)	5.0 (4.0, 7.0)
Hospital length-of-stay, median (Q1,Q3)	11.0 (7.8, 22.20)
Total hours of data, median (Q1,Q3)	46.5 (24.0, 72.2)
Nightly hours of data (20:00 to 8:00), median (Q1,Q3)	24.0 (12.0, 36.0)

Table 2:

Validation data from Reed dB meter and sound and light sensors. Data presented as mean dB ± std.

Test	Reed dB meter	Sensor A	Sensor B
Location A	49.5 ± 0.170	49.3 ± 0.691	49.8 ± 0.767
Location B	59.5 ± 0.374	56.7 ± 0.713	59.4 ± 0.828
Location C	47.2 ± 0.245	43.8 ± 0.754	46.9 ± 0.832
250Hz Sine	67.9 ± 0.330	65.2 ± 0.315	54.9 ± 4.047
500Hz Sine	57.3 ± 0.386	65.9 ± 0.203	54.8 ± 2.569
1000Hz Sine	60.9 ± 1.372	53.2 ± 1.407	52.0 ± 0.626
2000Hz Sine	64.6 ± 1.080	66.5 ± 0.242	57.1 ± 4.220
4000Hz Sine	60.1 ± 3.065	61.5 ± 1.670	52.3 ± 0.969
8000Hz Sine	51.6 ± 1.147	56.7 ± 0.384	51.8 ± 1.320

Table 3:

Validation data from Extech light meter and sound and light sensors. Data presented as mean lux ± std.

Test	Extech light meter	Sensor A	Sensor B
Location A	3156.2 ± 106.1	1232.8 ± 92.6	1241.5 ± 93.2
Location B	11.8 ± 3.8	1.0 ± 0.1	1.0 ± 0.1
Location C	683.8 ± 29.6	371.1 ± 18.5	375.5 ± 22.8