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Ambient Stimuli Perpetuate Nighttime Sleep Disturbances in Hospital Patients With TBI

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Abstract

Background and Objectives: The effect of the ambient environment, sound, light, and movement, on the nighttime rest-activity of patients hospitalized with moderate-severe traumatic brain injury (TBI) is poorly understood. The purpose of this study was to examine how sound, light, and movement in these patients' hospital rooms may contribute to nighttime awakenings. **Methods:** An observational design was used with 18 adult participants on a neuroscience step-down unit diagnosed with moderate-severe TBI. For up to five consecutive nights, actigraphy was used to capture nighttime awakenings while a custom-made multisensory device captured sound, light, and movement exposures in the participant's room. **Results:** Participants were awake for 24% (or about 3 hr) of the time during the designated nighttime period of 8 PM to 8 AM. Average nighttime exposures of sound was 52 dB, light was nine lumens, and movement, measured as a proportion, was 0.28% or 28%. With each stimuli exposure set at its average, there was a 20% probability of participant nighttime awakenings. Clinically meaningful reductions of movement in and out the participant's room and elevated sound significantly decreases the participant's probability of nighttime awakenings ($p < .05$), but reductions in light did not. **Conclusion:** The ambient environment seems to impede restful sleep in immediate post-injury phase of patients with moderate-severe TBI.

Keywords

noise, nocturnal awakenings, sleep, environment, TBI

Nearly 300,000 Americans are hospitalized for traumatic brain injury (TBI) each year (Taylor et al., 2017) and restful sleep is critical for neural recovery (Ouellet et al., 2015) in the immediate post-injury phase (Duclos et al., 2017). However, it is unclear how these ambient exposures such as clinician-led monitoring, surveillance (Inouye, 2013; Nelson et al., 2015), and hospital system operations (e.g., maintenance, air-handling, Busch-Vishniac et al., 2005) impede restful sleep in this phase of hospitalization during the nighttime hours despite evidence that patients hospitalized with TBI have poor and fragmented sleep (Chiu et al., 2013, 2014; Duclos et al., 2016; Williams et al., 2019; Wiseman-Hakes et al., 2016). The patients' exposure to noxious sound, light, and movement stimuli during the nighttime hours is duly important because these ambient stimuli are common to the neuroscience step-down unit (NSDU), a crucial post-injury phase of care where clinicians often evaluate the patients' discharge destination. Examining the influence of ambient stimuli on nighttime awakenings is a missed opportunity because evidence not only shows a clear linkage between sleep and recovery (Duclos et al., 2017), but also suggests that noxious ambient stimuli negatively affect post-TBI recovery (Callahan & Lim, 2018).

Purpose of the Study

To examine how ambient stimuli in the NSDU hospital rooms may contribute to nighttime awakenings in patients with

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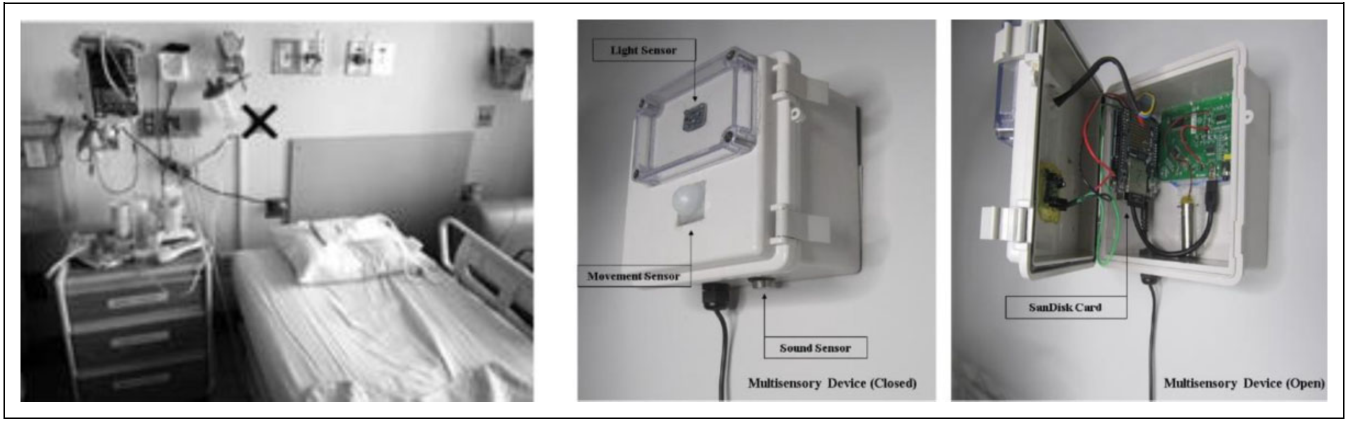

Figure 1. Wall placement and image of multisensory device. *Note.* The image on the left side of this figure shows an example of where the multisensory device was placed in the participants hospital room indicated by an "X." The image on the right side of the figure shows a multisensory device mounted on the wall.

moderate-severe TBI, we conducted an observational study to address three aims. Our first aim was to determine the participant's amount of nighttime awakenings. The second aim was to identify pattern(s) of exposure to ambient stimuli (sound, light, movement) in the hospital rooms throughout the night. Our third and final aim was to examine the combined effect of ambient stimuli on nighttime awakenings and to identify which ambient stimulus should be targeted to produce the greatest clinically meaningful reduction in nighttime awakenings.

Method

Participants and Procedure

The University of Washington Institutional Review Board (IRB) granted approval for all study procedures. Between June 2016 and January 2017, 20 hospitalized patients with moderate-severe TBI were recruited from a 36-bed adult neuroscience unit of a level 1 trauma center. Informed consent was obtained from either the participant or the legally authorized representative (LAR). Inclusion criteria: Eligible participants: (1) had an admission diagnosis of blunt TBI confirmed with radiological studies; (2) had a Glasgow Coma Scale score (GCS) between 3 and 11 on admission to the emergency department (ED) to indicate moderate-severe brain injury (Jennett & Teasdale, 1977); (3) were $\geq$18 years of age; (4) had a Rancho Los Amigos (RLA) Cognitive Functioning Scale score $\geq$5 to ensure they had adequate cognitive and functional ability to meaningfully contribute to actigraphy capture.

Rancho Los Amigos (RLA) Scale of Cognitive Functioning. The RLA is a reliable assessment of the awareness, cognition, and behavior (Hagen, 1997; Hagen et al., 1972; Malkmus & Stenderup, 1974) of purposeful interaction in people with TBI and its scoring ranges from 1 to 8. A score of 1 means the person has no response to external stimuli, while a score of 8 means the person responds purposefully and appropriately. Studies show that in the brain-injured population RLA has good reliability (Spearman's $\rho = .82$) and excellent concurrent validity ($r = .92$) with the Stover-Zeiger Scale—an equally canonical evaluation of post-TBI functioning (Johnston et al., 1991). Participants diagnosed with a pre-existing sleep condition or with a planned length of stay of less than 24 hr were excluded.

The hospital's trauma registry and electronic medical record (EMR) were used to screen and identify potential study participants and included reviews of the following: confirmation that GCS scores were between 3 and 11, history of present illness, chief complaint, nurse's notes, and physician orders. All study procedures, including data collection, were carried out for a maximum of 5 consecutive nights. Researchers installed a multisensory device on the wall in the participants' room (Figure 1) and placed an actigraphy watch on the non-dominant wrist or on dominant wrist if casts or IVs were present (see Instruments). Owing to incomplete files, the analytic sample used for data analysis, 85,659 observations, was derived from 18 participants.

Injury Variables

Glasgow Coma Scale. Extracted from EMR, the GCS scores the participants level-of-consciousness when they arrive to the ED and were used to determine intensity of neurological injury (range 3–15). When used in people with TBI, GCS reliability is high ($\alpha = 0.85$; Sadaka et al., 2012). A higher GCS (14 or 15) indicates the person is neurologically stable, while a lower GCS (3–6) indicates the opposite and is characterized by the person's inability to open their eyes, speak, or move purposefully.

Instruments

Two types of instruments were used in this study. The first, an actigraphy watch, was used to capture the outcome variable, nighttime awakenings. Second, a multisensory device was used to capture the ambient stimuli predictor variables of sound, light, and movement.

Actigraphy for nighttime awakenings. To measure the number of nighttime awakenings Actiwatch Spectrum Plus® (Phillips Respironics, Bend, OR, USA) wrist actigraphy-watches (48 mm × 37 mm × 15 mm; wt., 31 g with band) were used; watches were calibrated to measure in 30-s epochs. Actigraphy is reliable and valid for assessing sleep disturbances (Ancoli-Israel et al., 2003; Morgenthaler et al., 2015) and has been used in hospitalized patients with TBI (Chiu et al., 2013, 2014; Duclos et al., 2016; Williams et al., 2019). Data were scored with Phillips Actiware® software (Version 6.0.9) and a standard scoring algorithm developed by experienced sleep researchers at the University of Washington (Buchanan et al., 2017). Sleep diaries are often used to score actigraphy but were untenable in the current study for three major reasons. First, it was expected that the acuity of the participants injury and injury-related cognitive deficits would make their account of nightly rest-activity cycles unreliable (poor recall; Nazem et al., 2016). Second, the legally authorized representatives could not provide an accurate sleep diary account of the participant's nightly rest-activity cycle because they were not consistently present during the nighttime period. Finally, the participant's nurse may be different over the course of their time in the study or even sometimes during the night, making it untenable for the nurse to complete the sleep diary. Once scored, actigraphy data were indexed to only include wake-bouts (a binary variable renamed to nighttime awakenings) between the hours 8 PM and 8 AM. Visual inspection of actigraphy data showed that most of the participants were at rest between the hours 8 PM and 8 AM.

Multisensory devices for ambient stimuli. A custom-made, multisensory device was developed and built for this study and validated for use. The multisensory device, electronically powered and designed to discreetly blend in with the milieu of the hospital room (dimension 14 cm × 14 cm × 8.5 cm; color: off-white), was installed on the wall next to the head of the participant's bed (Figure 1). Sound, light, and movement were measured in 1-s epochs using three different sensors (one sensor per each stimuli) to capture continuous background levels of sound, light, and movement. The equipment was calibrated 1 hr before use (in a laboratory setting). All measurement data from the multisensory device were collected on an 8 GB SanDisk card. To be clear, no participant or provider conversations were collected because the device only captured sound pressure level (SPL). Output of the multisensory device was a plain text (.txt) file. Details of reliability and validation of each of the multisensory device's ambient stimulus components are as follows:

Sound. SPL, measured in decibels (dB[A]), is a continuous variable in the current study. To capture noise perception of the *human* ear, the sound sensor was configured to the "A"-weighted sound pressure filter and to the "slow" sound pressure speed, which together more closely align with the perception of human hearing. Therefore, of the four main sound pressure filters, called weightings ("A," "B," "C," and "Z"), the sound sensor was set to "A-weighting" and of the two main sound pressure speeds, fast and slow, the sound sensor was set to "Slow." The sound sensor could detect noise as low as ~40 dB (i.e., quiet bookstore) to noise as loud as ~140 dB (i.e., runway of jet-plane) with ±2 dB margin of error. Side-by-side reliability and validity testing of the sound sensor was conducted in a laboratory setting and on the hospital's neuroscience unit with a 3 M NoisePro dosimeter (gold-standard) and showed a high level of agreement ($R^2 = 0.99$). Details of this and 3 M Octave band analyses are reported elsewhere (Williams et al., 2016).

Light. Light intensity, measured in lumens (lux), is a continuous variable in the study. The light sensor's intensity detected exposure from as low as 0 lux to as high as 39,000 kilo lux. As with sound, side-by-side reliability, and validity testing conducted in a laboratory setting showed a high level of agreement ($R^2 = 0.90$) between the light sensor and its gold standard, the Digi-Sense® light meter.

Movement. Movement, measured by motion-activated passive infrared technology (PIR), and reported as a proportion (p), is a binary variable. As appropriate for the study's purpose, PIR only detects human movement. To validate the movement sensor, in the laboratory setting, we first connected to a laptop to display the real-time code-output for the PIR sensor. Second, a colleague stood 0.6 m in front of the sensor and, on command, sequentially stepped from left to right on an equidistant floor (0.3 m × 0.3 m) grid every 5 s. While there is no gold-standard assessment for PIR, the sensor showed adequate construct validity because it accurately measured movement as it occurs. The sensor fired when a human moved in front it and stopped firing when human movement ceased; both actions were confirmed with real-time code output.

Data Analysis

RStudio (R Version 3.3.1) was used to create a data file of observations for analysis after determining that a visual inspection of plots from the actigraphy watch and the multisensory device did not show any time lag between the devices. First, data from the multisensory device were aggregated from 1-s epochs into 30-s epochs using the maximum values of sound, light, and movement within the 30-s epoch. Second, complete data files from the actigraphy watch and the multisensory device were merged into a single file based on observation timestamps. Third, data were trimmed to have the same number of observations (observations $N = 85{,}659$) from both instruments. Finally, a file with participant characteristics and demographics was merged into that data set.

Aim 1 analysis. To address aim 1, determine the participant's number of total awakenings, we divided the total observed awakenings by the total number of observations recorded for the five nights of hospitalization. This calculation resulted in a percentage illustrating how much the participants were awake during the nighttime rest period.

Table 1. Identifying the Best Fitting Model for Explaining Nighttime Awakenings Using Bayesian Information Criterion (BIC) Value.

Model	BIC
Model 0: Intercept	82,710
Model 1: Sound	80,079
Model 2: Light	82,080
Model 3: Movement	77,069
Model 4: Sound & Movement	76,614
Model 5: Sound & Light	79,910
Model 6: Movement & Light	76,968
Model 7: Sound, Light, and Movement	**76,578**

Note. The best fitting model is in boldface. This model is the best-fitting because it is the lowest BIC value compared to the other models.

Aim 2 analysis. Aim 2, identify pattern(s) of exposure to ambient stimuli (sound, light, movement) in the hospital rooms throughout the night, was addressed using descriptive statistics (i.e., mean, standard deviation).

Aim 3 analysis. Furthermore, aim 3 had two parts and the unit of analysis for this aim occurs at the level of observation which is $N = 85{,}659$. Part 1 examined the combined effect of ambient stimuli on nighttime awakenings and required a three-step analytic approach. First, a hierarchical mixed logistic regression with fixed effects was conducted to account for clustered, within-person (nested) observations and to account for unequal number of observations per participant (Gelman & Hill, 2007). To do this, we used RStudio's Generalized Linear/Logistic Mixed-Effects function in the lme4 R package (Bates et al., 2014) to determine the combination of predictor variables (sound, light, and movement) that would provide the best fitting regression model to explain our outcome variable, nighttime awakenings. Second, we selected the best fitting model using the Bayesian Information Criterion (BIC). Therefore, the model (Table 1) with the lowest BIC value compared to the other models was deemed the best fitting. Initially we included gender, age, and race covariates, but none were significant in the model. Gender and race had limited variability in this sample. Therefore, the results presented in this paper are based on models that did not include gender, age, or race.

For our third and final step in analyzing part 1 of aim 3, we calculated the estimated probability of nighttime awakenings for our best fitting model (See Table 2, "Reference Model"), using resampling with replacement. We used resampling with replacement to: (1) minimize the likelihood of Type I & II error, a relevant concern when dealing with a large number of observations ($N = 85{,}659$ in our case; Lorah & Womack, 2019; Molinaro et al., 2005) and (2) to create 95% confidence intervals. The resulting estimated probability values represent the effect of all stimuli being present at levels observed in the current study (Table 2, "Reference Model").

Part 2 of aim 3 was to identify which ambient stimulus should be targeted to produce the greatest clinically meaningful reduction in nighttime awakenings. First, we reviewed the literature to identify values we could use to represent clinically meaningful reductions for each ambient stimulus, selecting a decrease by 5 dB(A) for sound (WHO, 2018), restricting light to no more than 5 lux at night (Burgess & Molina, 2014), and reducing clinical surveillance to 50% (Yoder et al., 2013) to represent a 50% reduction in nighttime movement. Then, we reduced the values produced in the analysis for aim 2 one stimulus at a time while leaving the other two stimuli unchanged. The reason we did this was to model the individual effect of each stimulus on reducing nighttime awakening probability (Table 2).

Results

Participant Description

The data used for these analyses were created by observing a sample of mostly white (94.4%) and mostly male (77.8%) participants with an average age 65.3 years ($SD = 17.4$). It was a severely injured group of participants ($Mean$ GCS = 9.1, $SD = 4.8$) with sufficient cognitive functioning to provide purposeful movement for actigraphy ($Mean$ RLA = 7.7, $SD = 0.75$). The average nightly length of NSDU stay was 3.3 nights ($SD = 1.6$). See Table 3 for demographics.

Aim 1

Amount of nighttime awakenings and ambient stimuli description. The total amount of nighttime awakenings among all participants and across all nights of observation was 24% (i.e., nearly 3 hr between 8 PM and 8 AM; Figure 2).

Aim 2

Pattern of exposure of ambient stimuli throughout nighttime hours. Values for sound, light, and movement levels were highest at 2000 hr (see Figure 2 for pattern of ambient exposures throughout night). Max Sound = 56.30 dB(A), $Mean$ = 52 dB(A), $SD = 8.35$. Max Light 21.18 (lux), $Mean$ = 9.97 (lux), $SD = 26.31$. Max Movement 0.48(p), $Mean$ = 0.28 (p), $SD = 0.45$. Values for sound was lowest at 0300 hr [Min = 50 dB(A)]. The light and movement levels were lowest at 0200 hr (Min = 2 (lux) and Min = 0.17 (p), respectively.

Aim 3

Modeling for nighttime awakenings of participants. Model 7 (Table 1) provided the best fit, showing that each ambient stimulus had a statistically significant effect on nighttime awakenings ($p < .001$). Using coefficients from this model, the estimated probability of nighttime awakenings was 20% (Table 2, "Reference Model").

Clinically meaningful reductions of ambient stimuli. When the value for a particular stimulus was reduced by a clinically meaningful amount and the values for other stimuli remained constant (Table 2), significant reductions in probability of nighttime awakenings were observed for sound and movement as shown

Table 2. Displaying the Estimated Probability of Nighttime Awakenings for the Combined Effect of Ambient Stimuli (Reference Model) and the Change in Estimated Probability of Nighttime Awakenings for Both the Clinically Meaningful Reductions for Each Stimulus and for All Ambient Stimuli.

Model	Sound *dB(A)*	Light *lux*	Motion *p*	Estimated Probability of Nighttime Awakenings, $P(NA)$	Change in Estimated Probability of Nighttime Awakenings, $\Delta P(NA)$	95% CI of $\Delta P(NA)$
Reference Model[a] (No clinical reductions applied)	52	9	0.28	0.201[b]		
Sound reduced by 5 dB(A), [c] from 52 dB(A) to → 47dB(A)	**47**	9	0.28	0.177	0.024*	(0.0115, 0.0360)
Light reduced to 4 lux, [d] from 9 lux to → 4 lux	52	**4**	0.28	0.198	0.002	(−0.0006, 0.007)
Movement reduced by 0.50, [e] from 0.28 to → 0.14	52	9	**0.14**	0.175	0.026*	(0.01982, 0.03399)
All three stimuli reduced by their respective clinically meaningful reduction	**47**	**4**	**0.14**	0.152	0.049*	(0.03744, 0.06237)

Note. [a]The reference model does not use any clinical reductions and the [b] estimated probability of nighttime awakenings generated from the reference model is based the mean value of all ambient stimuli. Bolded text indicates values that were reduced by clinically meaningful amounts that were identified in the literature. [c] Sound, reduced by 5 dB(a) per WHO (2018) report, [d] light was reduced to 4 lux in keeping with recommendation by Burgess and Molina (2014), and [e] movement was reduced by 50% in keeping with Yoder et al.'s (2013) recommendation for clinical surveillance. Units of measure: "dB(A)" stands for "decibels" that are "A-weighted" and is the unit that measures sound; "lux" stands for "lumens" and is the unit that measures light; "p" stands for "proportion" and is the unit that represents movement. As a proportion, the scale of measurement is between 0 and 1 and the proportion can also be written as a percentage. "P(NA)" stands for "probability of nighttime awakenings (NA) while "ΔP(NA)" stands for "the change in the probability of nighttime awakenings (NA)." ΔP(NA) was calculated by subtracting the reference model's [b]P(NA) from the P(NA) of each reduction. Both P(NA) and ΔP(NA) are probabilities and because the probability of an event can only occur between 0 and 1, the scale of measurement for these probabilities is between 0 and 1 and can also be written as a percentage. *$p < .05$ (within 95% CI) for a statistically significant reduction.

Table 3. Participant Demographics.

Characteristic	Value
Age	
Mean ± Standard Deviation	65.3 ± 17.4
Gender	
$N = 18$	
% Female	22.2
% Male	77.8
Race	
% White	94.5
% Hispanic	5.5
Glasgow Coma Scale (GCS)	
Mean ± Standard Deviation	9.1 ± 4.8
Nights of Observation	
Mean ± Standard Deviation	3.3 ± 1.6
Cognitive Functioning Rancho Los Amigo score (RLA)	
Mean ± Standard Deviation	7.7 ± 0.75

by their change in estimated probabilities of 2.4% (CI: 1.15%, 3.61%), and 2.6% (CI: 1.98%, 3.40%), respectively. No significant effect was found for light ($p > .05$). When clinically meaningful reductions for all stimuli were tested, the estimated change in probability for nighttime awakenings (4.9%, CI: 3.74%, 6.23%) was significant.

Discussion

We showed that the probability of nighttime awakenings in patients with moderate-severe TBI is significantly associated with continuous movement into and out of the patient's room and elevated sound ($p < .05$). Light was not significant. Movement had the greatest effect on probability of nighttime awakenings when it was decreased by its clinically meaningful amount. However, reducing all stimuli in our model by clinically meaningful amounts appears to have the most impactful decrease in probability of nighttime awakenings.

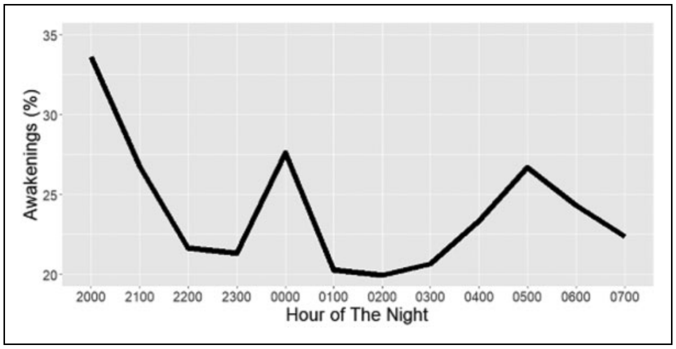

Figure 2. Nighttime awakenings throughout nighttime hours.

Our findings are consistent with studies that show poor sleep in hospitalized patients with TBI (Chiu et al., 2013, 2014; Duclos et al., 2016; Williams et al., 2019; Wiseman-Hakes et al., 2016) and also with studies that cite loud sound and care-provision as significant disrupters of nighttime sleep for hospitalized patients in a neuroscience unit (Thomas et al., 2012; Uğraş et al., 2015). Light not being a significant finding is consistent with other studies that explored subjective nighttime light exposure perception and rest-activity cycles in hospitalized patients (Gathecha et al., 2016) and that reported low nighttime lux in a hospitalized sample (Bernhofer et al., 2014; Fanfulla et al., 2011) and in a sleep lab (Gooley et al., 2011). Light may have a synergistic effect in the statistical and predictive modeling in our study, and perhaps a clinical intervention to only reduce light is not sufficient.

There are two important contributions our study makes to the science that explores sleep disturbances in hospitalized patients with moderate-severe TBI. First, we can *now* quantify both the sound, light, and movement stimuli and their nighttime patterns of exposure as they occur in the hospital room of these patients with TBI. Second, our findings suggest that these nighttime stimuli may lead to deleterious nighttime awakenings for a patient population already affected by poor sleep quality and fragmented sleep. Tandem exploration of nighttime awakenings and ambient stimuli in hospitalized patients with TBI on the NSDU using objective measures is a challenge because of the difficulty in studying a very ill and highly heterogenous cognitively vulnerable group and because of the variable lengths of stay and unique needs of this group (Nelson et al., 2015; Williams et al., 2019; Williams & Thompson, 2017). This type of exploration is also a challenge because there are few devices on the market that (1) collects and logs (continuous) multiple stimuli and (2) allows for seamless access to data with the time resolution necessary for answering research questions via rigorous statistical analyses.

In patients with TBI, restful sleep is a fundamental building block of neural recovery and aids in synaptic plasticity, improves neurological functioning, enhances memory consolidation, and improves emotional regulation and somatic functioning (Abel et al., 2013; Anafi et al., 2013; Ren et al., 2017; van Enkhuizen et al., 2014). Unfortunately, patients with TBI are already plagued by sleep disturbances that are intrinsic in origin; this origin of sleep disturbances is likely a result of mechanical damage to the neural networks responsible for sleep and wakefulness (Viola-Saltzman & Watson, 2012). Conversely, sleep disturbances of extrinsic origin, namely ambient stimuli, could further compound existing sleep disturbance as shown in a similar study that explored the effect of several ambient stimuli (measured objectively) on the sleep of critically ill pediatric hospitalized patients (Linder & Christian, 2012).

Movement in and out of the patient's room during the nighttime hours may likely be related to patient-care activities. Patient care occurs *throughout* the nighttime period of patients hospitalized on neuro ICUs (Uğraş et al., 2015) and in patients with TBI who are hospitalized on NSDU (Williams & Thompson, 2017). Literature that highlights this type of nighttime ambient exposure explains that it can be attributed to the frequency of vital sign assessments (Pellicane, 2014; Yoder et al., 2013), various nighttime patient-care activities (Uğraş et al., 2015; Williams & Thompson, 2017), and perhaps some aspects of nighttime indirect care (Desjardins et al., 2008) that require staff to enter and exit rooms without touching the patient. Some examples of these indirect care activities are: restocking linen closets, decluttering the room, updating care-plans on dry-erase boards, removing waste from trash bin, biohazard bin, and dirty linen hamper (E. T. Williams, observation, July 22, 2020).

Sound was the second significant contributor to the probability of nighttime awakenings, a finding that is consistent with work which shows significant associations between sound pressure levels (SPLs), patient-reported sleep (Thomas et al., 2012), and rest-activity cycles (Park et al., 2014). This has also been shown in non-hospitalized/sleep lab patients (Buxton et al., 2012). Although other studies assessed the measure of association between sound and the hospitalized patients rest-activity, they found no significant result (Fanfulla et al., 2011; Gabor et al., 2003, both ICU); this could be because continuous capture and logging of SPLs over 12-hr may have allowed us to capture the variability of background SPLs in the patient's room where as others may have only captured SPLs with spot-checking (typically captures a brief moment in time; Neitzel et al., 2011). Noise exposure assessment studies in the hospital setting suggest that the origin of sound variability is from the air handling system, noise derived from human conversations, and activity outside of the patient's room (clinician workstations, hallways; Busch-Vishniac, 2015; Busch-Vishniac et al., 2005). The average sound pressure levels in our study, 52 dB(A), far exceeds the WHO's (2009, 2018) 40-dB recommendation for indoor settings and is a health risk (Stansfeld & Matheson, 2003).

Limitations

Although the unit of analysis was the number of observations ($N = 85{,}659$), our study has a sample size of 18 participants, and this could limit how much the participant characteristics could be generalized. However, the analysis plan, the granularity, and volume of data points ($N = 85{,}659$) suggests that within-person analysis is stable (Gelman & Hill, 2007). Sleep diaries could not be collected, but a blanketed sleep time for all participants has been used in other studies describing the nighttime hospital environment of neuroscience patients (Thomas et al., 2012). Another limitation is the absence of other sleep variables and sleep-wake activity (sleep time, naps, sleep medication) in our analysis. Although reported elsewhere (Williams et al., 2019) and framed with a different research question, it may have been helpful to include other important sleep variables and the influence of certain medications. Nevertheless, we chose nighttime awakenings as the sleep parameter because it reflects episodic disturbances of sleep that are most likely caused by environmental factors like the ones measured in our study (sound, light, and movement). Nighttime awakenings were the principal sleep parameter in studies that examined the burden of nighttime awakenings in European and American (Ohayon, 2008, 2010) populations. No participant-observers were present; therefore, we cannot know the exact reason a person may have entered and exited the participant's room. We did not account for semi-private/shared rooms in our design. However, non-hospital personnel visitation hours were outside of the window for the nighttime period and the acuity of the sample made it highly unlikely that participants would get out of their beds without help from hospital staff.

Implications for Patients With Brain Injury

The hospital environment does not always allow for the restful sleep that is imperative to neural recovery in patients with acute TBI, which has the potential to undermine recovery efforts (Callahan & Lim, 2018; Duclos et al., 2017). This study shows both the course of nighttime awakenings for these patients and the potential negative influence ambient stimuli may have on sleep. From this point, clinicians and other stakeholders may be able determine ways to optimize rest in this group and ameliorate disturbance in the ambient environment. For example, stakeholders within hospital administration, can work with designers and architects to create thoughtful floor plans to ensure the patients' rooms are free from noise that originates from mechanical (i.e., HVAC systems) or human sources (i.e., visiting offices or workstations). Designers and architects can select materials to absorb sound (i.e., acoustic flooring, wall insultation) and reduce reverberation rates of known noise-producing areas within the built environment. Reducing movement in the patient's room is important and may also be achieved with thoughtful floor plans which can help decrease unnecessary foot-traffic. Additionally, nursing and medical staff can prioritize care bundling to reduce sleep disturbances that derive from movement. Non-clinician personnel can explore bundling and may start with interventions like frequent removal of waste and replacement of fresh linen during the *dayshift*. Where appropriate, mini sleep-holidays can help capitalize on the lull periods in the night where sound, light, and movement levels are low (Figure 2).

Conclusion

In summary, our work reveals that ambient sound, light, and movement in hospital rooms can significantly contribute to nighttime awakenings in patients with moderate-severe TBI, and that movement into and out of the patient's room seems to be the greatest contributor. The nature of the association we observed when we modeled the benefit of clinically meaningful reductions in ambient stimuli suggests that decreasing all nighttime stimuli may decrease nighttime awakenings as well. Our work has quantified a pattern of exposure for nighttime ambient stimuli in this group and suggests that these stimuli can contribute to nighttime awakenings of patients with moderate-severe TBI who are in the immediate post-injury phase of hospitalization. Further validation work can help confirm these findings and perhaps participant-observation can help stakeholders determine the exact sources of nighttime ambient stimuli.

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Author Contributions

Williams, E.T. contributed to conception and design; contributed to acquisition, analysis, and interpretation; drafted manuscript; critically revised manuscript; and gave final approval agrees to be accountable for all aspects of work ensuring integrity and accuracy. Bubu, O.M. contributed to interpretation, critically revised manuscript, gave final approval, and agrees to be accountable for all aspects of work ensuring integrity and accuracy. Seixas, A. contributed to interpretation, critically revised manuscript, gave final approval, and agrees to be accountable for all aspects of work ensuring integrity and accuracy. Sarpong, D.F. contributed to analysis and interpretation, critically revised manuscript, gave final approval, and agrees to be accountable for all aspects of work ensuring integrity and accuracy. Jean-Louis, G. contributed to interpretation, critically revised manuscript, gave final approval, and agrees to be accountable for all aspects of work ensuring integrity and accuracy.

Data Statement

Authors are willing to share de-identified data from reasonable inquiries.

Declaration of Conflicting Interests

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