DOI: 10.61782/fa.2025.0638

FORUM ACUSTICUM
EURONOISE 2025

NURSES' INTERPRETATION OF ICU SOUNDSCAPE: AN ANNOTATED SOUND LEVEL MEASUREMENT AT ERASMUS MEDICAL CENTER

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ABSTRACT

Intensive care nurses are regularly exposed to loud sounds, but it is crucial to understand which sounds they consciously perceive during their shifts. This study, conducted in the Adult ICU at Erasmus Medical Center in the Netherlands, used a mixed-method approach to explore nurses' auditory experiences. Over three weeks, the researchers continuously measured sound levels in patient rooms, nurse stations, and a corridor, focusing on morning shifts. Additionally, a context mapping study was conducted, by which nurses documented sound sources using portable audio recorders, arranged them on a timeline, and provided interpretations in semi-structured interviews. The findings indicate that nurses primarily hear environmental sounds and are particularly sensitive to alarm sounds during transitions. Their interpretation of ICU sounds varies based on their tasks, with both positive and negative appraisals. This suggests that ICU environments can be optimized by organizing sound events to better align with nurses' clinical needs. Understanding the sounds nurses consciously notice and react to can help improve working conditions and patient care. By refining acoustic environments, hospitals can reduce unnecessary noise while ensuring that critical alarms remain effective, ultimately supporting both staff efficiency and patient well-being in intensive care settings.

Keywords: *sound level measurement, hospital soundscape, ICU, listener-centric, sound-driven design.*

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1. INTRODUCTION

Nurses working in intensive care units (ICUs) are vulnerable listeners as they are exposed to excessive levels of sounds from sources such as alarms, the noise of patient support devices, loud conversations, and physical interactions with tools and equipment [1, 2]. In order to better organize sound-producing clinical events and prevent clinically unwanted or irrelevant sounds, researchers resort to sound level measurements to study the physical impact of sound on the acoustic environment of the ICU [3]. Although such measurements provide relevant insights into the overall evolution of sound levels over time or help define how certain sound sources contribute to the overall levels [4], they fail to provide specific information on the occurrences of sound sources. Moreover, sound level measurements are meant to represent the perceived qualities of sound (i.e., loudness) in physical terms [5] and therefore cannot be directly used for other specific purposes such as sound source identification or contextualization of the sound events.

The identification of sound sources is becoming more and more relevant in recent ICU soundscape research [6] to better understand a) the actual causes of noisy environments and noise pollution [7, 8] for preventive reasons, or b) the composition of soundscapes [9] for the (re)organization of sound-producing events that align with human needs. In an earlier study [10] that focused on the comparison of sound pressure level (SPL) measurements in old and new ICUs, we identified the reasons (that is, daily protocols, machinery, social habits) for a decrease in SPL by interviewing nurses and intensivists who helped annotate the averaged measurements. We also concluded that "to truly understand the effect of acoustic environments on its listeners, soundscape researchers need to ex-

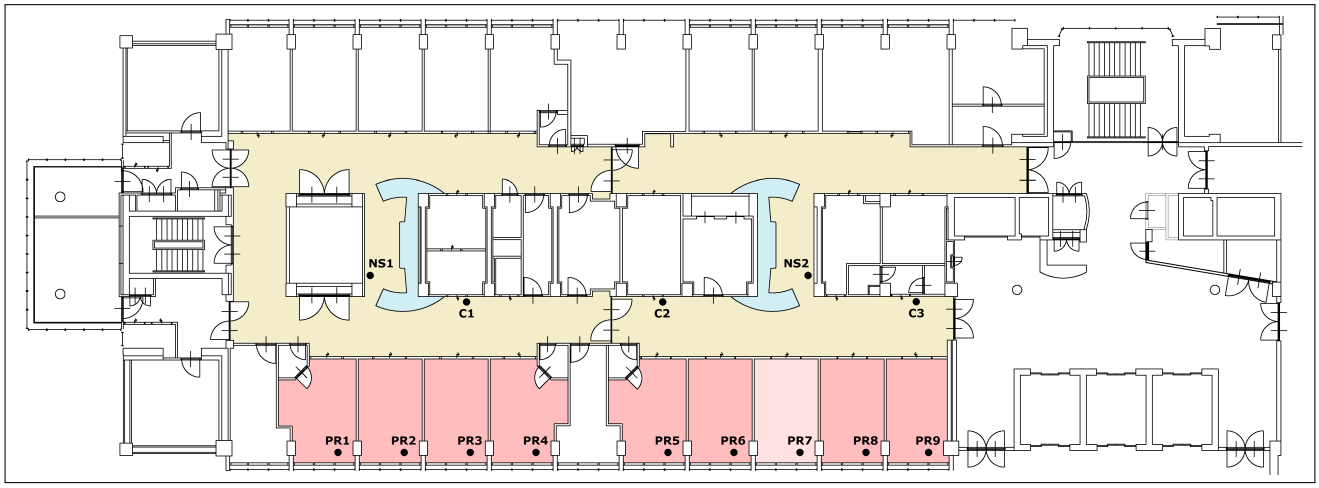

Figure 1. ICU planimetry showing the locations of the installed sensor units across three room types: NS = nurse stations (blue background), PR = patient rooms (red background), and C = corridor (yellow background). Points indicate the precise placement of each sensor unit.

plore the experience of soundscapes beyond physical measurements". Our previous study highlighted the importance of detailing the context by relying on sound source identification as a requirement for evaluating acoustic environments.

Another interest in sound source identification comes from the need for developing solutions to monitor acoustic environments with actionable and contextual information [11, 12]. Nurses need such insights to become aware of the impact of sound events on ICU soundscapes and prevent unwanted sounds by self-regulating the acoustic environment if possible (e.g., when a high number of alarms are observed due to patient hygiene protocols at 9:00 in the morning), which could normally make the ICU soundscape be perceived as 'chaotic', but this could also be perceived as 'lively' if it represents a moment for human connection. Thus, it is important to demonstrate that sound events are appraised and used differently by listeners at different times of day. Studying what listeners hear, notice, and identify also enhances the listener-centric approach to understanding listener-soundscape interactions.

In this study, we used a mixed-method approach (i.e., measure sound levels at an adult ICU and have the soundscape annotated by nurses with the help of a context mapping study) to gain further insights into the nurses' day shift. Our aim is to show correspondences and discrepancies in the measured acoustic environment and its experienced soundscape.

2. SOUND LEVEL MEASUREMENTS

Sound pressure levels within the adult ICU of Erasmus Medical Centre Rotterdam (the Netherlands) were recorded using the Quietyme system [13], a specialized sensor network designed for healthcare and shared environments. This system comprises 16 identical sensor units along with a coordinator hub, i.e., a Raspberry Pi microcomputer collecting wireless data from the sensors at a sampling rate of 1 kHz and transmitting it to the Quietyme servers over the Internet. Each sensor unit is equipped with sound level, light, temperature, and humidity sensors. For this study, only data from the sound level sensors were analyzed. As stated in Quietyme's technical specifications, each sound level sensor provides a single Z-weighted peak dB measurement per second, which will be referred to as the *SPL* value throughout this paper.

The 16 sensor units were deployed within one of the four ICU units as depicted in Fig. 1. Specifically, nine sensors were installed in patient rooms (one per room), which maintained a typical occupancy level throughout the study. Two additional sensors were placed in each of the two nurse stations, while the remaining units were distributed across the corridor (three sensors) and in other rooms (two sensors). All units continuously recorded SPL data over a period of three weeks. For this study, only data collected from patient rooms, nurse stations, and corridor between 07:00:00 and 16:00:00 will be analyzed.

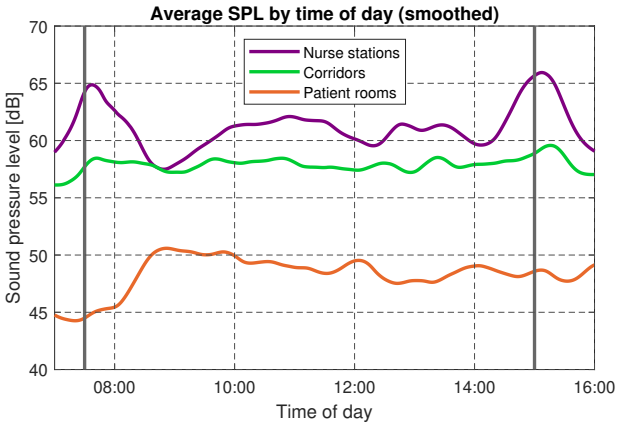

Figure 2. Average $L_{eq,M}$ by time of day between 07:00 and 16:00 in patient rooms, nurse stations, and corridor. For better readability, SPL curves have been smoothed with local regression using weighted linear least squares and a 2nd degree polynomial model. The two solid vertical lines represent shift changes (night shift to day shift and day shift to late shift).

A thorough inspection of the collected data revealed that some measurements were not transmitted to the Quietyme servers due to unexpected technical issues and temporary disconnections. Specifically, all data from one patient room (PR7) were lost, along with partial data from two of the three corridor sensors during weeks 2 and 3. In the subsequent analysis, these points have been simply treated as missing data. For analytical purposes, the raw SPL data—recorded every second by each sensor—were aggregated into minutely averages ($L_{eq,M}$). Given that the raw data were measured in dB, all averages were computed using the logarithmic, rather than the arithmetic, mean. In total, 828,620 $L_{eq,M}$ data points were collected.

Figure 2 presents the average $L_{eq,M}$ values across different times of the day for patient rooms, nurse stations, and the corridor. Each $L_{eq,M}$ data point represents the equivalent SPL for a single minute within one room of the corresponding type. The figure highlights pronounced peaks in nurse stations coinciding with shift changes, a pattern that is more weakly observed in the corridor too. Between these major peaks, nurse stations exhibit a series of significant fluctuations. In patient rooms, the most prominent peak occurs around 9:00, followed by smaller peaks recurring approximately every two hours.

Figure 3. Snapshot from the qualitative data analysis process.

3. CONTEXT MAPPING STUDY

To prepare for interviews with ICU nurses about sound events in intensive care units, we conducted two observations at the adult ICU. Two researchers observed at different times of the day – one in the morning and one in the afternoon – to be able to fully cover the morning shift with the handovers between night and evening shifts. Then, we interviewed seven ICU nurses (four male, three female) with an average of 13.6 years of experience (ranging from 1.5 to 25 years). To enhance their awareness of sound, participants were given sensitizing booklets and audio recorders. In the week before the interviews, they documented any sounds that made impact on them by taking notes, making drawings, and recording audio, detailing what they heard and when, where, and why a sound stood out. The sensitizing booklet included two main tasks: describing different sound moments throughout a work shift and recording the most remarkable ICU sounds. This process heightened their awareness of clinical sounds in their workspace.

Semi-structured interviews conducted in the ICU allowed for real-time discussions on specific sound-related experiences. Nurses described their daily activities, reflected on the sounds they recorded, and described the most typical moments by also discussing the cognitive load those sound events might bear. Data from booklets and interview transcripts were analysed (see Fig. 3) and categorised into key insights and overarching themes.

The study resulted in 10 main themes, which were organised into time-specific information based on the nurse

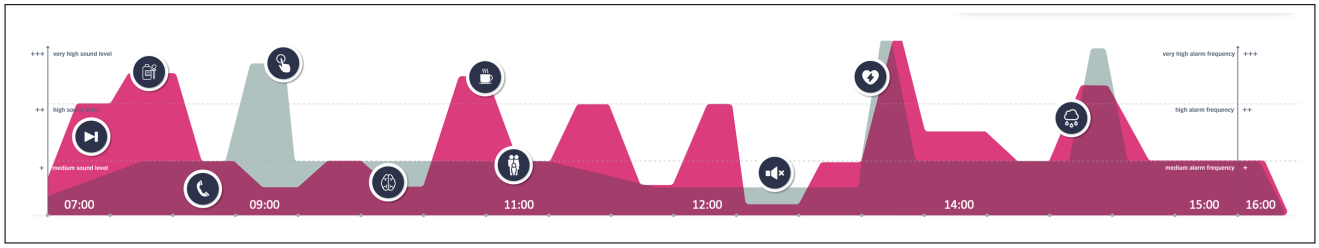

Figure 4. A fictional reconstruction of nurses' perceived sound level for environmental sounds (magenta curve) and perceived frequency for audible alarms (grey curve) covering the morning shift. Note that the timeline is for illustrative purposes only; time intervals are not represented with uniform spacing.

activities belonging to the morning shift (7:30–15:00), starting with when nurses arrive at the hospital and ending with when they leave (i.e., 7:00–16:00). The most frequently mentioned moments in the interviews and how loud nurses experienced these moments were used as a guide to draw a fictional sound level across the timeline. Nurses mentioned alarms in particular and environmental sound in general as sounds that are remarkable. Therefore, we drew two fictional curves based on perceived sound level for environmental sounds and perceived frequency for audible alarms, which can be seen in Fig. 4.

Alarms are described to continuously go off during the day at an average of one alarm per patient every 11 minutes. At the central desk, nurses hear the alarms of all patients at the ICU. Next to that, each monitor alarm goes off at the pager of the responsible IC nurse. Most of the sounds are false alarms, that do not require a direct medical action. According to ICU nurses in the interviews, the quantity of alarm sounds can differ because of unstable patients, transport of patients and alarm settings of their colleagues. The graph shows typical moments in which the alarm frequency is higher or lower. Some **environmental sounds** such as phones ringing, the food lift bell and visitors bell were mentioned to distract ICU nurses, because these require an action from the nurse (sometimes in moments in which they are very busy taking care of the patient). Other environmental sounds, such as chatting of colleagues, were mentioned to have quite a high impact on the overall sound level at the ICU.

4. NURSES' EXPERIENCE OF ICU SOUNDSCAPE AND COGNITIVE LOAD

In Fig. 5 we populated the timeline previously shown in Fig. 4 with the 10 themes identified based on the typical sound producing moments and activities in the order of occurrence throughout the day as mentioned by nurses. The moments representing the themes are labelled as follows: *From silence to kick-start*; *Get (your stuff) together*; *Ring, ring, who is there?*; *Mute that button*; *Brain & explain*; *Take a break!*; *Careful in contact*; *All focus at once*; *Odd silence*; *Start-up in the storm*. Only the *Mute that button* moment was exclusively attributed to alarms, and two more moments (*All focus at once* and *Start-up in the storm*) to alarms and environmental sounds together. Perceived loudness and frequency of alarms fluctuated throughout the day with three moments (*Get (your stuff) together*, *Mute that button*, *All focus at once*) described as the loudest. Only one moment (*Odd silence*) was recognised as the quietest moment in their shift. Below we present each theme supported with nurse quotes and their perception of the cognitive load (CL) caused by the corresponding sound events.

From silence to kick-start. Before the handover at 7:30, it is quiet and most patients are asleep. At the central desk, the ICU nurse teams discuss the status of every patient and who will handover to whom. After this relatively quiet meeting, the handover starts in duos and many nurses start talking to explain each other the patient status details. During the handover period, there are twice the amount of nurses (two shifts) at the same time talking in a small place behind the desk. The sound level goes up, and at the same time patients awake triggering alarms with their movement. *CL:* Going through the patients report, nurses need to pay close attention. One nurse remarked that it is sometimes hard to concentrate on the explanation of a colleague while others are chatting around.

"Many alarms go off and many people talk during the handover."—"Sometimes this gets messy, I would like to see this differently. Elsewhere they do the transfer in the coffee room, here it can be a point of unrest."—"At this

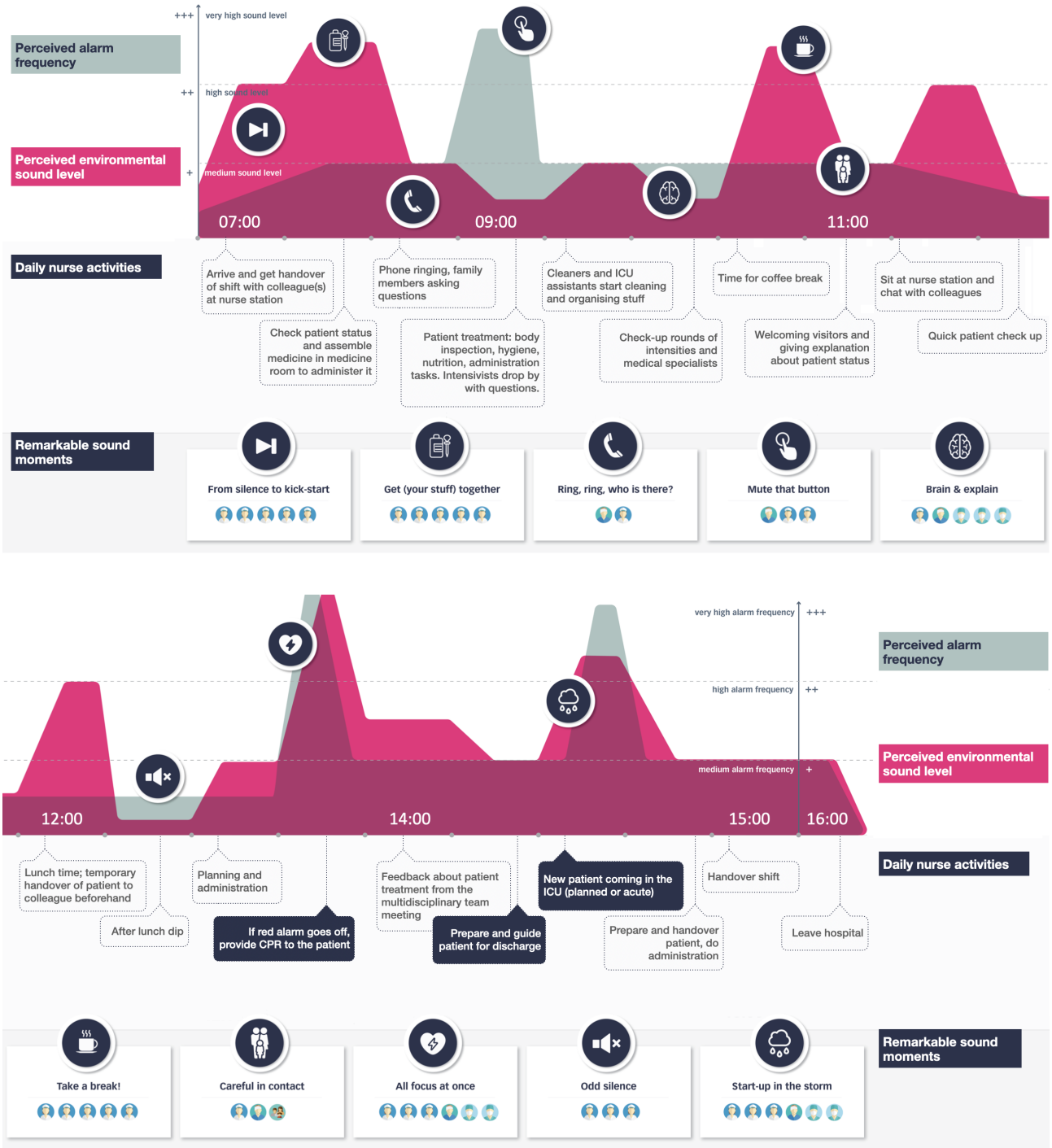

Figure 5. Remarkable sound producing moments and daily nurse activities as mentioned by nurses. For better readability, the original figure is split into two halves, which are presented in a vertical arrangement.

moment I take over all responsibility, so if the patient is in a critical condition I have to pay close attention."

Get (your stuff) together. After the handover, the ICU nurses need to assemble medicine in the medicine room. This is a small room used by both teams, often resulting in a crammed situation in which nurses bend over each other to get the material they need. It is also the first time of the shift in which colleagues are able to chat with each other and catch up. Many nurses remark this moment as a noisy moment, and one nurse told that if possible they avoid being in the medicine room at this time and rather visit a patient in the quiet room. *CL:* Some medicine recipes are more complex than others, which require more or less concentration of the ICU nurse.

"The handover is already busy, then everyone sprints to the medicine room. It really is a chicken coop then."—"Sometimes you plan to prepare medicine and all sorts of things come up in between."—"I sometimes wait until things are quieter."—"The best moment of the day is in the morning when you are alone with the patient and check how things are going."

Ring, ring, who is there? There is a local phone at the central desk. Family members often call to ask about the status of a patient, especially at the start or end of the day. Next to family members, many other medical professionals (e.g., the dietician, lab researchers, physiotherapists, radiologists, and ER nurses) call the central desk to provide information or ask questions about a patient. Often, most of the ICU nurses are not able to pick up the phone if they are in the patient room. *CL:* Only in situations in which the nurse is concentrating on, e.g., a formula of a medicine or stressed of working on other tasks, the telephone can be a distracting sound event.

"Everyone is in the patient room, sometimes the phone often rings then."—"At 8 am and 12 am, many family members call to check how the night or evening went."—"During busy shifts, the phone is sometimes off the hook."

Mute that button. Two nurses help each other in patient treatments, such as body inspection, patient hygiene, nutrition and medicine administration. During these activities, the sensors of the alarm systems are often disconnected or misplaced, which results in a sheer amount of false alarms that are ignored by some nurses and work as irritation factor for others. At the same time, not many nurses are at the central desk to check where the alarms are coming from. Nurses start asking each other to turn off their alarm. During these activities many medical professionals drop by nurses to provide information and ask questions about the patient. *CL:* Alarms cause sensory overload during regular patient care moments when calm is preferred. Nurses want to concentrate on their primary activity (i.e., patient care) and their fellow nurses but find it hard due to constant and high frequency bleeping.

"While treating the patient, I want peace and quiet! The alarms distract me from my primary activity at that time."—"If you sit at the nurse station during wash up, you go completely crazy."—"Washing the patient would actually be much better timed after noon (and doctor's visit between 8 and 11)."—"We would gain a lot by being stricter in the use of the 2-minute pause button."

Brain & explain. Normally, a group of 3-4 (resident) doctors discuss with each other the status and treatment plan in the hallway next to the patient room or in the patient room. They ask ICU nurses one by one to join the group. The nurse interrupts the general treatment of the patient to explain the doctor what the patient has gone through and how the treatment went. *CL:* In case the nurses need to concentrate on the protocol given by the medical professional, alarms are can be disturbing.

"During the doctors' rounds, there are many people standing in the patient room and many busy in the ICU."—"This is when the content is about important patient information. You don't want to be disturbed by alarms then."—"We then quickly close the door of the box to keep out noise from outside."

Take a break! Nurses chat and laugh with each other behind the central desk, as it is part of their working culture. Specific moments of chatting are during the coffee break or lunch break, behind the desk. Some nurses stated that this can sometimes be annoying and search for a quieter space, but cannot leave their patient. This might also have to do with the fact that the central desk is a crammed area. Planning a handover with a colleague is too much effort in such a situation. *CL:* Chatting of colleagues can influence the concentration level when nurses, e.g., are focusing on the formula of a medicine or administration of a drug. Breaks are not always relaxing.

"I unwind behind the counter and can tell my story."—"Sometimes I think, we could have a coffee room."—"Because of the chatter, I sometimes have to walk away to understand someone properly."—"Sitting in the nurse station sometimes I don't like anything, when it's so busy I leave and sit with the patient for a while."

Careful in contact. From 11:00 onwards visitor hours start, and sometimes the visitor bell can be heard ringing at the ICU. Before that time, ICU nurses try to be ready with their other activities to be able to talk with

family members. Sometimes family members come in big groups during their visits, which causes a lot of sound. *CL:* Especially when nurses have to give a thorough explanation or tell bad news to the family members, they need to concentrate on the conversations. Environmental and alarm sounds can distract them during conversations.

"Sometimes people come in large groups and I have to tell them it's too stressful for the patient to let them all in."—"You kind of have to be ready by 11 am."—"I find it disturbing when I'm in a difficult conversation with family members and my pager rings every time."—"Some cultures are extreme how they deal with the difficult situation their relative is in, get angry and bang on the walls."

All focus at once. When a patient is having a heart attack there is instantly a lot of sound because of the high and clear alarm sound which can be heard in the whole ICU. All ICU nurses immediately react to the alarm and possibly start running to the patient to see if they need help. Nurses need to get a trolley with an automated external defibrillator and other lifesaving supplies, making a lot of noise. Many ICU nurses and other medical professionals work together to provide cardiopulmonary resuscitation to the patient. *CL:* In this acute critical situation, nurses experience high concentration and adrenaline while helping the patient. They need to work together as a team. Nurses did not specify that sounds were experienced as disturbing at this moment.

"During CPR, there is a lot of noise for a short period of time."—"Everyone does look back when the heart alarm goes off to see what is going on."

Odd silence. As opposed to excessive sound, silence can bother ICU nurses. If no new patient comes in and there is lack of extra work to do, possibly resulting from the multi-disciplinary meeting with intensivist, a low sound level is experienced at the ICU. During night shifts, many ICU nurses experience tiredness between 5:00 and 6:00. Since there is less environmental sound, they become more sensitive to alarms and at the same time grumpier because of tiredness. *CL:* Apart from administration and patient treatment (if the patient is (un)stable), nurses do not experience problematic sound moments.

"Sometimes there are days after lunch when you think: now something may happen. Between 12 pm and 2 pm, there is often a kind of silence."—"A new intake in the afternoon is nice, in the morning it's dramatic."—"During a night shift you have a kind of dip between 5 and 6 am. At 6 am you start doing things again."

Start-up in the storm. When a new patient enters the ICU, especially following a traumatic event, the sound level rises. The patient needs to be connected to all alarm devices, but since boundaries are set to a healthy person, many alarms go off and need to be adjusted one by one. When starting up the devices a start-up sound is given, which for one interviewee specifically was an unnecessary annoying sound. Altogether, this is a hectic moment with many ICU nurses involved, working hard to stabilise the situation as soon as possible. *CL:* ICU nurses need to concentrate and work as a team. The unnecessary sounds can irritate them and distract them from their workflow.

"Someone is in a life-threatening state and we are hard at work. Then it is very irritating that during equipment start-up unnecessary start-up sounds go off and because of the default settings you have to adjust all the alarms separately."—"It's a hectic time when a lot of alarms go off."—"Those sounds then are really a horror!"

5. DISCUSSION AND CONCLUSIONS

This study investigated the acoustic environment of an adult ICU by combining objective SPL measurements with subjective context mapping techniques based on ICU nurses' experiences. The results highlight important correspondences and discrepancies between the measured acoustic environment and the experienced soundscape, offering valuable insights into the impact of sound on healthcare professionals.

The *SPL measurements* confirmed that the ICU is a highly dynamic acoustic environment, with significant fluctuations in sound levels throughout the day. Peaks in noise levels were observed during shift changes, patient care activities, and critical medical events. These patterns align with previous studies on ICU noise pollution, reinforcing the need for targeted noise management strategies.

The *context mapping* study provided a richer, more ecologically relevant understanding of the ICU soundscape. Nurses identified specific sound events that stood out due to their frequency, perceived loudness, and cognitive impact. Alarm sounds, for example, were frequently mentioned as a major source of auditory overload, leading to fatigue and reduced attentional focus. While SPL data suggests a high frequency of alarm occurrences, the context mapping study revealed that not all alarms had the same perceptual or cognitive impact. Nurses distinguished between expected alarms during routine procedures and disruptive alarms that added unnecessary stress to their workflow. This suggests that SPL data alone do not capture the nuances of how different sounds are perceived and processed by ICU nurses in their daily routines.

Environmental sounds such as conversations, telephones ringing, and equipment noises were also highlighted. While these sounds contributed to the overall SPL levels, their impact varied based on situational factors and individual nurses' tasks. Moments of social interaction, for example, were perceived positively in some cases, while in others, they were seen as distractions that hindered concentration. Another finding is that nurses' perception of loudness and sound significance fluctuates throughout the day, correlating with specific activities.

This study demonstrates that a mixed-method approach combining SPL measurements with contextual insights provides a holistic, ecologically relevant, and listener-centric understanding of ICU soundscapes. Studying how different sounds in the ICU are appraised and utilised can help reduce SPL values by discovering sound moments for possible sonic hygiene. Future research should explore interventions that enhance positive soundscapes while mitigating harmful auditory stressors, ultimately improving both well-being of healthcare professionals and quality of patient care.

6. ACKNOWLEDGMENTS

We thank the Erasmus MC Adult ICU nurses for their contributions to the context mapping study and Dr. Ir. Froukje Sleeswijk Visser for discussions during its setup. ICU sound event annotation is based on an observational study by Ir. Koen Bogers and Ir. Rosel van den Berg. This publication is partially funded by the SASICU project, supported by EU Innovative Health Initiative Joint Undertaking (IHI JU) under grant agreement No 101132808 and by Design United (NL) seed funding granted to Elif Özcan.

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