

Doplor Sleep: Monitoring Hospital Soundscapes for Better Sleep Hygiene

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ABSTRACT

Good sleep is conducive to the recovery process of hospital patients – and yet, in many wards, sleep duration and quality can often be suboptimal, in part due to modifiable hospital-related sounds and noises. At the neurological ward of the Reinier de Graaf hospital in Delft, the Netherlands, we developed and evaluated a prototype information exchange system to raise awareness of specific sounds as disturbing patients' sleep. The system both classifies different relevant sound events and tracks sleep quality (using a Fitbit device). This information is then visualized for patients and staff to present the influence of the soundscape on patients' sleep hygiene in a friendly and comprehensive way. We discuss the design process, including a context study and various evaluations of the technology, interface, and created affordances. Our initial findings indicate that visualizing hospital soundscapes may, indeed, support both patients and staff in their efforts towards better sleep hygiene.

CCS CONCEPTS

• **Human-centered computing** → Interaction design; Interaction design process and methods; User centered design; • **Applied computing** → Life and medical sciences; Health care information systems.

KEYWORDS

Sound-driven design, data visualization, design for healthcare

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1 INTRODUCTION

Sound is one of the environmental factors that can be disruptive to our daily sleep routine. Although people are unconscious during sleep, the brain can still receive external stimuli and get stimulated [1]. Noise during sleep also increases cardiovascular and physiological activity eventually disrupting sleep and further causing stress, fatigue or mental health problems [2]. Therefore, the unwanted effect of sound on sleep is seen as an important health and well-being variable for humans who deserve to rest especially during health recovery.

According to a clinical review article by Muzet [3], the sensitivity of the sleeper to sound depends on different factors. Some of these factors are sound dependent, such as the type of sound (e.g. continuous, intermittent, impulsive), intensity, frequency, spectrum, interval (e.g., duration, regularity), and the difference between the background noise level and the maximum amplitude of the occurring sound stimulus. Other factors are related to the sleeper, such as age, sex, personality characteristics, and self-estimated sensitivity to noise. Muzet also indicated that the objective measures of sleep disturbance could be quantified by number and duration of nocturnal awakenings, the number of sleep stage changes, and modifications in their amount.

A recent study by Wesselius et al. [4] uncovered sleep in Dutch hospitals to be suboptimal: patients on average sleep 83 minutes shorter than at home, take 21 minutes longer to fall asleep, and take 29 minutes longer to fall asleep again when disturbed in their sleep. Consequently, patients report feeling less refreshed, struggle more to fall asleep, feel lousier when waking up, and have an overall lower sleep satisfaction and sleep quality. When asked, patients most often ascribe disruptions of their sleep to noise, with alarms and staff conversations being most disruptive [5]. Indeed, there are no published results of hospitals meeting the World Health Organization sound level guidelines of a maximum of 40 decibels (dB) in patients' rooms at night – in contrast, reported nighttime noise in hospital has increased over the previous 45 years, with average levels increasing from 42 to 60 dB by 2005 [6]. This is problematic, as patients could be disturbed by sound levels above 55 dB, and arousals may also be due to the type of noise specifically found in hospitals and not just level.

The available literature on sound measurement and categorization in hospitals is limited to contexts more critical than the general ward. A study by Krueger et al. [7] classified the sources of sound in neonatal intensive care units as being either operational sounds (generated by the staff or equipment) or structural sounds (generated by the building, e.g., ventilation, air conditioning systems, and doors). According to Konkani and Oakley [8], the same classification scheme developed by Krueger et al. can be applied to all hospital noises. Konkani and Oakley have further specified the sound sources of intensive care units as conversations between the staff, medical professionals, and visitors; medical equipment alarms; caregiving activities such as hand washing, opening disposable equipment packages, storage drawers; telephones, pagers, and televisions; and closing doors and falling objects.

Based on Konkani and Oakley's study, Birdja and Özcan [9] mapped the sound-producing events from the patient's perspective to categorize them in patient monitoring sounds (i.e., audible alarms), sounds that originate from life-support devices (i.e., mechanical and air-interaction sounds of mechanical ventilators, dialysis machines), and sounds that are peripheral to the patients (conversations, structural sounds, and interaction sounds in the environment). Furthermore, at the intensive care unit of the Jeroen Bosch Hospital in 's-Hertogenbosch, the Netherlands, Park et al. [10] have collected and analyzed 67 hours of audio recordings. This study showed the distribution of sound-producing events over the sound categories: patient involved noise (31%), staff related sounds (57%), verbal and non-verbal staff-related sounds (38%), sounds related to caregiving activity (19%), medical alarms (30%), and operational sounds of life-supporting devices (13%).

Therefore, sound levels may not be the most important parameters to look at when determining whether the hospital is "suitable for sleep" or not: reducing loud sounds does not necessarily create a more acoustically friendly environment. We need to examine the effect of different sound sources on sleep, not only from the aspect of sound levels but also on the content and interpretation [11].

In this paper, we explore a sound-driven technological solution to overcome sleep disruption by environmental sounds in hospitals and present a scientifically informed evidence-based design solution based on small-scale testing. We track environmental sounds and sleep to help patients, hospital staff, and visitors regularly reflect on their sound-producing activities to take action to ensure a sleep-friendly sound environment. The concept can be viewed at the following link: <https://vimeo.com/460030331>.

2 CONTEXT STUDY

Our design project is initiated by Reinier de Graaf hospital in Delft, the Netherlands. Reinier de Graaf hospital seeks to find design solutions to tackle sound-induced sleep disruptions in the neurological ward. Therefore, we focused on this particular context to design an intervention that would enable sleep-friendly hospital environments. The neurological ward of Reinier de Graaf hospital is in the form of 9 single-patient rooms and 4 four-patient rooms connected through a long corridor. According to preliminary observations carried out in the ward, it was found that the sound environment is different than in intensive care units: for instance, the proportion of medical alarms is much smaller. Therefore, in order to better

understand the context and to inform our design solution, we implemented a study to (1) collect subjective opinions from nurses and patients regarding patients' sleep and the sound environment, and (2) identify the main sound sources disturbing the patient's sleep. In short, we first conducted individual interviews with nurses and ran a survey with patients to understand the overall quality of the sound/sleep environment in the ward. Then, we set up an experimental protocol with objective sound and sleep measurements to investigate which types of sound are most likely responsible for waking up patients during the night. The study protocol was approved by METC Leiden Den Haag Delft, with reference number N20.148.

2.1 Interviews with nurses

Seven nurses (all female, years of experience range between 2 and 20, average 10 years) working in the neurological ward participated in the interview. The interview covered several aspects of the nurses' work routine, with a particular focus on sound events happening in the ward, and their interaction with patients, including measures taken to facilitate their sleep. All responses were recorded, transcribed, and translated into English. The interview data were qualitatively analyzed by reading through the transcriptions and extracting the core ideas and keywords for each response. Keywords were finally gathered to help find patterns.

According to the results from the data analysis, sleep in the single-patient room is generally not disturbed by many sound events and patients might be unrested because they have sensors connected to their bodies and need to be woken up periodically for check-ups. On the other hand, patients staying in the four-patient rooms might be in lack of rest mainly because of the influence of other patients. For example, some patients talk loudly, and delirious patients leave their beds because they cannot fall asleep. As a result, such behaviours not only keep these patients from sleeping but also disturb other patients.

After gathering all the sources of sound mentioned by the nurses, different sound categories were generated, such as sounds generated by visitors, patients, hospital staff, environmental sounds, and sounds from medical equipment (Figure 1). This way of categorizing the sounds is based on how the stakeholders involved in the context would react to the sound. For example, the nurse reacts to the sounds generated by visitors differently than the sound produced by his/her colleagues.

2.2 Patient survey

Twelve patients (7 female, age range 25-60 years) hospitalized in the ward participated in the survey. The survey included standard questions from the Pittsburgh Sleep Quality Index (PSQI) [12] and additionally inquired how frequently certain sound sources occurred and how much they disturbed the patient's sleep on 5-point Likert scales (1 = never, 5 = always). The list of sound sources used for these last two items was taken from [10]. Patients accessed the questionnaire through an iPad provided by the hospital.

For the sake of brevity, we hereby only report in full the results from the survey items inquiring frequency and level of disturbance by sound. Figure 2 shows that the frequency of occurrence of sound events is in line with their level of disturbance, yet the difference

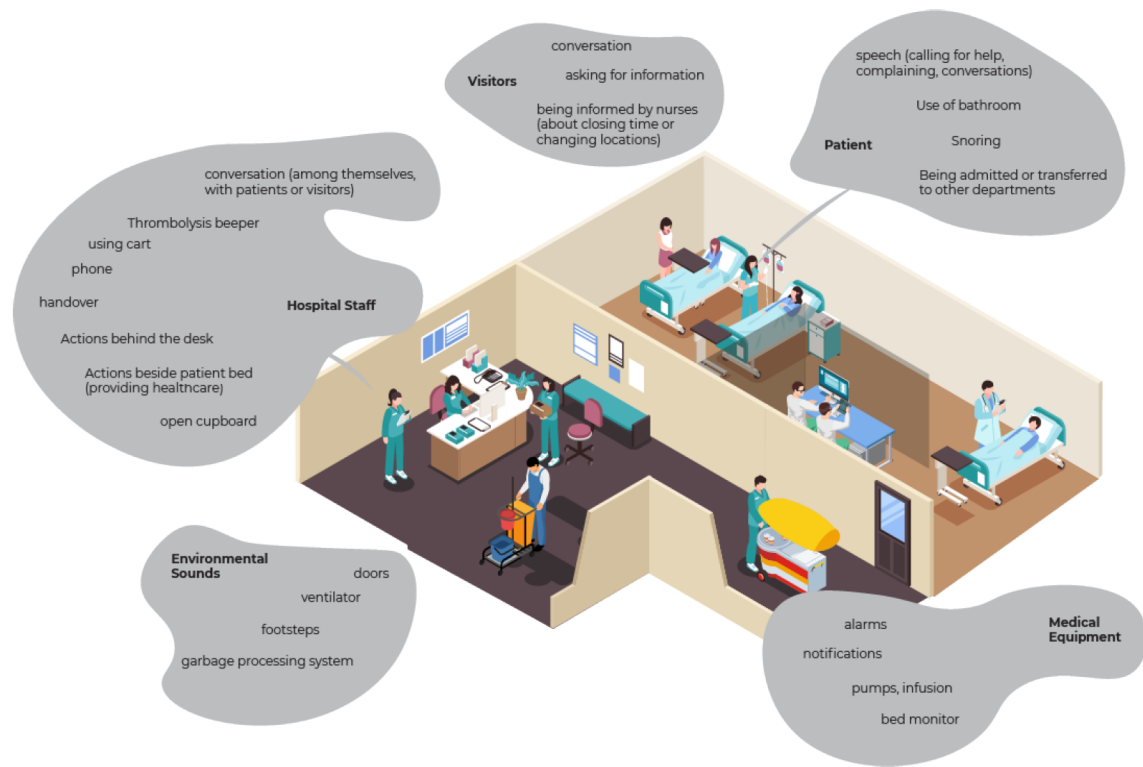


Figure 1: The authors’ categorization of sound events considered by nurses as potentially harming for patients’ sleep. The illustration does not represent the actual layout of the hospital ward.

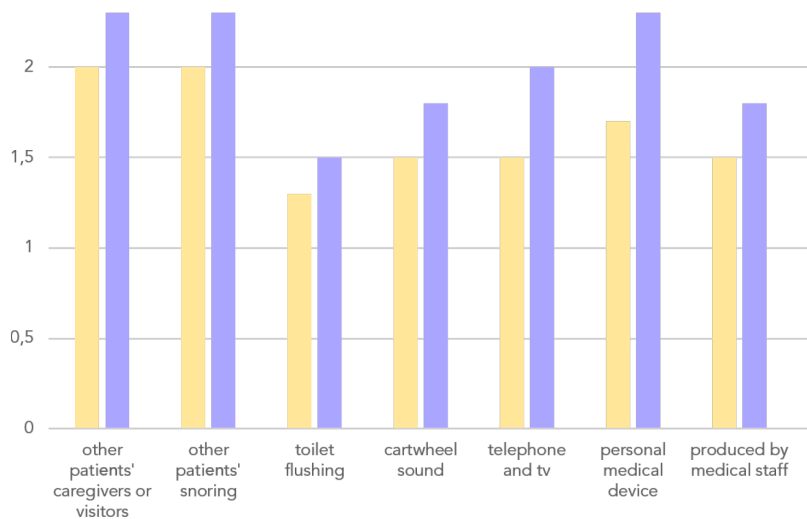


Figure 2: Sound events rated by patients as a function of how often they occur (yellow bars) and how often they disturb (purple bars).

in score among the individual events is not outstanding. The other survey items confirmed that sleep quality in the ward is overall

worse than at home, and that most patients woke up to sounds occurring at night.

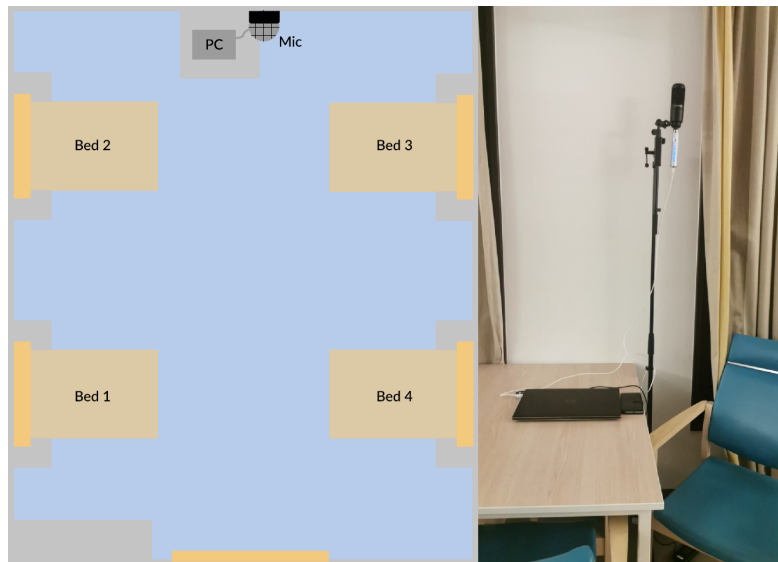


Figure 3: Experimental setup: sketch of a four-patient room (left) and detail of the sound recording system (right).

2.3 Experimental study

We took sound recordings inside the neurological ward for 14 nights, 10 consecutive hours per night for a total of 140 hours of recording. Each night, we recorded sound through a single Audio-Technica AT2020 cardioid microphone placed on a microphone stand close to the wall farthest from the entrance door inside one of the four-patient rooms (Figure 3), based on patient occupancy and availability. The microphone was powered by a Blue Icicle preamplifier and connected to a PC running a MATLAB-based software. During the 10 consecutive hours, the software continuously collected and stored the A-weighted root mean square (RMS) sound pressure level and a time/frequency representation (spectrogram) of the recorded sounds. In order to ensure the privacy of all the individuals in the ward, the actual sound recordings could not be stored. Notably, we found that the average sound level during late evening hours is about 10 dB(A) higher than at night, suggesting that it might be difficult for some patients to fall asleep because of sound disturbances.

Every night, three of the patients sleeping in the sound-monitored room wore a Fitbit Inspire HR health tracking bracelet each, which monitored their sleep. In order to avoid the first-night effect [13], the bracelets were worn only by patients who had been already hospitalized for one night at least. All patients, including those who slept in the monitored room but did not wear a bracelet, gave their informed consent for being part of the research. The Fitbit bracelets are capable of collecting information about the user’s overnight sleep stages with a 30-second resolution. The four sleep stages are: awake, REM sleep, light sleep, and deep sleep. Compared to polysomnography, i.e., the gold-standard (yet intrusive) scientific method for sleep tracking, the Fitbit technology has been seen to be reliable in detecting transitions from deeper sleep stages to awake [14], but mostly fails at distinguishing deep from light sleep stages [15]. Therefore, we considered significant arousals (or awakenings) all the transitions from either a deep or light sleep stage to awake.

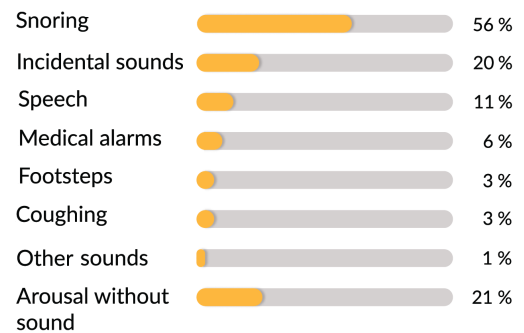


Figure 4: Distribution of sound class labels across arousals.

As a result, a total of 474 arousals have been recorded across the 14 nights.

The recorded data were time stamped for synchronization and analysis purposes. Once all the data were collected, we annotated the sound data recorded in correspondence of every single arousal, i.e., the 30 seconds of the spectrogram immediately preceding an arousal, by visual inspection of the spectrogram itself. Specifically, according to the sound events recognized in the corresponding spectrogram, each arousal was annotated with the following seven possible sound class labels: snoring, coughing, speech, medical alarms, incidental sounds, footsteps, and other sounds. This categorization is based on the underlying meaning of sounds, i.e., sounds with similar time/frequency representations that cannot easily be distinguished in an automatic way are merged in one group (e.g., patients talking and nurses talking are both considered “speech”). The “other sounds” label was used only when a sound could not be recognized as belonging to any of the six other classes. Please note that an arousal could be related to one, more than one, but even no sound classes.

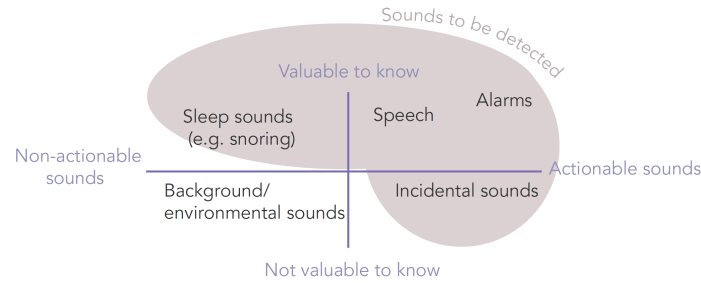


Figure 5: Categorization of hospital sounds to be considered for designing a sound-driven intervention.

Figure 4 reports the results of the categorization step, which are overall in line with those from the patient survey reported earlier. It can be concluded that snoring from other patients seems to be the leading source of sound-induced sleep disturbances in the hospital ward, although a direct cause-effect relationship could not be established. At the same time, above 30% of the arousals collectively correspond to incidental sounds, speech, and medical alarms.

3 THE CONCEPT: DOPLOR SLEEP

Sound provides information about the state of the world and indicates possibilities for (non-)action [16]. Considering that awareness towards environmental sounds and their potential for threat (or not) may improve patients' sleep, we aim to design an intervention that can monitor the sound environment of the hospital and inform patients and nurses regarding sound events in the ward. Identifying sound events will help patients ask more customized care and encourage nurses to find quick remedies to comfort patients further or motivate ward management to reconsider the nurses' workflow and care procedures.

Therefore, we put together all the results of our context study (Figures 1, 2, and 4) and categorized sound events further to conclude on which sounds are worth monitoring by our system. As shown in Figure 5, sleep sounds (i.e., snoring), speech, incidental sounds, and medical alarms are considered as the target sounds to be detected because it is valuable to know if the sound is present and/or this sound can be reduced by taking actions. For instance, snoring is valuable to be detected because nurses can protect sensitive patients by moving them to another room; and alarms are actionable because the threshold of the alarming system can be adjusted if the situation allows.

Based on suggestions from the literature and our context research, we have agreed on the following product requirements for the system:

- 1. the system integrates an app for the patients' experience of nocturnal sounds and sleep, and a display device as a reference for nurses;
- 2. the product should be capable of capturing the sound-producing events and tracking the sleep cycle of patients;
- 3. the product should be capable of visualizing the relationship between sound-producing events throughout the night and the sleep stage transitions of the patient;

- 4. the visualization of sound and sleep information should be comprehensible by both nurses and patients;
- 5. the app design for patients should be attractive to the users, so they are encouraged to use the product, proactively take in the information that the product is trying to convey, and become more aware of the influence of sound-producing events on sleep.

At the Critical Alarms Lab of Delft University of Technology, the Netherlands, Redert [17] developed Doplor as an auditory feedback device to make the hospital staff more aware of their influence on the environment and encourage them change their sound-producing behavior by offering calming and pleasing real-time visualizations. In Doplor, sound levels are presented visually and in a metaphoric way to indicate how friendly or hostile the sound environment is. Furthermore, Doplor offers a more nuanced account of the auditory context by going beyond sound pressure levels and using signal processing algorithms to detect and categorize sound sources, count their frequency of occurrence, and make inference on the quality of the sound environment in the form of visual representations that use recognizable objects as sound event sources. The Doplor Sleep concept is inspired by the Doplor project, but tailored for the sleep environment in general hospital wards.

3.1 Sound classification

In Doplor Sleep, sound classification is enabled by continuously analyzing the spectrogram of the incoming audio stream to reveal the spectro-temporal features of different sound categories. As shown in Figure 6, different types of sounds have peculiar and distinct features on the spectrogram: incidental sounds appear as sharp, broadband transitions along the temporal axis; alarms as discrete and repetitive patterns of tones; snoring as a noisy yet repetitive signal; and speech as an unpredictable signal evolving in time and frequency.

A machine learning model to classify sounds based on multiple temporal and spectral features is currently under development. As a proof of concept, we first designed an algorithm based on empirical rules. Specifically, we window the incoming audio signal in short-time segments and calculate the FFT for each segment. For those segments where the total power exceeds a minimum heuristic threshold ("active" segments), the Harmonic to Noise Ratio (HNR) is calculated. Then, we look for periodicity across the active segments (with a minimum period of 5 s) by calculating the autocorrelation of the signal, and classify segments according to the following scheme:

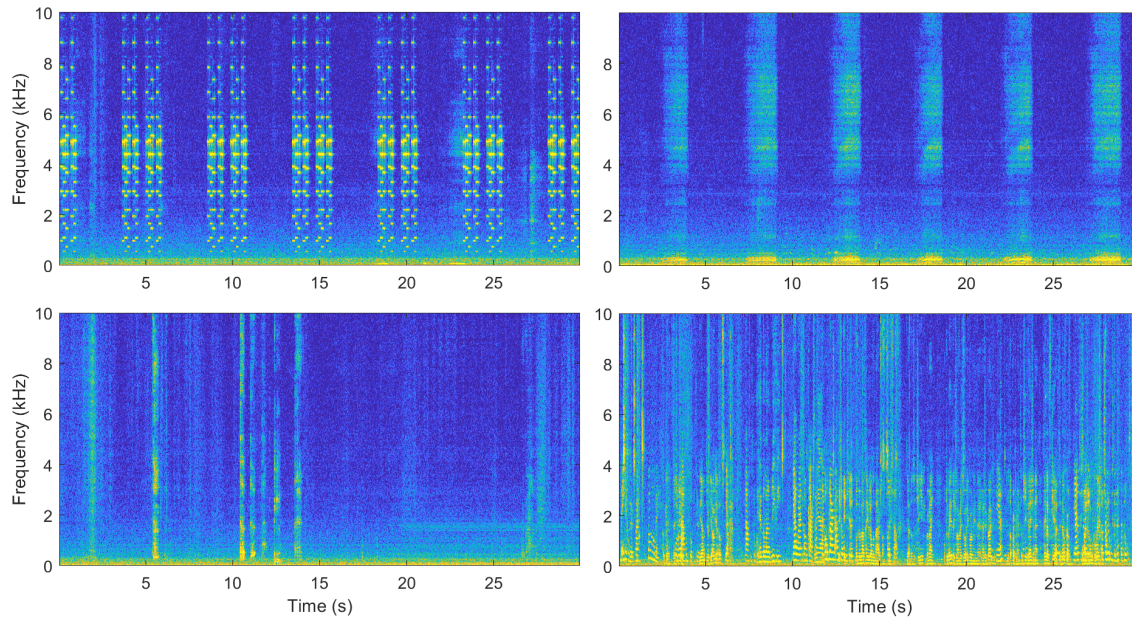


Figure 6: Typical spectrograms for alarm sounds (top left), snoring sounds (top right), incidental sounds (bottom left), and speech sounds (bottom right).

- low HNR + low periodicity: incidental sounds;
- low HNR + high periodicity: snoring sounds;
- high HNR + high periodicity: alarm sounds;
- high HNR + low periodicity: speech sounds;

with a hard threshold separating the high and low HNR/periodicity regions.

3.2 Visual display

The Doplor project [17] used the analogy of sea waves to indicate sound intensities, i.e., different sea waves' levels of violence indicated different soundscapes, and different icons represented different sound sources. As these analogies were validated by nurses previously, we decided to use a graphical style image (animation) as an analogy for the overall soundscape, and different elements in the image to represent different sound-producing events.

A similar analogy to the sea waves, the river, was used in the Doplor Sleep concept. Ripples on the river represent a calmer version of sea waves, which is considered more suitable for the night. Furthermore, the river is often used as a representation of a timeline in data visualization, which also motivated the decision to use the river as an analogy. As Figure 7 illustrates, a boat drifting on a river is used to represent the person's sleep. We also used a picnic icon to represent speech sounds, rocks for incidental sounds, flashlights for medical alarms, and bubble icons to represent snoring sounds.

We further classified the soundscape into three levels.

- Quiet: sound events are seldomly present. The ward is quiet (under 45 dB(A) on average) at night. There is no need to worry or take any action.

- Soothing: sound events are sometimes present, but the sound level is under control if nurses act a little more carefully. The loudness level is from 45 to 55 dB(A) on average at night.
- Uncomfortable: a considerable amount of noise is produced. The ward's environment is hostile for patient sleep, and attention should be paid immediately. Actions need to be taken to reduce the currently present sounds. The loudness level is above 55 dB(A) on average at night.

On the nurse-end of the application, a dynamic animation is played during the night to show the ward's real-time soundscape. Weather conditions and the state of waves indicate the soundscape levels (Figure 7, left panels). On the patient-end of the application, sound is recorded during the night. The following morning, the patient can see a report of the night's soundscape and his/her sleep journey (Figure 7, right panel).

4 THE FINAL DESIGN

The Doplor Sleep system is a software-based application consisting of two components: the patient-end of the application installed on a smartphone, and a nurse-end displayed on a computer screen. The patient's sleep is tracked by a Fitbit device and nocturnal hospital sounds are tracked by the microphone incorporated in the smartphone. The integrated development environment (IDE) of Doplor Sleep is Android Studio, a Java-based IDE for building Android applications. Currently, the patient-end of the application is built to run on an Android smartphone. The nurse-end is chosen to fit the screen of an Android tablet (e.g., Nexus 7). The idea is to use a Google Chromecast to display the application on a TV screen in the hospital ward's multifunctional room where nurses meet during the break or in between shifts.

The nurse-end of the application consists of:

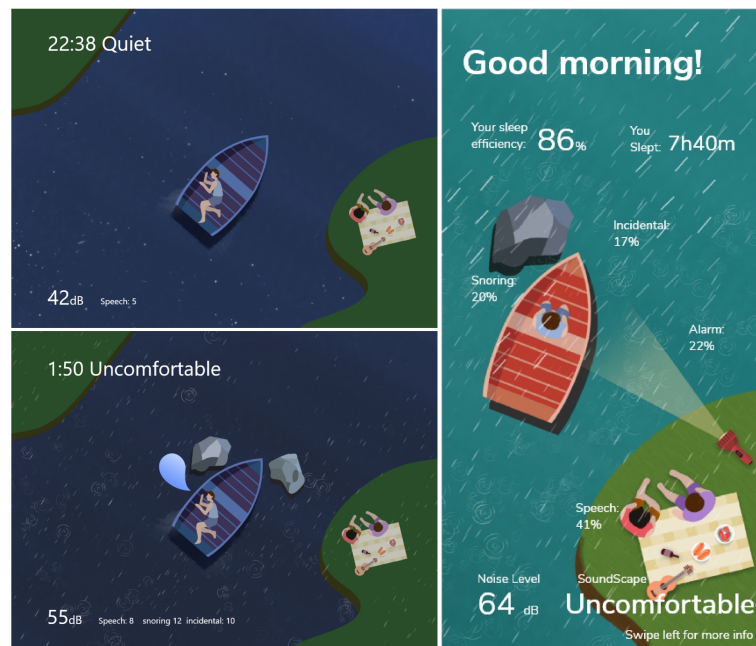


Figure 7: Graphical representation on the nurses' end (left) and the patient's end (right) of the application.

- 1. the real-time animation presenting the current soundscape and sound sources (Figure 7, left panels);
- 2. a dashboard presenting a summary of how each patient slept and the correlations between the patient's sleep pattern and sound events.

The patient-end of the application consists of:

- 1. a login page;
- 2. the sound capturing function, triggered by pressing on a boat icon;
- 3. a summary page of the patient's sound and sleep journey during the night, shown right after the patient presses on the boat icon again to finish recording (Figure 7, right panel);
- 4. a scrollable visualization of sleep stages and sound events during the night;
- 5. a page where the patient can rate the subjective sleep quality and give feedback to the hospital.

The background of the summary page indicates the average sound level during the night. Swiping to the left, the scrollable visualization is shown. The boat serves as a pointer and is fixed in the middle of the screen. The river represents the timeline. By scrolling the river, a boat riding scene is simulated, with icons showing the points in time when a certain type of sound was present. The background of this page also changes according to the sound level, which is averaged across smaller time intervals. When swiping again to the left, the patient can select their subjective feeling about sleep and leave comments. The input of the patient is sent to the nurse application and shown on the dashboard.

4.1 Design evaluation

A user test has been conducted to evaluate the functionalities and user experience of Doplor Sleep. The final prototype was evaluated by both laypeople (representing patients) and nurses from the Neurology Department at Reinier de Graaf hospital. Due to the COVID-19 emergency, it was not possible to recruit hospitalized patients for the test. In total, seven laypeople and seven nurses participated in the user evaluation.

Laypeople were asked to wear a Fitbit device and use the product installed on an Android smartphone for two nights. During the first night, no sound intervention was added to their sleeping environment. During the second night, a sound clip containing various hospital sounds was played through a tablet in their sleep environment. Participants were asked to take screen recordings of the summary and scrollable pages. The screen recordings were used to help them answer a questionnaire on Google forms, which included several open questions on their quality of sleep according to the app and to their own perspective, as well as 7-point Likert scales for rating the clarity and pleasantness of the Doplor Sleep visualizations.

The participants generally found that the data visualization delivers a friendly meaning, with all scores ranging from 6 to 7. The clarity scores were more scattered, with some participants giving high ratings and other ones giving low ratings. For instance, while they generally found the bubble and picnic icons very intuitive representations for snoring and speech, respectively, the rock and flashlight were seen to be too abstract by some participants.

The evaluation for nurses was organized in the form of a session where the nurses first watched four showcase videos of the nurse-end of the application, then answered a questionnaire. Nurses were required to provide their understanding of the visualizations in

each video, and to rate their clarity and friendliness on 7-point Likert scales. Most nurses found the concept both clear and friendly (ratings were all higher or equal to 5). However, some nurses questioned whether it is possible or not to show each patient's data separately to deliver a personalized service.

4.2 Limitations

A few limitations of the current prototype need to be considered prior to reproduction or further development. First, the current prototype is designed for only three users at the same time. Each user is assigned with an anonymous Fitbit account created by the designer. The aim is to protect the privacy of the users when the prototype is used for research purposes. Second, the Fitbit API has an access token, which expires in thirty days. Once the access token expires, a new token needs to be requested from the Fitbit SDK website. Third, the summary presented to the nurses only used the sound data gathered by the device of one user. Ideally, the sound data of all three users should be taken into account. Lastly, the visualization of the scrollable page in the patient application needs to be improved.

The project approach contains a considerable amount of literature study, but not enough design activities such as brainstorming or co-creating sessions due to the pandemic-induced restrictions. The understanding of context and problem is also highly based on the knowledge gained from literature. More diverse research activities, such as context mapping and user journey mapping, could help synthesize and facilitate creative thinking. Without the COVID-19 issue, more observations and conversations with nurses could have been carried out in the ward of Reinier de Graaf hospital. Currently, there are also limitations to the technology implemented in the product. However, we consider this as a first approach to understand the dichotomy of sound and sleep and offer a user-centered solution that addresses sound awareness in hospitals. It is advised that a subtle approach might be equally effective as laying down stricter rules and guidelines regarding sounds, though less intrusive to the practices and habits of the hospital staff [9].

5 CONCLUSIONS

This sound-driven evidence-based design study allowed us to understand the challenges of monitoring the sound events of complex environments. We went beyond the common practice of measuring sound levels and using them as a reference to understanding the environment with its events that are beneficial (or not) to one's wellbeing. Therefore, we invite the community to propose new computational methods for understanding the sound environment by events. Furthermore, using sound-driven data with sleep data was a novel approach to sleep or sound tracking apps, and we found challenges in that too. Thus, new ways of integrating different bodies of data are worthy of investigation.

The current findings and outcomes of the project led to the following future opportunities. The current version of Doplor Sleep could be further developed to bridge the gap between home sleep disturbances and hospital sleep disturbances in two different ways. First, hospital sounds could be used at home by Doplor Sleep before admission to the hospital to habituate future patients to potential hospital sounds and train them for their meaning. Second, healthy

people's sleep habits can be identified by Doplor Sleep together with potential auditory disturbers to sleep in order to create awareness to one's sleep habits with nocturnal sounds.

Another exciting research direction is to index sleep disturbances. This requires further experimentation in the hospital to measure sound, detect sound categories, and track patients' sleep in a rigorous way, in order to define their experiential quality. Further research can be conducted to identify environmental sleep-disturbing factors in general extending sound to light, temperature, and so on. A good scenario would be the one where multiple designers with different interest areas (e.g., lighting, sound, etc.) team up to design for a larger system that influences the hospital's sleep environment, in the form of an IoT system.

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