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SOUNDscapes: A DASHBOARD FOR PROMOTING A HEALTHY SOUND ENVIRONMENT IN THE NEONATAL INTENSIVE CARE UNIT

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ABSTRACT

According to recent studies, the number of auditory alarms and other sound disturbances has a significant negative impact on both the health of patients and the performance of medical staff in neonatal intensive care units (NICUs). This paper presents SOUNDscapes, a digital platform concept where sound events occurring within the NICU are localized and visually mapped. The platform displays the NICU soundscape in real time and assesses the quality of the environment by two main visualizations, i.e., sound level trends and constellation map. The main goal of providing real-time feedback is to make healthcare operators aware of specific (sound) behaviors and their consequences by assessing and observing their collective impact on the unit, ultimately triggering a behavior change. The SOUNDscapes concept and visualizations have been evaluated through expert interviews and a user test with healthcare professionals. Results show that SOUNDscapes provides informative data and powerful visualizations. However, providing information is not enough unless such information becomes actionable.

Keywords: *noise reduction, neonatal intensive care unit, evidence-based design, sound-driven design, soundscape dashboard.*

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1. INTRODUCTION

Despite numerous attempts to reduce unwanted sounds in hospitals, there has been a constant upward trend in sound levels since 1960 [1-2]. Hospitals are extremely sensitive environments in which sound can both affect how well medical staff work and worsen patients' health issues [3-4]. In this context, Neonatal Intensive Care Unit (NICU) patients are particularly likely to experience physiological limitations, central nervous system limitations, and dependency on intensive care because of acoustic pollution [5-8]. Therefore, it is crucial to raise everyone's awareness of the issues and problems caused by the amount of sound that devices and individuals produce especially in shared acoustic spaces, in which listening and sound-making depends on individuals and their purpose [8-14].

In our previous work [15] we discussed various research initiatives undertaken to determine the NICU's needs for a healthy sound environment and to identify potential design opportunities to be developed, with the ultimate goal of locating a technological solution to the issue. These initiatives included a semi-systematic review of the subject of environmental sound in the NICU, a user study with nurses at Erasmus Medical Center’s NICU, and a technology search on the most recent sound monitoring solutions. Our study identified an opportunity to occupy a position in the field in the form of an intelligent system that can foresee potential damages caused by sound pollution and actively recommend a collective behavior change. A lack of such tools is also corroborated by another study that systematically investigated the status quo of available technologies for monitoring and representing indoor soundscapes, especially of healthcare environments [16].

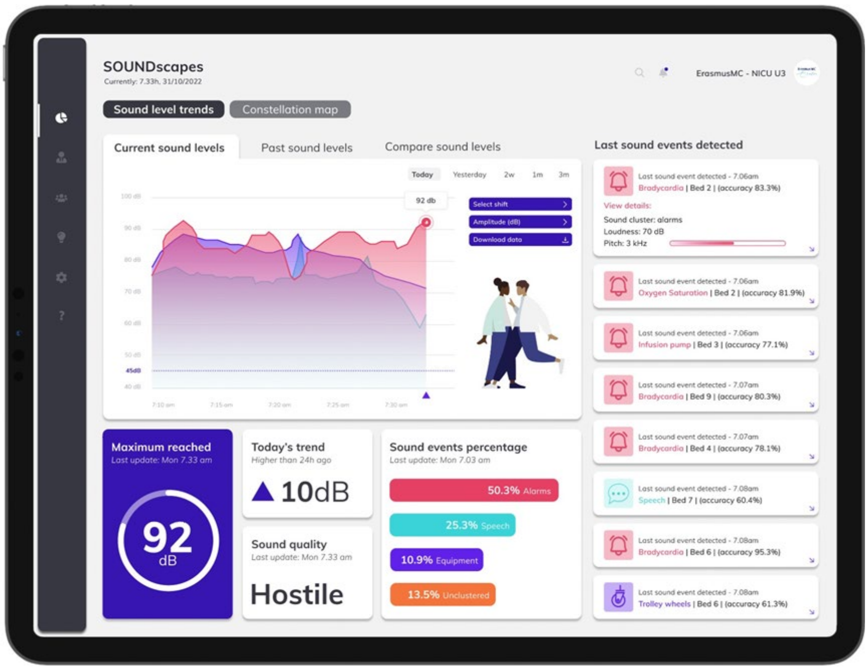

Figure 1. "Sound level trends" visualization page of the SOUNDscapes dashboard.

This paper describes a concept for a sound monitoring system, called SOUNDscapes. We describe the design principle of this system and its architecture, as well as its evaluation by expert users and NICU nurses. We also compare the results of nurses' attitudes towards the NICU acoustic environment before and after they are introduced to the interactive graphical user interface of this system which served as a prototype for our study.

2. CONCEPT

SOUNDscapes is a digital platform by which sound events occurring within the NICU are localized and visually mapped. The platform displays the NICU soundscape in real time and assesses the quality of the environment by two main visualizations, i.e., sound level trends and constellation map. The goal of providing real-time feedback is to make healthcare professionals, and nurses in particular, aware of specific behaviors and their consequences by observing their collective impact on the unit. The underlying system aims at mapping and localizing sound sources, from alarms to speech and medical equipment. It consists of a microphone array that captures, processes, and localizes multiple sound events via a sound event detection system, and a device displaying the visualizations. The concept was developed upon a state-of-the-art review on the available technologies and the needs of NICU nurses related to the acoustic environment, followed by a co-creation session and a focus group with NICU nurses [15].

2.1 Sound level trends

The aim of this visualization, reported in Fig. 1, is to give an overview of the data the system captures and processes in real time. The screen serves as a dashboard and displays sound levels together with sound events detected. The top left portion of the page reports three tabs, i.e., current sound levels, past sound levels, and compare sound levels. Each tab provides a visualization of the sound levels ascribable to alarms, speech, and medical equipment. The "current sound levels" tab shows the sound levels over the last 20 minutes by displaying three overlapping graphs for alarms, speech, and medical equipment sounds. A horizontal dotted line shows the sound level threshold recommended by the WHO [17]. Alternatively, the user can choose to visualize sound level trends among different shifts (on the same day) or download the data for further analysis. The "past sound levels" tab retrieves data from either the day before or two weeks, one month, or three months ago. The "compare sound levels" tab aims at comparing sound levels from two different periods.

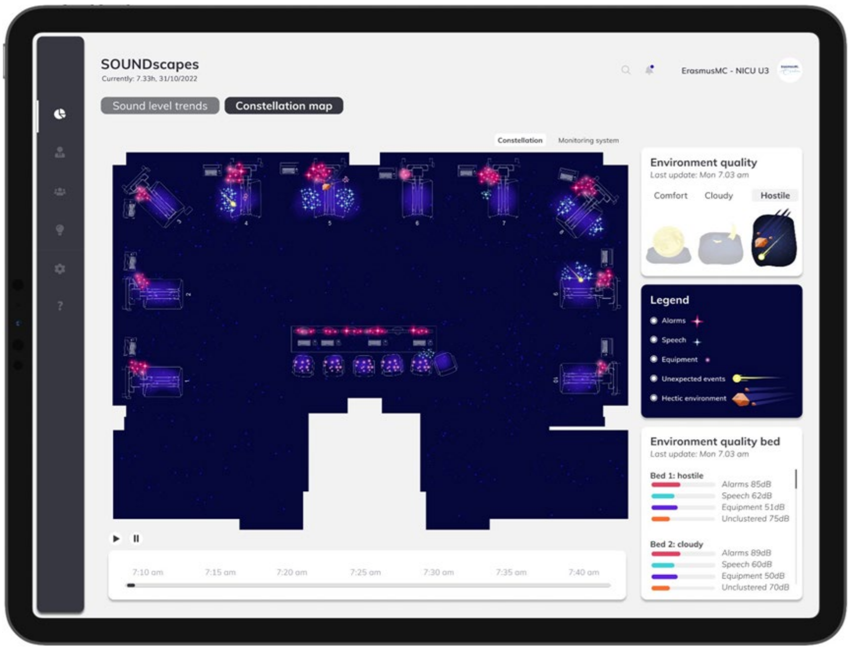

Figure 2. "Constellation map" visualization page of the SOUNDscapes dashboard.

The widgets in the bottom left side of the page provide the maximum dB level reached in the last 24 hours, the average difference with respect to the previous day, and an overview of sound quality – assessed more specifically in the constellation map – as an affective attribute (e.g., "hostile"). The bottom center panel displays the distribution of the detected sound events among four different classes (alarms, speech, equipment, other).

Finally, the right portion of the screen shows a chronology of the last sound events detected by the system, together with their localization (incubator number or nurse station) and the detection confidence. The estimated loudness and pitch (in the case of alarms and speech) is also shown.

2.2 Constellation map of sound events

The goal of the second visualization, reported in Fig. 2, is to map the multiple sound events that the system detects and localizes, with the analogy of a constellation map. The idea is that each sound event is mapped in real time to the area where it is localized within the unit and represented by an icon identifying its category (alarm, speech, or equipment).

Specifically, alarms and speech are represented by pink and light blue stars, respectively, whose size depends on loudness (the louder the bigger) and whose brightness depends on pitch (the higher the brighter). Instead, medical equipment sounds are represented by purple stars with steady brightness and size based on loudness.

Furthermore, a widget in the top right portion of the page shows an assessment of the environment sound quality according to three affective attributes, i.e., comfort, cloudy, and hostile. In case of unexpected events, a meteorite flies over the constellation map in correspondence of the NICU area where the event has been detected. In case of a hectic environment, e.g. when alarms repeatedly sound for more than 10 seconds or speech levels are higher than 65dB, asteroids fly over the NICU area where the majority of the sounds responsible for it have been detected. The remaining two widgets show a legend of the icons and a summary of the environment sound quality by NICU area.

2.3 Proposed system architecture

Beside being visualized on a screen, SOUNDscapes should have a system architecture able to capture and process spatial auditory information. We propose a sound measurement system composed of an array of microphones positioned below the ceiling and covering the whole area of the unit (see Fig. 3). The configuration we tested initially has four GRAS 40PP microphones hanging 50 cm below the ceiling and arranged along a rectangle, connected to a NI-9234 dynamic signal acquisition module [18]. Audio is collected in real time and sent to a workstation where it is processed and interpreted with the help of sound event detection, source separation, sound event localization and, more in general, machine listening algorithms. This requires an intensive data collection and training phase which goes well beyond the scope of the present study. We also propose that the SOUNDscapes dashboard be displayed on a tablet device positioned in the nurses' workstation.

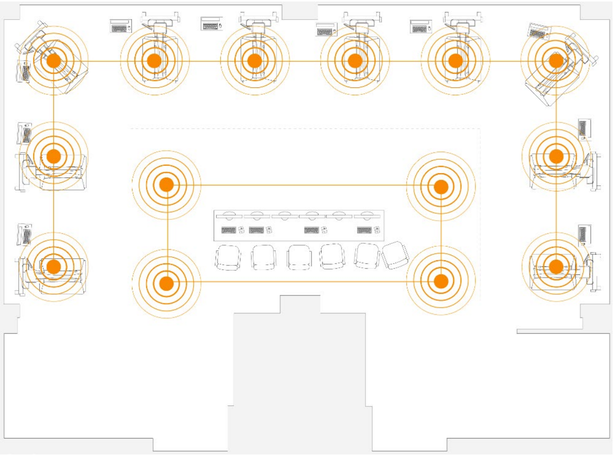

Figure 3. Microphone array system reflecting the NICU layout (incubators and nurse station).

3. EXPERT INTERVIEWS

In order to point out common pitfalls and enhance the SOUNDscapes design concept, we conducted a number of expert interviews. Four key areas of interest of the design were evaluated, with experts in different fields providing a representative and critical view on the design. These four key areas are (1) human-computer interaction; (2) machine listening; (3) healthcare management; and (4) medical staff acceptance, with nurses as principal users.

3.1 Participants

The experts were professionals from either TU Delft or Erasmus Medical Center and are hereby presented.

Alessandro Bozzon (AB) is a professor from the faculty of Industrial Design Engineering of TU Delft. His expertise is at the intersection of human-computer interaction, human computation, user modelling, and machine learning.

Dave Murray-Rust (DM) is an associate professor in Human-Algorithm Interaction Design at the faculty of Industrial Design Engineering of TU Delft. His research lies in the messy area between humans and technology, and he has a particular interest in artificial intelligence and creative practice, with applications to music.

Irwin Reiss (IR) is professor and head of the Neonatology Department of Erasmus Medical Center – Sophia Children's Hospital, with almost 30 years of experience in preterm infants. His expertise lies in neonatology, lung chronic disease in premature infants, healthcare transformation and family-centered care.

Lieke Zuidema (LZ) is an intensive care nurse who works at the Neonatology Department of Erasmus Medical Center – Sophia Children's Hospital, with 20 years of experience.

3.2 Methodology

All experts were contacted via email. The interviews were conducted on an online videoconferencing platform, and experts were interviewed separately. The interviews all followed the same structure: first the interviewer gave a brief explanation of the project's context, problem definition, and design solution. The SOUNDscapes concept and visualizations were shared with them to illustrate the main functions and used as an artifact to initiate discussion. Nonetheless, as all experts were available for a restricted time, semi-structured interviews were prepared to make sure that all key aspects of the expert field were covered. The questions prepared for each expert were used as statements to initiate discussion and evaluate certain aspects of the design. The interviews provided insights that were analysed and clustered in five different categories. These were: (1) general observations about the concept; (2) triggering behaviour change; (3) bridging the human factor with technology: (4) envisioning a data coordination center; and (5) challenges of machine listening applications. All interviewees gave consent for their quotes to be used in the analysis phase and in future publications.

3.3 Results

Below we present a summary of the principal observations in each of the aforementioned five categories, supported by sampled quotes from the experts.

3.3.1 General observations about the concept

The prevailing opinion was that the project is a good starting point for sound management and that it is relevant enough to be considered as a minimum viable product (MVP). However, from a critical perspective, there were some prevalent concerns. The first point regards the technology challenges in mapping sound sources in such a noisy environment and the level of accuracy that the system could achieve. The second one was about the overload of dashboards and the interaction that individuals have with such technology. Implementation is key in providing clear steps on what the product is going to be used for, because otherwise it would be an addition that would not succeed in the long run.

"(...) I think this is the first time that people are making visible what they listen, and this is perfect!" (IR)

"A classical issue with dashboards is that they are designed to impress, but not to be useful." (AB)

"We have to think about the next step. How are you going to implement this and then by the implementation process, how to adapt nurses' needs to your system?" (IR)

3.3.2 Triggering behaviour change

The experts reported that the ultimate goal of such a dashboard would be to trigger behavior change in individuals working permanently at the NICU. In this case, nurses are targeted as the primary users of this dashboard. However, the network of professionals that this product should reach also includes staff such as doctors, ambulance staff, and care assistants who perform their work at the unit more sporadically. Additionally, implementing this dashboard in the NICU is not necessarily imperative for success. Dashboards need to be actionable, which means that they need to tell or suggest people what to do with the information provided. Experts also reported another point linked to actionability, i.e., awareness. It goes without saying that the digital dashboard will provide awareness regarding the sound environment at the NICU. However, the experts outlined that awareness must be applied to a specific context, otherwise it might lead to a stressful situation for the user. The system must suggest potential actions to take, instead of just displaying data and analyses.

"If I look at the constellation, I see that there is a lot of noise due to speech… I would approach my colleagues and suggest them to move the conversation somewhere else." (LZ)

"Awareness makes sense in a given context and it is also useful if it is actionable." (AB)

"So, I think if you really wanted to give something which is really useful to them, you need to try to maybe elicit some reactions, not only about the UI per se, but also about what they will actually use it for." (AB)

3.3.3 Bridging the human factor with technology

Some of the experts' concerns were on how to address the interaction that nurses would have with technology. On one side, technological tools are aimed to ease the workload of medical professionals. However, if not appropriately designed, they might do more harm than good, leading to a situation in which people do not make use of technology. Currently, nurses are oversaturated with dashboards and devices. Certainly, they are a valuable tool for conducting their clinical work, but to some extent the number of alarms that they hear can overstimulate them. If this growth continues to be exponential, they will not be able to attend to all the information provided. This critical point was stressed by the experts, who claimed that designers are the advocates for bridging technology and humans by providing the proper strategies addressing this issue.

"We have to take care that we are not going to overload our nurses and if you would put this on the wall on a unit, how are you going to catch them and see: here is a problem?" (IR)

"You know, you have to attend to all the alarms, but sometimes you are with one baby and cannot attend all of them at once and they keep going on and on." (LZ)

"Interesting, because reducing sound levels feels a bit like one you might want to do in real time. You might want to have a big red light that goes on when people are making too much noise which would be quite an interesting intervention to play with." (DM)

3.3.4 Envisioning a data coordination center

According to some experts, creating a data coordination center would be one alternative to move away dashboards from nurses, and let them focus uniquely on care activities. In this department, professionals would analyze the level of care they provide and act consequently to sound issues spotted by the system. By analyzing all these data streams from the NICU, they could address problems directly with nurses. However, in this vision, it is not clear how such a data coordination center would deal with all the quantity of dashboards. Otherwise, there would be the same actionabilty problem, i.e., abundance of data streams but not actionable information. In any case, there is a consensus that this dashboard can provide excellent analytics data for nurses and healthcare developers. It is a useful measurement tool to evaluate sound quality and localize harmful sound events and certain trends in the data.

"There are so many monitors that it is impossible for nurses to look at them simultaneously." (IR)

"My ideal vision is to have a data coordination center where you sit, and you see dashboards, you see real time alarms. Then, people who are managing this coordination center, take responsibility." (IR)

"In my opinion I think it does not help people if you show that there are high sound levels… It is helpful for management, people like me to deliver high quality of care." (IR)

3.3.5 Challenges of machine listening applications

There was a strong concern among experts regarding the technical feasibility of the product. The main point they all reported was having a system with high accuracy, which is very difficult given all amount of noise and overlapping sounds that occur at the unit. In fact, not only being so accurate about the sound sources but also localization of these sources is ambitious. Nonetheless, some sound sources might be easier to cluster than others, which is the case of alarms. In fact, the design of alarms themselves makes the detection and the sound characterization easier. The evaluation that the system does regarding the quality of the environment was seen as positive, and experts suggested that characterizing sound quality might be easier than characterizing single sound events.

"I think getting some characteristics is easier than getting the individual sound effect of sound events, by quite a long way, because there's a lot of them that are properties of the system." (DM)

"It is certainly not easy in general, I guess the good thing is that alarms are designed to be distinctive. So, you have a good hope that you might be able to pull them out." (DM)

"Careful, because being so accurate about the source of noise is difficult. With the current techniques it is very difficult to obtain such high accuracy." (AB)

"(...) I think doing all of it is probably hard specially to do a full-on source separation thing, but I suspect doing a classification thing is a lot more doable, but definitely not impossible." (DM)

These interviews have been useful not only for the quality of feedback but also for obtaining an unbiased perspective from stakeholders who have not been involved in the development process. The major takeaways from this first evaluation are:

- the SOUNDscapes concept is an excellent starting point for sound monitoring. However, an evaluation plan would give healthcare managers guidelines on the implications of such a product;
- the dashboard must show clear actionability to nurses. Otherwise, it is only a showcase of what the system is capable of doing;
- it might be very challenging to map all the sound-producing events at the unit. Given the designed pattern that alarms have, starting with mapping these events should be the priority.

4. EVALUATION WITH END USERS

While the goal of the evaluation with experts was to obtain overarching feedback on the design concept, substantiating its strengths and weaknesses, this second part of our evaluation aims to validate the possible effects on the end users, i.e., nurses. The goal here is to test the desirability of the design rather than usability.

4.1 Participants

A total of 6 nurses (5F, 1M) working at the NICU of Erasmus Medical Center – Sophia Children's Hospital participated in the experiment during either their lunch break or their end of shift. Their age ranged between 31 and 58 (mean=46.8, std=10.5), and their seniority ranged between 4 and 21 years (mean=14, std=6.9). The recruitment was conducted during the COVID-19 pandemic; hence, participation rate of nurses was low due to ICUs being closed to externals and limited allocation of time. We will therefore be cautious in generalizing the interpretation of quantitative results.

4.2 Methodology

The evaluation test with nurses consisted of a paired pre- and post-test, the purpose of which was to investigate the design intervention's effect on nurses' awareness and understanding of the soundscapes at the NICU and validate the design goal. The test consisted of the following four 5-point Likert scale questions (1=strongly disagree, 5=strongly agree):

- Q1 (confidence): I am confident in knowing the sound levels at the NICU;
- Q2 (awareness): I am aware of the sound levels at the NICU;

- Q3 (understanding): I have knowledge of the sound sources in the NICU;
- Q4 (actionability): I am confident in taking action to reduce certain sound sources at the NICU.

In between the two tests, participants freely interacted with and explored an implementation of the SOUNDscapes interface with toy data.

4.3 Results

Although limited by the small sample size, we chose to apply non-parametric tests to look for statistically significant differences between paired pre- and post-test data. Therefore, four separate Wilcoxon signed-rank tests, one per question, were run. The outcome of the tests (see Fig. 4) is that only Q3 (understanding) shows a mildly significant improvement in the post-test compared to the pre-test ($Z = -1.841$, $p = .066$), while differences in the outcomes of Q1, Q2, and Q4 were not significant.

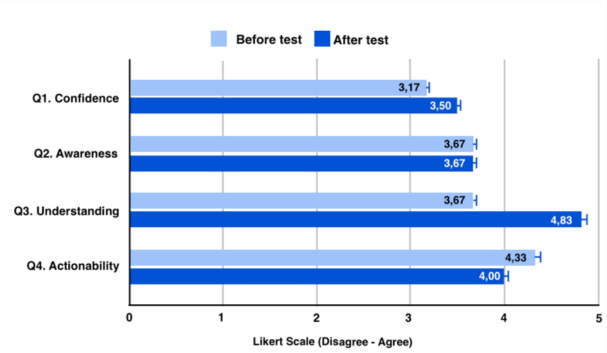

Figure 4. Mean scores for pre- and post-tests on nurses' confidence, awareness, understanding, and actionability.

5. DISCUSSION

In this section we cross-reference the findings from the expert interviews and the questionnaires, addressing how the evaluations answer the design goal and how the findings present challenges for the upcoming future scenarios in the hospital's ecosystem. The design goal aims to strengthen the 'understanding of sound environment' by nurses at the NICU while supporting them to take action regarding sound-related issues. The constellation map proved to be a powerful way of giving a sound interpretation of the environment, but not actionable enough for all participants. Overall, the evaluation results show that SOUNDscapes provides enough data to inform the primary sound sources at the unit but does not provide enough tools to act. One main takeaway from the evaluations is that providing nurses with information is not enough unless this information becomes actionable.

Actionability became a key concept during the evaluations. In fact, from the expert interviews, awareness – which SOUNDscapes aims to provide – was found to be only applicable to a given context and only if it was actionable. It is interesting that actionability was not considered a significant requirement for the dashboard early on, but it became more relevant towards the end of the project.

Throughout the evaluation process, we found that nurses might be the pioneering users of such a dashboard. In the upcoming years, the dashboard could go beyond nurses as principal users and be used for developers to analyze and quantify the quality of care they deliver.

Furthermore, medical professionals will be unable to keep up with the exponential growth of data dashboards. A data coordination center would mean a more centralized way of managing data where experts manage, control, and analyze data. One of the main advantages of having such a coordination center is that nurses would be moved away from interacting with technology and have more time to devote to their patients. The technical specialists working in this centre would address sound-related issues with the nurse lead and the department head. However, the discussion about a data coordination center is not limited to the NICU but would go beyond other departments such as the adult intensive care unit (ICU). The details of such a solution have been extensively discussed in another study by Özcan et al. [14].

6. CONCLUSIONS

The SOUNDscapes concept has proved to be a good starting point to visualize and map potentially problematic sound events in the NICU. This might be a more feasible strategy than trying to solve the overarching problem of high sound levels as introduced in the literature [1-9]. The drawback that its design presents is the difficulty of displaying correct information for every potential user, as the impact that sound has on nurses might be different. Hence, a follow up study is needed to better understand the listening needs of NICU occupants (i.e., patients, families, nurses) making the dashboard more versatile but also more-human centered, allowing for sound-induced action [11]. Moreover, a soundscape study is required to identify and map the frequently occurring sounds, their localization, and also their affective quality (pleasantness and eventfulness).

The future direction that SOUNDscapes provides is a scenario where nurses must deal with several data analytics dashboards. Even considering that the dashboard must be improved with more iterations, mainly on the actionability side, the nurses' role could mean reframing their role as a technical operator. In the upcoming years, more dashboards and devices displaying clinical data will be incorporated into the units. Removing unnecessary dashboards that do not contribute to primary care will allow nurses to have more cognitive time to devote to their clinical job. This will also require better sound-driven algorithms suited for detecting, identifying, and representing sound events and their overall time- and context-dependent behavior in complex acoustic environments [16].

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