SOUNDSAFE: TOWARDS AN INTEGRATED ASSESSMENT OF SOUNDSCAPE QUALITY IN A NEONATAL INTENSIVE CARE UNIT

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Abstract

It is widely reported that noise levels in neonatal intensive care units (NICU) exceed WHO recommendations, disrupting infant development, family bonding, and staff performance. SoundSafe develops the first integrated soundscape assessment platform for NICUs, combining privacy-preserving Machine Listening, perceptual modeling, and human-centered design. Given the sensitivity of the environment, we embed privacy by design by automatically filtering speech in audio recordings. We deploy a multichannel audio array in Hospital Universitario de Donostia NICU, filtering speech via Universal Speech Codec while classifying sound types using YAMnet and extracting psychoacoustic features. Families and medical staff rate affective qualities per ISO/TS 12913-2. We develop a SoundSafe Quality Index (SSQI) that integrates acoustic, event, and perceptual layers to predict soundscape quality for infant patients, family members, and medical personnel. Co-designed with healthcare professionals via participatory workshops, the SSQI dashboard provides real-time, actionable insights on hospital tablets. Preliminary measurements show 51-56 dBA daytime levels vs. WHO 35 dBA target. Hospitals need a sustainable solution to assess soundscape quality. SoundSafe advances data-centric soundscape assessment for healthcare, supporting Spain's Digital Health Strategy 2021-26. This conference paper presents the background, goals, and methods of the project.

Keywords: *soundscape, neonatal intensive care, machine listening, design*

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1. Introduction

Of all shared spaces in society, neonatal intensive care units (NICU) in hospitals are especially vulnerable environments in which patients, their families, and healthcare professionals are subject to harmful consequences of excessive sounds [1], [2], [3]. Having a prematurely born baby taken into a NICU is an extremely stressful experience for both the infant patient and their caretakers. The optimal functioning of life support, such as respiratory support systems and medical interventions, are of primary importance. Yet comprehensive environmental quality and comfort, continuous emotional support, immense patience, and luck also matter. SoundSafe focuses on one of the most important environmental factors: noise.

While it is well known that noisy acoustic environments at hospitals negatively impact patients, families, and healthcare staff, solutions might appear intractable, because noise, per definition, is an unwanted side effect from some action or event which might be of primary importance. Neonatal ICUs exceed WHO/AAP 45 dBA limits more than 90% of the time, day and night [4]. Noise is an environmental stressor that tends to escape our attention yet has insidious long-term effects. In NICU patients, unfamiliar and loud sounds can lead to developmental, behavioural, and physical problems. The NICU context reflects a complex acoustic environment with multiple sound events, yet producing a predictable overall soundscape. It consists of layers - incubator, caregivers, room, ward – each containing its own set of sound sources: some beneficial, others detrimental. We further distinguish between continuous sounds in the background (life support systems, HVAC, traffic), intermittent midground (distant voices, crying, foot steps), and sudden foreground (alarms with differing degrees of urgency, close voices, movement of doors and furniture). Our previous study of the soundscape in a hospital ward [5] showed that staff conversations and activities are significant contributors to nighttime sleep disturbances, alongside numerous non-human sound sources.

For prematurely born babies, the ideal soundscape should be consistent with the intrauterine environment [6]. Noise is a major stressor, evidenced in changes in heart and respiratory rates, blood pressure, oxygen levels and saturation, intracranial pressure, vagal tone, skin blood flow, and palmar sweat [7]. Excessive and unfamiliar sounds can disrupt vital signs, sleep, and behavior, and may cause long-term developmental issues, including delayed language acquisition [8]. For caregivers, SoundSafe is also concerned with how noise influences their wellbeing in particular the mother and father; for their own sake, and because it is likely to mediate the long-term health of the baby. For healthcare professionals in critical care units, certain sounds (such as medical alarms) create a stressful environment that can provoke unwanted desensitisation [9], and affect job satisfaction and performance [10]. Besides alarms, staff conversations and noises from regular activities are the most disturbing sound sources [11] along with other mechanical sounds, such as ventilation systems, telephones, and delivery trolleys [12]. While training to decrease noise production is an important step, many nurses are unaware of their contribution to noise and might feel a lack of agency [13], [14]. Traditional noise-monitoring technologies rely on sound pressure level (SPL), which is not easily understood by non-experts and fails to capture the emotional quality of specific sound types.

2. Goal

Considering this situation of the NICU soundscape, the overarching goals of the SoundSafe project are framed within the Spanish National Health System's Strategic Action for the "development of tools, technologies, and digital solutions for health and healthcare" [15]. The project's activities align with priority areas by combining quantitative and qualitative approaches to computationally model the relationship between the physical and the perceived properties of the acoustic environment [16] through the following research questions:

1. What are the main contributors to the quality of the NICU soundscape, and how are they perceived by the different NICU populations?
2. What are the appropriate indicators to algorithmically model a sound quality index based on the relationship between the physical and the perceived properties of the NICU soundscape?
3. How does a digital platform for caregivers represent the quality of the NICU soundscape in an insightful, actionable way while complying with privacy?

3. Methods

The SoundSafe project sets out three objectives:

1. Collect and analyse new soundscape data via privacy-transformed audio recordings (and eventually real-time capture), for source identification, ratings of affective qualities (e.g. annoyance, pleasantness), acoustic and psychoacoustic measurements (e.g. loudness), together with qualitative information from questionnaires and interviews [17];
2. Define, develop, and validate a SafeSound quality index (SSQI) for NICU that combines the automatic classification of sound events, the evaluation of their acoustic and psychoacoustic properties and the assessment of their affective qualities, for different users;
3. Integrate SSQI into designing a prototype, novel solution that allows for privacy-compliant data collection and insightful display of information so that NICU professionals can act to improve the soundscape.

3.1. Acoustic environment

The project is focussed on the NICU at Hospital Universitario de Donostia-San Sebastián; the third author of this paper is a leading member of its team of healthcare professionals. Hospitals in the Basque Country are subject to Spain's national acoustic framework [18], EU rules [19] and building regulations [20]. Hospitals are classified as acoustically sensitive, with strict noise control criteria. For critical areas like ICUs, WHO-aligned guidelines recommend a maximum of 35 dBA by day and 30 dBA by night (L_{Aeq}) [21]. In reality, hospitals struggle to keep levels within the recommended ranges. Although regulations in the Basque Country are relatively strict, enforcement and practical noise-reduction measures remain the main challenge.

Preliminary SPL measurements during visits in January 2026 indicated significantly higher levels during daytime. In occupied wards and a corridor, levels ($L_{\mathrm{Aeq,3\,min}}$) were between 51 and 56 dB. Even in an empty ward on standby, with no patients or staff, the level was 41 dB. Interestingly, in this room, SPL inside the incubator (unoccupied) was 42 dBA at the foot end and 45 dBA at the head end (near a single temperature-regulating fan). The next step of the project will extend acoustic measurements using staff-worn dosimeters. Integrating audio privacy (discussed below), an array of microphones in the rooms and corridors of the NICU will allow capturing a wide range of descriptors [22], both acoustic, psychoacoustic, affective, and by sound event type.

3.2. Patient data

Detailed inclusion or exclusion criteria for patients, family members, and nurses participating in the study are currently being prepared for the ethics review. With caregiver consent, selected infant patients will be assessed by certified hospital staff using the Neonatal Behavioural Assessment Scale [23]. It is a comprehensive neurobehavioural exam for newborns (including preterm from 37 weeks) assessing 28 behavioural items, 20 reflexes, and 7 supplementary stress items across domains like habituation, social interaction, motor maturity, state regulation, and autonomic stability.

3.3. Interviews and soundscape ratings

Family caregivers and healthcare professionals are invited to semi-structured interviews (in Spanish, Basque, and English) and soundscape ratings [17]. Family members are interviewed upon admission, after several weeks ('mid-way'), upon discharge, plus an optional follow-up. Open-ended questions include: "What are your thoughts about the visual and acoustic environment at the NICU?" and "From your perspective, what role does sound play in the daily functioning of the NICU?". Nurses and doctors are interviewed about their observations of the acoustic and multisensory environment, probing for example "a moment when you felt that the soundscape was very good and helpful for your patient". We also ask medical staff to rank the importance of 'core measures' [24], including Healing Environment, Partnering with Families, Safeguarding Sleep, and Minimising Stress & Pain, and how they may relate to sound. Both groups will evaluate recordings of NICU sounds to create a taxonomy [5], [25] and fine-tune machine listening models. From preliminary onsite visits, we have identified around 15-18 sound types including Incubator fan, Doors, Footsteps, HVAC, Alarms, Voices, and Coughing.

In a preliminary interview in January 2026, one of the NICU doctors said: "alarms are useful for us, but bad for the baby. We can distinguish between those that are important and those that aren't... They are more of an auditory display than alarms... It takes about two days to learn to recognise the critical alarms". Meanwhile, family members might not always be aware that alarms have different levels of urgency: "We are very aware of what the alarms mean, and act only when needed... Parents tend to focus more on the monitors than on the baby. They look at the baby, too, but mainly they look at the monitors... They become very quick in identifying what each sound means, and expect us to act on pre-alarms [lower priority], when we might be busy with something else". Furthermore, medical staff regularly work long shifts. "When we are on duty, we often do not go outside for 24 hours... We cannot even open the windows, we are not allowed to - the system goes crazy... I keep hearing the alarms even when I am at home, it is horrible". While at work, personnel must find a pace to allow for micro-pauses, but space constraints might inadvertently cause additional noises: "When we relax... we are less conscious of the noise we make - sometimes we are asked to shut up because maybe we are laughing and next door they are handling bad news... Sometimes we produce sound, too, for instance, we tap on the top glass of the incubator when we stand around the baby".

3.4. Machine listening

SoundSafe will conduct audio data collection over long stretches of time using multiple microphones in the NICU. Previous Machine Listening (MLi) methods have focused mainly on outdoor settings due to privacy concerns in hospitals [1]. From the viewpoint of audio analysis, a hospital ward is a specific kind of an 'in the wild' environment, and privacy requirements place strong limitations [5]. Speech may possess semantic information that is sensitive to the people involved and not essential to the present study. Our workflow retains only information about the amount and loudness of speech, paralinguistic vocalisations (crying, coughing, sighing), and non-semantic emotional characteristics (arousal, valence, anger, sadness, happiness) [26]. The process has three stages running in near real-time:

1. Speech vs. non-speech separation [27], [28] using a supervised separation model at the signal level (mask-based DNN or time-domain separator for near-realtime application) [29], [30], [31] fine-tuned on our NICU recordings with annotated background stems.

2. Paralinguistic analysis. On the speech stem only, extracting psychoacoustic descriptors (loudness, sharpness, roughness) as well as emotion-related features using a speech emotion recognition (SER) frontend [32].

3. Privacy protection. For future auditability and before storage or sharing, we avoid keeping identifiable raw speech. Where speech must be retained, we either keep only high-level, non-invertible features (e.g. SER outputs and psychoacoustic descriptors), or apply a speaker-privacy-oriented representation such as a Universal Speech Codec (REF) semantic embedding, which has been shown to preserve much of the paralinguistic and sentiment-related information while substantially reducing speaker-identifying attributes [33]. We will explore federated, semi-supervised training for SER [34] to keep data on-device and therefore reduce central aggregation of sensitive speech.

The outputs of this analysis will contain stems of non-speech elements and a set of speech-related descriptors, such as paralinguistic vocalisations and speech-related emotions. Where strictly necessary, the analysis can retain a privacy-transformed representation of speech. On the non-speech elements, an automatic pretrained audio neural network classifier such as YAMNet DNN [35] using AudioSet-521 embeddings fine-tuned on the NICU taxonomy (around 15 classes) that the project will develop.

3.5. SoundSafe Quality Index

The MLi method allows extraction of conventional acoustic (SPL, SNR, $L_{90/50/10}$) and psychoacoustical descriptors (time-varying loudness, tonality, sharpness, roughness, and fluctuation strength). We explore multivariate linear regression [36] and a dual-branch convolutional neural network with cross-attention [37]. Modelling is informed by integrating layers of information: which sound source is impacting the quality of the soundscape (event classification), in what way (affective qualities), and how (acoustic-physiological and psychoacoustic mechanisms). In a tentative model, Eventfulness (Ev) and Annoyance (An) depend on sound-type classification. SpeechRatio (SpR) indexes the relative prominence of speech in an acoustic scene and may be operationalised using speech-to-background ratio and speech intelligibility. Different user profiles (patients, family, personnel) would determine weightings (w_i). For example:

$$\mathrm{SSQI} = w_1 \cdot \mathrm{SPL} + w_2 \cdot \mathrm{Ev} + w_3 \cdot \mathrm{An} + w_4 \cdot \mathrm{SpR} \quad (1)$$

We envisage SSQI as an integrated metric that will continuously communicate relevant information of sound level, soundscape affective qualities, and health impact.

3.6. Human-centred design

An automatic, human-centred solution to monitor and predict the emotional and acoustic quality of NICU environments will support better healthcare outcomes and sustainable working conditions. The project will develop user interactions with information towards real-world evaluation by:

1. Defining human-centred design requirements with nurses by employing data probes (i.e., semi-functional mock-ups of the platform with visual data representation) and qualitative research methods (e.g., observations, interviews, user diary) to better understand the User Journey and what to achieve (desirability, viability);

2. Co-creating with nurses the prototype of the SoundSafe platform that connects the computational model with the context and user experience of the NICU. Methods will include participatory design sessions, data-driven prototyping, physical/digital mockups manufacturing using digital fabrication methods;

3. Evaluating a live prototype of the digital platform that integrates the SSQI with the data interactions shaped through co-creation. This minimal yet functional implementation will be critical to capture and evaluate the response of NICU users to such a digital platform in a controlled environment and in-situ. Evaluation will combine quantitative data from the platform, questionnaires to assess cognitive load, usability and technology acceptance and qualitative in-depth interviews with nurses and other staff members involved in the implementation.

4. Discussion

An ICU admission of a child is an event that highly impacts the lives of families and young patients. At the same time, it is a highly demanding and stressful environment for healthcare professionals. Today, hospitals around the world are actively supporting the transition towards a smart working environment that leverages big data to identify harm and threats in real-time and mitigate stressful situations on professionals, patients, and their families. Our research supports this effort by developing a data-driven solution for the automatic interpretation of real-time audio to allow an understanding of sound and its impact on humans, and prototyping a visual dashboard by which information is displayed in a usable manner so that NICU healthcare personnel can act to reduce stressors.

A recent review [1] shows that current technological solutions for the assessment of indoor acoustic environments in the hospital context mainly collect, measure, and display SPL. However, a single-digit value is difficult for non-experts to interpret correctly [38] and a 'traffic light' visualisation is not on its own sufficient for describing affective qualities of the soundscape - sounds can appear as pleasant, calming, chaotic depending on context [16]. Furthermore, SPL does not identify the causes of unwanted sounds. A core objective of the project is to raise awareness of sounds among healthcare professionals to enable them to understand their positive and negative impacts.

To date, computational models of source classification and affect mainly focus on outdoor environments [39], [40]. This is due to international legislation requiring periodically monitoring and mapping the noise levels in urban spaces [19] and increased prevalence of low-cost sensor networks for the automatic collection of large volumes of audio data [41]. Soundscape analysis was initially develooped for outdoor environments [42], and the application of these protocols indoors is at the stage of defining appropriate descriptors [36]. Effective algorithms to model and predict the human response to indoor sound pollution are still missing.

Conducting this research inside a NICU environment presents several challenges. In general, it might be very difficult to obtain data, especially audio recordings and eventually real-time capture, and to recruit caregivers and healthcare professionals. The SoundSafe project has already commenced by engaging Donostia NICU professionals via the preliminary study and a seminar. Once the full data collection commences, we may encounter further challenges in that the data might not be fully relevant, representative, inclusive, and sufficient for us to develop a proper analysis and obtain significant conclusions. To handle this challenge, the SoundSafe core team, with experience in soundscape, design, and medicine, will be able to call on additional resources as needed.

There is a knowledge gap in the capability to model the affective qualities of the acoustic environment in hospitals. Our research will boost soundscape studies by providing empirical knowledge and data-driven

models of environmental perception. The SoundSafe project has access to an extremely sensitive and protected environment for data collection, analysis, and experimental evaluation. The research will provide essential new knowledge for soundscape studies, data-centric design, acoustics, psychoacoustics, audio computing, as well as to the broader scientific community (social sciences, healthcare, computer sciences). Thus, by examining the NICU soundscape and its different levels of experiences, the project will have a scientific impact in that it develops novel solutions to a technological gap and a social impact in that it empowers healthcare professionals to act against sound pollution. In the medium term, the insights gained will inform staff training programs and guide design interventions to improve NICU soundscapes. Long-term benefits include the strategic planning of NICU layouts, workflows, and infrastructure by hospital management, based on robust acoustic data.
Overall, SoundSafe results will accelerate data-driven design research in Spain for greater societal and potential economic impact through industrial patents and models.

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