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Towards a quieter neonatal intensive care unit: Current approaches and design opportunities

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Towards a quieter Neonatal Intensive Care Unit: Current approaches and design opportunities

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Abstract: Recent studies show that the well-being of patients and the performance of healthcare professionals in modern neonatal intensive care units (NICUs) are severely affected by the amount of auditory alarms and sound nuisance. This paper presents a semi-systematic review on the topic of environmental sound in the NICU, where current themes, insights, and limitations are highlighted. Furthermore, it outlines the results of an observation of the NICU environment and an interview with nurses at Erasmus Medical Center, in order to understand the users, their context, and the technology that can enable design interventions. The insights gathered from the literature and the users, together with a technology search, lead to potential design opportunities to be developed further. Based on these, we propose a technological solution towards a healthy sound environment in the NICU.

Keywords: sound reduction; Neonatal Intensive Care Unit; semi-systematic review; evidence-based design

1. Introduction

We, as a society, have developed a certain tolerance towards environmental sounds, and they have become part of our everyday life. Yet, several studies have shown that sound pollution has adverse effects on many populations, from infants to adults (Teixeira *et al.*, 2021; Gupta *et al.*, 2018), in different environments and workplaces. Among these, hospitals are highly sensitive environments that deserve special attention, since sound can both aggravate patients' health issues and impair the performance of healthcare professionals (de Lima Andrade *et al.*, 2021). Medical alarms, sounds from medical equipment, and the continuous human activity within units cause patients to perceive the typical hospital soundscape as poor (Bliefnick *et al*., 2019).

Despite many attempts in reducing sound in hospitals, there is a clear trend of rising sound levels consistently from 1960 to the present day (Busch-Vishniac *et al.*, 2005; Busch-Vishniac & Ryherd, 2019). Besides, because of adaptation, individuals are often unaware of the sound they produce or the one they are exposed to. Therefore, there is an urgent need to create a shared awareness about the sound pollution that devices and individuals generate and its consequences.

Inside the hospital's ecosystem, there are several environments worth investigating. This research focuses on the Neonatal Intensive Care Unit (NICU). Compared to the adult Intensive Care Unit (ICU), the NICU is designed for premature neonates who are not necessarily ill upon their arrival. Nonetheless, they need special care to grow and survive, and their likelihood of getting ill inside the NICU is high since their bodies are not fully developed. Moreover, neonates are likely to experience physiological limitations, central nervous system limitations, and dependency on intensive care, which makes them more vulnerable to the whole acoustic environment of the NICU (Blackburn, 1998).

Concerns regarding the impact of acoustic stimuli in the NICU were first addressed during the 1970s (Lawson *et al.*, 1977) through direct observation of the environment. Later in the 1990s, an increased awareness of how environmental stimuli affect neonates' clinical conditions and their neurodevelopment was recorded (Philbin *et al.*, 2000); this led to a number of studies by which sound level measurements were carried out in the NICU with professional equipment such as sound level meters (Thomas, 1989; Thomas & Uran, 2007). Sound measurement studies continued throughout the years, providing recommendations for reducing the high sound level issue through room redesign (Chen *et al.*, 2009), use of earmuffs (Duran *et al.*, 2012), or the implementation of educational programmes (Elander & Hellström, 1995; Calikusu Incekar & Balci, 2017).

Following a strategic design approach, this paper presents different research activities carried out to identify the needs of the NICU in terms of a healthy sound environment and to come up with candidate design opportunities to be developed, with the final aim of identifying a technological solution to the problem. This research was done in collaboration with the NICU of the neonatology department of Erasmus Medical Center. Activities include (1) a semi-systematic review on the topic of environmental sound in the NICU, presented in Section 2; (2) a technology search on the currently available sound monitoring solutions, discussed in Section 3; and (3) user research with nurses at Erasmus Medical Center, described in Section 4. Finally, Sections 5 and 6 conclude with our proposed evidence-based design opportunities and technological solution.

2. Sound quality in the NICU: A semi-systematic review

This section reports a semi-systematic literature review carried out to have an overview of the sound monitoring studies that had been conducted inside the NICU. Contrary to systematic reviews, which identify and analyse all the available empirical evidence to quantitatively answer particular research questions or hypotheses, a semi-systematic review

has a broad research question, examines research areas and follows their evolution over time, and synthesises the main themes from the literature using meta-narratives instead of quantitative methods (Snyder, 2019). The resulting themes allow collecting insights and limitations from the literature, which will be later translated into opportunities for research and design in Section 5.

2.1 Methodology

Our research started by identifying relevant studies on environmental sound in the NICU. First, in order to retrieve relevant titles, we queried the popular academic literature search engine PubMed with the following search string, *(NICU OR (Neonat* AND "Intensive Care")) AND (Noise OR "Sound Level*")*.[1] The query returned 77 articles. Then, we excluded (1) articles published more than 20 years ago, i.e., before 2001; (2) articles written in another language than English; (3) non-journal publications; (4) entries without a full text available; (5) duplicate entries. After this filtering phase, 59 articles were left.

Upon carefully reading all the 59 articles, we generated a table of different factors that could hint at potential research themes, such as targeted listener (e.g., neonate, nurse, family); methodologies used for assessment (e.g., measurements, questionnaires, structured interviews); devices used for sound monitoring. Finally, we further excluded those articles that did not actually report the results of environmental sound recordings inside a NICU.

The final sample included 41 articles. Thematic analysis, i.e., a qualitative data analysis method, was used to code, analyse, and report patterns in the form of themes (Braun & Clarke, 2012). In particular, the coding phase consisted of highlighting sections of text and coming up with shorthand labels, or *codes*, to describe their content. For this task, the ATLAS.ti 9 software was used. Once codes were written for all articles, higher-level categories were formed from patterns in the codes. Lastly, categories were clustered in four main themes. When interpreting and explaining themes, insights and limitations emerged. Figure 1 schematically reports the above-described process.

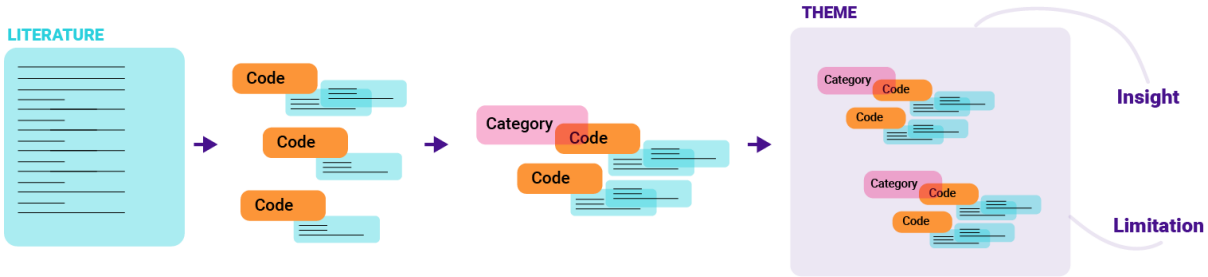

Figure 1. Thematic analysis as a semi-systematic review methodology.

[1] Traditionally, researchers in the medical field consider the term “noise” as “unwanted sound”; this is why we use it as a search term.

2.2 Results

Table 1 reports an overview of the four themes that emerged from the thematic analysis. Each theme covers a number of categories, which are listed below it. We now present an overview of the themes along with the corresponding insights and limitations.

Table 1. The four main themes from the thematic analysis and their underlying categories.

Theme 1: Collecting and processing sound	**Theme 2: Assessing the NICU environment**
Length of the study	Standards and organisations
Measurement intervals	NICU occupancy
Outcome variables	Monitoring area
Monitoring devices	Device placement
Device calibration	Comparing different environments
Theme 3: Interactions with sound	**Theme 4: Beyond sound measurements**
Sound sources in the NICU	Subjective factors and outcomes
Environmental variables	Qualitative assessments
Noise control	Behavioural programmes
Alarm management	Sound education
	Structural changes

Theme 1: Collecting and processing sound focuses on methods used for sound measurement and recording, along with their outcomes.

1. Measurement time spans are generally scattered, and studies hardly follow the same protocol (for instance, a 24-hour period every week for a total of 44 weeks (Brandon *et al.*, 2007), 168 consecutive hours (Aita *et al.*, 2021), or eight separate 1-hour recordings (Krueger *et al.*, 2007)). Currently, all we can find are studies that are episodic rather than continuous. Most of them focus on measuring sound levels to report how harmful the auditory environment can be, but do not focus on implementing potentially long-lasting sound monitoring solutions.
2. Sound level meters are the most used devices for measurement, followed by sound dosimeters (Liu, 2010; Ramm *et al.*, 2017; Smith *et al.*, 2018). Only a few studies use available sound level monitoring solutions for healthcare (Milette, 2010; Casey *et al.*, 2020) or smaller devices such as probe microphones (Surenthiran *et al.*, 2003) to measure the neonates' exposure to sound. Sound level meters generally provide extremely accurate yet objective measurements of the auditory environment. More intuitive interpretations are needed to give individuals a concrete means of evaluation of the sound environment as they experience it.
3. The outcome variables are almost exclusively measurements expressed in decibels (*dB*), most often A-weighted (*dBA*). Only a few studies also conduct spectral analysis, therefore analysing sound power at different frequencies (Surenthiran *et al.*, 2003;

Livera *et al.*, 2008; Lahav, 2015). However, excluding a time-frequency analysis from a sound recording limits a complete perspective about sound events occurring in the NICU. Privacy issues might be the main reason why sound recordings are not stored and analysed, which limits their possible use as training data for sound event detection approaches.

Theme 2: Assessing the NICU environment is about the environmental factors and experimental configurations that studies aim to assess.

4. The goal of the majority of the considered studies is to report sound levels exceeding the recommended thresholds. Baseline levels are established by national and international organisations such as the American Academy of Pediatrics (AAP), the US Environmental Protection Agency (EPA), or the World Health Organisation (WHO) (Darcy *et al.*, 2008; Williams *et al.*, 2007). The general problem with these baseline levels is that they are seen as too low and therefore hard to reach within an environment that several different individuals visit or work in.
5. A substantial number of studies focus on not only reporting sound levels in a specific unit but comparing different environments: for instance, NICUs of different levels of care (Levy *et al.*, 2003), open bay units versus single-family rooms (Liu, 2012; Szymczak & Shellhaas, 2014), or before versus after a structural change in the unit (Krueger et al., 2007; Aita *et al.*, 2021). These comparisons aim to report and give evidence on the most suitable environment for the well-being of neonates, parents, and nurses. Unfortunately, the NICU characteristics in which every study is conducted are unique. Among the characteristics that change we can count patient census, number of beds, number of nurses working during shifts, presence of parents, to name but a few. All these factors can potentially contribute to an increase in average and/or peak sound levels. It is even more challenging to compare outcomes from different studies since they do not share the same settings.
6. In the analysed literature, most researchers explain where measurement devices are positioned. If the goal is to measure environmental sound, devices are often positioned at the centre of the room (Livera *et al.*, 2008; Lahav, 2015). Conversely, they are placed close to neonates' heads when the goal is to measure either subjective exposure or care activities nearby the incubator area (Surenthiran *et al.*, 2003; Liu, 2010). A few studies give a more extensive mapping by placing measurement devices in several different locations within the unit (Krueger *et al.*, 2005; Wang *et al.*, 2014). As single measurement devices are used, measurements in different locations are not time synchronised. The main reason for this experimental choice could be the lack of resources and/or budget. The use of a set of independent devices would give a more complete picture of sound levels and events within the unit.

Theme 3: Interactions with sound is about auditory events in the NICU and how the staff (mainly nurses) deal with them.

7. There is consensus on the most relevant sound sources in the NICU. The most cited categories are related to equipment, i.e., alarms, incubators, mechanical ventilation systems (Lasky & Williams, 2009; Liu, 2012; Restin *et al.*, 2021), and speech (Lahav, 2015; Hernández-Salazar *et al.*, 2020). Alarm levels can neither be set below a certain threshold, nor turned off, meaning that alarm-induced sound level issues can only be addressed through rules and regulations and with the collaboration of stakeholders involved in the manufacturing and supply chain. Furthermore, it is very difficult to avoid voice communication, especially in such a human-centred environment. The goal towards reducing sound levels must go in accordance with the care activities carried out in the unit.
8. Nurses are naturally considered as the main source for human-induced sound nuisance because of their constant presence and continuous activities within the NICU. Although nurses commit to keeping a quieter NICU environment for the wellbeing of neonates, a commonly seen issue is that they are unaware of how loud the sounds they produce can be and how susceptible their environment is (Darcy *et al.*, 2008; Ahamed *et al.*, 2018). The lack of (real-time) feedback in the NICU, such as a visual representation of the impact of human activity on the overall sound level, might deprioritise individual sound awareness.

Theme 4: Beyond sound measurements includes assessments outside the domain of sound, as well as strategies aimed at reducing sound levels.

9. Subjective measurements are necessary to assess individual sound exposure. The literature generally presents two different approaches, depending on the targeted population. In the case of neonates, it is correlated to alterations in heart rate, blood pressure, and oxygen saturation (Williams *et al.*, 2009; Smith *et al.*, 2018). Conversely, questionnaires and interviews are the classical methods used to evaluate staff tolerance and awareness towards sound (Darcy *et al.*, 2008; Trickey *et al.*, 2012). However, studies that focus on the repercussions of the sound environment on parents are scarce, if not absent.
10. Alongside structural changes, behavioural change strategies and the implementation of educational programmes are recurrent patterns in literature (Milette, 2010; Wang *et al.*, 2014; Ahamed *et al.*, 2018), although some authors already point out that they are not effective in the long term (Liu, 2010; Carvalhais *et al.*, 2015). It is indeed uncertain to which extent behavioural strategies can be sustained in the long term without periodic reinforcement. Therefore, it can be possible that the found effects are only temporary.

3. Current sound monitoring solutions

To complement the literature review, we conducted a preliminary technology search to identify those products that are available in the market and could potentially serve as a solution to reducing sound in the NICU, as well as possible market gaps. The search was initially based on sound monitoring solutions for hospitals but was soon extended to companies that released similar products and services for applications outside the healthcare sector. The following solutions were analysed:

- SoundEar A/S (https://soundear.com/), an easy-to-understand monitor that makes sound levels visually represented in three different colour levels (green, yellow, red);
- Sonicu (https://www.sonicu.com/), a wireless remote monitoring technology and cloud-based management platform for virtually any monitoring application;
- Quietyme (https://www.quietyme.com/), a server-based environmental sensor system specifically designed for healthcare and communal settings;
- Sound Intelligence/CLB (https://www.soundintel.com/), a third-generation monitoring solution which differentiates sounds and assigns them different priorities;
- McLennan Sound Monitoring (https://www.mclennansound.com/), a sound level monitor which provides automatic and instant sound level information;
- Pulsar SafeEar (https://pulsarinstruments.com/), a sound control sign that lights up when sound levels are too loud.

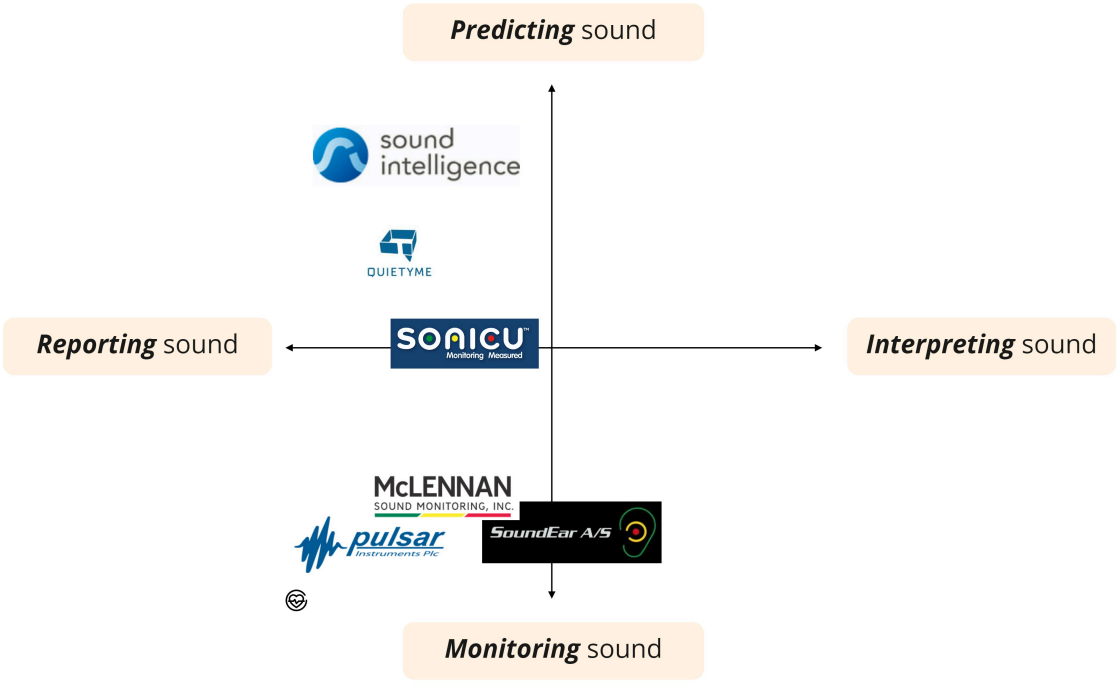

Figure 2. Two-dimensional plot of currently available solutions for sound monitoring rated by interpretative and predictive power.

After analysing the purpose, specifications, and application areas of each of these six technological solutions, we displayed them in a number of two-dimensional plots in order to identify potentially interesting market gaps. Among the attributes that appeared on the axes, we chose product complexity (individual to system product), type of feedback (passive to active), customisation (one-size-fits-all to fully customisable), predictive power, and interpretative power. The latter two attributes represent how much the technological solution is able to go beyond basic sound monitoring, adopting algorithms to classify and/or predict sound events, and to give a meaning to the identified sounds, respectively. The representation that carries these two attributes along its axes is displayed in Figure 2. The figure shows the most significant gap among all representations, i.e., the current lack of technologies in both predicting and interpreting sound events (top right quadrant), which is both a challenge and an opportunity.

4. Exploring the NICU context

While the literature review helped us to understand some of the underlying sound-related issues at the NICU, more insight from the NICU is needed to explore human factors as well as the physical environment. The goal of this section is to gain insights from the NICU by carrying out observations and on-site activities with nurses, in order to explore how nurses perceive the auditory environment.

As mentioned in the introduction, the context of this research is the Level IIIC NICU of the neonatology department of Erasmus Medical Center. The NICU has 35 beds in total, divided among four different units – which differ on the type of care they provide to neonates, being one unit for high care and three units for intensive care – and four single rooms. Patients of the NICU mainly consist of neonates who were born at a gestational age of less than 32 weeks, or who suffered from birth asphyxia.

4.1 Methodology

The NICU context was studied in three consecutive stages. First, we conducted direct observations to get familiar with the NICU physical environment, its objects, and the residents with their roles (i.e., neonates, families, and nurses). Secondly, we wanted to prepare nurses for the interview session with the help of a sensitisation task that allowed them to focus on NICU sounds. Finally, the third stage was reserved for the interviews with nurses.

We conducted a total of three observation rounds. The first one, carried out in Unit 3, helped to get a sense of the physical and auditory environment. The second round, again in Unit 3, allowed shadowing a senior nurse and observing the different care activities during her shift. Finally, the third round, which took place at the recently built Unit 4, helped observe the new structural changes and how they affected the overall sound environment.

Shortly after the third observation round, we conducted user research with nurses to collect more insights about their thoughts and experiences. Six nurses working in the neonatology

department of Erasmus Medical Center were recruited as participants. Their level of seniority ranged from 3 to 30 years (with an average of 15 years) and all nurses were female.

A sensitising booklet was designed to engage participants in their sound experience at the NICU. The tool followed the principle of "path of expression" (Sanders & Stappers, 2012), where the participant first thinks about the present, is then brought into the past to understand the underlying needs, and is finally guided into the future. The core section of the booklet (Figure 3) aimed at identifying sounds from those found during observation and from the literature review and connecting them to an affective quality (Bones et al., 2018).

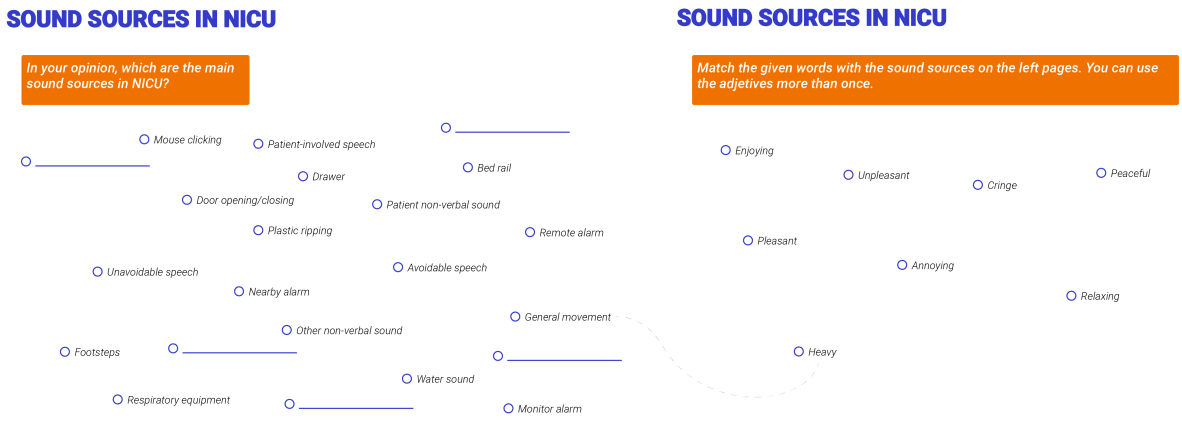

Figure 3. The core section of the sensitising booklet.

As a follow-up activity to the booklet, we conducted a semi-structured interview divided into three parts, aimed at providing more detailed, rich, and in-depth data. The interview was set up according to Patton's (2002) guidelines for qualitative research. The sensitising booklet was analysed prior to the interview and used as an icebreaker for starting the conversation. Then, the first part of the interview explored the participant's experience with sound. The second part identified how they felt about certain sound events, actions that triggered such events, and related behaviours. The third and last part consisted of exploring how familiar the participant was with technology and training through digital platforms. Each interview lasted approximately 30 to 45 minutes. Due to limited time availability, only four out of the six participants completed the interview. The participants signed a consent form allowing us to audio record their interview and transcribe it.

4.2 Results

The observations both confirmed patterns that were seen in the literature and provided new insights. In particular, the nurses' workstation gets busier during shift overlaps. During these time frames (approximately an hour, three times a day) we observed an increase of vocal communications due to patient handovers and informal conversations. On the other hand, sound events due to care activities and other healthcare professionals (e.g., neonatologists, ambulance staff) or parents entering the unit are unpredictable. The only recurring pattern

from the equipment is that of alarms, with medium-priority monitor alarms (known as *yellow* alarms) representing the large majority of the alarm patterns occurring in the unit.

The booklet data helped us mapping sound sources within the NICU. The result is reported in Figure 4, which visualises the location of the most frequently cited sources along with their emotive counterparts (i.e., enjoyable, annoying, unpleasant). Overall, high-priority monitor alarms (*red* alarms) and staff talking were consistently ranked as most unpleasant sounds.

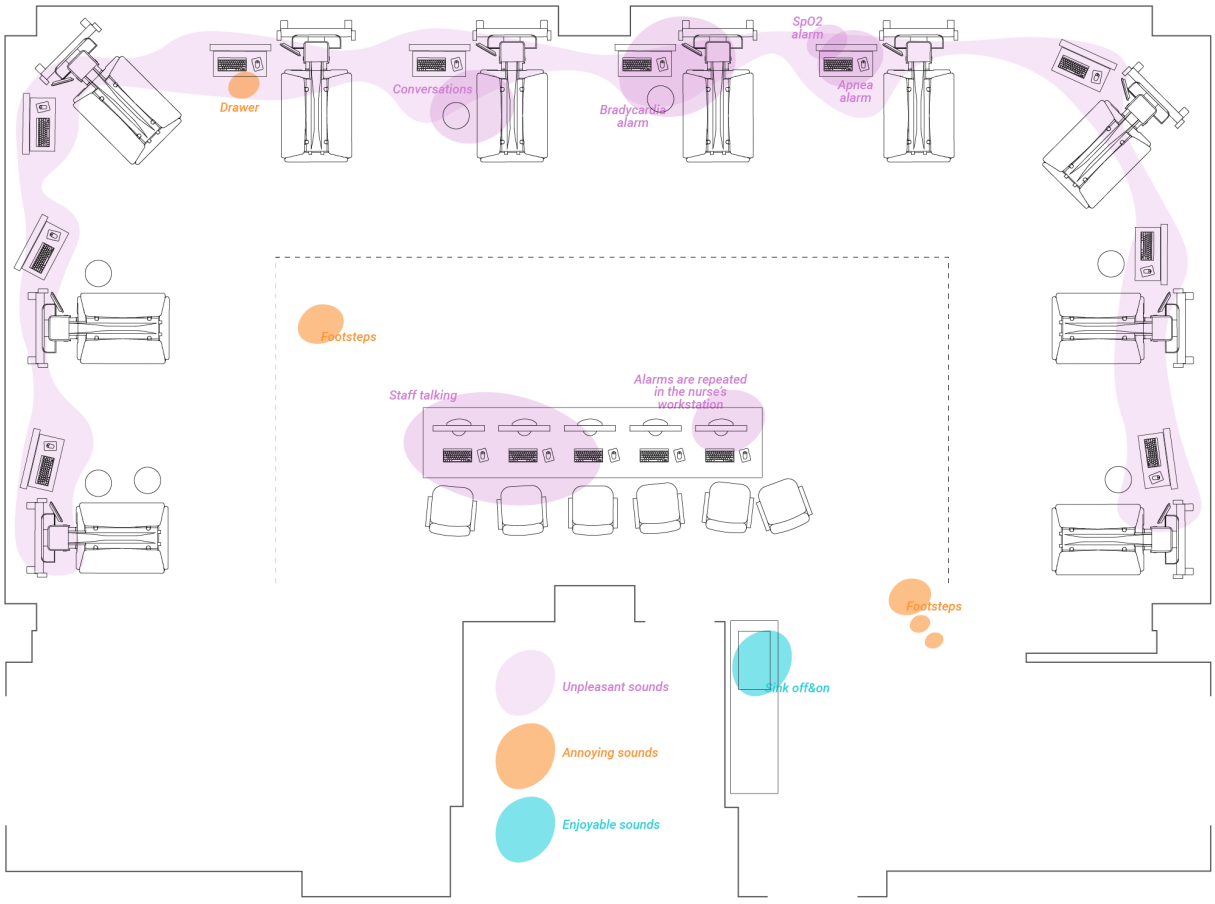

Figure 4. Unpleasant, annoying, and enjoyable sounds in the NICU. The floor plan representation is based on direct observations.

Data from the four interview transcripts were analysed through thematic analysis (Braun & Clarke, 2012), with a similar process to the one depicted in Figure 1. The digital whiteboard software Miro was used in this process. As a first step, quotes from the interviews were selected and placed on digital sticky notes. Then, following interpretation of the quotes, the following relevant themes emerged.

Theme 1: Low perception of sound control. This theme describes the chain of effects that sound causes at the unit. Some participants described that when someone starts talking loudly, the next person will speak a little louder, and so on. While some degree of control can be granted in communications between nurses, it becomes more complex when other healthcare professionals are at the unit as well. Lastly, participants frequently mentioned

that people are unaware of where they should have conversations, and the most common place where this happens is next to the neonate's bed.

Theme 2: Helplessness in interpreting sound. All participants agreed that implementing sound reduction strategies is necessary. One of the participants mentioned that when the results from a previous sound monitoring study were reported to her, she was incredibly surprised by how loud environmental sounds were. However, products providing red-light feedback to extremely loud events such as SoundEar (introduced in the previous section) were reported to not be impactful. As a matter of fact, SoundEar was used for a period of time at the unit without success, because it did not provide meaningful information to nurses.

Theme 3: Alarm overstimulation. Alarms were undoubtedly the most unpleasant sound that the participants mentioned, mostly red alarms. It was observed that senior nurses are slightly more sensitive to alarms than mid-senior nurses. This did not show to be a factor that immediately affects them at the beginning of their shift, yet something accumulative. Additionally, participants reported that it is mentally draining for them to constantly scan the alarms and detect straight away when an alarm is critical. Occasionally, some participants even reported using protective gear. On the other hand, sound events other than alarms or speech have hardly been recalled as unpleasant or annoying.

Theme 4: External stimuli contributing to a pleasant environment. Despite the noisy environment at the NICU, participants could recall moments of pleasantness. For instance, when the light is very soft, people would be more careful when talking since that could act as a cue for silence. Moreover, moments in which nurses are focused on conducting care activities were also reported to be pleasant. Lastly, another factor contributing to having a pleasant environment was the presence of colleagues working on that shift.

Theme 5: Changing actions and behaviours. This last theme refers to actions and behaviours that participants reported as being relevant for a more pleasant environment. In most cases, actions such as responding to alarms were mentioned, although it is not always possible to respond promptly because colleagues would either ignore alarms or be too occupied with other care activities. On the other hand, participants mentioned several unintended behaviours from other staff members, whose behaviour change would significantly improve the sound environment in the unit. One participant stated that *"Sometimes it's just a lot of people and everybody's running around and talking (...) everybody's too busy with their own stuff. So, they do not see the whole picture."*

5. Research synthesis: Towards a technological solution

The findings of the semi-systematic review (Section 2), the technology search (Section 3), and the observations and user research (Section 4) helped us translate the current limitations, knowledge and market gaps, and user needs into opportunities for design or further research. These represent a loose design guideline, the aim of which is to provide

design directions to be evaluated and discussed with the relevant stakeholders for future implementation. A total of six design opportunities have been identified:

1. **Continuous monitoring:** switching from episodic to continuous and permanent sound monitoring.
2. **Sonic analogies:** translating the standard sound level measurement units to meaningful and useful interpretations.
3. **Smart NICU:** introducing intelligent systems for sound event detection and control.
4. **Auditory footprint:** providing people with a visual representation of their contribution to the auditory environment for increasing awareness.
5. **Inclusive design:** providing a pleasant sound environment for specific and individual needs of staff, parents, and neonates, without violating the needs of others.
6. **Behaviour reinforcement:** using digital tools to periodically reinforce episodic behavioural strategies.

We conducted a preliminary assessment of how these design opportunities can address the needs of Erasmus Medical Center from a user-centred design perspective. Specifically, we (i.e., the six authors of this paper) assessed each of the above six items with a rating from 1 to 5 for desirability, viability, and feasibility:

- *Desirability*: Would it address the needs of the current stakeholders at the NICU, and nurses in particular?
- *Viability*: Is it technically feasible to implement with the help of current technology?
- *Feasibility*: What is the likelihood that Erasmus Medical Center will adopt it?

Our ratings are reported in Table 2 below.

Table 2. Desirability, viability, and feasibility of pursuing the proposed design opportunities for the NICU of Erasmus Medical Center.

	Desirability	**Viability**	**Feasibility**	**Overall**
Continuous monitoring	2	5	2	9/15
Sonic analogies	5	4	4	13/15
Smart NICU	5	3	3	11/15
Auditory footprint	4	2	3	9/15
Inclusive design	3	3	2	8/15
Behaviour reinforcement	4	4	3	11/15

We are currently assessing these opportunities together with the stakeholders at Erasmus Medical Center for possibility for implementation. Although a design solution embracing all six of them would ideally address most of the current issues, a careful selection of the most

important aspects will be carried out to ideate and develop a viable and feasible design concept.

According to our self-evaluation, the most sought-after aspects of a technological solution towards a healthy sound environment in the NICU are *sonic analogies*, *smart NICU*, and *behaviour reinforcement*. These aspects could serve as the functionalities for a solution yet to be defined. We propose that the synthesis of the results of our investigation converges into an intelligent system for sound event detection and interpretation that facilitates behaviour change towards sound amongst the NICU inhabitants. Basically, such a system could be defined as a *soundscape dashboard* that collects acoustic data, interprets it in terms of sound-induced potential harm, and visually presents the sound information with concepts easily comprehensible by NICU nurses and families. The aim of this dashboard would be to periodically, and when necessary, encourage people in the NICU to take precautions against sound pollution. Such a sound dashboard would also create awareness towards the sound environment and instigate a collective effort towards the problem.

While such an intelligent sound system would benefit from a *continuous monitoring* functionality for more accurate results, this may cause issues regarding the privacy of NICU inhabitants (e.g., audible conversations or sensitive sound events). A functionality such as *auditory footprint* could also suffer from privacy issues. However, if the sound monitoring solution does not capture human speech in itself but only its basic properties, then continuous monitoring with auditory footprints could provide specific information regarding individual sound behaviours in a personal way. This would also allow the *inclusive design* approach in such a way that the intelligent sound system takes individual needs into account. For example, neonates have different needs with regards to sound (e.g., mother's voice is important, but alarms are too harsh for the developing ear) compared to families who need a conversation with nurses. Such individual needs can be catered for in later stages of development as the basic functionalities (sonic analogies, smart NICU, and behaviour reinforcement) should be established first.

6. Conclusions

In this paper, we established a technological solution towards a healthy sound environment in the NICU. Our proposal is based on a series of studies that investigated the context of sound-induced issues with NICU nurses. The semi-systematic review resulted in early system requirements focusing on the need for collecting and processing sound to assess the quality of the NICU environment, as well as the need for tools to understand human interactions with sounds. Interviews with nurses shed a more user-centred light into the problem with issues raised regarding low perception of sound control, helplessness in interpreting sound, and overstimulation caused by alarms. However, nurses also seem to rely on each other for workflow, and changing behaviour is a collective effort that makes the work environment pleasant.

Our analysis on the state-of-the-art technologies in sound monitoring provided an opportunity to occupy a niche in the field: ambitiously, this would be an intelligent system able to predict potential harms in the context of neonates' healthy development and parent-child bonding without stress. This system would then proactively suggest a collective behaviour change (Özcan *et al.*, 2022). All in all, as a result of our investigations, we propose a soundscape dashboard for creating awareness towards sound sources in the NICU with the help of visual representations based on sound data and their interpretation.

With the tremendous number of trends happening in the technological landscape, it is likely that the NICU of the future will be a place that uses technology to map and assess the quality of the environment that nurses are working in. However, this should not mean overloading nurses with devices and dashboards to interact with; in other words, technology should not prevent nurses from focusing on their patients. Complementary non-digital solutions, such as interior architecture, incubator design, time and resource management, and collaborative ruling strategies, should also be considered as part of the design challenge.

We also need to consider the current possibilities and limitations of sound monitoring systems. As our semi-systematic review and assessment of state-of-the-art technologies highlighted, a continuous sound data collection and analysis did not surface in the literature yet. Such a data collection and annotation effort would be necessary to train an artificial intelligence (AI) model in successfully detecting different sound sources such as alarms, and human speech. Today, AI algorithms show trustworthy performances in even differentiating between individual speech in conversations, but these performances work best with ideal environments where various microphones are used, and the background noise is minimal. In contrast, the NICU offers a challenging sound environment. There is also an added challenge when working with continuous data collection and intelligence analysis of this data, on ethical grounds as well. The question of how to render such a data collection and AI-based monitoring without jeopardising privacy concerns remains a research line in itself.

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