Positive listening experiences for intensive care patients
A listener-centric, need-based approach to ICU soundscape design

Louwers, G.L.M.

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A listener-centric, need-based approach to ICU soundscape design

Gijs Louwers

Propositions

Accompanying the dissertation

Positive listener experiences for intensive care patients:

A listener-centric, need-based approach to ICU soundscape design

by

Gijsbrecht Leonardus Maria LOUWERS

1. A listener-centric approach, grounded in fundamental needs, provides a strong basis for designing soundscape interventions that improve ICU listening experiences. (this dissertation)
2. ICU departments should actively manage soundscapes by preserving wanted sounds, reducing unwanted sounds, and introducing new sounds to provide more patient-centered intensive care stays. (this dissertation)
3. Sonic ambiances are the affective connotations that listeners associate with soundscapes. (this dissertation)
4. Sound compositions designed by modulating four key parameters—eventfulness, sonic ambiance types, narrative structures, and sound categories—can help transform ICU soundscapes into functional resources. (this dissertation)
5. Studying soundscape descriptors, such as pleasantness and eventfulness, in relation to listeners' needs is essential, as those shape how sounds are perceived and experienced.
6. New standards for designing soundscape interventions should base design processes on contextual factors—such as listeners' needs and preferences—bridging soundscape evaluation and design.
7. Designers in complex healthcare contexts must understand design problems from multiple perspectives—patient, caregiver, and other stakeholders—to create solutions that address their needs and integrate into healthcare workflows.
8. Documenting environmental preferences—such as sound, lighting, and sleep-related factors—into patient records is a necessary step towards truly patient-centered, humanized care.
9. Light, sound, or audiovisual ICU interventions should integrate patients' environmental preferences with contextual factors of critical care, ensuring the safety and effectiveness of ICU care while honoring patients as individuals.
10. A doctoral degree in design makes you simultaneously under- and over-qualified for human-centered design in practice.
11. No one really knows how to deal with the unexpected, said Wayne Shorter about jazz. Designing new products is just like jazz improvisation: you cannot practice the unknown, so you make due with trying to get to the right idea based on timing, your experience, and readily available imagination amidst an unknown sea of endless possibilities.
12. Design research is like surfing: it requires balancing between control and adaptation, riding the waves of uncertainty with skill, intuition, and an openness to unexpected insights.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors dr. E. Özcan Vieira, prof. dr. S.C. Pont, and prof. dr. D.A.M.P.J. Gommers.

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A listener-centric, need-based approach to ICU soundscape design

Gijsbrecht Leonardus Maria LOUWERS

Positive listening experiences for intensive care patients:

A listener-centric, need-based approach to ICU soundscape design

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus prof. dr. ir. T.H.I.J. van der Hagen,
chair of the Board for Doctorates
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by

Gijsbrecht Leonardus Maria LOUWERS

Master of Science in Design for Interaction,
Delft University of Technology, Delft, the Netherlands
born in The Hague, the Netherlands.

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	chairperson
Dr. E. Özcan Vieira	Delft University of Technology, promotor
Prof. dr. S.C. Pont	Delft University of Technology, promotor
Prof. dr. D.A.M.P.J. Gommers	Erasmus Medical Center, promotor

Independent members:

Dr. F. Aletta	University College London, United Kingdom
Prof. dr. ir. J.H. Eggen	Eindhoven University of Technology
Prof. dr. J.A.C. Rietjens	Delft University of Technology
Prof. dr. ir. R.H.M. Goossens	Delft University of Technology
Prof. dr. ir. P.M.A. Desmet	Delft University of Technology, reserve member

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We need something more than the satisfaction of vision alone;
we need to create the world of things unseen.

Raoul Dufy

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SUMMARY

In this dissertation it was investigated how the acoustic environment perceived by patients, or soundscapes, in Intensive Care Units (ICUs) could be optimized to support more human-centered ICU stays. The dissertation had two objectives: first, to explore how human-centered design could contribute to positive listener experiences for ICU patients with a need-based, listener centric soundscape approach; and second, to evaluate the effectiveness of this approach, i.e., to what extent designed soundscape interventions could benefit patients in terms of soundscape perception, emotional states, and stress. To achieve these objectives, a combination of listener-centric, evidence-based practices was employed rooted in human-centered design and sound-driven design. The five studies in the dissertation featured a mixture of qualitative and quantitative methodologies, including interviews, questionnaires, and physiological measurements. The project was a collaborative effort between the faculty of Industrial Design Engineering of TU Delft, the Critical Alarms Lab, the Adult ICU department at Erasmus Medical Center, and Philips.

The experiences of patients with soundscapes of single-patient ICU rooms were examined to form an understanding of the context of ICU soundscapes and patients as its listeners (Chapter 2). Using a mixed-methods approach of interviews and questionnaires with 26 ICU patients, the study identified six themes in sound-related experiences: Orientation through sound, Coping with disruptions, Human auditory presence, Monotony and variation, Associations and hallucinations, and Communication behind closed doors. Findings indicated that while single-patient rooms mitigated excessive noise, they also deprived patients of essential auditory cues, which impacted their ability to orient themselves and feel connected to their social surroundings. Three insights emerged: first, positive auditory elements from corridors, such as distant staff activity, may be unnecessarily removed in single-patient ICU rooms, contributing to emotional distress and disorientation; second, medical alarm sounds, though often regarded as disruptive, served an unexpected supportive role for patient reassurance; and third, there is a lack of accessible and appropriate auditory stimulation. Associated with a lack of fulfilment of fundamental psychological needs, these findings highlighted the need to balance the mitigation of unwanted sound by preserving access to wanted sounds and diversifying the soundscape with new sounds.

Another study focused on the relationship between sound and fundamental psychological needs, and specifically whether fundamental needs could form a basis for ICU soundscape design (Chapter 3). The study examined nine needs—such as Autonomy, Comfort, and Recognition—through an online survey where participants described imagined sound environments that fulfilled these needs. The findings revealed that sound category distributions could be categorized into four groups—human, natural, musical, and technological. It was found that the soundscapes people associated with the ideal fulfilment of the needs were distinctive. Certain needs, such as Beauty, were strongly associated with natural sounds, whereas others, like Competence, often included technological sounds. Human sounds were most commonly associated were the most common across all needs. The results suggested that soundscape interventions should be tailored to specific needs to support well-being, underscoring the need for a flexible soundscape approach in ICUs that allows for individual adaptation rather than a rigid, one-size-fits-all solution.

With a collaborative workshop, concept directions were investigated for improving ICU soundscapes to enhance patient well-being (Chapter 4). The study built on the insights gained from ICU survivors' sound-related experiences, and incorporated the perspectives of ICU nurses, resident doctors, and researchers to generate practical design solutions. Three system concepts were developed: a Smart Environmental Assistant, Patient Soundscape Dashboard, and Familiar Wake-ups concept. These concepts aimed to respectively provide patients with greater control over their auditory environment, adapt soundscapes to personal preferences, and integrate familiar sounds to enhance comfort and orientation. Analysis of the concepts revealed five essential design characteristics for effectively improving ICU soundscapes: user-friendliness, personalization, humanization, integration, and familiarity. The findings highlighted that including the perspectives of different ICU stakeholders ensured that concepts were aligned with clinical needs. The results emphasized that collaborative approaches to soundscape design is essential for ensuring that interventions are both effective and feasible in clinical practice.

Following the insights of the preceding studies, in two studies it was investigated how tailored soundscapes can enhance ICU patients' well-being based on the fulfilment of fundamental psychological needs (Chapter 5). A structured approach was developed to design soundscape interventions by identifying four types of sonic ambiances—Comfortable, Pleasurable, Motivating, and Stimulating—based on perceptions of

soundscapes' pleasantness and eventfulness and underlying fundamental needs. In the first study, qualitative and quantitative data were gathered to determine how different soundscapes related to specific needs. The research outlined a design process for designing compositions of Natural, Human, Musical, or Technological sounds as soundscape interventions. Four design parameters were identified for creating the sound compositions: eventfulness, sonic ambiance qualities, narrative structure, and sound distribution. These were used by a sound artist to develop tailored, need-based sound compositions. In the second study, these compositions were tested in a simulated ICU setting. Results showed that designed soundscapes could positively influence perceived pleasantness, eventfulness, and experienced emotions, confirming the validity of the proposed approach for creating supportive ICU environments.
It was then investigated whether the effects of the designed soundscape interventions could be replicated in a real-world single-patient ICU setting (Chapter 6). The results of this study were in line with the findings of the simulated ICU setting. The study was conducted in a single-patient ICU room with healthy participants who listened to simulated ICU soundscapes, including alarm and ventilator sounds. The study featured sound compositions with Natural, Human, and Technological sounds and Comfortable, Pleasurable, and Stimulating sonic ambiance types as soundscape interventions. The soundscape interventions were introduced to the patient room to assess their effects on perceived pleasantness, eventfulness, emotional state, and physiological stress responses through questionnaires and electrocardiogram (ECG) measurements. Results showed that interventions significantly enhanced pleasantness and eventfulness, improving participants' emotional states and potentially reducing stress. The findings also emphasized that ICU soundscapes should be listener-centric and adaptive, tailored to patients' sound-related needs and the existing acoustic environment.

The dissertation provides practical contributions for designers in the form of the developed listener-centric, need-based approach, insight cards of the sonic ambiance types, as well as of the six themes found in patient experiences. It also contributes to a paradigm shift in soundscape research and knowledge for humanization of ICU stays, moving beyond mere noise reduction towards personalized, adaptable ICU sound environments. It was suggested that future research and development of soundscape interventions in ICUs should test the effectiveness of the approach with patient populations. Also, it should be investigated whether documenting/integrating patients' environmental preferences and whether automatic, preference-based, multi-modal systems can be implemented to further humanize ICU care. By implementing the findings of this dissertation, hospitals could transform ICUs into more human-centered spaces, where soundscapes actively contribute to patient recovery and overall quality of care.

SAMENVATTING

In deze dissertatie is onderzocht hoe de geluidsomgeving, oftewel de soundscape, van Intensive Care Units (ICU's) door patiënten wordt waargenomen, en hoe deze geoptimaliseerd kan worden om menselijkere ICU opnames te bewerkstelligen. De dissertatie had twee hoofddoelen: ten eerste, te onderzoeken hoe human-centered design kan bijdragen aan positieve luisterervaringen voor ICU-patiënten met een op gebruikersbehoeften gebaseerde, luisteraar-gerichte soundscape aanpak; en ten tweede, de effectiviteit van deze aanpak te evalueren, specifiek met betrekking tot in hoeverre ontworpen soundscape interventies de perceptie van ICU geluiden, emoties en stress kunnen verbeteren. Om deze doelen te bereiken, werd een combinatie van luisteraar-gerichte, onderszoeksgedreven methoden toegepast gebaseerd op human-centered design en sound-driven design. De vijf studies in de dissertatie omvatten zowel kwalitatieve als kwantitatieve methodologieën, waaronder interviews, vragenlijsten en fysiologische metingen. Dit project was een samenwerkingsverband tussen de faculteit Industrieel Ontwerpen van TU Delft, het Critical Alarms Lab, afdeling IC Volwassenen van het Erasmus Medisch Centrum en Philips.

De ervaringen van patiënten met soundscapes in eenpersoons ICU patiëntenkamers werden onderzocht om een beter beeld te krijgen van de geluidomgeving van ICU's en van patiënten als luisteraars (Hoofdstuk 2). Als resultaat van een mixed-methods studie, waarbij de geluidsgerelateerde ervaringen van 26 ICU patiënten in kaart werden gebracht door middel van interviews en vragenlijsten, kwamen zes thema's aan het licht: Orientation through sound, Coping with disruptions, Human auditory presence, Monotony and variation, Associations and hallucinations en Communication behind closed doors. De bevindingen toonden aan dat hoewel eenpersoonskamers overmatig geluid verminderden, ze patiënten ook essentiële geluidssignalen ontnamen waardoor hun oriëntatie vermogen en verbondenheid met de sociale omgeving werd beïnvloed. Dit leidde tot drie belangrijke inzichten: ten eerste, positief gewaardeerde geluiden uit de gangen, zoals van activiteit van zorgpersoneel, kunnen onnodig worden verwijderd in eenpersoonskamers, wat bijdraagt aan emotionele stress en desoriëntatie; ten tweede, medische alarmsignalen vervullen, ondanks hun verstorend karakter, een onverwachtse ondersteunende rol bij de geruststelling van patiënten; ten derde, er is een gebrek aan toegankelijke en geschikte auditieve stimulatie.

Omdat deze tekorten de vervulling van fundamentele psychologische gebruikersbehoeften raken, werd benadrukt dat een balans nodig is tussen het verminderen van ongewenst geluid, het behouden van gewenst geluid, en het variëren van de soundscape met nieuwe geluiden.

Een andere studie richtte zich op de relatie tussen geluid en fundamentele psychologische gebruikersbehoeften, en onderzocht of deze behoeften als basis konden dienen voor ICU soundscape design (Hoofdstuk 3). In een online vragenlijst beschreven deelnemers soundscapes die bij zouden dragen aan de vervulling van negen behoeften, zoals Autonomy, Comfort en Recognition. De resultaten toonden aan dat geluidscategorieën in vier groepen konden worden onderverdeeld—menselijk, natuurlijk, muzikaal en technologisch. Het onderzoek toonde aan dat verschillende behoeften werden geassocieerd met andere geluidscategorieën, zoals natuurlijke geluiden voor Beauty en technologische geluiden voor Competence, terwijl menselijke geluiden het meest consistent aanwezig waren bij alle behoeften. Dit suggereerde dat soundscape interventies op maat gemaakt zouden moeten worden om welzijn te kunnen ondersteunen. Het suggereerde ook dat een flexibele soundscape aanpak noodzakelijk is in ICU's welke ruimte laat voor individuele adaptatie in plaats van een universele, rigide oplossing.

Door middel van een co-creatie workshop werden conceptrichtingen onderzocht om ICU-soundscapes te verbeteren om het welzijn van patiënten te verbeteren (Hoofdstuk 4). Dit onderzoek bouwde voort op de bevindingen uit ICU patiëntervaringen en integreerde de perspectieven van ICU verpleegkundigen, artsen en onderzoekers om praktische ontwerpoplossingen te genereren. Drie systeemconcepten werden bedacht: een Smart Environmental Assistant, een Patient Soundscape Dashboard, en een Familiar Wake-ups-concept. Deze concepten waren erop gericht om respectievelijk patiënten meer controle te geven over hun geluidsomgeving, soundscapes aan te passen aan persoonlijke voorkeuren en vertrouwde geluiden te integreren om comfort en oriëntatie te bevorderen. De analyse van de concepten leidde tot vijf essentiële design karakteristieken voor de verbetering van ICU soundscapes: gebruiksvriendelijkheid, personalisatie, humanisering, integratie en vertrouwdheid. De bevindingen toonden aan dat samenwerking met verschillende ICU stakeholders essentieel is om effectieve en klinisch haalbare interventies te ontwikkelen.

Vervolgens werd in twee studies onderzocht hoe aangepaste soundscapes het welzijn van ICU-patiënten zouden kunnen verbeteren op basis van fundamentele psychologische gebruikersbehoeften (Hoofdstuk 5). Er werd een gestructureerde aanpak ontwikkeld om soundscape interventies te ontwerpen op basis van vier sonic ambiance types: Comfortable, Pleasurable, Motivating en Stimulating—gebaseerd op de perceptie van pleasantness en eventfulness van soundscapes en onderliggende behoeften. In de eerste studie werd kwalitatieve en kwantitatieve data verzameld om te onderzoeken hoe verschillende soundscapes relateerden aan specifieke gebruikersbehoeften. Een design proces werd gepresenteerd voor het ontwerpen van composities van natuurlijke, menselijke, muzikale, of technologische geluiden als soundscape interventies. Vier ontwerpparameters werden geïdentificeerd voor het ontwerpen van deze interventies: eventfulness, sonic ambiance qualitiets, narratieve structure en sound distribution. Deze parameters werden vervolgens gebruikt door een componist om behoefte-gestuurde geluidscomposities te ontwikkelen. In de tweede studie werden deze composities getest in een gesimuleerde ICU omgeving. De resultaten toonden aan dat ontworpen soundscapes positief bijdroegen aan de perceptie van pleasantness, eventfulness en emotionele beleving, wat de validiteit van de gestructureerde aanpak bevestigde voor het creëren van ondersteunende ICU omgevingen.

Daarna werd bekeken of de effecten van de ontworpen soundscape interventies konden worden nagebootst in een echte ICU omgeving (Hoofdstuk 6). De resultaten van de studie waren consistent met de resultaten in de gesimuleerde ICU omgeving. Experimenten werden uitgevoerd in een eenpersoons patiëntenkamer op een ICU afdeling, waarbij gezonde vrijwilligers luisterden naar gesimuleerde ICU soundscapes, bestaande uit alarm- en beademingsgeluiden. De ontworpen geluidscomposities werden gebruikt als soundscape interventies in de studie, en bestonden uit natuurlijke, menselijke en technologische geluiden, geordend in de sonic ambiance types Comfortable, Pleasurable en Stimulating. De soundscape interventies werden geïntroduceerd aan de patiëntenkamer om de effecten te meten op perceptie van pleasantness, eventfulness, emoties, en fysiologische stress met vragenlijsten en elektrocardiogram (ECG) metingen. De resultaten lieten zien dat de interventies significant bijdroegen aan de perceptie van pleasantness en eventfulness, de emotionele toestand van de vrijwilligers verbeterde en mogelijk stress verminderde. Deze bevindingen benadrukten ook dat ICU soundscapes luisteraar-gecentreerd en adaptief moeten zijn, aanpasbaar op de geluidsgerelateerde behoeften van patiënten en de bestaande geluidsomgeving.

De dissertatie biedt ontwerpers praktische inzichten door de ontwikkeling van een luisteraar-gecentreerde, op behoeften gebaseerde aanpak, evenals insight cards over sonic ambiance types en zes thema's van patiëntervaringen. Het draagt ook bij aan transitie binnen soundscape onderzoek en de humanisering van ICU-zorg, en pleit voor een verschuiving van louter geluidsvermindering naar gepersonaliseerde, aanpasbare ICU geluidsomgevingen. In toekomstige stappen voor onderzoek en ontwikkeling dient de effectiviteit van de voorgestelde aanpak verder onderzocht te worden met patiënt populaties. Ook is het wenselijk om te onderzoek of het documenteren/integreren van de omgevingsvoorkeuren van patiënten of automatische, op voorkeuren gebaseerde, of multisensorische systemen de ICU zorg verder kunnen humaniseren. Door de inzichten van deze dissertatie te implementeren zouden ziekenhuizen hun ICU's kunnen transformeren tot menselijkere omgevingen, waarin soundscapes actief bijdragen aan het herstel en welzijn van patiënten.

Chapter

1

Introduction

1.1 THE INTENSIVE CARE UNIT (ICU): A STRESSFUL ACOUSTIC ENVIRONMENT

Figure 1.1. Intensive care room with hospital bed and advanced medical equipment. Photo used with permission of Levien Willemse

Imagining the sounds of an ideal healing environment might evoke associations with music, birdsong, or just peace and quiet. Yet, in the built environment our daily lives are often heavily dominated by unwanted sound and regrettably, healthcare environments form no exception. In 1858, Florence Nightingale said that "unnecessary noise is the cruelest absence of care which can be inflicted upon either the sick or the well" (Nightingale, 1858). Intensive care units (ICUs) in particular are notorious for their cacophonous auditory experiences. ICUs are spaces in hospitals that are specialized in treating life-threatening medical conditions of critically ill people. Due to the critical health status of these patients, they need constant and careful monitoring and life support in specifically equipped rooms (see Figure 1.1). Automated mechanical ventilators, patient monitoring systems, and many other advanced medical technologies are essential in this effort (Kelly et al., 2014). Healthcare outcomes of patients have improved much owing to these innovations (Vincent & Singer, 2010). However, this development also established an environment centered around technical rather than human aspects of care (Velasco Bueno & La Calle, 2020). This shift is particularly evident in the acoustic environment, with continuous streams of sounds provided by medical devices contributing to sound levels that far exceed internationally recognized safety standards (Berglund et al., 1999; Darbyshire

Scan the QR code for an impression of what ICUs can sound like.

& Duncan Young, 2022; Johansson et al., 2012). ICU patients spend increasing amounts of time awake during their stay due to trends towards lighter sedation (Holm & Dreyer, 2017; Vincent et al., 2016). Many patients are therefore conscious of these sounds during their stay, often perceiving them as unwanted and therefore consider them as noise.

Not only are ICU sounds bothersome to patients, but they are perceived as stressors by patients, relatives, and care staff (Krampe et al., 2021). Studies have found that patients describe acoustic environments of ICUs as disturbing or stressful (Johansson et al., 2012). Noise exposure in ICUs is associated with increased stress during patient stays (Elbaz et al., 2017; Horsten et al., 2018), and these stressful auditory experiences can lead to substantial harm both during the ICU stay and after discharge. Researchers demonstrated that ICU sounds disrupt sleep (Burdick & Callahan, 2020) leading to discomfort, anxiety, and disorientation for patients (Zaal et al., 2013). In particular, noise-induced sleep disruptions and disorientation increase the risk of delirium, a confused mental state (Mart et al., 2021). Negative auditory experiences in ICUs are also a known risk factor for developing post-intensive care syndrome (PICS) (Darbyshire et al., 2019). This condition affects approximately 70% of ICU survivors (Myers et al., 2016). PICS includes psychological impairments such as post-traumatic stress disorder (PTSD) and depression (Geense et al., 2021), which can hinder full recovery. Stressful experiences with ICU sounds may thus indirectly contribute to increased mortality and decrease the likelihood of a complete recovery (Schwitzer et al., 2023).

1.2 LISTENERS AND SOUND SOURCES

The perceived acoustic environment, or soundscape, of ICUs consists of a complex web of sound-induced interactions between listeners and sound sources. The complexity of these interactions lies in the cacophony of sound sources present at any given time, and that the listeners present in ICUs, such as patients, nurses, relatives, and intensivists, listen to the same acoustic environment with different motivations. They might therefore experience the ICU soundscape differently (Özcan et al., 2022).

A soundscape is defined as an acoustic environment as perceived by a person or by people in context (ISO 12913-1, 2014). ICU soundscapes are primarily composed of medical alarms and human conversation, which can originate both from within patient rooms as well as from external corridors (Tegnestedt et al., 2013; Xie et al., 2009). The ubiquity of alarms may contribute to stress for patients, but also for care staff, which may lead to alarm fatigue (Cvach, 2012). Sounds made by medical machinery at the patient bedside, such as the ventilators, monitors, and infusion pumps, are also prevalent (Xie et al., 2013). Another study revealed that human communication in ICUs was most common among these categories during daytime, while at night alarms were more dominant (Dawson et al., 2022). These studies are illustrative of the effort that it must take for critically ill patients to derive meaning from such soundscapes.

Listening to sounds is not a passive process and is inherently driven by context: factors such as social and cultural influences or personal goals and needs can influence how sounds are perceived (Özcan, 2014). People therefore listen differently to the same soundscapes dependent on individuals' intentions (Özcan et al., 2022). The process of listening is understood to be a heterogenous, action-oriented, and intentional activity of meaning-creation (Delle Monache et al., 2022; Tuuri et al., 2007). In ICU soundscapes, the complex interactions of nurses and patients with sounds likely hinge on the concept of intentionality. Due to differences in listening modes (Tuuri & Eerola, 2012), nurses and patients derive different meanings based on the same sounds. For example, nurses may listen functionally to an alarm to decide how to react, while patients listen semantically to that alarm to attribute meaning to their wellbeing. With little control over hospital surroundings (Andrade et al., 2017), patients are dependent on soundscapes as a channel for orientation and information. Their intent, to derive meaning from this channel, is often hindered due to the abundance of unwanted—or lack of wanted—sounds (Naef et al., 2022), complicating the fulfilment of basic psychological needs, such as safety or reassurance (Andringa & Lanser, 2013). Human behavior, including listening, is motivated by the fulfilment of psychological needs (Maslow, 1943). We therefore consider the concept of need fulfilment interchangeable with listener intentionality in this context, as intentional listening is ultimately driven by a desire to meet psychological needs.

1.3 CURRENT HOSPITAL SOUNDSCAPE INTERVENTIONS

Hospitals are increasingly aware of the importance of providing people-centered care environments in ICUs (Özcan et al., 2020; Rodriguez-Ruiz et al., 2025), introducing soundscape interventions at three different levels: at the source, along the path (i.e., between source and receiver), or at the receiver (Bush-Vishniac & Ryherd, 2023). Soundscape interventions have shown to significantly reduce sound levels in hospitals and improve the comfort of both patient and care staff (Delaney et al., 2019; Luetz et al., 2019; Vreman et al., 2023). At the source level, manufacturers are developing new interoperability standards to reduce and redesign alarms generated by medical devices, aiming to create more pleasant, smarter and quieter ICU environments (Philips Healthcare, 2024; SASICU Project, 2023). Hospitals implement 'quiet-time' protocols to limit noise during specific hours to support patient rest and recovery (Jun et al., 2021). Also, industrial designers develop soundscape monitoring tools for noise awareness among staff (Lu et al., 2023; Spagnol et al., 2023), or create speculative designs for replacing alarms with musical harmonies (Özcan et al., 2021). Along the path, private, sound-proofed ICU rooms are implemented for infection control and noise protection. The Erasmus Medical Center in Rotterdam renovated their department this way (see Figure 1.1 and 1.2), reducing sound levels significantly by allocating one patient per room, introducing sound-proofed doors, and relocating nurse stations, among other changes to architectural layouts (Özcan et al., 2024). Studies have also shown that incorporating sound-absorbing materials in patient rooms can significantly decrease overall sound levels (Luetz et al., 2016). At the receiver level, patients are provided with protective devices, such as earplugs and noise-canceling headphones, against environmental sounds (Litton et al., 2016; Schlesinger et al., 2017).

Figure 1.2. The renovated Erasmus MC Adult ICU ward with one patient per room and sound-proofed doors, separating patients from nurse stations and corridor

Other studies at the receiver level have investigated the effects of soundscape interventions that reintroduce sounds, such as birdsong or music, to ICU soundscapes (Özcan et al., 2023). The therapeutic value of incorporating natural elements, aligned with biophilic (the human attraction to nature) design principles, has been well-documented in clinical settings (Tekin et al., 2023; Ulrich, 1984). By integrating birdsong into the rooms, mechanically ventilated patients were provided relief of psychological stress and pain (Saadatmand et al., 2015). Rijnstate Hospital made a roof-top garden accessible for ICU patients (Rijnstate, 2023), and researchers are currently working on ICU room redesigns that integrate natural sounds and visuals (Tronstad et al., 2023). Other studies investigated the potential effects of digital recreations of natural scenes on delirium and patient comfort (Kim, 2024). The health benefits of music in hospitals are widely supported (Iyendo, 2016). Studies have shown that live music therapy (where specially trained musicians perform live to reduce stress and promote healing) in ICU settings can promote both psychological and physical well-being (Almerud & Petersson, 2003; Thorn et al., 2024). Studies with personalized playlists demonstrated that opioid intake in ICU patients significantly decreased (Chlan et al., 2013), and helped to prevent or lessen the effects of delirium (Khan et al., 2017).

Nevertheless, ICU soundscape interventions may not always benefit patients as intended because of the importance of contextual factors. A study suggested that ICU soundscapes affected by source, path, or receiver interventions can be perceived by patients as peaceful but also as too quiet, depending on the time of day (Johansson et al., 2012). Furthermore, while some researchers found that personalized music interventions in ICUs contributed to decreased levels of anxiety (Chlan et al., 2013), other studies reported no such effects, concluding instead that the efficacy of music interventions is likely context-dependent (Kakar et al., 2023). Cultural and socio-demographic differences may also impair the effectiveness of ICU soundscape interventions. Studies have shown that individuals from diverse socio-cultural backgrounds hold differing attitudes toward sounds (Aletta et al., 2016). Researchers found that European participants associated natural soundscapes with pleasantness more strongly than Chinese participants (Aletta et al., 2023), and that natural soundscapes could even evoke negative associations for some social groups (Moscoso et al., 2018). These studies strongly suggest that listeners' motivations, personal preferences, and other contextual factors cannot be overlooked when designing and implementing soundscape interventions for ICU patients. Instead, creating effective soundscape interventions for ICUs requires a contextually sensitive, listener-centered approach that is adaptive to the psychological needs of patients.

1.4 A NEED FOR LISTENER-CENTRIC APPROACHES IN ICU SOUNDSCAPE DESIGN

In soundscape research, contextual factors are considered central to understanding how people perceive and interact with acoustic environments. The study of soundscapes forms a well-researched domain of acoustics. Popularized by Schafer with the book 'The Tuning of The World' (Schafer, 1977), soundscapes represent a holistic view of how people experience the acoustic environment (Kang et al., 2016). Contrary to traditional forms of sound evaluation such as sound level, in soundscape evaluations the context of listening is inherently considered. This context—defined as 'the interrelationships between person and activity and place, in space and time' (ISO 12913-1, 2014)—shapes how sounds are appraised, with factors such as cultural background or psychological needs influencing whether the meaning of individual sounds is perceived as positive or negative (Aletta et al., 2018). To assess these appraisals and any changes as a result of interventions, researchers measure the perceived quality of soundscapes with descriptors and semantic scales (ISO 12913-2, 2018). Several sets of soundscape descriptors have been proposed for outdoor (Axelsson et al., 2010), indoor (Torresin et al., 2020), or hospital environments (Mackrill et al., 2013). These frameworks consist of two dimensions, constructing a circumplex grid. Using such frameworks, researchers showed that in soundscape design, target soundscapes could be achieved by mapping the soundscape in terms of an existing and desired perceived quality (Cain et al., 2013). However, despite the well-established recognition of context within soundscape studies, contextual factors such as the psychological needs of listeners have yet to take center stage as a basis for this design process.

In human-centered design practices, the needs of users are used as starting points for ideation and conceptualization. Designers typically develop functions of products or services that should address user needs. A similar approach could be adopted when designing soundscape interventions of ICUs to support the psychological needs of patients with regards to the soundscape. Studies into human values showed that some psychological needs are universally present for any individual (Tay & Diener, 2011). These universal values are called fundamental needs. Historically, theoretical frameworks such as self-determination theory (Deci & Ryan, 2000) were proposed to index such needs. Researchers revised those initial typologies, devising a design-focused classification that consisted of 13 fundamental needs (Desmet & Fokkinga, 2020) and 26 need facets (Huang & Desmet, 2023). An example is the need for Relatedness, i.e., seeking warm, mutual, trusting relationships with people who you care about. In user experience research, the fulfilment of fundamental needs has been associated with positive user experiences, leading to positive emotions, and enhanced psychological well-being (Milyavskaya & Koestner, 2011); unfulfilled or frustrated fundamental needs have been linked to negative user experiences, stress and negative emotional responses (Deci & Ryan, 2000).

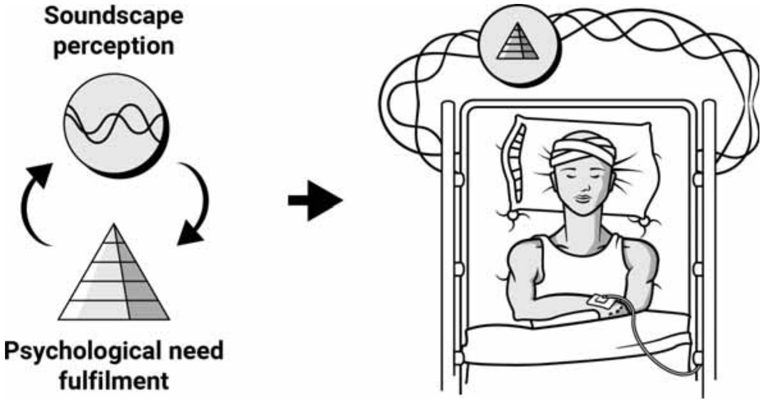

Figure 1.3. Listener-centric approach to soundscape design

Unifying soundscape approaches with need-based design principles (see Figure 1.3) can empower designers to create tailored and supportive functionalities for ICU soundscapes that address specific patient needs. This listener-centric, need-based approach remains unexplored in ICU soundscape design. However, evidence from soundscape research in other healthcare settings highlight its potential benefits. For instance, in dementia care, studies have shown that targeted soundscape interventions—designed to enhance mood or evoke memories—can generate positive experiences for patients with severe behavioral dementia (De Pessemier et al., 2023; Devos et al., 2019; Voisin et al., 2021). Similarly, ICU soundscapes could be intentionally redesigned to serve specific functions, such as providing distraction during clinical procedures, guided by patients' psychological needs and desired soundscape characteristics. In doing so, ICU soundscapes could be transformed into restorative resources for patients that support patient recovery, rather than adding to the stress of critical illness.

1.5 THIS DISSERTATION

With this dissertation, my first objective was to investigate how human-centered design could contribute to positive listener experiences for ICU patients with a need-based, listener centric soundscape approach. My second objective was to evaluate the effectiveness of this approach, i.e., to what extent interventions designed with this approach could benefit patients with regards to their perception of ICU soundscapes, emotional states, and stress.

To achieve these objectives, I collaborated with the faculty of Industrial Design Engineering and the Critical Alarms Lab at TU Delft, Adult ICU department at Erasmus MC, and Philips. The five studies presented in this dissertation employed a combination of listener-centric, evidence-based practices rooted in human-centered design and sound-driven design. Further, standardized models of soundscape perception (ISO 12913-1, 2014; ISO 12913-2, 2018; ISO 12913-3, 2019) and a design-oriented framework of fundamental need fulfilment (Desmet & Fokkinga, 2020) were used. Recognizing that individuals not only perceive sounds differently, but also form unique conceptual representations of them (Delle Monache et al., 2022), insights from diverse ICU stakeholders were integrated. These included ICU patients, their relatives, healthy individuals, ICU nurses and doctors, industry experts, designers, and design researchers. A mixed-methods approach was adopted, combining qualitative methods, such as interviews, with quantitative methods, including questionnaires and physiological measurements.

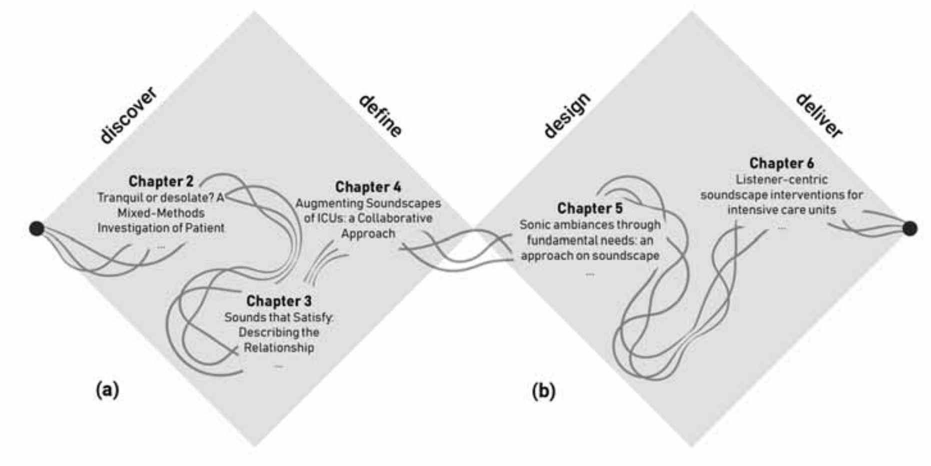

Figure 1.4. Double diamond dissertation outline

1.6 HOW TO READ THIS DISSERTATION

The dissertation consists of three journal articles and two conference papers. The structure of its narrative bears similarities to the well-known double-diamond process (Design Council, 2015) (see Figure 1.4), which is typically divided into Diamond 1 (Fig 1.4a): Discover and Define, and Diamond 2 (Fig. 1.4b): Design and Deliver. This visual representation of typical design and innovation processes outlines Discovering (Chapter 2 and 3), Defining (Chapter 4), Designing (Chapter 5), and Delivering (Chapter 6) phases. In the first diamond (Fig. 1.4a), Chapter 2 is aimed at gaining an understanding of the design problem, in terms of the context of sound and critical care, the patients themselves, and their sound-related needs. Chapter 3 presents the basis for an approach for how this design problem may be dealt with. In Chapter 4, the insights gained in Chapter 2 are evaluated with a multi-disciplinary team of ICU stakeholders aiming to challenge the design problem with soundscape interventions. In the second diamond, Chapter 5 presents an approach for designing these interventions; an evaluation of this approach is also included in this chapter. Chapter 6 extends this effort by presenting how the approach translates to the real-world context of single-patient ICU rooms. Finally, the implications of preceding chapters are discussed in Chapter 7, Conclusions.

The studies discussed in the dissertation chapters include an online survey study, an interview study with ICU survivors, a workshop, a lab-study in a simulated ICU setting, and an in-situ study in the Erasmus MC Adult ICU. The results of these studies are presented in the following chapters:

Chapter 2: Tranquil or desolate? A mixed-methods investigation of patient sound experiences, needs and emotions in single-patient ICU rooms

To understand the essence of the sound-related problems faced by ICU patients, Chapter 2 revolves around the question: 'How do ICU patients experience the soundscapes of single-patient ICU rooms, and which fundamental needs and emotions underlie these experiences?'. Through interviews and surveys with surviving ICU patients, insights into this complex design problem were found in the form of recurring themes, (un) fulfilled fundamental needs, and positive/negative affect.

Chapter 3: Sounds that satisfy: describing the relationship between sound and need fulfilment

We investigated the following question in this chapter, providing a basis for designing interventions for needs encountered in Chapter 2: 'Which sounds are associated with the fulfilment of different fundamental needs?'. The findings of this study, i.e., differences in sound categorization between imagined soundscapes of considered needs, were expanded upon in Chapter 5.

Chapter 4: Augmenting soundscapes of ICUs: a collaborative approach

Given the insights gained in Chapter 2, we investigated in this chapter 'Which design characteristics are important to consider when designing soundscape augmentation systems for ICUs?'. The outcomes of a workshop provided a basic concept for a personalized and contextualized soundscape system and characteristics that should be considered in its design and implementation.

Chapter 5: Sonic ambiances through fundamental needs: an approach on soundscape interventions for intensive care patients

Following insights from Chapter 3, we aimed to derive and evaluate an approach on the design of soundscape interventions for ICU patients. Specifically, we considered the following question: 'How can we design need-based soundscape interventions that establish perceptually and qualitatively distinctive soundscapes, and what are their effects on listeners' soundscape perception and experienced emotion?'. Together with a sound artist I created sound compositions, and their respective effects were evaluated with healthy volunteers in a lab experiment.

Chapter 6: Listener-centric soundscape interventions for intensive care units: creating positive sonic ambiances in single-patient rooms

In this chapter, we sought to evaluate whether the findings of Chapter 5 could be replicated in the real-world context of a single-patient room in Erasmus MC adult ICU. We considered the following question: 'To what extent do the designed soundscape interventions have an effect on the soundscape perception, emotional response, and stress relaxation of healthy volunteers in single-patient ICU rooms?'. In the presence of medical alarm signals and mechanical ventilation the measured effects provided insights into the feasibility and desirability of such interventions inside a real ICU environment.

Chapter 7: Conclusions

In the last chapter, I evaluate how preceding chapters contribute to the objectives set in Chapter 1, bringing together these insights into a general discussion of the main findings. In this chapter, I also discuss how our findings add to the field of soundscape design, and the implications of those contributions. Lastly, the limitations of our findings are discussed, proposing indications of how future design research may expand upon our insights.

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Chapter 2

Tranquil or desolate? A mixed-methods investigation of patient experiences, needs, and emotions in single-patient ICU rooms

This chapter presents an investigation of the sound-related experiences of patients with soundscapes in single-patient ICU rooms using a mixed-methods study of interviews and questionnaires with ICU survivors. Findings established a foundational understanding of ICU soundscapes and its listeners, informing the design processes explored in later chapters.

This chapter is based on:
Louwers, G., Gommers, D., Van Der Heide, E. M., Pont, S., & Özcan, E. (2025). Tranquil or desolate? A mixed-methods investigation of patient sound experiences, needs and emotions in single patient ICU rooms. Intensive and Critical Care Nursing, 89, 104031.

ABSTRACT

The sound environment, or soundscape, of intensive care units (ICUs) can be stressful for patients. Soundscapes are defined as acoustic environments as perceived by people. Single-patient rooms mitigate noise, but may deprive patients of essential auditory cues. This might harm basic psychological needs, such as safety. Experiences, needs and emotions regarding soundscapes of single-patient ICU rooms remain unexplored. We aimed to understand how patients experienced these soundscapes. This mixed-methods, single-center study involved semi-structured interviews and questionnaires five days after ICU discharge. Patients experienced the soundscapes during their ICU stay, shared experiences in interviews, and selected one to rate on need fulfilment (with a researcher-developed questionnaire), and emotions (with a validated questionnaire). Using thematic analysis, we analyzed interview transcripts by labelling sound-related experiences, sounds, and emotions.

We interviewed 26 patients. We labelled 259 sound-related experiences, 264 sounds, and 281 emotions, from which six themes emerged: Orientation through sound; Coping with disruptions; Human auditory presence; Monotony and variation; Associations and hallucinations; Communication behind closed doors. Eight patient-selected experiences involved positive emotions. Need fulfilment scores varied: scores were low for communication-related experiences, but relatively high for those involving human presence. Our findings demonstrated that experiences with single-patient ICU room soundscapes can be positive or negative. For future implementation of such rooms, three insights merit consideration: positive sounds originating from corridors may be unnecessarily removed; alarms in single-patient rooms serve key supportive functions for patients; there is a lack of accessible and appropriate auditory stimulation. We recommend that these insights are taken into consideration to ensure more positive and restorative ICU stays. In ICUs, balanced approaches that consider both positive and negative aspects of soundscapes may benefit patients in future interventions for noise mitigation. Diversifying the variety of sounds inside patient rooms could further support well-being.

2.1 LISTENING IN CLINICAL ICU ENVIRONMENTS

The advances in critical care have led to increasingly favorable odds for patients to survive their stay on intensive care units (ICUs) (Kelly et al., 2014), but they may develop long-term psychological, physical and cognitive problems that persist after discharge (Geense et al., 2021). Psychological impairments such as post-traumatic stress disorder and anxiety are partially attributable to the environmental conditions of ICUs (Darbyshire et al., 2019). In fact, patients, healthcare providers and relatives rate hearing alarms, medical device sounds, and sounds produced by other patients as particularly stressful (Krampe et al., 2021)]. These stressors turn ICUs into hostile acoustic environments for both caregiver and patient. For caregivers, this environment can lead to alarm fatigue, still one of the most pressing problems for nurses (Albanowski et al., 2023). Patients suffer from disturbed sleep-wake rhythms (Dawson & Johansson, 2020), potentially resulting in increased incidence and severity of delirium (Mart et al., 2021). Sensory deprivation was also identified as a pressing matter in ICUs, leading to a lack of stimulation and loneliness (Naef et al., 2022). Improving the acoustic environment of ICUs as perceived by patients, also called the soundscape (ISO, 2014), could instead contribute to favorable outcomes (Erfanian et al., 2019; Birdja & Özcan, 2019).

The interventions that have been proposed for the improvement of ICU soundscapes have primarily involved the reduction of noise (Bush-Vishniac & Ryherd, 2023), such as single-patient room floorplans or the use of technological solutions (e.g., headphones). These interventions were effective (Özcan et al., 2024), and positively affected patient and staff experience (Luetz et al., 2019; Vreman et al., 2023; Delaney et al., 2019). Nevertheless, assigning ICU patients to single-patient rooms could negatively impact patient wellbeing due to the removal of vital auditory cues. ICU patients listen with intent (Tuuri & Eerola, 2012) to their auditory environment for cues that fulfill their needs for reassurance, safety, and information (Özcan et al., 2019; Van den Bosch et al., 2018). Considering trends towards lighter sedation in ICUs (Holm & Dreyer, 2017), other psychological needs, such as pleasure or dignity, could also characterize patients' experiences of soundscapes in single-patient ICU rooms (Özcan et al., 2020). While ICU soundscapes have been studied in the past (Almerud et al., 2007; Johansson et al., 2012), the experience of soundscapes of single-patient ICU rooms has thus far not been explored. A detailed understanding comprising patient experiences, needs and emotions regarding those soundscapes is therefore necessary to inform future medical innovation in this domain.

To address this, we conducted a mixed-methods study with recently discharged ICU patients who had stayed in single-patient rooms of a state-of-the-art ICU in a Dutch academic hospital. The aim of this study was to gain a rich understanding of how patients experienced the soundscapes of these rooms.

2.2 VISITING AND INTERVIEWING DISCHARGED ICU PATIENTS

2.2.1 Design and setting

In this study, we used both qualitative and quantitative methods: we sought to find themes in transcripts of sound-related patient experiences with interviews; we expanded this understanding with questionnaires regarding psychological need fulfilment and experienced emotions. The study followed a convergent mixed-methods design, where qualitative and quantitative data were collected and analyzed in parallel, and then integrated.

The recruitment and study activities were all conducted in Dutch by a male PhD candidate (GL) trained in qualitative research methodologies. During the inclusion period, patient files of all discharged ICU patients were screened by GL for eligibility. Participants were recruited using convenience sampling, based on availability and eligibility according to the inclusion criteria. In the ICU of the hospital, patients reside in single-patient rooms (see Figure 2.1) with automatically closing, sound-proofed doors. Also, patients have access to a bedside call bell and an LCD-screen with television and radio channels. The unit follows a standard closed-door policy. Detailed descriptions of sound levels, routines, and policies in this layout are provided in earlier research (Özcan et al., 2024).

Figure 2.1. The hospital's ICU with corridor between rooms (left) and patient room (right)

Patients meeting the criteria were approached in the general ward of the hospital. During two screening visits at the patient's bedside, GL explained the characteristics of the study. Patients confirmed that they had memories of the sound environment, and gave informed consent. Patients were interviewed by GL during a planned third visit. Aside from the patient and a researcher, a relative was present. Relatives were not formal participants and did not provide answers on behalf of patients. They were present for emotional support and, if needed, to help patients to recall specific details when asked. Their comments, if any, were recorded with their verbal consent. Interview findings were discussed regularly with the other authors to avoid bias and evaluate saturation. Data saturation was assessed by reviewing emerging themes on a weekly basis through team discussions between authors (GL, EÖ, SP), and was considered achieved when three consecutive interviews yielded little to no new themes or insights. Transcripts were not returned to participants for feedback, comment and/or correction. The study was conducted in accordance with the Good Reporting of A Mixed-Methods Study (GRAMMS) framework (suppl. S1) (O'cathain et al., 2008), Standards for Reporting Qualitative Research (SRQR) guidelines (O'Brien et al., 2014) and the Consolidated criteria for reporting qualitative research (suppl. S2) (COREQ) (Tong et al., 2007).

2.2.2 Population

From February until October 2022 all adult patients that resided in the ICU for 72 consecutive hours or more and remained on a hospital ward between five days and four weeks after ICU-discharge were considered eligible for inclusion. Exclusion criteria were having no memory of the sound environment, not speaking Dutch, having impaired consciousness, and having hearing disabilities. Impaired consciousness was defined as any level of cognitive impairment severe enough to prevent meaningful engagement in an interview, assessed by the treating nurses on general wards at the moment of screening visitation. Hearing disability was defined as clinically diagnosed hearing impairments to both ears that would have prevented the patient from experiencing sound during their ICU stay. Patients who used hearing aids were not excluded. All participating patients provided written informed consent for the collection of demographics, and clinical, audio(transcripts), and questionnaire data.

2.2.3 Data collection

Figure 2.2 shows the data collection steps. Prior to a session, patient demographics and clinical characteristics of the ICU stay were obtained from patient files.

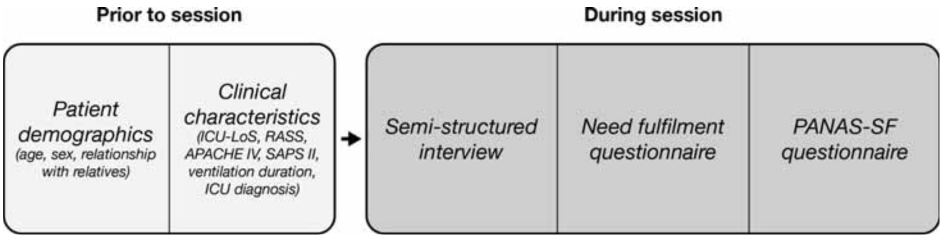

Figure 2.2. Steps taken in data collection prior to and during session

The semi-structured interviews were recorded for transcription on a voice recorder. At the start of the interview, a 20-second 360° video was played of an ICU room in the hospital with a headmounted virtual reality (VR) device. Exposure to VR after discharge is studied in ICU survivor populations (Vlake et al., 2021), and can recreate sensory cues that facilitate autobiographical memory recall (Bohil et al., 2011). This video was thus meant as a gentle reminder participants of their ICU stay, rather than their stay at the general ward. The visual recording consisted of a static, 360° view from the point-of-view of a patient bed in a single-patient room. The video included minimal audio (i.e., ambient room ventilation and a faint monitoring tone) added in post-processing. To avoid the introduction of bias or stress, the video explicitly did not include any dynamic or potentially distressing visual or auditory cues such as door movement, moving personnel, alarms, or patient interactions. GL informed patients in advance about the video content and its purpose, and offered them the option to skip the video if they felt uncomfortable.

During the interview, participants were informed that they could share as much or as little as they felt comfortable with and could withdraw at any time. An interview guide (suppl. S3) was followed which consisted of a set of open questions supplemented by follow-up questions. This guide was optimized after pilot interviews with the first three participants. A laddering approach (Miles & Rowe, 2008) was followed to probe into the reasoning behind participants' answers. Participants were asked which sounds they remembered, to describe sound-related experiences, and select one experience that stood out to them the most. Member checking was employed after interviews by summarizing the answers of participants to each of the questions in the topic guide based on rough field notes. Participants were invited to reflect or clarify this interpretation. As such, any gaps or misinterpretations could be adjusted during data collection to ensure accuracy. At the end of the interview, participants assessed their need fulfilment and emotional state at the time of their selected experience with two questionnaires.

2.2.4 Questionnaires

Previous studies have shown that need fulfilment in user experiences can be measured by scoring statements pertaining to a specific need (Sheldon et al., 2001; Partala & Kallinen, 2012). Psychological needs are understood to be drivers of human motivation. Some of these needs are universally innate to humans across cultures or contexts (Tay & Diener, 2011). These universal drivers are therefore called fundamental needs and their fulfilment is associated with enhanced subjective well-being (Milyavskaya & Koestner, 2011). The fundamental needs included in this study originated from a comprehensive typology consisting of 13 fundamental needs, such as Autonomy (Desmet & Fokkinga, 2020). In absence of an existing research instrument for measuring these 13 needs, we constructed a need fulfilment questionnaire: two authors (GL, EÖ) drafted and iteratively revised two statements for each need, e.g., "I felt that I was able to make my own choices" for Autonomy. Statements were sourced from the typology (Desmet & Fokkinga, 2020). The 26 statements and translations are provided in supplementary materials (S4). These statements were used to assess to what extent the 13 fundamental needs were (un)fulfilled. Statements were in Dutch, preceded by "At the time of this experience I felt ...", and were rated on 5-point scales.

The emotional state of participants was measured with the Positive and Negative Affect Schedule – Short Form (PANAS-SF) (Watson et al., 1988). This questionnaire is widely used to measure mood or emotion, designed to measure emotional states in relation to current or past experiences. It consists of 20 items, with 10 items for positive affect (e.g., strong, determined) and 10 items for negative affect (e.g., irritable, nervous). The Dutch version of the questionnaire (Engelen et al., 2006) was provided to participants in its validated and original format. Items were preceded by "At the time of this experience I felt ..." and were rated on 5-point scales.

2.2.5 Data analysis

The study was underpinned by a methodological orientation of thematic content analysis (Braun & Clarke, 2006). The audio recordings collected during the study were anonymized and transcribed verbatim (i.e., maintaining the speaker's exact words). Statements by relatives were transcribed to contextualize patients' experiences but were not included in analysis. We studied the transcripts with the inductive thematic analysis method to understand how patients experienced the ICU soundscape during their ICU stay. In this process, quality guidelines for thematic analysis by Braun and Clarke were followed (Braun & Clarke, 2021). Transcripts were analyzed in ATLAS.ti (https://atlasti.com/).

The analysis of transcripts was divided into four steps. First, GL identified sections where participants mentioned sound-related experiences. Second, authors (GL, EÖ) assigned codes for each sound-related experience (e.g., nurse entering), sound (e.g., door creaking), and emotional state (e.g., annoyed) mentioned by the participant. Third, these initial codes were discussed among authors (GL, SP, EÖ), and reduced in number through elimination and combination of identical or related codes. Fourth, two authors (GL, EH) looked for patterns in codes and developed key themes. These themes were refined and discussed among all authors to ensure that the themes accurately represented the experiences. Disagreements were discussed to reach a consensus, reducing individual bias and increasing the consistency of thematic identification. We assessed co-occurrences of codes for sounds and emotional states within each emerging theme in ATLAS.ti, an approach recommended in qualitative research to explore relationships in a non-quantitative manner (Miles et al., 2014). This allowed us to determine what characterized each theme in terms of sound sources and emotional responses, contributing to a richer interpretation of the data.

Based on the scores of participants regarding their one selected sound-related experience, a need fulfilment (NF) variable was calculated for each of the thirteen needs from the need fulfilment questionnaire. NF was calculated by averaging the ratings for the two statements per need, resulting in an NF score between 1 and 5. For each participant, a positive affect (PA) and negative affect (NA) variable was also calculated from their responses to the PANAS-SF questionnaire. This was computed by cumulating the scores given by participants for negative and positive items, resulting in a PA or NA score between 10 and 50 (Watson et al., 1988). Means and standard deviations were calculated for NF, PA, and NA. These variables were tested against the demographic/clinical characteristics of the sample for possible significant correlations with Pearson's r or Spearman's rho.

To integrate the qualitative and quantitative data, a structured approach was used in which themes resulting from thematic analysis of interview transcripts were compared with questionnaire responses. First, sound-related experiences selected by participants were categorized under one of the themes by the authors (GL, SP, EÖ). Second, corresponding NF, PA, and NA scores were assigned to each experience based on participant responses. Third, average NF, PA, and NA scores were computed per theme, allowing for comparison of need fulfillment and emotional state between themes. This provided a comprehensive interpretation of how patients' sound experiences in single-patient ICU rooms aligned with their psychological needs and emotional states.

2.2.6 Ethics approval

All patients who participated provided written informed consent according to the protocol of this study, approved by the Institutional Review Board of the Erasmus Medical Center on 11th of November 2021 (MEC-2021-0758). Participants could withdraw consent at any time. All procedures were in accordance with the ethical standards of the Erasmus MC research committee and with the 1964 Helsinki Declaration and its later amendments.

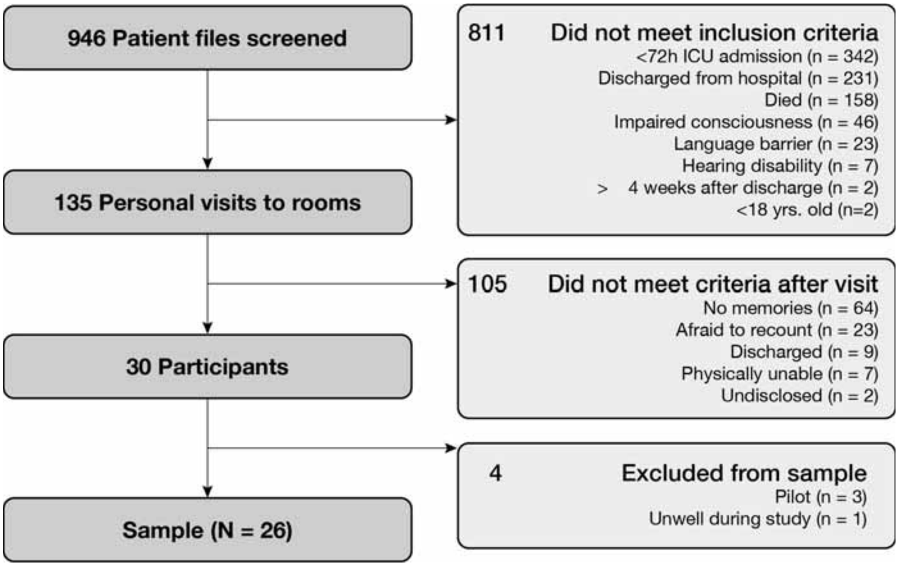

Figure 2.3. Flowchart of inclusion

2.3 SOUND-RELATED EXPERIENCES, NEEDS, AND EMOTIONS OF PATIENTS IN SINGLE-PATIENT ICU ROOMS

2.3.1 Demographics and clinical characteristics

A total of 946 discharged ICU patients were screened of which 916 patients either did not fulfill inclusion criteria or were excluded based on the screening visits (see Figure 2.3). Of the remaining 30 patients, 3 participants took part in pilot sessions to optimize the interview guide, and one participant was excluded due to fatigue, resulting in a total sample of 26 participants.

Their demographics are shown in Table 2.1. Additionally, Table 2.1 shows clinical characteristics related to ICU stay, including ICU length of stay (ICU LoS), duration of sedation, and duration between discharge from the ICU ward and our interviews. The distributions of these durations (suppl. S5) and the relationship between ICU LoS and the ICU LoS not spent in unarousable or deep states of sedation (RASS ≥ -3) (suppl. S6) are included in the supplementary material. Half of the participants were within an age range of 48 to 66 years. APACHE IV scores indicated moderate levels of illness severity. Additionally, a high proportion of the sample was mechanically ventilated (88%), nearly half were transplant patients (42%), and a quarter (27%) had cardiovascular diagnoses. No significant correlations were found between demographic or clinical characteristics and questionnaire measurements of need fulfilment and emotional state.

Table 2.1. Demographics of participants paired with clinical characteristics related to ICU stay

Demographic/clinical characteristic	**N = 26**
Sex, n (%)	
Male	18 (69)
Female	8 (31)
Relative relationship, n (%)	
Partner	18 (69)
Sibling	1 (4)
Parent	2 (8)
Child	5 (19)
Age, years (median [IQR])	60.5 [48.3 – 66]
ICU Length of Stay (LoS), days (median [IQR])	8.0 [3.8 – 29.8]
ICU LoS spent sedated (RASS < -3), days (median [IQR]) [a]	1 [0 – 6]
ICU discharge to interview, days (median [IQR])	8.9 [6.7 – 12.5]
APACHE IV score (median [IQR]) [b]	57 [48 – 73.3]
SAPS II score (median [IQR]) [c]	36 [29.8 – 42.3]
Mechanically ventilated, n (%)	23 (88)
Mechanical ventilation duration, hours (median [IQR])	35 [26 – 245]
Diagnosis at ICU admission, n (%)	
Transplant	11 (42)
Cardiovascular	7 (27)
Other	15 (58)

IQR: Interquartile Range

[a] Richmond Agitation-Sedation Scale (RASS) score of -3 corresponds to “Moderate sedation”

[b] Acute Physiology and Chronic Health Evaluation (APACHE) IV, higher scores indicate greater disease severity

[c] Simplified Acute Physiology Score (SAPS) II, higher scores indicate more severe illness

2.3.2 Themes

Data saturation was reached after 26 patient interviews. Each session lasted approximately 30 minutes (median = 31.4, IQR = [28.0 – 35.9]) with participants spending around 15 minutes being interviewed (median = 17.3, IQR = [15.0 – 20.6]), and the rest of the time spent on the questionnaires. Eleven relatives provided contextual commentary (i.e., 1 – 3 comments) to assist patients in recalling details. None of the participants chose to skip the video. In total, we coded 259 sound-related experiences, 264 sounds, and 281 emotional states. The applied codes and their frequency of (co-)occurrence have been included as supplementary materials (S7).

By analyzing the coded sound-related experiences for patterns, we found six recurring themes: 1. Orientation through sound, 2. Coping with disruptions, 3. Human auditory presence, 4. Monotony and variation, 5. Associations and hallucinations, and 6. Communication behind closed doors (Table 2.2). In co-occurrence analyses for each theme the most frequently mentioned sounds and emotions were found. In Table 2.2, the themes and most occurring sounds and emotions are shown together with a representative quote, and the number of transcripts the theme was based on.

Table 2.2. For each of the six themes found in the thematic analysis: related co-occurring sounds and emotions, and a translated representative quote

Theme	Co-occurrences (N)		Representative quote
	Sounds	Emotions	
Orientation through sound	Silence (14), infusion pump alarms (9), alarms (unspecified) (9)	Lost (7), Fearful (5)	P12: ‘Sound is your only support. You orient on sound, and you are worried about what is going on. … You have nothing to orient on, so you are looking for elements to hold on to.’
Coping with disruptions	Infusion pump alarms (17), alarms (unspecified) (13)	Annoyed (23), Frustrated (8)	P8: ‘The annoying part … is that you have so much difficulty getting to sleep, and then you are being woken up by that pump. Yes, that is so annoying. That is just the opposite of what you want.’
Human auditory presence	Corridor (8), footsteps (7), silence (7)	Pleasant (12) Annoyed (7)	P15: ‘… I found it a calming feeling when I heard voices from the hallway. … you are alone in a room. … and yes, that was just like “Yes, I am not lying here all alone”.’
Monotony and variation	Music (9), infusion pump alarms (6)	Pleasant (8), Annoyed (5)	P25: ‘…music was almost the only thing … for distraction. Reading did not work, watching TV was too tiring, so … the distraction of music was actually the only thing that offered relief.’

2

Table 2.2. *Continued*

Theme	Co-occurrences (N)		Representative quote
Associations and hallucinations	Infusion pump alarms (4), patient monitor alarms (3)	Fearful (4), Annoyed (3)	P18: 'You see animals that do not exist. … those sounds were not made by those animals, but by the machinery … annoyance and … a lot of fear. … The sound accentuated everything, just like in a movie.'
Communication behind closed doors	Silence (11), infusion pump alarms (10), alarms (unspecified) (10)	Fearful (17), Lonely (15)	P17: '… my alarm bell fell on the ground … I started shouting … your fear starts building, if something really happens, then they do not come … I do not think that everybody finds it pleasant having that door closed.'

Theme 1: Orientation through sound

Sixteen participants described the soundscape as unfamiliar, unusable and without meaning, because it mainly consisted of unrecognizable sounds. As their primary source of orientation and information, participants emphasized how important their hearing was to them in early stages of their ICU stay after waking from sedative states. But listening to the few sounds present in their rooms—such as infusion pump alarms—they were unable to identify their meaning. Participants thus experienced the soundscape as empty or silent, regardless of the sounds present. This resulted in states of fear and alertness. Contrastingly, participants experienced alarms as meaningful by learning that nurses will respond. Thus, these sounds also caused feelings of safety and anticipation.

Theme 2: Coping with disruptions

Twenty participants expressed their annoyance and frustration about sounds disrupting the soundscape. These disruptions made participants feel restless and annoyed and kept them in a state of wakefulness. The participants did not understand why it was necessary that infusion pump alarms went off so often in the room, which then had to be resolved by clinical staff. Awakening or being kept from sleep by infusion pump alarms and staff entering caused anger and annoyance. Thus, participants remembered that disruptions were not only caused by alarm events. When the sliding door of their room was opened, the soundscape would change, exposing them to footsteps, voices and laughter of clinical staff.

Theme 3: Human auditory presence

Listening to the presence of people formed a recurring topic for 19 participants. The experiences involved sounds of clinical staff such as footsteps, impacts of objects and speech, but also sounds originating from other patients. Listening to voices of clinical staff offered participants a sense of relatedness offering relief from the isolation of the room. Others mentioned feeling safe due to these sounds, confirming the availability of support in their vicinity. But it could also be experienced as annoying, especially during the night or when attempting to fall asleep. Sounds initiated by other patients, such as shouts, were also considered as negative.

Theme 4: Monotony and variation

Thirteen participants made statements regarding the lack of variety and monotony of the soundscape at certain times of day. They experienced periods without direct interaction when relatives were not present and visits by clinical staff were less frequent due to fewer necessary care activities and closed-door policies. Participants only had a limited selection of sounds to listen to, causing them to feel weary. Moreover, the periods of time spent in absence of a wider variety of sounds or visits caused participants to involuntarily focus their attention on annoying sounds, such as the sound of a clock in their room. The participants felt that their options to be distracted from this annoyance and monotony were limited, due to the effort it took to listen to radio or watch TV for extended periods of time. Nevertheless, some participants were successful in distracting from or masking the sounds they preferred not to hear.

Theme 5: Associations and hallucinations

As the sources of sounds were unclear to participants in some stages of their stay, they misinterpreted the meaning of sounds in the ICU room. Eight participants mentioned associating sounds with other sound sources, such as associating air flows with rain or voices. Some participants experienced these misinterpretations as positive, since the meaning they connected to these associations was connected to positive experiences or memories. Contrastingly, others experienced intensified hallucinations or melodies that would remain stuck in their heads.

Theme 6: Communication behind closed doors

Nineteen participants expressed feelings of powerlessness and fear due to being secluded. They explained that failed efforts to communicate or get attention from behind closed doors, except with the alarm bell, led to the feeling that if something would go wrong, nobody would notice. Consequently, the alarm bell became a lifeline to the outside world, and its misplacement evoked panic. The participants felt dependent and were not confident they could reach the ones they depended on. Instead, they felt abandoned. Pressing the alarm bell provided no feedback that it had been received or heard. Indicative of this lack of reassurance and trust, when alarms would go off participants felt they had to notify clinical staff by pressing their alarm bell. The following minutes were stressful.

2.3.3 Need fulfilment

In the interviews, participants were asked to select one sound-related experience and scored their fulfilment of needs and emotional state. The selected sound-related experiences and their corresponding questionnaire scores were assigned to one of the six themes based on their codes. See the supplementary materials for the distribution of selected experiences per theme and central tendency of need fulfilment scores (S8). In Figure 2.4, the mean need fulfilment scores per theme were plotted and arranged into spider-plots.

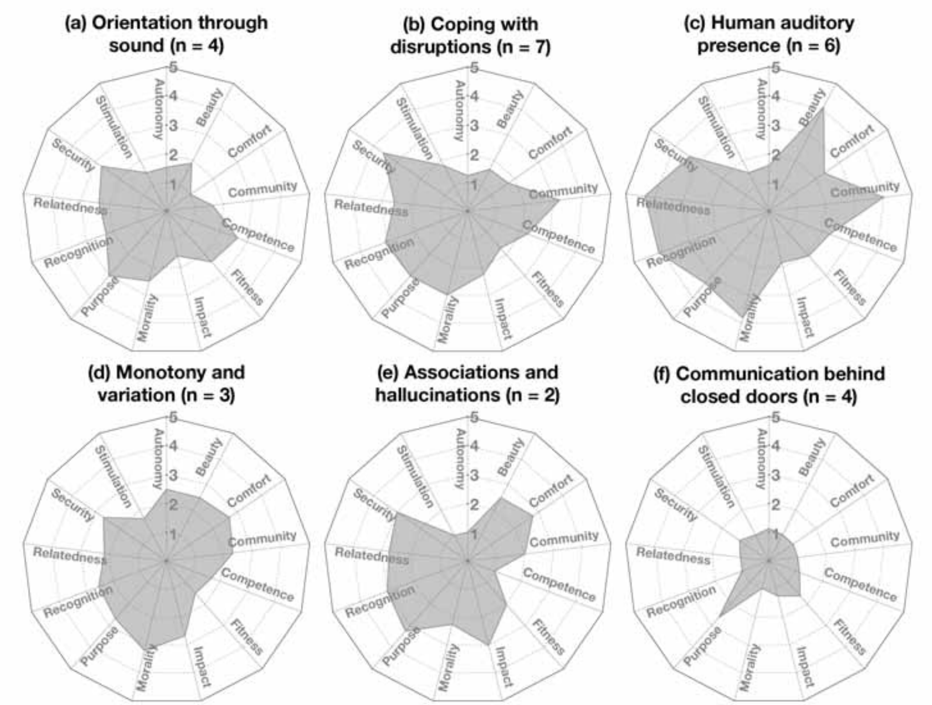

Figure 2.4. Spider plots of mean need fulfilment scores for thirteen needs, divided by theme

The spider plots signified several differences in fundamental need fulfillment between different themes. Human auditory presence (Fig. 2.4c) shows high scores on several axes, such as Relatedness and Community. This suggested that experiences selected by participants within this theme involved a high fulfilment of these needs. In contrast, Communication behind closed doors (Fig. 2.4f) yielded low scores across axes, indicating that participants tended to rate that experience as less fulfilling in terms of their needs. Orientation through sound (Fig. 2.4a), Coping with disruptions (Fig. 2.4b), Monotony and variation (Fig. 2.4d), and Associations and hallucinations (Fig. 2.4e) showed mixed need profiles. Scores for Stimulation were consistently low, suggesting that participants did not experience the fulfilment of this need in any of the selected sound-related experiences.

2.3.4 Emotional state

The calculated cumulative Positive Affect (PA) and Negative Affect (NA) scores are included in the supplementary materials (S8) and were plotted as datapoints shown in Figure 2.5. The datapoints were labeled with each participant's selected sound-related experience, a shape indicating the theme.

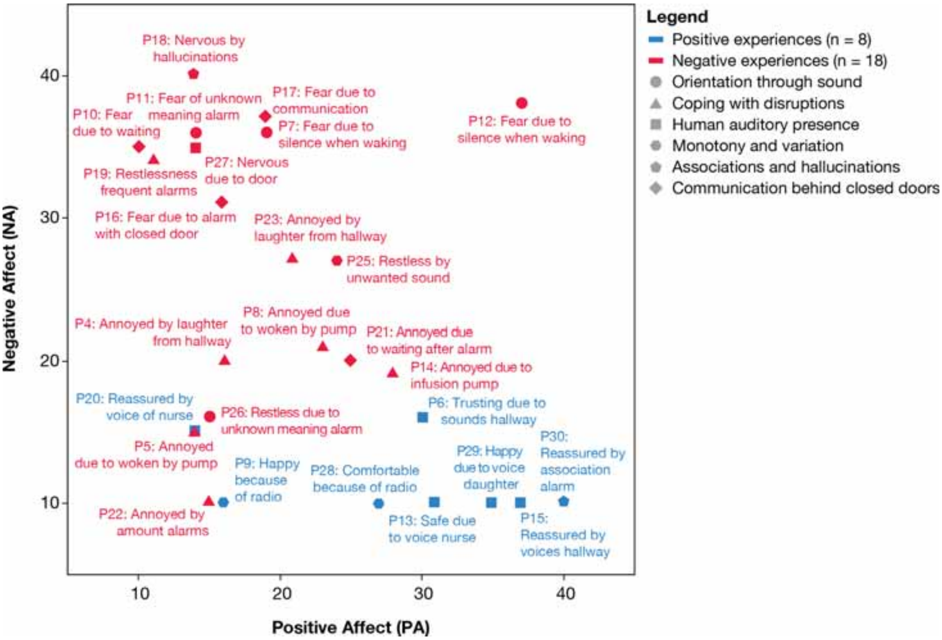

Figure 2.5. Plot of computed Positive Affect (PA) and Negative Affect (NA) scores for each selected sound-related experience

The scatterplot illustrates the distribution of experiences across both PA and NA with the axes representing PA (x-axis) and NA (y-axis). The data points are spread across the plot, with experiences from the themes appearing in various clusters in the graph. Eight positive and eighteen negative experiences were found. Positive experiences tended to cluster in areas with higher PA and lower NA scores in the bottom right involving feelings of reassurance and happiness. In contrast, negative experiences were mainly clustered in the top half of the plot with lower PA and higher NA scores. These experiences involved feelings of annoyance, fear, and nervousness.

2.4 THREE INSIGHTS FOR FUTURE ICU SOUNDSCAPE INTERVENTIONS

In this mixed-methods study, we aimed to gain a rich understanding of how adult ICU patients experienced the soundscapes of single-patient ICU rooms. Through interviews, themes were identified related to patients' sound-related experiences, while questionnaires on need fulfillment and emotional experiences expanded this understanding. By integrating qualitative and quantitative findings, the themes, needs and emotions we encountered three main insights.

First, our findings suggested that single-patient ICU rooms may be overly reductive of sounds that originate from outside the room. Participants shared negative experiences with sounds caused by clinical staff, but those sounds also provided reassurance and comfort. This ambivalent stance towards human sounds was found in previous research in open-bay ICU room layouts as well (Johansson et al., 2012). However, single-patient rooms isolate patients from both the positive and negative aspects of this outside soundscape. These qualitative findings aligned with quantitative results regarding the needs and emotions of participants: the fulfilment of all needs in theme 6: Communication behind closed doors (Fig 2.4f) was minimal, whereas in theme 3: Human auditory presence (Fig. 2.4c), fulfilment of several needs (i.e., Beauty, Community, Comfort, Recognition, Relatedness, Security, and Purpose) was high. Likewise, high scores of PA were found for experiences related to human sounds, see Figure 2.5. Most current innovations view human sound as inherently negative and obtrusive (Bush-Vishniac & Ryherd, 2023). But our findings suggest that future innovations to ICU soundscapes could take a more balanced approach. Interventions such as flexible open-door policies could be implemented as a facet of larger, multimodal patient-centered care strategies, such as the eCASH concept (Vincent et al., 2016). Those policies could reduce the incidence and duration of delirium with improved sleeping patterns (Horsten et al., 2018) due to diurnal changes in average sound levels (Telias & Wilcox, 2019; Fontana et al., 2019).

Second, our results indicated that alarms in single-patient ICU rooms might serve a supportive function that should not be overlooked. Experiences of participants with alarms included both negative and positive aspects. Infusion pump alarms were mainly mentioned as their source. The occurrence of alarms in negative sound-related experiences was expected since it forms a major contributor to sound levels in ICUs (Bush-Vishniac & Ryherd, 2023; Tegnestedt et al., 2013). More unexpected were positive experiences regarding alarms. Safety attributed to alarms has been observed before (Johansson et al., 2012). However, our findings indicated that alarms in single-patient ICU rooms may serve a communicative and informational purpose, offering relief and anticipation. The scores of needs and emotions provided further clarifications. High need fulfilment was observed in theme 2: Coping with disruptions (Fig. 2.4b), while seven out of 18 negative experiences were related to this theme (Fig. 2.5). Furthermore, in line with previous ICU soundscape studies (Almerud et al., 2007; Johansson et al., 2012), participants who experienced the soundscape as empty reported low need fulfilment (Fig. 2.4a) and negative emotions (Fig. 2.5). This should therefore be taken into account for future innovations, since current medical device manufacturers work towards new interoperability standards to jointly silence alarms in patient rooms (Philips Healthcare, 2024). By directing alarm sounds outside of patient rooms, such standards enable the creation of a “silent” ICU. Our results support that alarm reduction would indeed be a sensible intervention, but that the standalone removal of alarms could prove less effective for improving patient experiences. In absence of alarms in silent ICUs, their provision of safety, relief, and anticipation should be offered to patients in other ways. Future research and design efforts could investigate how to optimally provide this. Also, future research should be conducted to confirm the merit of providing such systems alongside alarm reduction solutions.

Finally, our findings showed that while the single-patient ICU rooms offered some sources of auditory stimulation, they may lack accessible auditory stimulation that meets the preferences of patients. Room soundscapes included alarms, air conditioning, and mechanical ventilation. Television and radio were available through digital interfaces on LCD-screens. Several participants used these interfaces, e.g., for distraction with the classical music radio channel. For those participants, their interactions led to positive user experiences (see Figure 2.5), as indicated by high positive affect scores. An explanation could be the relatively high fulfilment of the need for Autonomy in theme 4: Monotony and variation (Fig. 2.4d), compared to other themes. This is consistent with previous findings: being able to adjust hospital environments promotes patient comfort and satisfaction (Andrade et al., 2017). Nevertheless, such experiences may be accessible to only a select few. Physical impairments, delirium, or sedation may require others to operate these LCD-screens instead. But relatives can only be present during visiting hours and involvement of nurses implicates additional workloads. Further, overall low fulfilment of Stimulation (see Figure 2.4) suggested that auditory stimulation was insufficient in each experience, consistent with earlier findings (Naef et al., 2022; Ma et al., 2024). This may indicate that auditory stimulation should not only be present, but also match the preferences of patients. For resting, patients might desire music with low beats-per-minute; for distraction during clinical procedures such as endotracheal suctioning, upbeat music may be preferred. Studies have explored the benefits of personalized playlists in ICUs tailored to musical preferences (Khan et al., 2017; Kakar et al., 2023). By relying on patient preferences, such measures may enhance individuality by supporting their need for Autonomy (Sheldon et al., 2001; Desmet & Fokkinga, 2020). However, future research efforts should investigate how such preferences may be related to supportive functions for patients (e.g., distraction). Future innovations could thus provide patients with personalized, and contextual listening experiences (Louwers et al., 2024).

Concluding, our findings provide an optimistic perspective of current soundscapes of single-patient ICU rooms. Presently, they may be consequences of treatment and life support. But in the future, these soundscapes could become a functional and supportive element of ICU stays. By supporting the psychological needs of patients, more positive soundscape experiences and favorable patient outcomes may lie ahead.

2.4.1 Limitations

The activities of the present study were conducted in the ICU of a single academic hospital. As differences might exist in workflows, protocols, organizational structures and layouts between hospitals, multi-center studies with different ICU departments with single-patient rooms could provide a more comprehensive overview. Also, the composition of participants included in the sample should be considered: of the surviving and physically able proportion of patients, a large number (n = 64) we visited could not remember any of the sounds of their stay in the ICU and were subsequently excluded. Other patients were excluded for other reasons. Participants were of a similar age (i.e., between 48 and 66 years old), and the severity of patient conditions as indicated by APACHE IV scores were mostly moderate; additionally, the high proportion of ventilated patients (i.e., 88%) and transplant recipients (i.e., 42%) should be considered. However, this focused cohort provided valuable thematic insights regarding soundscape experiences, needs, and emotions in single-patient ICU rooms, which could be explored further in future studies with regards to ICU populations with different clinical profiles.

The time participants spent awake (i.e., not in deep or unarousable states of sedation) in the single-patient ICU rooms could be expected to influence which/how many sound-related experiences they shared in the interviews. For example, it is possible that a group of patients who were awake for only a short period would only form memories to a limited set of similar events. We acknowledge the substantial role that this awake-time bias could play. In our sample however, participants spent at least a full day awake (up to 179 days). Additionally, we confirmed with recruited patients that they indeed had active memories to their ICU stay. Nevertheless, our insights should be considered in light of these limitations. Finally, patients may experience memory distortion with regards to their ICU experiences (Fukuda et al., 2022). This was minimized by involving relatives and conducting interviews with patients soon after their ICU stay (i.e., five days) to ensure proximity to the experiences themselves. Despite these measures, in studying human experiences some recall bias may remain. Future studies could collect additional data such as from ICU diaries to increase the overall accuracy of shared experiences.

Due to practical considerations—minimizing participant burden—quantitative measures were collected for only one selected experience per participant. Not all experiences shared in interviews were thus explored through a mixed-methods lens. Still, aligning these experiences with identified themes led to a comprehensive understanding of soundscape experiences. Future research could adopt a deductive approach to investigate a larger number of experiences.

2.5 CONCLUSION

In this mixed-methods inquiry, we explored how patients experienced soundscapes of single-patient ICU rooms. We found that for future improvements of ICU soundscapes, a more balanced approach regarding noise mitigation may be required to better accommodate the psychological needs of patients. Our results showed that indiscriminate eliminations of sound can lead to stressful experiences. Thus, interventions such as sound-proofed doors should only be implemented with the awareness that certain positive elements are removed as well. Also, efforts should be made to diversify the variety of sounds in single-patient ICU rooms with the reintroduction of new sounds, such as music or natural sounds. With the insights of this study, future interventions could perhaps turn single-patient ICU rooms into a place of tranquility rather than desolation.

SUPPLEMENTARY MATERIAL

See supplementary material at https://doi.org/10.5281/zenodo.14866454:

1. Subjective evaluations of need fulfilment and emotional state
2. Codes and co-occurrences of thematic analyses

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Chapter 3

Sounds that satisfy: describing the relationship between sound and need fulfilment

With Chapter 2 highlighting the impact of sound on ICU patients' psychological needs, this chapter examines whether soundscapes can support these needs. Using an online survey, the study explores how different soundscapes are associated with the fulfillment of nine fundamental needs. This chapter lays the groundwork for designing need-based soundscape interventions, which are developed in Chapter 5.

This chapter is based on:
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ABSTRACT

Psychological needs of users as a basis for design are at the core of de-sign practice, yet the importance of fundamental human needs when designing soundscapes has not been studied specifically. This paper investigates the relationship between nine fundamental human needs and the affective qualities and categories of soundscapes. In a free-labeling survey study, we collected descriptions of imagined sound environments for the fulfilment of the needs, as well as ratings of the perceived affective quality of these environments. We found that needs were associated with pleasant soundscapes, while their eventfulness varied. 'Human' sounds were a common category for each of the nine needs considered in this study, but systematic variations of the categories were found de-pendent on the need. Results suggest that designing categorically different soundscapes dependent on the users' needs will have beneficial effects.

3.1 SOUNDSCAPES AND NEED FULFILMENT

Sound connects our physical and psychological world, bridging the outer physical world with our inner emotional one through vibrations (Bennett, 2019). It is a powerful, universal variable that accompanies us our entire lives. Even though our experience of the world is dominated by the preference of vision over other modes of sensory perception (Posner, 1976), our senses of touch and hearing are stimulated before that of vision, as a mother's tissue will block most all light. Aside from being one of the first senses to allow us to comprehend the world, it is possibly the last one to go in a person's final moments. Research has shown that some unresponsive patients receiving palliative care before an expected natural death can still respond to auditory stimuli, up until the last hours of their lives (Blundon et al., 2020).

Although sound forms this ever-present, instinctive, and fundamental property of human life, our daily *acoustic environment* (ISO, 2014), leaves much to be desired. In Europe, daily environmental noise places a major burden on human health and well-being, like sleep disturbance, cognitive impairment in children, tinnitus and annoyance (WHO, 2018). This negative experience with our environment implies that certain psychological needs are being harmed by it, or at the least remain unfulfilled. Deci and Ryan (2000) proposed that psychological needs form the basic nutriments for an individual's growth, integrity, and well-being, and that the fulfilment of these needs is an ongoing source of meaning and pleasure (Deci & Ryan, 2000). The implementation of needs as a basis for design can support a systematic approach to design for positive experiences and subjective well-being (Desmet et al., 2001; Desmet & Hekkert, 2007). Being characteristically interested in understanding the complexities of users' individual needs to characterize an intended user experience, designers can offer a unique perspective in positively changing acoustic environments, by being able to consider the intended experience from the starting position of a user's psychological needs, and the surrounding circumstances (Wiklund-Engblom et al., 2009; Langeveld et al., 2013; Özcan, 2014).

The focus of this paper is to determine what categories of sounds are associated with different psychological needs. First, the paper introduces a typology of psychological needs, a taxonomy for the categorization of sounds, and a framework for the perceived affective quality of soundscapes from existing literature. Following this, the results of an online free-labeling survey study are presented, reporting participants' responses in terms of affective ratings, and describing the frequency of occurrence of sound categories.

3.1.1 Need fulfilment

Cross-cultural studies into needs and subjective well-being have shown that certain needs are universal and exist regardless of cultural differences, and that the fulfilment of fundamental human needs contributes to subjective wellbeing, provided that each need is fulfilled to some extent (Tay & Diener, 2011). Several need typologies have been developed over time towards classifying the basic psychological nutriments driving human motivation and pursuit of well-being: the deficit and growth needs of Maslow's need hierarchy (1943), Deci and Ryan's needs as part of self-determination theory (2000), and the model of candidate needs proposed by Sheldon et al. (2001) being chief examples (Maslow, 1943; Deci & Ryan, 2000; Sheldon et al., 2001). In a revision of these typologies, Desmet and Fokkinga (2020) developed a complete, design-focused typology of human needs, consisting of 13 fundamental human needs: the need for *Autonomy*, *Beauty*, *Comfort*, *Community*, *Competence*, *Fitness*, *Impact*, *Morality*, *Purpose*, *Recognition*, *Relatedness*, *Security*, and *Stimulation* (Desmet & Fokkinga, 2020). This typology is intended to be utilized as a source for positive, user-centered design practice, with a focus on user experience and well-being. Hassenzahl et al. (2010) showed that a positive relationship between need fulfilment and experiences with technology exists, that sets of needs combined into 'need-profiles' can characterize a user's experience (Hassenzahl et al., 2010), and Hassenzahl and Diefenbach (2012) showed that individual, positive experiences can often be characterized by a single, dominant need (Hassenzahl & Diefenbach, 2012). Additionally, previous studies into need fulfilment and user experience (Partala & Kallinen, 2012; Sheldon et al., 2001; Hassenzahl et al., 2010) have shown a methodology with adapted surveys to measure the extent to which psychological needs in peoples' experiences are fulfilled/thwarted, making this approach both measurable and operationalizable.

3.1.2 Environmental sounds and soundscapes

As the perception of isolated environmental sounds disregards the role of the daily contexts in which psychological need fulfilment takes place, sounds should be considered as a part of a *soundscape*. Originally rooted in acoustic ecology, the term soundscape was first mentioned in the work of

Southworth (Southworth, 1969), and popularized by Canadian composer and environmentalist R. Murray Schafer, in his book The Tuning of the World (Murray Schafer, 1977). The term soundscape was standardized in 2014 by the International Standard and defined as 'the acoustic environment as perceived or experienced and/or understood by a person or people, in context' (ISO, 2014); in this definition, a soundscape can be seen as the perceptual representation of the entire collection of sounds (i.e. acoustic environment). In soundscape studies, the emphasis lies on the holistic experience of the acoustic environment.

Categorizations of sounds allow for the identification of individual sound sources, while still perceiving soundscapes as a whole. Several taxonomies for the classification for sounds have been proposed (Gaver, 1993; Özcan et al., 2014). A taxonomy is a system by which categories are related to each other, in different levels of categorical representation (Rosch et al., 1976). Super-ordinate categories are widely inclusive, like Schafer's (1977) referential aspects, categorizing different sounds as 'Natural sounds' (e.g., sounds of water, sounds of seasons, sounds of fire), 'Human sounds' (e.g., sounds of the body), 'Sounds and society' (e.g., sounds of entertainment), 'Mechanical sounds' (e.g., trains and trolleys), 'Quiet and silence', and 'Sounds as indicators' (e.g., bells and gongs), and Krause's taxonomy of sound sources (Krause, 1987; Krause, 2008): the geophony (natural sounds emanating from nonbiological sources in a given habitat), biophony (all of the biological sources of sound from microscopic to megafauna that transpire over time within a particular territory) and anthrophony (all of the human-generated sounds that occur in a given environment).

At a lower level of specification, basic categories carry the most information, and are best distinguishable from one another (e.g., weather, wind, water). Finally, below the basic level, specific, sub-ordinate categories are positioned, like waterfalls, rain, and thunder. Axelsson et al. (2010) used super-ordinate categories of 'Natural', 'Human', and 'Technological' sound categories to assign dominant sound categories to soundscapes, and Lenzi et al. (2021) presented a three-tier structured taxonomy of all previously mentioned taxonomies of sounds (Axelsson et al., 2010; Lenzi et al., 2021). These classifications make it possible to compare and generalize perceived soundscapes in terms of their composition of distinctive elements, as well as the perception of the soundscape as whole.

3.1.3 Soundscape descriptor: perceived affective quality

The perceptual constructs associated with soundscape perception are called *soundscape descriptors*, and defined as measures of how people perceive the acoustic environment (ISO, 2018). Following a principal component analysis, Axelsson and colleagues (2010) found three dimensions for the soundscape descriptor 'perceived affective quality' of soundscapes: *pleasantness*, *eventfulness* and *appropriateness* (Axelsson et al., 2010).

Affective attributes found on the first dimension described an unpleasant–pleasant relationship, on the second dimension an uneventful–eventful relationship, and the third dimension of inappropriate–appropriateness. This orthogonal, three-dimensional framework was developed into the Swedish Soundscape Quality Protocol (SSQP) and has shown to accurately distinguish between soundscapes and assess their perceived affective quality in urban environments (Axelsson, 2015). The pleasantness and eventfulness axes of perceived affective quality create quadrants (clockwise) of exciting/vibrant, chaotic, monotonous/boring, and calm. Being able to measure and position the perceived affective quality of current as well as intended soundscapes, it is possible to quantify and compare the influence of sound interventions in specific contexts.

3.1.4 Relevance for sound-driven design

Research has shown that removing unwanted sounds is not always appropriate, as it can create anxiety, due to the absence of events (Stockfelt, 1991). Interestingly, in studies on a similar framework as the framework of Axelsson et al. (2010), Cain et al. (2013) showed that dB(A) levels of urban soundscapes corresponded to roughly similar levels, yet were perceived very differently on calmness and vibrancy axes (Axelsson et al., 2010; Cain et al., 2013). This incidentally shows that objective measures (e.g., loudness) alone are not sufficient to evaluate a listener's perceptions. Studies in parks and cities have shown that perceptual properties of soundscapes are better at predicting perceived soundscape quality than psychoacoustic measures. These studies seem to suggest that positively perceived elements of urban soundscapes are associated with natural sounds (e.g., water, birds), and negatively perceived elements with technological ones (e.g., traffic, cars) (Nilsson, 2007; Guastavino, 2006).

Cain et al. (2013) showed that if an existing soundscape is positioned within the perceptual space indicating the perceived quality of said soundscape, a target for an intervention can be identified, by indicating its position in the perceptual space too. In order to move the perception of the soundscape from the first position to the second, however, it is necessary to know what that intervention then should consist of, taking into account both the context and the listener. By making use of fundamental human needs as a basis for design, categorizations of sounds related to those needs, and perceived affective quality, designers can introduce sounds that can result in a positive perceptual outcome, which in turn is associated with increased well-being and quality of life.

3.1.5 Present study

In the pursuit of a systematical approach to compose soundscapes to satisfy human needs, we tested which sounds are associated with a selection of psychological human needs, and how these needs compare in terms of their perceived quality. To this aim, we performed an online survey study with open-ended questions, into imagined, need-specific sound environments, for a set of nine pre-selected needs.

3.2 ONLINE SURVEYS WITH HEALTHY VOLUNTEERS

3.2.1 Participants

Participants were adults of no specific nationality, proficient in English and without a history of hearing impairment. Participants were between 23 to 52 (M = 27.9 years, SD = 5.5) years of age. All participants (17 male, 17 female) voluntarily completed the survey after filling in a consent form. No monetary compensation for their participation in the study was offered. A survey generally took under 60 minutes to complete (M = 53.2, SD = 24.3). Our study protocol with human subjects was approved by the Human Research Ethics Committee (HREC) of Delft University of Technology on the 21st of October 2021.

3.2.2 Sensitizing with audio samples

Four audio samples were designed as sensitizers for soundscapes, to be presented before the survey in which the relationships between needs and soundscapes were investigated. Each audio sample was twenty seconds in duration. Audio sample 1, representing a pleasant and eventful soundscape, was designed to be perceived as 'exciting/vibrant' and featured a blackbird, European robins and a dunnock with additional sounds of footsteps along a gravel path, with cars passing and soft sounds of wind through trees forming a keynote. Audio sample 2, representing an unpleasant and eventful soundscape, was designed to be chaotic and featured cars passing and wind, but included a superimposed recording of busy traffic. Audio sample 3, representing a pleasant and uneventful soundscape, was designed to be calm and featured background cars and wind, but with only a lone blackbird's song. Audio sample 4, representing an unpleasant and uneventful soundscape was designed to be boring/ monotonous and featured the atmospheric tone of an empty computer room with a continuous humming sound. The samples are available on Zenodo, see the supplementary material.

To validate our sensitizers, the audio samples were reviewed independently by five researchers in a rank-order task, without labels indicating their corresponding pleasantness or eventfulness attributes of the soundscapes. The reviewers were first asked to rank the randomly presented audio samples in terms of relative pleasantness and then relative eventfulness. All reviewers ranked the soundscapes correctly as intended in its respective design. The audio samples were consequently deemed appropriate to serve as sensitizers for pleasantness and eventfulness in this survey study.

3.3.3 Fundamental needs and need-specific imagined environment

A set of nine fundamental needs were selected from the typology of Desmet and Fokkinga: the need for Autonomy, Beauty, Comfort, Competence, Fitness, Recognition, Relatedness, Security and Stimulation. This selection was made to limit the amount of time spent on the surveys. The nine selected needs were argued to be clinically most relevant for the authors' area of research, being designing for the needs of critically ill patients on intensive care wards. Participants were asked to imagine an environment that would satisfy a specific need within the selected set. They were given the instruction to 'Try to imagine an environment that makes you feel [need-specific feeling]. Please describe it in the text box below'. For each of the nine need-specific feelings, this instruction was accompanied by definitions: e.g., the need for beauty, 'Feeling a sense of beauty: Feeling that the world is a place of elegance, coherence and harmony, rather than feeling that the world is disharmonious, unappealing or ugly.' An overview of the needs and definitions is shown in Table 3.1. Participants could use a multi-line text field for their response to this open question.

Table 3.1. Needs and definitions provided to participants

Need	Need definition
Beauty	Feeling that your environment is a place of elegance, coherence and harmony, rather than feeling that it is disharmonious, unappealing or ugly.
Stimulation	Being mentally and physically stimulated by novel, varied and relevant impulses and stimuli, rather than feeling bored, indifferent or apathetic.
Comfort	Having an easy, simple relaxing life, rather than experiencing strain, difficulty or overstimulation.
Security	Feeling that your conditions and environment keep you safe from harm and threats, rather than feeling that the world is dangerous, risky or a place of uncertainty.
Competence	Having control over your environment and being able to exercise your skills to master challenges, rather than feeling that you are incompetent or ineffective.
Relatedness	Having warm, mutual, trusting relationships with people who you care about, rather than feeling isolated or unable to make personal connections.
Fitness	Having and using a body that is strong, healthy and full of energy, rather than having a body that feels ill, weak, or listless.
Autonomy	Being the cause of your actions and feelings that you can do things your own way, rather than feeling as though external conditions and other people determine your actions.
Recognition	Getting appreciation for what you do and respect for who you are, instead of being disrespected, under-appreciated or ignored.

Participants were asked to answer an open-ended question for each of the 9 need-specific situations and corresponding descriptions of an imagined environment: 'What things (or events) are happening in this environment?'. Responses were recorded in a multi-line text field. Regarding the events described within the context of the need-specific environment, participants responded to the question: 'What sounds would these events make?'. Responses were again recorded in a multi-line text field.

Table 3.2. Examples of participants responses to three survey items with labels.

Need	Environment	Events	Sounds	Labels
Beauty	A natural environment with bright light and colours. A nice beach with waves clashing at the shore and a strong wind. I am looking at it from higher up. Standing at the cliff.	Waves clashing at the shore. Sitting at the cliff. Drinking a beer.	The sound of the waves and the wind wooshing. Maybe some seagulls.	Biophony (1), geophony (2)
Security	At home, comfortable on the couch when it is raining outside	I am sitting on the couch. There are other people around me. Its raining outside. We have lit a fire.	Rain. Fire place cracking. Soft sound of voices/ people talking.	Geophony (1), geophysics (1), voice (1)

3.2.4 Sound-categories in three-tiered taxonomy

In this survey study, we aimed to collect descriptions of individual sound events, corresponding to specific needs as input for need-specific imagined environments. Since the process of listening involves meaning creation based on action-sound couplings (Tuuri & Eerola, 2012), participants were guided towards describing sounds in several steps, examples of which are shown in Table 3.2. First, they described an imagined environment based on the presented need in the survey. Then, participants described events taking place in this imagined environment. Finally, they described which sounds took place as a result of these events. We used the results of the final stage (i.e., sounds) for further analysis.

During the analysis of participants' responses, based on the taxonomies of sound categorization mentioned in the introduction and responses of participants, a three-tiered revised taxonomy of sound categories was made, consisting of four super-ordinate categories: Human, Natural, Musical, and Technological. This taxonomy is shown in Figure 3.1. The Human category represented all of the human-generated sounds that occur in an environment, like speech and bodily sounds (e.g., rustling clothes); the Natural category represented all biological and non-biological sources of natural sounds that occur in a given environment, and the Technological category consisted of all sounds generated by machines, electronics, cars. As sounds perceived as music can be both labeled as Technological (e.g., music from a speaker) and Human (e.g., music made by interacting with an instrument), a separate Musical category was added, in line with observations made by Lenzi et al. (2021) (Lenzi et al., 2021). The Musical category represents all vocal, electronic or instrumental elements music comprises of in a given environment. 3

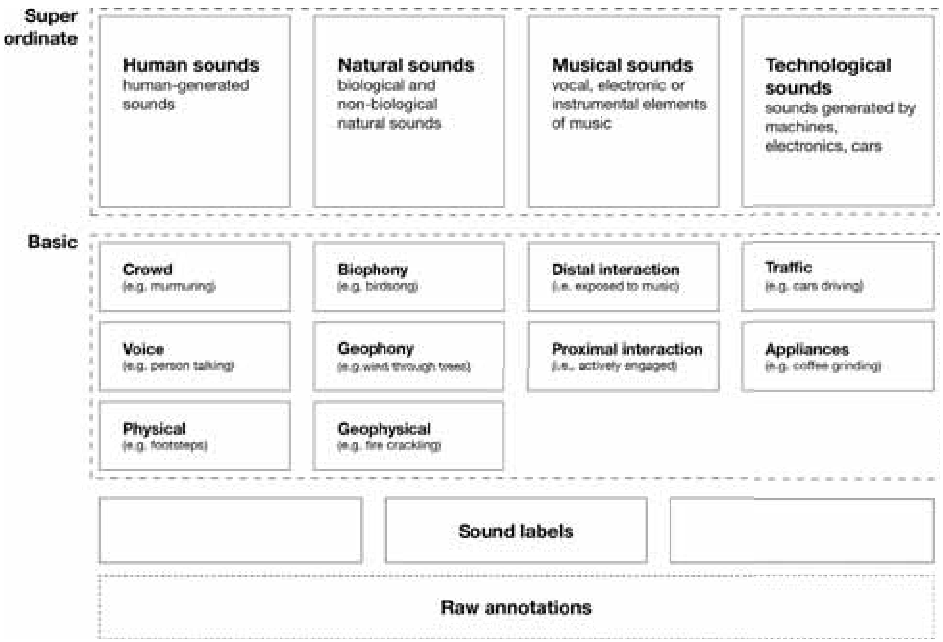

Figure 3.1. Schematic representation of superordinate and basic categories of sounds.

The super-ordinate level categories represent ten basic level categories: the Human category includes Crowd (e.g., murmuring), Voice (e.g., person talking), Physical (e.g., footsteps). The Nature category includes Biophony (e.g., birdsong), Geophony (e.g., wind through trees), Geophysics (e.g., fire crackling). The Music category includes a Proximal interaction (i.e., actively engaged) and a Distal interaction (i.e., being exposed) with the music. The Technology category includes Traffic (e.g., cars driving), and Appliances (e.g., coffee grinding). Raw annotations of sounds were separated into labels and matched to the basic categories. Examples of these labels are shown in Table 3.2.

3.2.5 Perceived affective quality of the imagined environment

The described imagined environment, events and sounds formed a need-specific imagined soundscape. Its perceived affective quality was assessed by the two affective attributes of pleasantness and eventfulness. They were both measured on a 7-point scale, ranging from ‘Unpleasant’ to ‘Pleasant’ and ‘Uneventful’ to ‘Eventful’ respectively.

3.2.6 Procedure

This survey study was performed with Qualtrics (www.qualtrics.com), and was accessed by participants through a link in an invite distributed by email. The survey consisted of 3 parts: (1) introduction and demographics, (2) listening to audio samples, and (3) imagining and rating need-specific soundscapes. All materials were in English. Participants were asked to use headphones or earphones for the audio stimuli included in this survey, to be in a quiet environment where they felt comfortable throughout the duration of the survey, and to perform the survey on a personal computer or laptop for optimal performance of the visual layout of the survey. Finally, participants were asked to complete the survey alone and in one session.

Participants were first introduced to the study, explaining the aims and the tasks to be performed. Following their consent, they were asked to fill out their date of birth and sex. They were then presented with the audio samples. The audio samples were labeled with ‘pleasant/eventful’, ‘unpleasant/eventful’ and ‘pleasant/uneventful’ or ‘unpleasant/uneventful’. Participants were allowed to listen to the soundscapes as many times as they wanted.

Afterwards, descriptions of need-specific imagined soundscapes and corresponding ratings in terms of perceived affective quality were collected. The order in which need-specific situations were presented was randomized, and each featured the same subset of measures: (i) need-specific imagined environment, (ii) descriptions of imagined events, (iii) event-based imagined sounds, (iv) perceived pleasantness, and (v) perceived eventfulness.

3.3 PERCEIVED QUALITY AND SOUND DISTRIBUTIONS OF SOUNDSCAPES

All rating data were exported from Qualtrics, and saved as a data sheet in a local computer for analysis. Out of the completed surveys (N=34), five participants in total completed the survey with missing entries; of these five participants, the first had missing text responses for Security, Competence, and Autonomy, another had two missing text responses for Competence and Comfort, a third participant had one missing response for Autonomy, a fourth for Recognition, and a fifth for Comfort. All participants rated pleasantness and eventfulness even for the missing text responses for event description. Ratings for these participants with missing text were replaced by the mean of the respective rating per item. To accommodate for personal differences between judgements of participants with regards to perceived affective quality, participants' raw pleasantness and eventfulness ratings were normalized to a 0-1 ratio, with reference to their baseline measures and the normalized data were used for further analysis: Normalized rating = ((raw value – minimum rating given)/maximum new rating given)

Table 3.3. Means and standard deviations of perceived affective quality.

Need	Mean pleasantness (M_{PL})	SD pleasantness (SD_{PL})	Mean eventfulness (M_{EV})	SD eventfulness (SD_{EV})
Beauty	0.91	0.16	0.50	0.32
Stimulation	0.69	0.30	0.82	0.29
Comfort	0.85	0.29	0.36	0.38
Security	0.82	0.25	0.33	0.38
Competence	0.61	0.33	0.54	0.38
Relatedness	0.79	0.27	0.63	0.34
Fitness	0.66	0.33	0.71	0.34
Autonomy	0.80	0.28	0.46	0.39
Recognition	0.64	0.30	0.70	0.31

3.3.1 Means of perceived affective quality

For each of the need-specific imagined environments, means and standard errors were calculated for normalized ratings of perceived affective quality. Normalized means and standard deviations are presented in Table 3.3, and plotted in Figure 3.2. All imagined sound environments were rated as relatively pleasant (M_{PL}= 0.75, SD_{PL} = 0.28). Means of eventfulness ratings for each sound environment and needs ranged between 0.33 and 0.82, with medium eventfulness score for all ratings (M_{EV} = 0.56, SD_{EV}= 0.35). Agreement between participants for pleasantness ratings was higher than those of eventfulness ($SD_{PL}(0.28) < SD_{EV}(0.35)$).

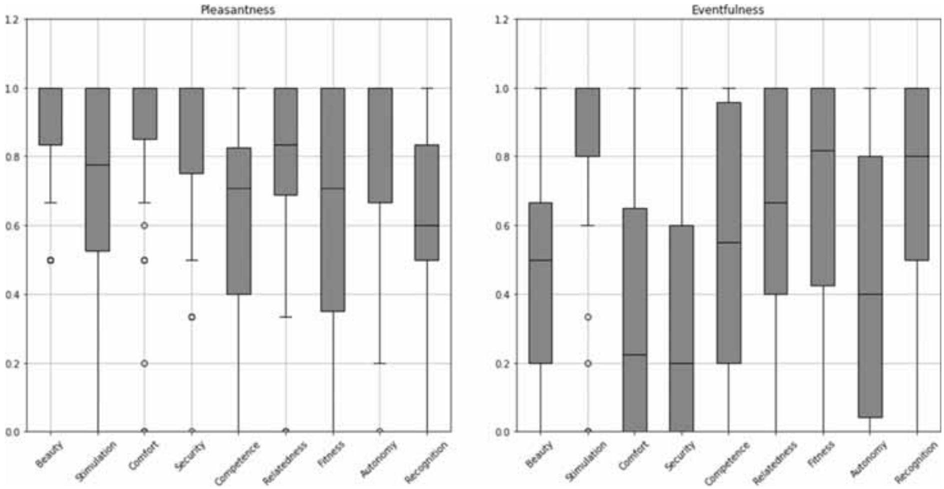

Figure 3.2. Means and standard deviations on normalized data between needs. Left: pleasantness, right: eventfulness.

3.3.2 Frequencies of sounds

In figure 3.3, the distributions of the frequencies of the four super-ordinate sound categories have been plotted. Out of all labels mentioned for the nine needs (see Total), 50.8% (N = 454) of the responses included sounds belonging to the superordinate category of Human. This was followed by the category of Natural sounds, covering 25.2% (N = 225) of the responses, and Technological, for 14.6% (N = 130); finally, Music related sounds were mentioned the least overall, representing 9.4% (N = 84) of the labels.

Out of the nine needs, Human sounds were mentioned most often for *Recognition* (80%), followed by *Relatedness* (72.3%), and *Stimulation* (56.5%), and least often for *Beauty* (29.2%), *Security* (37.6%), and *Autonomy* (39.8%). Natural sounds were most commonly encountered for *Beauty* (55.7%), *Security* (32.9%), and Fitness (30.8%), and least common for *Recognition* (6.7%), *Stimulation* (7.4%), and *Relatedness* (8.9%). The category of Technological sounds was most occurring for *Autonomy* (26.9%), *Competence* (21.7%), and *Stimulation* (20.4%), and least occurring for *Beauty* (8.5%), *Recognition* (8.9%), and *Comfort* (9%). Finally, Music related sound labels were regularly found for *Stimulation* (15.7%), *Security* (12.9%), and *Competence* (9.8%), and uncommon for *Recognition* (4.4%), *Beauty* (6.6%), and *Autonomy* (7.5%).

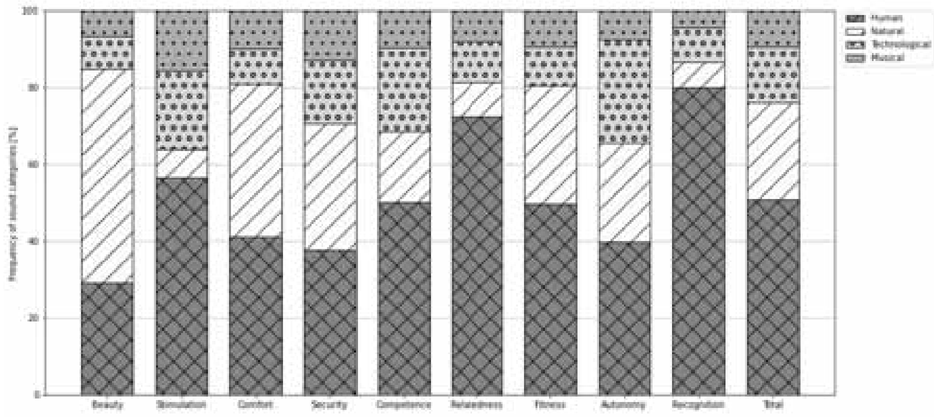

Figure 3.3. Distributions of four superordinate categories per need.

Illustrated in figure 3.4, the distributions of the ten basic categories of sounds per need, and in Table 3.4 the relative frequencies have been shown. Out of all labels mentioned for the nine needs (see Total), sound labels belonging to the category of Voice were mentioned most often (27.2%), while the least commonly mentioned, over all nine needs, was Geophysics (2.4%). Crowd was found to be common for Recognition (18.9%), yet not present for Security, and seldom mentioned for Beauty (1.9%).

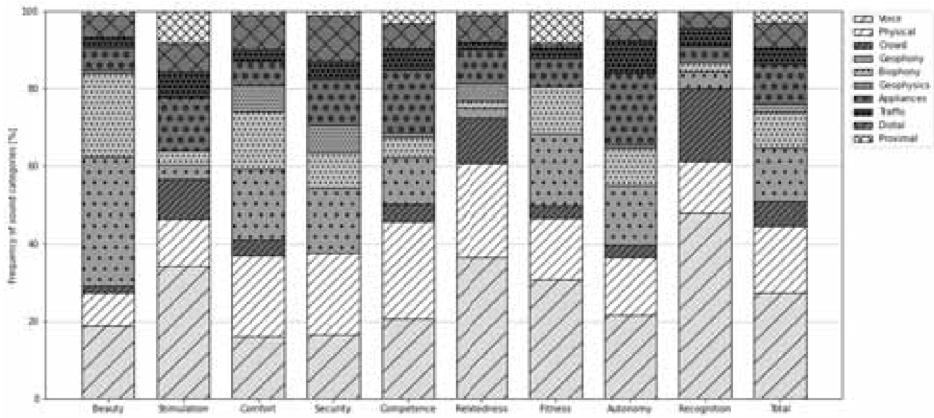

Figure 3.4. Distributions of ten basic categories per need.

Voice was frequently mentioned for *Recognition* (47.8%), and rarer for *Comfort* (16%). Physical related sounds were typically mentioned for *Competence* (25%), and little mentioned for *Beauty* (8.5%). Biophony was mentioned most often for *Beauty* (21.7%), and least often for *Relatedness* (1.8%).

Table 3.4. Relative frequencies of super-ordinate and basic categories of sounds (%). Maxima are indicated in bold, minima in italic.

Superor.	Basic	Beauty	Stim.	Comf.	Secur.	Compet.	Relat.	Fitness	Auton.	Recog.	Total
Human	Crowd	1.9	10.2	4.0	*0.0*	4.3	11.6	2.8	3.2	18.9	6.4
	Voice	18.9	**34.3**	16.0	16.5	20.7	**36.6**	**30.8**	**21.5**	**47.8**	**27.2**
	Physi.	8.5	12.0	**21.0**	**21.2**	**25.0**	24.1	15.9	15.1	13.3	17.2
Natural	Bioph.	21.7	3.7	15.0	9.4	5.4	1.8	12.1	9.7	2.2	9.1
	Geo.	**33.0**	3.7	18.0	16.5	12.0	2.7	18.7	15.1	4.4	13.8
	Geop.	0.9	*0.0*	7.0	7.1	*1.1*	4.5	*0.0*	*1.1*	*0.0*	*2.4*
Music	Distal.	5.7	7.4	9.0	11.8	6.5	7.1	0.9	5.4	4.4	6.4
	Proxi.	*0.9*	8.3	*1.0*	1.2	3.3	*0.9*	8.4	2.2	*0.0*	3.0
Techn.	Traffic	2.8	6.5	3.0	4.7	5.4	1.8	2.8	8.6	4.4	4.4
	Appl.	5.7	13.9	6.0	11.8	16.3	8.9	7.5	18.3	4.4	10.2

Geophony was commonly found for Beauty (33.0%), and uncommon for Relatedness (2.7%). Geophysics related sounds were found in Security (7.1%), but were not present for Recognition, Stimulation, or Fitness. Distal interaction was most often mentioned in items related to Security (11.8%), whereas little mention was made in items related to Fitness (0.9%). Proximal interaction was mentioned most often for Fitness (8.4%), yet not mentioned for Recognition, and least often for Relatedness (0.9%). Traffic was commonly found for Autonomy (8.6%), and uncommon for Relatedness (1.8%). Finally, Appliances popped up most often for Autonomy (18.3%), and unusually so for Recognition (4.4%).

3.4 SYSTEMATIC DIFFERENCES BETWEEN NEED-BASED SOUNDSCAPES

3.4.1 Perceived affective quality

The results of this study on the relationships between human needs and imagined soundscapes show that there are systematic differences between the composition and affective qualities of those soundscapes, dependent on the needs. The perceived affective qualities of the imagined soundscapes showed that ratings of the soundscape descriptors of pleasantness and eventfulness vary between needs. Expectedly, all soundscapes were rated to be relatively pleasant, while eventfulness ratings varied between needs, and within need-specific descriptions of environments. Consequently, when designing soundscapes for psychological need fulfilment, designers should in all cases pursue a pleasantly rated sound environment. One might argue that responses given by participants were impacted while listening to the audio samples; while this concern is justified, our results show that pleasantness and eventfulness are manifested in other sound categories than merely the ones used in the design of the audio samples (i.e. majority of natural sounds for pleasant, majority of technological sounds for unpleasant). This shows that, while we gave an example of what could be a pleasant/unpleasant soundscape, it did not introduce a bias towards specific sound categories in the rest of the survey.

In terms of eventfulness of soundscapes, due to the large differences in means and standard deviations, it can be concluded that designing for this dimension should be considered within the context of the specific need. This shows that designers can play with the eventfulness of a soundscape, while still achieving the fulfilment of the specific need, provided that a selection of sounds categories is used that corresponds to the need in question. In this study, the third dimension found by Axelsson et al. (2010) (i.e., familiarity/appropriateness) was not taken into consideration, because of unfamiliarity seeming to be mutually exclusive towards personal, imagined soundscapes. This dimension in light of appropriateness of sound within context (i.e., lack of a fundamental need in a specific situation) should, however, be included in future research into fundamental need fulfilment and soundscape perception.

It could be argued that due to the fact that participants rated imagined soundscapes, instead of listening to soundscapes in situ, inconsistencies can occur. Aletta et al. (2016) however showed in their conceptual framework for developing predictive soundscape models that a combination of data collection methods like recall, and narrative interviews, and semantic scales can be used to measure the affective quality of specific soundscapes (Aletta et al., 2016); the majority of experiences being based on familiar situations to the participant, it can be assumed that their responses are reliable. Additionally, Özcan and Van Egmond (2007) showed that sounds can be easily reproduced in free recall tasks (Özcan & Van Egmond, 2007). The differences in eventfulness, and relative differences in pleasantness, could however be explained by variations in described themes within the context of a specific need; this should therefore form part of a future thematic content analysis of the qualitative data related to the imagined environments and events collected in the survey.

3.4.2 Occurrence of categories of sounds between needs

The results of this study into the relative frequency of occurrence for categories of sounds within fundamental needs suggest that people associate specific categories of sounds with different fundamental needs, and that certain sounds, present within the context of one need, are absent, or not as important within another. In this way, different sounds can be used by designers to satisfy different needs. *Beauty* is strongly associated with Biophony, like birdsong in woods during long hikes, while Competence stands out with a frequent association to Appliances, like the sound of pedals turning on a bike.

The high frequency of occurrence of sounds belonging to the 'Human' super-ordinate category shows the importance of context in the operationalization of these findings. Sounds made by people, like turning the pages of a book, or the murmur of a crowd in the background, are associated with a degree of fundamental psychological need fulfilment in all of the nine needs included in this study, yet differences exist in expression of this category between needs. In the need for *Beauty*, Human sounds most often occur in the form of indistinguishable conversation and background chatter, while for the need for *Relatedness* these sounds dominate the environment, illustrated by examples of two responses by participants: for *Beauty*, "a dog or a person walking by (maybe quickly greeting each other), the sound of a little breeze and some traffic very far away", and for *Relatedness*, "The sound of talking. Beer glasses hitting the table. Rustling of people in the background. People entering and leaving. Music in the background.".

It was expected that for certain needs like *Beauty* and *Relatedness*, specific categories of sounds would be most frequently mentioned (i.e., high vs. low frequencies of Natural sounds versus Human sounds), yet for other needs, results were more surprising. Participants most often mentioned Technological sounds in *Autonomy*, and least often in *Beauty*, while they most often mentioned Music sounds for *Stimulation*. Noticeably, Music was mentioned by relatively few participants; this could be due to the fact that in the survey items, the phrasing suggested action-sound couplings. Out of the ten basic categories, participants mentioned the presence of sounds related to Voice most often, suggesting that in soundscapes related to fundamental need fulfilment, sounds of people talking and expressing themselves play a vital role.

These outcomes indicate that when designing soundscapes for positive user experiences, the sounds are especially relevant within the context of the specific need. With this assumption in hand, designers can use the outcomes of this study as suggestions for which categories of sounds to consider, when trying to establish the fulfilment of this specific need. When designing with sounds for the fulfilment of a need for *Recognition*, for example, the results of the study could be used to denote which specific kinds of sounds should be used, as sounds related to voices (e.g., a conversation, laughter) or the physical (e.g., moving pots and pans in the kitchen) can serve as inspiration towards composing the elements making up the soundscape, using the relative frequencies of the sound categories within the need-specific imagined environments as a guide.

These rich, personal accounts could be used, within the context of the respective need, to compare imagined soundscapes based on their relative perceived affective quality, and relative differences in frequencies of occurrence of sound categories between these themes; in correspondence analyses, the responses of perceived affective quality could also be used to identify which categories of sounds and which fundamental needs are associated with relatively more/less pleasant or eventful imagined soundscapes. In this way, designers could identify or characterize a target soundscape in terms of a current and desired quadrant (i.e., calm, chaotic, exciting, boring) within the pleasantness and eventfulness framework, as proposed by Cain et al (2013). Positive experiences with acoustic environments in a wide variety of contexts will in this way be achievable by selecting a target quadrant. A currently chaotic (i.e., unpleasant/eventful) soundscape could in this way be directed towards a calm (i.e., pleasant/uneventful) one, by identifying the need to be fulfilled, and, within this context, by matching this with sounds that contribute to the intended experience of the soundscape.

3.5 CONCLUSION

The main conclusions of this paper are:

1. When designing for fundamental need fulfilment, designers should compose soundscapes that are rated as pleasant, and there is room for variation in terms of eventfulness.
2. ‘Human’ sounds are most commonly associated with the fulfilment of each of the nine fundamental needs considered in this study.
3. The nine fundamental human needs are associated with different categories of sounds; designers should consider composing soundscapes consisting of the most prominent sound categories, dependent on the need.

In the process of designing soundscapes that satisfy psychological needs towards facilitating a positive user experience, the results of this study have provided indications that soundscape interventions should be evaluated within the context of the respective experience. In experimental setups investigating the impact of introducing new sounds to an existing context, efforts should be made to simulate the existing and preferred context.

SUPPLEMENTARY MATERIAL

See supplementary material at https://doi.org/10.5281/zenodo.15622240 for:

1. Four sensitizer audio samples

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Chapter 4

Augmenting soundscapes of ICUs: a collaborative approach

Building on insights from Chapters 2 and 3, this chapter takes a collaborative turn to explore ICU soundscape interventions. Through a workshop with ICU nurses, doctors, industry experts, and researchers, system concepts are developed to enhance ICU soundscapes. The chapter presents five characteristics for effective and feasible ICU soundscape interventions and emphasizes the importance of stakeholder collaboration.

This chapter is based on:
Louwers, G., Pont, S., Van der Heide, E., Gommers, D., & Özcan, E.(2024). Augmenting soundscapes of ICUs: a collaborative approach. In DRS2024 Boston proceedings.

ABSTRACT

In this study we investigated characteristics for designing soundscape augmentations within Intensive Care Units (ICUs). We introduced soundscape perception and fundamental needs as the basis of design strategies for augmenting soundscapes experienced by critically ill patients. We used results of a previous study, where in interviews regarding current ICU soundscapes, patients revealed four concerns and underlying needs. They found that ICU soundscapes were alienating, unvaried, unfamiliar, and disruptive. These insights were used as contextual inputs in a collaborative workshop with ICU nurses, resident doctors, and researchers. In separate groups, they developed three system concepts named Smart Environmental Assistant, Patient Soundscape Dashboard, and Familiar Wake-ups. Based on qualities of these concepts, we found five characteristics for designing effective soundscape augmentation systems for ICUs: personalized, user-friendly, integrated, humanized, and familiar. These characteristics, rooted in perspectives of various ICU experts, are essential for reshaping the ICU soundscape into a more positive listening experience.

4.1 IDEATING SOUND-DRIVEN SOLUTIONS FOR ICUS

When critically ill patients are recovering in intensive care units (ICUs) it is desired to provide them with the optimal environmental conditions necessary for them to heal. But instead, they tend to experience this environment as stressful. This stressful experience can come to haunt patients even after discharge through the onset of post-traumatic stress disorder (PTSD) and anxiety (Geense et al, 2021). The stress experienced by patients during ICU stays is a known risk factor for the development of these symptoms, collectively named post-intensive care syndrome (PICS). In particular, their experiences are characterized by stressors such as pain, anxiety, and the development of the confused mental state called delirium (Ouimet et al., 2007). The incidence of delirium is often intensified by environmental factors (Zaal et al., 2013). Disorienting environmental stressors in the vicinity of the patient, such as unwanted sounds, result in sleep disruption and loss of awareness of the surroundings consequently contributing to PICS (Darbyshire et al., 2019). Researchers have consistently found elevated sound levels associated with ICUs to exceed 50 dB(A) LAeq, with peaks between 80-100 dB(A) (Darbyshire et al., 2022). The World Health Organization recommends a maximum of around 30-35 dB(A) (Berglund et al., 1999). In fact, studies have shown that patients, relatives and healthcare professionals (HCPs) rank hearing alarms, medical device sounds, or other patients among the highest in severity of perceived stressors in ICUs (Krampe et al., 2021).

If we would simply reduce the amount of noise, would that then be enough to improve patient outcome? Unfortunately, while noise reduction has been the primary interest of many ICU-related interventions (Kim et al., 2021; Luetz et al., 2019), its effectiveness on patient-centered outcomes remains inconclusive (Delaney et al., 2019). An explanation is that the perceived meaning and quality of the perceived sounds in ICUs play a major role. There are accounts of ICU patients experiencing fear and helplessness due to the unfamiliarity and unexpectedness of sounds (Johansson et al., 2012). This seems indicative of the importance of an ICU soundscape, i.e., the acoustic environment as perceived and understood by a person or people in context (ISO, 2014), that is positively appraised, aside from mere compliance with psycho-acoustical regulations. Moreover, collaborative approaches may benefit the design and implementation processes of sound-driven solutions for healthcare (Özcan et al., 2018). A thorough understanding of how patients in ICUs experience soundscapes should therefore be central when all stakeholders such as clinical professionals, designers and engineers consider how to improve or *augment* it.

In this paper, we therefore conducted a collaborative, sound-driven design workshop to generate system concepts for augmenting ICU soundscapes. We used previously collected qualitative insights from interviews and surveys with former ICU patients as inputs. Specifically, we explored which design characteristics of system concepts were deemed important by multi-disciplinary stakeholders for augmenting the soundscapes of ICUs. The design thinking process in the workshop yielded three system concepts proposed by groups of workshop participants. By evaluating the qualities of these three system concepts, five design characteristics were identified that recurred across concepts, key to the provision of effective soundscape augmentations across different ICUs.

4.1.1 Listening as a tool for collaborative design

We cannot solely base the design of interventions on the experiences of ICU patients alone, as experiences reside in actions situated in specific contexts. Within the perspective of ecological perception, the connection between perceiver and environment is understood to be a reciprocal relationship between perception and action (Clarke, 2005). The act of listening is thus not seen as a passive activity, but rather as an idiosyncratic, action-oriented, intentional activity of meaning creation on the basis of a sonic experience (Tuuri et al., 2007; Delle Monache et al., 2022). The same sonic experience can even evoke contradictory levels of interpretations, meanings and emotions between different listeners based on their intention towards listening (Tuuri et al., 2012; Özcan et al., 2022). In ICUs, these distinctions between listeners are evident in the intent of ICU nurses listening to alarm sounds, switching between functional, causal, and empathic listening, while patients may want to find the cause of those same sounds by switching between causal and semantic listening.

These differences in the intentions of listeners also translate to their respective conceptual representations of sounds. Delle Monache et al. (2022) identified a semantic gap in how stakeholders involved in multi-disciplinary, sound-driven design discourse talk about and represent sound. They found that experts that have experience with using sound in a specific context (e.g., nurses) and experts working in sound and design (e.g., design researchers and sound designers) attribute distinct meanings to the concept of sound, respective to their intention and the ways of listening proposed by Tuuri et al. (2012). The different ways of listening and expression of the concept of sound therefore play a critical role in shaping design processes. Accordingly, in order to complement the perspective offered by patients, other stakeholders involved in the sound-driven design process, such as sound designers, engineers, design researchers, and expert sound users should be taken into account when designing augmentations for soundscapes of ICUs.

4.1.2 Soundscape perception

We can assess the perceived quality of a soundscape by evaluating it on independent dimensions of pleasantness (i.e., annoying to pleasant) and eventfulness (i.e., uneventful to eventful) (ISO, 2018). These two dimensions are inherently related to the dimensions of affect (valence and arousal) proposed by Russel (2003). As such, soundscapes are an important source of meaning and affect (Devos et al., 2019; Fiebig et al., 2020). We can determine a soundscape's quality by positioning it in the two-dimensional perceptual space of pleasantness and eventfulness (Mitchell et al., 2022). The difference in soundscape quality between locations, or before and after an augmentation, can be compared in this space. In the same way, designers can set a goal in terms of soundscape quality at the start of their design process. By assessing a soundscape's position, they can then propose improvements to achieve a shift in soundscape quality from one quadrant to the other (Cain et al., 2013). For example, they could aim to change a soundscape from being unpleasant and uneventful (i.e., monotonous) to pleasant and eventful (i.e., vibrant).

The strategies available for soundscape augmentation consist of either removing sounds, changing sounds, adding sounds, or combinations of the three. However, augmentations to ICU soundscapes primarily involved just the removal of sound through single patient room layouts, sound-absorbing materials, noise-canceling headphones, foam earplugs, and behavior protocols. This positively affected patient and staff comfort (Kim et al., 2021; Vreman et al., 2023). But the ineffective results of sound reduction could be explained by the necessity of sound from an evolutionary perspective (Van den Bosch & Andringa, 2018). To only remove sounds in ICUs without replacing them with new, more positively appraised ones does not necessarily result in a more positively appraised soundscape (Cain et al., 2013; Stockfelt, 1991). This could instead lead to having no effect or actually an opposite effect on patient stress.

Redesigning sound sources in ICUs such as alarm systems is a promising alternative to the removal of sound, associated with benefits for both patients and healthcare professionals (Schlesinger & Shirley, 2019). Nevertheless, as this field remains subject to global medical device regulations and agreements between medical device manufacturers, redesigning sound sources can be problematic (Edworthy et al., 2018; Özcan et al., 2020; Özcan et al., 2018). Enriching an existing soundscape with new sounds is an intriguing third option. The addition of sounds such as birdsong or music can have beneficial effects on ICU soundscape perception and patient outcomes (Özcan et al., 2023; Kakar et al., 2023). Furthermore, in addition to providing sounds from nature or music, other categories of environmental sounds such as human (e.g., background murmur in café) or technological (e.g., coffee grinding) sounds could be considered to augment the soundscape (Louwers et al., 2022). In another field, the value of this approach was shown for similarly vulnerable patients. With specific additions of sounds to secluded rooms of patients with dementia, they evoked positive associations with the soundscape (Devos et al., 2019; De Pessemier et al., 2023).

The importance of continuing to reduce unwanted sound and redesign of medical devices cannot be overstated. But parallel to these developments, we propose that designers can consider the stratagem of designing systems that augment ICU soundscapes with new sounds for more positive experiences. The need for designing these augmentations should however also depend on soundscape-related concerns of ICU patients, nurses and doctors.

4.1.3 Fundamental need fulfilment

The source of positive user experiences is generally understood to be the fulfilment of psychological needs (Hassenzahl & Diefenbach, 2012). When researchers examined user interactions with technological products, they found that positive user experiences could in fact be characterized by specific needs (Hassenzahl et al., 2010). An individual's needs are therefore commonly used in design practice as an inspirational starting point for designing positive user experiences (Wiklund-Engblom et al., 2009). Similar to how nutriments are essential for an organism's well-being, psychological needs can be considered as crucial inputs for people to grow and thrive (Deci & Ryan, 2000). If needs are universally present for every individual regardless of cultural differences, they are called fundamental (Tay & Diener, 2011). Although many typologies of fundamental needs have been proposed in the past, only recently a comprehensive typology was proposed that is intended for user-centered design practice (Desmet & Fokkinga, 2020). This typology consists of thirteen fundamental needs such as the needs for Autonomy, Competence, and Relatedness.

In designing for ICU patients in general, this need-based approach is becoming increasingly relevant. The field of intensive care is moving away from dehumanized care where the individual is overshadowed by the importance of treatment and technology (Velasco Bueno & Heras La Calle, 2020). Instead, it is shifting towards a people-centered care model where an individual's needs are considered (Van Mol et al., 2016). This approach extends to the ICU soundscape, where taking a listener-centric approach could offer possibilities for humanization (Özcan et al., 2022). We should therefore consider ICU soundscapes as functional entities which can contribute to the fulfilment of patients' needs (Louwers et al., 2022). If soundscape augmentation will be used as such, we should start from the vantage point of patient concerns and their needs regarding current ICU soundscapes.

To incorporate this patient perspective into the multi-stakeholder, sound-driven design process proposed by Delle Monache et al. (2022), we collected the concerns of ICU patients regarding the soundscape in a previous study. These were consequently used as inputs for a collaborative workshop with other stakeholders of the ICU to generate system concepts for effective soundscape augmentations.

4.2 ORGANIZATION AND FACILITATION OF AN ICU STAKEHOLDER WORKSHOP

4.2.1 Participants

We recruited eight stakeholders, joined by four of the authors (also stakeholders) of this paper as participants in the workshop. The resulting 12 participants (m = 6, f = 6) consisted of three senior ICU nurses and one ICU junior resident from an academic hospital, one ICU junior resident from a teaching hospital, four industry experts in health technology specialized in critical care, two researchers with a background in design and one researcher with a background in psychophysics. Finally, the workshop was lead and facilitated by a service designer and professional focus group moderator. The participants were divided into groups of four, with each group comprising of at least one ICU nurse or doctor. Each participant gave informed consent prior to the workshop. Ethical approval for the workshop was obtained from the Human Rights Ethics Committee of Delft University of Technology on the 25th of November 2022.

4.2.2 Workshop input

In former research, we approached patients who were discharged from an adult ICU ward with exclusively single patient ICU rooms in an academic hospital (Louwers et al., 2025). The participants were still recovering from their ICU admission in general wards of the hospital when we interviewed them. In these interviews, a total of 26 participants reflected on their experiences regarding the soundscape during their ICU stay. Furthermore, in this former study, we evaluated with surveys to which degree thirteen fundamental needs proposed by Desmet & Fokkinga (2020) characterized the experiences of patients with ICU soundscapes. Among these thirteen needs, the lack of fulfilment of needs for *Autonomy*, *Stimulation*, *Comfort*, *Beauty*, *Community*, *Recognition*, *Relatedness*, and *Morality* stood out. Additionally, we searched interview transcripts for indications of specific underlying themes of their experience in a thematic analysis (Braun & Clarke, 2021). We found that the soundscape of single patient ICU rooms was considered *alienating*, *unvaried*, *unfamiliar*, and *disruptive* by patients. In the current paper, we assume these themes to represent patients' current concerns regarding the ICU soundscape, and that these needs underlie them. We defined each soundscape concern by providing it with descriptions as shown in Table 4.1.

Table 4.1. Concerns and descriptions from patient interviews regarding ICU soundscape experiences.

Soundscape concern	Description
Alienating	Patients are secluded in single-patient rooms with sound-proof sliding doors. These doors protect patients from unwanted sound, but also cause patients to feel like they are on their own. When alarms start going off behind closed doors, this is a terrifying experience.
Unvaried	Patients feel the desire to be distracted, but do not find it in the environment. There is a lack of variation in the soundscape. This causes feelings of loneliness and emphasizes their feelings of isolation. The diversions available to them such as TV and radio are often too demanding.
Unfamiliar	Patients wake-up from sedation to an unfamiliar soundscape. Unable to open their eyes, patients search the soundscape in vain for sounds they recognize, and subsequently feel disoriented and lost. In contrast, when they recognize sounds such as voices, they feel grounded and safe.
Disruptive	Patients are continuously exposed to a soundscape of disruptive alarms they have no control over. Continuous alarms make patients feel wakeful and vulnerable. While overwhelmingly negative, alarm sounds also announce care staff visits, providing anticipation and safety.

These patient concerns capture the conceptual representation of sound and intentionality from the perspective of the patients. The patient concerns, together with the underlying needs, were presented to participants during the workshop. They were used as inputs in order to explain the current experience of ICU soundscapes to participants, and to give participants a patient-centered vantage point for their creative process.

4.2.3 Procedure

The workshop lasted one afternoon and was hosted in a co-creation space at Philips Design on the High-Tech Campus in Eindhoven. Based on the 'Co-Creation Process', a Philips Experience Design implementation of design thinking (Nazeem, 2022; Philips, n.d.), the workshop was divided into four sequential phases: a Discover, Frame, Ideate, and Build phase. In the Discover-phase, participants immersed themselves in information about the user group and context. In the Frame-phase, participants defined the problem based on the situations provided to them in the Discover-phase, and defined what would constitute a better future than the current one. Then, in the Ideate-phase, participants found solutions to the problem they defined in the Frame-phase through creative thinking and shared them with each other. Finally, in the Build-phase, participants made their ideas tangible by thinking of how the ideas from the Ideate-phase could be evaluated.

During the Discover-phase, in a plenary discussion, participants familiarized themselves with the hospital's ICU context. They were provided with an isometric ICU floor map, see Figure 4.1, and overviews of nurse routines. Additionally, the first author presented the four soundscape concerns and underlying needs we found in the former study. At the end of the Discover-phase, the facilitator explained the workshop activities and schedule and assigned participants to their groups. At this point, the first author joined one of the groups as a participant.

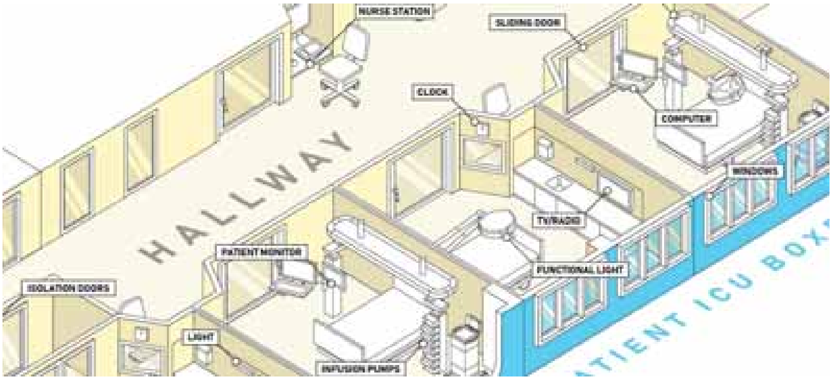

Figure 4.1. Isometric floor map of ICU, used in Discover-phase to familiarize patients with the hospital's adult ICU context.

In the Frame-phase each group picked one of the four soundscape concerns found in the ICU patient interviews. For the selected patient concern, participants formulated two so called *"From.. To.."* statements. First, participants described the current situation in a *"From ..."* statement e.g., "... from feeling disoriented and uninformed ...". After, they described the future, ideal situation by coming up with a *"To ..."* statement e.g., "... to feeling oriented and informed.". The groups then formulated a question how they might achieve this *From-To* transition in a *"How might we ...?"* format. They concluded the phase by presenting to other groups and receiving feedback.

In the Ideate-phase, groups generated ideas to solve their *"How might we ...?"* question. The facilitator of the workshop divided this phase into three timed parts. First, all participants individually performed a brainwriting task by writing their first ideas on post-its. Second, participants shared these ideas within their group, and each group clustered the ideas by grouping post-it's on whiteboards. Finally, each group chose one or multiple idea clusters to work on as their final idea direction using concept posters. These posters provided sub-questions including an idea *description*, *benefits for patients* and *care staff*, and *risks*. The groups then presented these posters to each other.

During the Build-phase, groups explored what would be necessary to evaluate their system concepts. Specifically, participants developed experimental designs for their system concepts. Finally, the groups presented these to each other.

4.2.4 Data analysis

We analyzed the outputs in the form of descriptions of the Frame- and Ideate-phases (i.e., From-statements, To-statements, concept descriptions, benefits, and risks). Through thematic analysis (Braun & Clarke, 2021), we considered which qualities of concepts were present, and which overarching design characteristics recurred across system concepts. We identified and coded qualities, and discussed them between the authors. We grouped and iteratively (re)named the concept qualities into representative design characteristics. For the scope of this paper, we excluded the Build-phase outputs, since that phase did not target qualities of concepts but characteristics of experimental designs.

4.3 THREE SYSTEM CONCEPTS AND FIVE DESIGN CHARACTERISTICS

4.3.1 System concepts

The workshop outputs of the Frame- and Ideate-phases are shown in Table 4.2. The table includes the patient concern, question and detailed description of the system concepts for soundscape augmentation in ICUs for each of the three groups. The first group devised a ‘Smart Environmental Assistant’, giving patients control over the soundscape with options such as masking sounds or opening the door. The second group developed a ‘Patient Soundscape Dashboard’ a contextualized and personalized soundscape adaptive to the preferences of patients, patient-state, and requirements for care activities. The third group created a ‘Familiar Wake-ups’ system concept being recognizable, familiar sounds from the patient's home environment to offer comfort and orientation during planned or unplanned wake-ups.

Table 4.2. 'How might we' questions and detailed system concepts for each soundscape concern.

	Smart Environmental Assistant	**Patient Soundscape Dashboard**	**Familiar Wake-ups**
Soundscape concern	Alienating	Unvaried	Unfamiliar
How might we…	… offer patients a sense of control and of what's coming, as well as feeling heard when necessary or desired?	… increase a sense of comfort and autonomy through contextualized and personalized soundscapes?	… create an environment that makes patients feel oriented, informed and connected to loved ones?
Description	• A multi-sensory, smart environmental assistant. • Gives patients the ability to control their surroundings regardless of their sensory impairments.	• A personalized, patient-state related and contextualized soundscape dashboard. • Controlled by the patient. • Provides patients with personalized soundscapes at specific moments during admission.	• An audio system designed for patients during wake-ups. • For planned or unplanned wake-ups from sedation. • Provides familiar sounds from the home-environment of the patient for orientation.
Benefits for patients	• Feeling in control. • A patient centered, comfortable space.	• Less PICS/PICS-F • Increased quality of care	• Reduces incidence of stress, PTSD and anxiety. • Feeling safer when waking.

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Table 4.2. *Continued*

	Smart Environmental Assistant	Patient Soundscape Dashboard	Familiar Wake-ups
Benefits for care staff	• Comfortable patient, happy care staff. • More time for personal care.	• Decreased delirium incidence • Improved workload • Decreasing length of stay	• Having a calm and cooperative patient. • Less sedatives. • Less anxiolytic medication necessary.

4.3.2 Design characteristics

The three system concepts outlined in this workshop were distinct examples of how ICU soundscapes could be augmented based on the perspectives of various ICU stakeholders. Each concept had their own prominent qualities. We found that the concept qualities extracted from the workshop results corresponded to five distinct characteristics: *user-friendly, humanized, integrated, personalized* and *familiar*. These design characteristics represented the user-friendliness of concepts for multiple users, the importance of humanizing the system, the necessity of concepts to be integrated, a strong emphasis on personalization, and a familiar interaction with the system. We will briefly introduce each characteristic here, with examples from the three concepts. We listed the soundscape concerns, concept qualities, and the representative design characteristics in Table 4.3.

Table 4.3. Concepts, concept qualities, and design characteristics for designing soundscape augmentation systems.

Soundscape concern	Concept quality	Design Characteristic
Alienating	Usable in different stages of consciousness by patients.	User-friendly
	Provides feedback to the patient.	User-friendly
	Accessible through a multitude of senses.	User-friendly
	Supports the quality of human contact.	Humanized
	Does not replace nurse visits.	Humanized
	Usable by family and staff.	Humanized
	Centrally connected per bed into departmental management.	Integrated
	Integrated in workflow of staff.	Integrated
	Personalized to preferences collected in advance of admission.	Personalized
Unvaried	Easy to use by patients.	User-friendly
	Includes an option for silence.	User-friendly
	Is customizable.	User-friendly

Table 4.3. *Continued*

Soundscape concern	Concept quality	Design Characteristic
	Offers patients the ability to choose auditory content.	User-friendly
	Involves relatives and care staff.	Humanized
	Supportive of different care activities.	Integrated
	Able to adapt soundscapes to sudden events in the room.	Integrated
	Has both pre-populated and personalized functionalities.	Integrated
	Supportive of patient circadian rhythms.	Integrated
	Connected to patient vital signs.	Integrated
	Not too dynamic for patients.	Personalized
	Provides separate listening experiences for each single patient.	Personalized
	Makes use of patient profiles constructed before admission.	Personalized
Unfamiliar	Allows for family's and caregiver's input during admission.	User-friendly
	Involves sounds sourced from the patient's home environment.	Familiar
	Reconnect patients to reality.	Familiar
	Provides patients with information about their environment.	Familiar
	Involves the input of patients' relatives.	Humanized
	Is connected to a generic database of sounds.	Integrated
	Is related to early, middle or late stage of admission.	Integrated
	Makes use of a preference profile acquired before hospitalization.	Personalized

User-friendly: accessible and inclusive for patients, family, and care staff

The co-created concepts were mentioned to have to be inherently user-friendly. First and foremost, the workshop groups found it important to evaluate how patients themselves could access such a system considering their lack of physical abilities and mental capacities. The three system concepts showed that several aspects have to be taken into account when considering this characteristic. First, impairments of vision, either pre-existing or developed during ICU stay, could frustrate the interaction with systems. Additionally, some patients would be unable to control a potential system due to being unable to move their hands. Or patients suffer from hearing loss. These impairments would likely arise due to neuromuscular disorders such as ICU acquired weakness, contracted after extensive periods of time spent on an ICU (Stevens et al., 2009). The workshop groups therefore deemed it important that the interactions with systems would have to incorporate equally accessible auditory, tactile or visual cues.

This is especially emphasized in the Smart Environmental Assistant concept by the need for multi-sensory interaction as an essential feature. For example, voice-assistance feedback could be implemented in addition to visual interfaces. Second, the groups proposed to consider how patients in different stages of consciousness can interact with soundscape augmentation systems. Nevertheless, standardized profiles would instead have to be implemented for patients who are sedated or unarousable. Third, it was emphasized that the environment should be customizable by patients during their ICU stay up to a degree, as included as functionalities in both the Smart Environmental Assistant and Patient Soundscape Dashboard concept. Last, all groups argued that the user-friendliness in soundscape augmentations should extend to other users of these systems. By providing clinical staff and relatives with an accessible system, they would be able to customize the system to the patient's preferences.

Personalized: pre-defined preferences and real-time feedback

The workshop groups claimed that augmentation of soundscapes within ICUs should rely on individual preferences and needs, as every patient is unique with regards to their personality and condition. They suggested that systems should therefore provide a personal listening experience for patients. All three groups emphasized the importance of personalization in their concepts and proposed that, in case of planned admissions, patients could be asked about their daily routines, preferences, personal values, and interests. This information could both be used to tailor daily care activities and as input for systems such as for sourcing sounds or sound categorizations from the patient's home environment.

In this way the system can provide a recognizable environment after surgery as stated in the Familiar Wake-ups concept. In the Patient Soundscape Dashboard, a self-learning soundscape was suggested that could collect feedback from patients or relatives during the ICU stay, optimizing the soundscape to the patient's preference over time. Another idea was proposed in the Smart Environmental Assistant concept to control the amount of noise in the room using patient profiles and preferences collected before admission. For unplanned admissions or when patients are unable to provide feedback, systems could rely on the input of relatives to provide the information needed for personalized experiences. Additionally, personalization of different system concepts could be achieved without putting additional strain on clinical staff by providing pre-populated, standard augmentations to the soundscape.

Humanized: enabling human involvement

Modern ICUs are perceived to be highly technological and void of human interaction (Wilson et al., 2019). Therefore, the role of relatives and care staff in augmenting the ICU soundscape was seen as an essential factor to consider for the derived system concepts. As relatives and nurses cannot always be present, workshop groups suggested that to effectively implement augmentations to the ICU soundscape, systems would need to be people-centered and therefore, avoid dehumanizing the environment further by replacing this essential human contact. Therefore, the involvement of the people around the patients, in addition to the patient themselves, should be central to the design process. Specifically, they suggested that systems should allow for participation of relatives, as indicated in Familiar Wake-ups, both out of practical considerations for the personalization of the system for the patient, as well as to give relatives control over a situation that feels uncontrollable. Furthermore, since ICU room visits often form highlights of a patient's day worth looking forward to, it was stressed that these moments should be supported rather than replaced. While particularly salient in the Smart Environmental Assistant concept, for all system concepts it was emphasized that strengthening the quality of human contact would be key to the success of augmentations to ICU soundscapes.

Integrated: respecting care staff activities and routines

The three system concepts generated in the workshop showed that the nature of the ICU as a place of critical care and emergency situations has to be taken into account in the design process. The groups therefore suggested that any functionality of soundscape augmentation systems would have to be integrated relative to that context. This was especially apparent in the Patient Soundscape Dashboard concept, where participants suggested that the system would have to offer soundscapes for the support of care activities of clinical staff. Also, it was emphasized that the adaptability of the system concepts to different stages of admission, patient status and the critical situations in patient rooms, implies integration with patient data systems. As was shown in the Smart Environmental Assistant system concept, integration of smart devices per patient bed or room into a centrally managed departmental control system is also key. Additionally, in the Patient Soundscape Dashboard concept, participants suggested that through centralized control, systems could support care workflows as well as offer clinical staff with accessible features for distracting or calming patients during care activities like early mobilization therapy or breathing trials. Finally, standardized options of pre-populated, standard soundscapes such as the ones suggested in the Patient Soundscape Dashboard and Familiar Wake-ups, would keep the additional efforts required of clinical staff at a minimum.

Familiar: providing a recognizable environment

We discovered familiarity as the fifth and final characteristic for designing soundscape augmentation systems. While only the workshop group of Familiar Wake-ups specifically emphasized the necessity of this in their system concept, the importance of this characteristic was indirectly stated by the other workshop groups. In the Smart Environmental Assistant, this was reflected by features of the system concept that restore patients' agency towards adapting the noise preferences and other environmental conditions to what the patient is accustomed to. The Patient Soundscape Dashboard included this characteristic by incorporating functionalities that offer patients the choice of familiar, auditory content. Furthermore, by providing a familiar interaction with recognizable auditory cues for information, such as in Familiar Wake-ups, patients could be grounded in reality by being anchored to their known environment, providing orientation.

Related to this, the three groups recognized the importance of providing familiar auditory features in soundscape augmentations during vulnerable stages of admissions, such as providing orientating familiar sounds from home during wake up in the Familiar Wake-ups concept, to decrease disorientation. Furthermore, strongly related to the characteristic of personalization, the groups' efforts to emulate everyday surroundings and preferences of patients from normal life to the ICU soundscape as a way of augmenting it, signal that this could be an important strategy for designers to consider.

4.4 DISCUSSION OF WORKSHOP OUTCOMES

In this paper, we set out to find design characteristics for future systems that could augment the soundscapes of ICUs. By analyzing the outputs of the workshop, we found that for the effective design of soundscape augmentation systems for ICUs, workshop participants found it important that their designs were user-friendly, personalized, humanized, integrated, and familiar. When considering the prevalence of these five design characteristics in the three system concepts generated in the workshop, it can be deduced that at least four characteristics (i.e., user-friendly, personalized, humanized, and integrated) were represented in each concept. We found that the fifth characteristic, familiar, was only directly represented in Familiar Wake-ups, but also indirectly in the other system concepts. We will investigate the feasibility and effectiveness of incorporating these design characteristics into a soundscape augmentation system in future studies. Additionally, the three system concepts (and by extent, the coded concept qualities and design characteristics) were based on diverse patient concerns regarding the soundscape of one hospital's ICU ward. Regardless of this diversity, future research efforts should investigate whether the design characteristics will be relevant when designing soundscape augmentation systems for similar soundscape concerns in different ICUs (Johanssen et al., 2012), such as in multi-patient rooms. Also, aside from the potential benefits, future research efforts could also evaluate the risks involved with implementing soundscape augmentation systems, starting with the ones proposed in the workshop.

We followed a collaborative approach due to the importance of including multi-disciplinary groups of stakeholders in sound-driven design processes (Delle Monache et al., 2022). In our collaborative workshop, we included ICU nurses, medical doctors, industry experts in health technology specialized in critical care, and researchers with backgrounds in design and psychophysics as expert ICU stakeholders. As was expected from taking this approach, the different types of conceptual representations of sound by the different stakeholders seem to have indeed provided unique angles to the sound-driven design problem the groups were faced with in the workshop. This could be gleaned from the individual concept qualities presented in this paper such as the functional intention of the nurses and doctors towards the soundscape. For example, this was evident by clinical experts relating soundscape augmentation to patient conditions and the place of these systems in clinical staff workflows. In this way, the results of our study bear resemblance to at least two out of the four sound-driven design orientations proposed by Delle Monache et al. (2022). In line with our expectations regarding this collaborative approach, the diverse perspectives of ICU stakeholders thus provided unique insights essential for enhancing the overall patient experience.

4.4.1 Limitations

The results show that primarily the orientations of ‘designing sound for expert users’, and ‘designing with sound’ were represented. In an ideal scenario, however, we would include the other two idiosyncratic design orientations in this process as well, by involving acoustical engineers and sound artists as was also proposed by Özcan and Van Egmond (2008) in an earlier study. The inclusion of acoustical engineers could have contributed to more mitigative, but practical concepts, because of their personal qualification of sound as noise (Delle Monache et al., 2022). The contrasting viewpoint of sound designers/artists as listeners in the process of sound creation could have offered depth to the concepts generated in the workshop in terms of the listening experience offered to patients.

Most importantly, future research efforts could include former ICU patients in the actual collaborative workshops as well, to reach outcomes that address each of these four orientations, and are patient-centered. The addition of the input by these stakeholders especially will be valuable to make soundscape augmentation systems technologically viable and acoustically pleasant in the future.

4.5 CONCLUSION

This paper highlights insights gained from a collaborative approach aimed at the augmentation of soundscapes in intensive care units (ICUs). We used the results of a previous study, revealing patients' soundscape concerns of ICU soundscapes as alienating, unvaried, unfamiliar, and disruptive, and a related lack of fulfilment of fundamental needs. A collaborative workshop produced three system concepts for soundscape augmentation within ICUs named Smart Environmental Assistant, Patient Soundscape Dashboard, and Familiar Wake-ups. The analysis of workshop outputs identified five essential design characteristics for soundscape augmentation systems—user-friendliness, personalization, humanization, integration, and familiarity. The prevalence of the design characteristics in each of the three system concepts suggests that while the concepts themselves may depend on different patient concerns, the characteristics are applicable to each of these situations. These characteristics are offered to inform designers and healthcare management in order to guide the development and evaluation of interventions for effectively augmenting the soundscapes within critical care settings. By applying these design characteristics when designing augmentations to ICU soundscapes, we can establish more positive experiences with ICU soundscapes and prioritize the recovery and well-being of patients.

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Chapter

5

Sonic ambiances through fundamental needs: an approach on soundscape interventions for intensive care patients

Following patient insights gained in Chapter 2, theoretical foundations in Chapter 3 and conceptual directions of Chapter 4, this chapter develops and evaluates an approach to designing soundscape interventions. It introduces a design approach of four types of sonic ambiances and four design parameters, tested through a listening experiment. These insights serve as a comparative basis for real-world validation in Chapter 6.

This chapter is based on:
Louwers, G., Pont, S., Gommers, D., van der Heide, E., & Özcan, E. (2024). Sonic ambiances through fundamental needs: An approach on soundscape interventions for intensive care patients. The Journal of the Acoustical Society of America, 156(4), 2376-2394.

ABSTRACT

We explored the underpinnings of providing positive listener experiences for ICU patients with compositions of added sounds. Our objective was to derive an approach on such interventions based on soundscape perception and need fulfilment. In one study, we gathered qualitative empirical data about imagined soundscapes where nine fundamental needs were fulfilled. Hierarchical clustering and thematic analysis showed that imagined soundscapes clustered into four types of sonic ambiances, i.e., affective connotations with soundscapes: Comfortable, Pleasurable, Motivating or Stimulating ambiances. We derived four design parameters to achieve these ambiances with sound compositions: eventfulness, sonic ambiance qualities, narrative structure, and sound distribution. A sound artist was asked to use these parameters to create sound compositions. In a listening experiment we examined their effects on perceived pleasantness and eventfulness of soundscapes, and on listeners' experienced pleasure and arousal. Soundscapes were perceived as pleasant with varying eventfulness in line with our structured approach. We found a strong correlation of pleasantness with listener's pleasure and a moderate correlation of eventfulness with listener's arousal. Finally, we suggested that in future research, three sonic ambiance types should be considered rather than four. Concluding, we showed that our need-driven approach could form a promising way to support ICU patients.

5.1 CONNECTING SOUNDSCAPE PERCEPTION AND FUNDAMENTAL NEED FULFILMENT

Since the days of Florence Nightingale, intensive care units (ICUs) evolved into highly advanced and complex care environments, increasing chances of survival of the critically ill (Kelly et al., 2014). Nevertheless, an estimated 50% of patients survive their ICU stay with lasting psychological impairments such as post-traumatic stress disorder and anxiety (Geense et al., 2021). A well-known risk factor for the development of these symptoms is stress experienced while in the ICU (Lee et al., 2020). Sub-optimal environmental conditions are known to contribute to this stressful experience (Darbyshire et al., 2019). Among environmental stressors, patients, relatives, and clinical staff rank sound among the highest in perceived severity (Krampe et al., 2021). Listening to sounds caused by other patients, staff conversations, alarms or machinery (Xie et al., 2009) cause sleep disruptions (Elbaz et al., 2017) and loss of orientation (Ballard, 1981). As a result, ICU soundscapes, i.e., the acoustic environment as perceived or experienced by a person or people in context (ISO 12913-1, 2014), are experienced negatively (Johanssen et al., 2012). The elevated sound levels associated with ICUs are widely documented, amounting to 50 dB(A) LAeq, with peaks of over 100 dB(A) (Darbyshire et al., 2022).

Some hospitals responded by introducing single-patient room layouts as part of noise reduction strategies, which positively affected patient and staff comfort (Luetz et al., 2019; Vreman et al., 2023; Delaney et al., 2019). However, while solving the initial problem of sound level (Özcan et al., 2024), we discovered that the seclusion of patients to single-patient rooms could also lead to new issues. In a previous qualitative investigation, we found that patients in single-patient ICU rooms experienced the soundscape as alienating, unvaried, unfamiliar, and disruptive (Louwers et al., 2024). Medical alarms, sound-proofed doors, and a lack of variety in room soundscapes negatively impacted patients' experiences, resulting in wakefulness, anxiety and disorientation.

There are opportunities to utilize the soundscapes of secluded single-patient rooms as a source of restoration and other positive user experiences. In a collaborative workshop with ICU stakeholders (Louwers et al., 2024), we developed concepts for hospital soundscape interventions (Busch-Vishniac & Ryherd, 2023) for ICUs that provide patients with compositions of sounds inside their rooms. Other studies have shown the merit of providing such interventions for comparably vulnerable patients (in dementia care) to evoke positive associations (Devos et al., 2019; De Pessemier et al., 2023). In single-patient ICU rooms, a soundscape augmentation could evoke various familiar, positive associations through meaningful sensory representations (Özcan & Van Egmond, 2007) of added sound compositions that are not provided by the existing soundscape. For example, providing physical access to nature is not feasible for ICU patients, with some exceptions such as a rooftop terrace provided to ICU patients by Rijnstate Hospital (Rijnstate, 2023). By adding natural sounds to existing pediatric ICU soundscapes, significant improvement on perception of pleasantness of the soundscape was achieved in an experimental set up (Özcan et al., 2023).

This positive effect could be explained by the affective evaluation associated with the soundscape, which we will refer to as the *sonic ambiance*. Previous research established that perceived affective meanings of soundscapes can affect listeners' valence and arousal (Russel, 2003; Fan et al., 2015). Given these effects, sonic ambiances could serve as functions of ICU soundscapes to address the needs of patients. As product functions are commonly developed to address specific user needs (Hassenzahl & Diefenbach, 2012; Wiklund-Engblom et al., 2009), sonic ambiances should be dependent on auditory needs of the listener, such as safety or information (Van den Bosch et al., 2018). But due to recent trends towards lighter sedation, ICU patients are awake more than before (Holm & Dreyer, 2017). This requires the consideration of a more comprehensive view of needs, such as pleasure, dignity, or a sense of purpose (Özcan et al., 2020).

While patients may seem to have different motivations than healthy individuals, studies into psychological needs and well-being have shown that in essence the same needs are present for everyone and exist regardless of culture, age or lifestyle (Sheldon et al., 2001; Tay & Diener, 2011). We assume that patients, like healthy individuals, listen with varying intent (Tuuri & Eerola, 2012; Özcan et al., 2022) for auditory cues to fulfil their psychological needs. For example, patients find reassurance by listening to footsteps or voices of nurses coming in from the hallway. Since these needs, such as reassurance, are present for every individual, they are considered *fundamental* to human experience. Revising earlier fundamental need typologies, researchers created a design-focused framework made up of thirteen fundamental human needs: the needs for *Autonomy*, *Beauty*, *Comfort*, *Community*, *Competence*, *Fitness*, *Impact*, *Morality*, *Purpose*, *Recognition*, *Relatedness*, *Security*, and *Stimulation* (Desmet & Fokkinga, 2020). Naturally, the manifestations of these needs (i.e., subneeds) for patients and healthy individuals (Huang & Desmet, 2023) may be different dependent on the situation.

Here we address the question whether soundscapes are need-specific and distinctive. For example, would soundscapes that provide distraction during painful care procedures (e.g., Stimulation) have different characteristics than soundscapes that provide reassurance during long stretches of time without visitation (e.g., Relatedness)? There are many ways to compare these characteristics of soundscapes. They could be compared in terms of their psychoacoustic indicators, such as loudness or sharpness (Engel et al., 2021). But co-existing with the more objective characteristics of sound, the subjective features of hospital soundscapes may be equally important (Mackrill et al., 2013). For example, they could be compared by their sonic ambiance qualities (e.g., distracting/reassuring), sound sources (Lenzi et al., 2021), or spatial-temporal organization of elements (Çamci, 2022). Alternatively, soundscapes can be compared in terms of perception. Semantic perceptual dimensions such as pleasantness and eventfulness are used to measure soundscape perception in outdoor environments (Davies et al., 2014; Aletta et al., 2016). Comfort and content are generally used for indoor residential environments (Torresin et al., 2020; Torresin et al., 2023). Lastly, they can be compared in terms of their effect on listeners in terms of their emotional state, being pleasure and arousal (Fiebig et al., 2020).

In the present paper, we investigated the perceptual, qualitative, and emotional relationships between fundamental needs and soundscapes. Specifically, our objectives were to derive an approach for designing sound compositions based on soundscape perception and fundamental need fulfillment, and to assess its effectiveness in a lab ICU setting. We therefore performed two studies with two independent participant populations, see Figure 5.1.

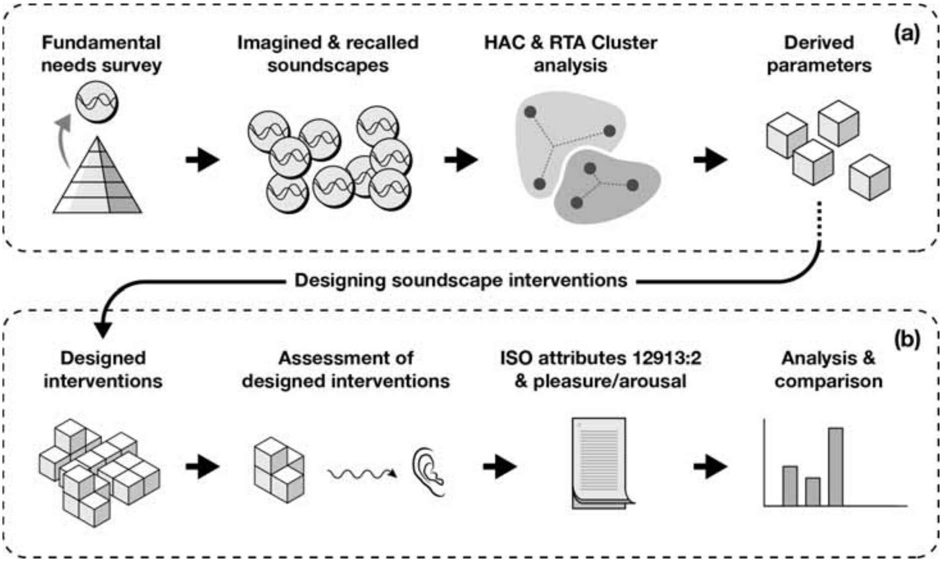

Figure 5.1. Flow diagram of steps taken in Study 1 (a) and Study 2 (b)

In Study 1 (Fig. 5.1a), we developed our design approach. We gathered qualitative and quantitative data via a survey and conducted a hierarchical agglomerative clustering (HAC) and reflexive thematic analysis (RTA). On the basis of the results, we derived four design parameters based on perceptual (i.e., pleasantness/eventfulness) and qualitative (i.e., sonic ambiance qualities, narrative structure, sound categorization) characteristics of soundscapes that we found to be related to the fulfillment of specific needs. Next, a sound artist designed various sound compositions based on these design parameters, which are included in the supplementary materials.

In Study 2 (Fig. 5.1b), we evaluated the effectiveness of our approach in a lab ICU setting. We evaluated the effects of the designed sound compositions on perceptual (i.e., pleasantness and eventfulness (ISO 12913-2, 2018)), emotional (i.e., pleasure and arousal), and qualitative (i.e., sonic ambiance quality and sound distribution) levels. In our analysis, we compared these effects to the intended design parameters.

Hence, the research questions addressed in this paper were the following:

i. Can perceptual and qualitative characteristics of soundscapes be related to the fulfilment of different fundamental needs and serve as design parameters for creating need-based sound compositions? (Study 1)

ii. To what extent do these sound compositions have an effect on perceived pleasantness and eventfulness of soundscapes and pleasure and arousal of the listener? (Study 2)
iii. Are the effects of sound compositions measured in Study 2 similar to the effects as described in Study 1, and do listeners perceive the characteristics of the sound compositions as we designed them?

Study 1

In Study 1 we performed an online survey study to evaluate whether and how the fulfilment of different psychological needs related to the perceptual and qualitive characteristics of imagined or recalled soundscapes. We adapted this methodology of recalling or imagining soundscape characteristics from other qualitative methods related to soundscapes, such as narrative interviews (Schulte-Fortkamp & Fiebig, 2006; Aletta et al., 2016).

5.2 AN ONLINE SOUNDSCAPE SURVEY (STUDY 1)

5.2.1 Participants

A total of 34 healthy volunteers (17 male, 17 female) in the age of 23 to 56 participated. Participants originated from Western-Europe (31), Southern Europe (2), and Asia (1), and all resided in the Netherlands. Participants had no experiences with staying or working in an ICU. Exclusion criteria were not being proficient in English and hearing impairments. After giving informed consent, participants received an English online survey by email. They did not receive financial compensation. The study protocol was approved by the ethics committee of the Delft University of Technology on the 21st of October 2021 (ID#1847).

5.2.2 Materials

Following consensus between the authors and ICU staff at an academic hospital, nine fundamental needs from the typology of Desmet and Fokkinga (2020) were selected: the needs for Autonomy, Beauty, Comfort, Competence, Fitness, Recognition, Relatedness, Security and Stimulation, see Table 5.1.

Table 5.1. Nine fundamental needs and corresponding need-specific feelings.

Need	Need-specific feeling
Autonomy	Being the cause of your actions and feeling that you can do things your own way, rather than feeling as though external conditions and other people determine your actions.
Beauty	Feeling that your environment is a place of elegance, coherence and harmony, rather than feeling that it is disharmonious, unappealing or ugly.
Comfort	Having an easy, simple relaxing life, rather than experiencing strain, difficulty or overstimulation.
Competence	Having control over your environment and being able to exercise your skills to master challenges, rather than feeling that you are incompetent or ineffective.
Fitness	Having and using a body that is strong, healthy and full of energy, rather than having a body that feels ill, weak or listless.
Recognition	Getting appreciation for what you do and respect for who you are, instead of being disrespected, under-appreciated or ignored.
Relatedness	Having warm, mutual, trusting relationships with people who you care about, rather than feeling isolated or unable to make personal connections.
Security	Feeling that your conditions and environment keep you safe from harm and threats, rather than feeling that the world is dangerous, risky or a place of uncertainty.
Stimulation	Being mentally and physically stimulated by novel, varied and relevant impulses and stimuli, rather than feeling bored, indifferent or apathetic.

These needs were deemed most relevant with regards to current patient experiences on ICU wards, and thus were used in the online survey. For each of those nine needs, participants were asked to think of a soundscape where they felt that the need in question was fulfilled. We did this in three steps. First, participants were asked to describe the environment they thought of. With this question, a description of a related need-specific feeling was shown, i.e., a positive experience associated with pleasurable and meaningful events that satisfies the need in question (Sheldon et al., 2001). The descriptions of these feelings were sourced from the typology by Desmet & Fokkinga (2020), see Table 5.1. Second, participants were asked which events took place in the described environment. Third, we asked them which sounds they connected to those events.

We will refer to these responses as Environments (question 1), Events (question 2), and Sounds (question 3), which together form an imagined soundscape: an ideal, imagined or recalled sound environment where a particular need is fulfilled. An example is shown in Figure 5.2. We also asked participants to rate every imagined soundscape in terms of pleasantness and eventfulness on 7-point semantic scales, ranging from 'Unpleasant' to 'Pleasant' and 'Uneventful' to 'Eventful'. We familiarized participants to these four attributes at the start of the survey.

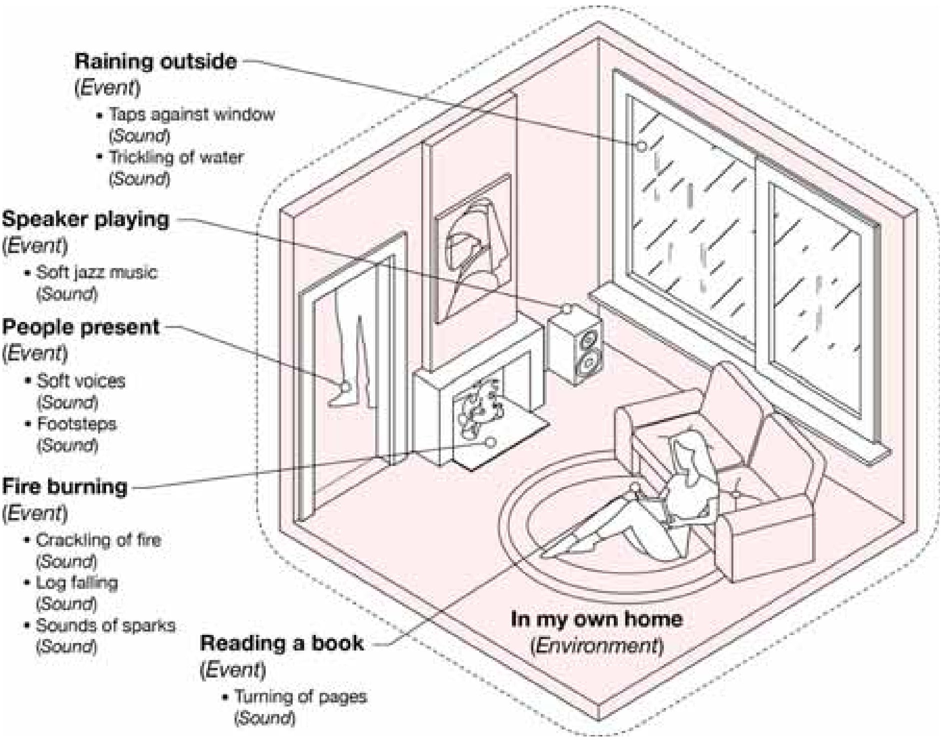

Figure 5.2. Example elements of imagined soundscapes for the need for Comfort.

5.2.3 Procedure

We used Qualtrics (www.qualtrics.com) to distribute and conduct the surveys through email invitation. Participants were recruited through professional mailing lists at Delft University of Technology. Participants were asked to fill in the survey by themselves, in one sitting, in a quiet environment where they felt at ease. The survey consisted of two parts, (1) demographics, and (2) imagining and rating of their nine imagined soundscapes. The order in which the nine needs were presented to the participants was randomized. Participants' responses to multi-line, open-ended questions and rating data were exported from Qualtrics, and saved on faculty servers for analysis.

5.2.4 Data analysis

We did a quantitative analysis of pleasantness and eventfulness ratings to assess differences in these ratings between imagined soundscapes of different needs. We tested for statistical differences with two separate one-way repeated measures ANOVAs with pleasantness and eventfulness as dependent variables and different needs as within-subjects factor. We followed up with post-hoc tests (with an adjustment for multiple comparisons using a Bonferroni correction) to determine significant differences between imagined soundscapes for need pairs. Next, we did a hierarchical agglomerative clustering (HAC) analysis using Ward's Linkage (Ward Jr, 1963) to determine whether imagined soundscapes could be grouped together.

After this quantitative analysis, we did a qualitative analysis of the imagined soundscapes belonging to each cluster discovered in HAC. The responses in terms of Environments, Events and Sounds were grouped per cluster and imported into Atlas.ti (www.atlasti.com). We analyzed the data with reflexive thematic analysis (RTA) and held to its quality guidelines (Braun & Clarke, 2021). First, researchers (GL, EÖ) coded (parts of) responses where participants mentioned qualities of the imagined soundscape (e.g., harmonious). Second, the qualities were discussed among researchers (GL, SP, EÖ) and reduced in number through elimination and combination of identical or related qualities. Third, researchers (GL, SP, EÖ) determined whether these qualities formed a pattern which might represent an overarching theme pertaining to the cluster. We also searched statements for characteristics of narrative structure and sound category distributions.

5.3 THE DEVELOPMENT OF A LISTENER-CENTRIC APPROACH (STUDY 1)

The survey took about 60 minutes (M = 53.2, SD = 24.3) to complete. In Table 5.2, examples of a participant's imagined soundscapes are shown, in terms of their responses to the three open-ended questions (i.e., Environment, Events, Sounds) repeated for each of the nine needs considered.

Two participants (P18/34) were removed from the sample because of the number of missing responses (6 and 9 respectively, out of 27) in their surveys. Another participant (P23) only had missing responses for one need and thus remained in the sample. Ratings for this need were replaced by the mean of the respective rating per item. With jackknife (or leave-one-out) resampling (Efron & Stein, 1981) for both pleasantness and eventfulness ratings separately, we identified three further participants (P26, P32, P33) as outliers and their entries were removed from the set. The remaining sample (N = 29) was further analyzed. As each participant provided nine imagined soundscapes, we collected 261 imagined soundscapes in total.

5

Table 5.2. Examples of participant (P20) responses for needs for Beauty and Security to the three consecutive open-ended questions: describe an environment that makes you feel a sense of [need-specific feeling] (Environment), which events are happening in that environment (Events), which sounds would those events make (Sounds)?

Need	Environment	Events	Sounds
Beauty	Beach with waves clashing at the shore and a strong wind.	Waves clashing at the shore. Sitting at the cliff. Drinking a beer.	The sound of the waves and the wind whooshing. Maybe some seagulls.
Security	At home, comfortable on the couch when it is raining outside.	I am sitting on the couch. There are other people around me. It's raining outside. We have lit a fire.	Rain. Fire place crackling. Soft sound of voices/ people talking.

5.3.1 Quantitative analysis

For each of the nine needs, we calculated means and standard deviations for pleasantness and eventfulness (see the supplementary material). Results of one-way repeated measures ANOVAs showed significant main effects in pleasantness ($F(8, 224) = 6.475$, $p < .001$, $\eta^2 = .188$) and in eventfulness ($F(8, 224) = 9.308$, $p < .001$, $\eta^2 = .249$) between needs. In post-hoc analysis, we conducted pairwise comparisons for mean differences (see supplementary material). Pleasantness ratings for Beauty soundscapes were significantly higher than for those for Stimulation ($p = .027$), Competence ($p < .001$), Fitness ($p = .027$), and Recognition ($p = .007$); they were also significantly higher for Comfort soundscapes than those for Competence ($p = .006$), and Recognition ($p = .034$); those for Security soundscapes were rated significantly higher than those for Competence ($p = .030$); those for Relatedness were also rated significantly higher than those for Competence ($p = .011$); participants rated those for Autonomy soundscapes significantly higher than those for Competence ($p = .046$). In terms of eventfulness ratings, participants rated those for the need for Stimulation soundscapes significantly higher than those for Beauty ($p < .001$), Comfort ($p < .001$), Security ($p < .001$), Competence ($p = .013$), Relatedness ($p = .043$), and Autonomy ($p = .003$); those for Fitness soundscapes were rated significantly higher than those for Comfort ($p = .006$) and Security ($p = .024$); those for Recognition soundscapes were rated higher than those for Comfort ($p = .004$) and Security ($p = .010$). Effects between unmentioned pairs were not significant.

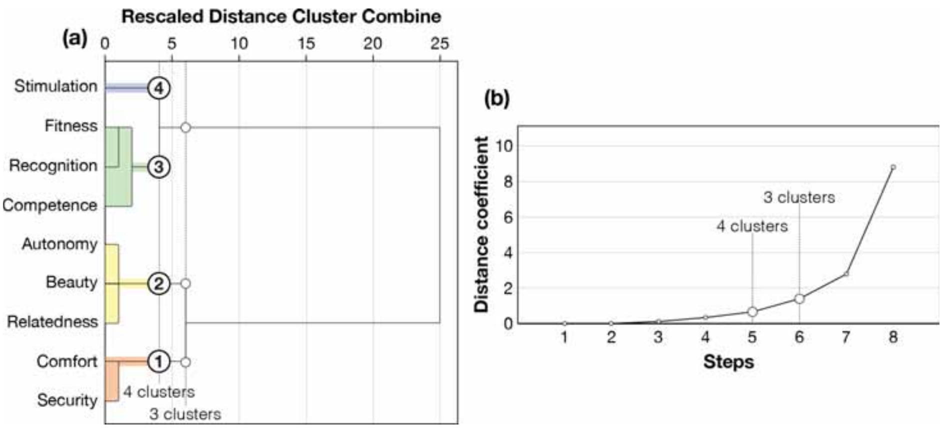

Figure 5.3. (a) Dendrogram with clustering steps of the HAC for a three/four-cluster solution; (b) elbow diagram of distance coefficients in agglomeration schedule

We performed HAC to further analyze the two-dimensional distribution of the data. The clustering steps of the nine different needs are shown in a dendrogram (Fig. 5.3a). The related agglomeration table is included in the supplementary material. The impact of the clustering steps on distance coefficients between clusters is depicted in an elbow diagram (Fig. 5.3b). In the elbow diagram, the coefficients in the agglomeration table are plotted for each combination step. The elbow method (Thorndike, 1953) suggests that the ideal stopping point would be at step six/seven or five/six Fig. 5.3b), located at the elbow of the graph.

Table 5.3. Mean pleasantness and eventfulness of combined needs in clusters from HAC.

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**
Pleasantness	6.33	6.29	5.29	5.44
Eventfulness	3.64	4.71	5.36	6.34

Given the significant differences found in post-hoc analysis, we chose the four-cluster solution for further analysis. Cluster one consisted of Comfort and Security soundscapes, cluster two of Relatedness, Autonomy, and Beauty soundscapes, cluster three of Competence, Fitness and Recognition soundscapes and a fourth cluster comprised of Stimulation soundscapes. The clusters were numbered in ascending order of eventfulness, where cluster one was the least eventful, and cluster 4 the most eventful, see Table 5.3. The means in pleasantness and eventfulness with 50th percentile contour plots for the four clusters were plotted in Figure 5.4.

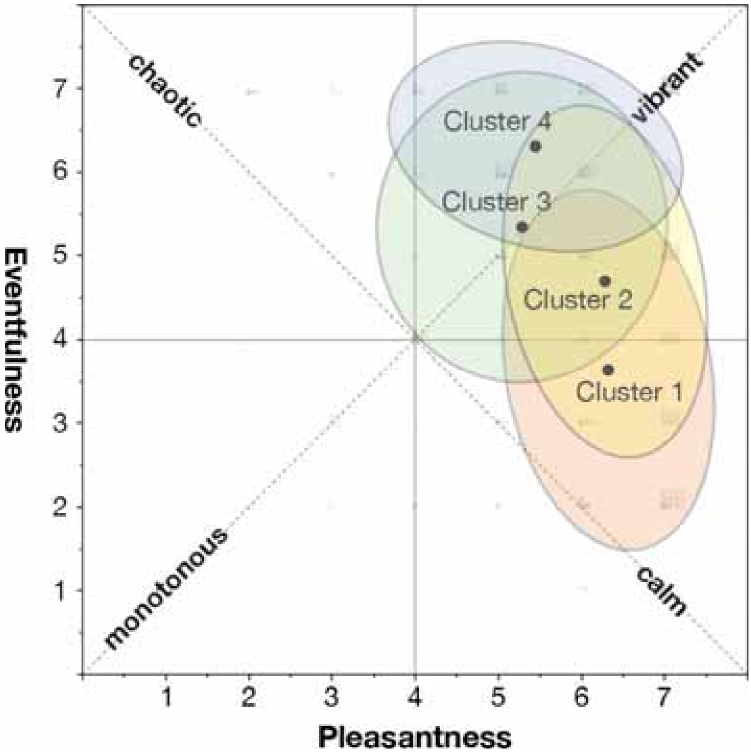

Figure 5.4. Means of clusters from HAC in pleasantness and eventfulness. Colored ellipses indicate 50th percentile density contours.

5.3.2 Qualitative analysis

In our analysis of the qualitative results, we found that the sonic ambiance qualities we coded corresponded to distinctive sonic ambiance types for each cluster. Cluster 1 (Security, Comfort) included descriptions that featured a Comfortable sonic ambiance type, characterized by ambiance qualities that were called familiar, safe, and relaxed. In cluster 2, (Relatedness, Autonomy, Beauty) imagined soundscapes had a Pleasurable ambiance type. Ambiance qualities were called harmonious, momentous (i.e., not everyday), and engaging. Cluster 3 (Competence, Fitness, Recognition) involved descriptions that had a Motivating sonic ambiance type and qualities that were called energetic, focused and positive. Finally, in cluster 4 (Stimulation) descriptions of imagined soundscapes had a Stimulating sonic ambiance type, characterized by ambiance qualities that were called vibrant and inspirational. These four different sonic ambiance types are presented in Table 5.4 with their qualities. In the appendix, Table 5.6, the qualities are shown with example quotes.

Table 5.4. Clusters from HAC with needs, ambiance types, and qualities.

Cluster	Needs	Sonic ambiance type	Sonic ambiance qualities
1	Security Comfort	Comfortable	Familiar Safe Relaxed
2	Relatedness Autonomy Beauty	Pleasurable	Harmonious Momentous Engaging
3	Fitness Competence Recognition	Motivating	Energetic Focused Positive
4	Stimulation	Stimulating	Vibrant Inspirational

Aside from finding recurring patterns within clusters regarding sonic ambiance qualities and types, we found that the participants' descriptions of imagined soundscapes followed a specific organization regarding the Environment, Events and Sounds. In each description, we found that the individual events and sounds that took place in the imagined soundscapes were bound up together in a narrative:

> *"I imagine this environment as picturesque English countryside in late summer. It's evening, just before sunset, when the sky becomes hazy and pink. I'm meandering through a field next to a river that's flowing under an old stone bridge. There's a collection of birds—sparrows, blackbirds and house martins—flitting about in the trees and hedges. Grass and earth rustling beneath my feet, birds' wings flapping, bird calls (each one distinguishable by the type of bird), water flowing gently, maybe church bells occasionally in the distance."* (Beauty, P24).

Within this narrative the components of the imagined soundscapes and the participant's position relative to the sounds and events were organized in space, such as in terms of characterizing location (e.g., picturesque English countryside) or figure-ground (e.g., church bells occasionally in the distance). The narrative also followed a progression of time, i.e., temporality (e.g., first walking through the field, then hearing the river or birds in the trees), and defined the listener's role in the cause of the present sounds and events (e.g., "Grass and earth rustling beneath my feet"). We thus concluded from the qualitative responses that the narratives were organized by a (1) characterizing location, (2) figure-ground relationships, (3) temporality, and (4) listener role.

Furthermore, we found that differences existed between the four clusters in terms of sound category distributions of sound sources. In a previous study, we labeled, counted, and compared the distributions of sound categories between the nine needs (Louwers et al., 2022). We created a taxonomy of four super-ordinate (i.e., human, natural, musical, technological) and ten basic sound categories, which was based on earlier categorizations (Gaver, 1993; Axelsson et al., 2010; Özcan et al., 2014; Lenzi et al., 2021). The relative distributions of these sound categories across participants for the four sonic ambiance types are graphically illustrated in Figure 5.5.

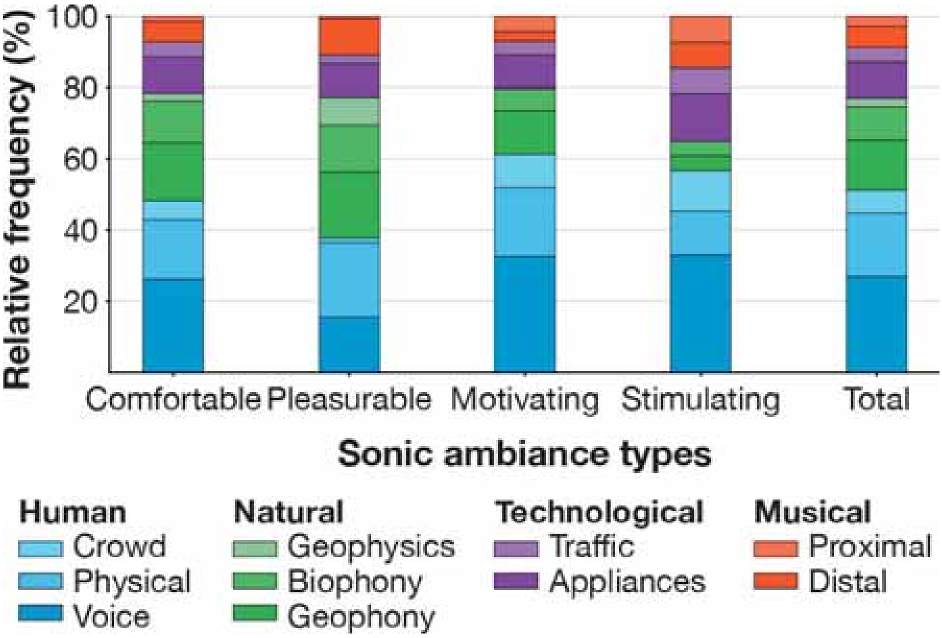

Figure 5.5. Distributions of super-ordinate and basic sound descriptions for four types of sonic ambiances.

We used this taxonomy to compare the sound category distributions between Pleasurable, Comfortable, Motivating, and Stimulating ambiance types with a Chi-square test for independence. We found that there was a significant association ($X^2(9, N = 806) = 52.62, p < .001$) between sonic ambiance type and sound category. The contingency tables can be found in the supplementary material. Out of the four sound categories, as illustrated by the Total bar, we most frequently encountered human sounds (i.e., 51.2% of all sound labels) in responses for all types of sonic ambiances, followed by natural (25.8%), technological (14.3%), and musical (8.7%) ones. In 209 out of 261 (80.1%) imagined soundscapes, at least one human sound label was counted.

5.4 A DESIGN PROCESS FOR CONCEPTUALIZING SOUND COMPOSITIONS (STUDY 1)

In Study 1 we evaluated whether characteristics of imagined soundscapes related to the fulfilment of different fundamental needs could serve as design parameters for creating need-based sound compositions. We analyzed their perceptual characteristics, i.e., pleasantness and eventfulness, and qualitative characteristics, i.e., sonic ambiance qualities, narrative structure, and sound categorization. Based on our findings, we propose four design parameters for designing sound compositions for fundamental need fulfillment.

The level of eventfulness of sound compositions was defined as our first design parameter. The substantial variation in eventfulness between the four clusters implied that it could play a role in defining the sonic ambiance. Events or activities that fulfil fundamental needs are experienced as pleasurable (Sheldon et al., 2001), which could explain the lower variation in pleasantness between clusters. We therefore disregarded the level of pleasantness of sound compositions as a possible design parameter, but rather considered the positive level of pleasantness of sound compositions as a prerequisite of the design process. The level of pleasantness and eventfulness of sound compositions could thus direct existing soundscapes towards a desired quadrant, e.g., from monotonous to vibrant (Cain et al., 2013).

We defined sonic ambiance quality as our second design parameter. Depending on the need-profile of the listener, i.e., the grouping of needs in varying saliency (Hassenzahl et al., 2010), ambiance qualities define the desired experience of the sonic ambiance. The narrative structure of sound compositions was defined as a third design parameter. Characterizing locations, different figure-ground relationships, changes in temporality, and listener role were encountered as characteristics of narratives in imagined soundscapes. This suggested that in designed sound compositions, individual sounds could be organized in space and time according to those same narrative characteristics. Since auditory order and variation are important indicators of eventfulness (Aletta et al., 2014; Fiebig et al., 2020), the narrative structure could therefore be manipulated to attain the desired levels of eventfulness. Also, this parameter could serve to achieve the desired sonic ambiance qualities, as emotional responses are heavily influenced by the narratives constructed while listening (Juslin & Vastfjall, 2008).

Lastly, variation in sound distribution was defined as the fourth design parameter. The positive potential of natural sounds is widely accepted (Alvarsson et al., 2010; Ratcliffe et al., 2013; Medvedev et al., 2015). But the large proportion of human sounds counted in each cluster implied that other sounds, such as the background murmur in a café, could also play a role in designing sound compositions for need fulfilment. This design parameter relates to the personal preference for certain sounds, or the appropriateness of soundscapes, in a given context (Jo & Jeon, 2020). Elements of need-based sound compositions could therefore be selectively sourced from these four major sound categories to personalize and contextualize content. For example, being deprived of most categories of sound in single patient ICU rooms, patients might experience listening to sound compositions with appropriately balanced human, natural, technological, and musical elements as a positive addition.

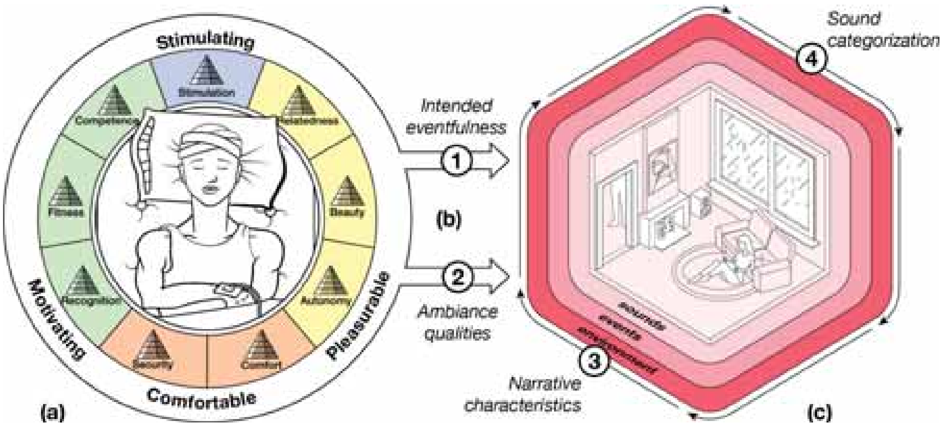

Figure 5.6. Process of conceptualizing pleasant sound compositions based on fundamental need fulfilment.

In Figure 5.6, we have outlined the process of conceptualizing pleasant, need-based sound compositions based on these four design parameters. This process is aimed towards improving patients' experiences of ICU stays through need fulfilment by added sound compositions to the existing soundscape. It illustrates an approach that starts by picking a need that should be addressed from the context (Fig 5.6a). Then, the sonic ambiance type can be identified. Based on this, the eventfulness of the sound composition and the ambiance qualities can be derived (Fig 5.6b). Then (Fig 5.6c) the sound composition can be designed with those in mind by manipulating the narrative characteristics and sound category distribution.

Study 2

In Study 2, we used the design parameters from Study 1 to create sound compositions which were tested in a simulated ICU lab setting. We evaluated to what extent designed sound compositions had an effect on soundscape descriptors and emotional state. Also, we compared whether the effects of the sound compositions measured in Study 2 were similar to the effects as described in Study 1, and whether listeners perceived the characteristics of the designed sound compositions as we designed them. All sound compositions were intended to address fundamental needs. Hence, their perceived level of pleasantness was considered a prerequisite of the design process.

5.5 LISTENING EXPERIMENTS IN A SIMULATED ICU ENVIRONMENT (STUDY 2)

5.5.1 Participants

We recruited 30 healthy individuals (11 male, 19 female) of mixed nationalities at Delft University of Technology through academic mailing lists and posters. None of the participants of Study 1 participated in Study 2. Inclusion criteria were adults (age 28.9 ± 5.9 years), proficient in English, and reported no hearing impairments. Participants gave written informed consent prior to participation and were financially compensated for their time. Similar to Study 1, participants had no experiences with staying or working in an ICU. The study ran from the 5th of December 2023 until the 18th of January 2024. The protocol of the study was approved by the ethics committee of Delft University of Technology on the 18th of August

2023 (ID#3342). Participant responses were anonymized through assigned case numbers.

5.5.2 Sound compositions

A conservatory trained, experienced sound artist designed sound compositions in Ableton Live at a sampling rate of 44.1 kHz stereo with 16-bit depth, together with one of the authors. They used the design parameters and workflow for creating sound compositions as presented in Figure 5.6. This resulted in sixteen sound compositions, see Table 5.5. In their design, the sound compositions were intended for playback through a set of mounted speakers as a patient intervention in ICU rooms. Playback through speakers was preferred over headphones due to hygienic and nurse workflow advantages. The sound compositions were used in Study 2 as stimuli. Samples of the sound compositions and spectrograms are available in the supplementary materials. In Table 5.7 in the appendix, psychoacoustical indicators are shown for each sound composition.

Table 5.5. Sixteen variations of sound compositions created by the sound artist with the design parameters.

Ambiance type	Intended eventfulness [a]	Keynote	Natural	Musical	Human	Technological
Comfortable	Uneventful	Rain	Fireplace	Home office	Synthesized	Train compartment
Pleasurable	Somewhat uneventful	Flowing water	Forest	Terrace	Strings	Urban backyard
Motivating	Somewhat eventful	Wind	Park	Beach	Melodic	Boats
Stimulating	Eventful	Traffic	Countryside	Market	Rhythmic	City

[a] Relative eventfulness within dominant sound category

The eventfulness and sonic ambiance qualities of pleasant sound compositions were derived from the four sonic ambiance types. As was shown in Table 5.3, eventfulness gradually increased from Comfortable (cluster 1), Pleasurable, (cluster 2), Motivating (cluster 3) and Stimulating (cluster 4) ambiance types. The sound artist layered keynote and signal sounds to model the respective sonic ambiance quality after the qualities defined in Study 1 and presented in Table 5.4 (e.g., a Motivating sound composition would be experienced as energetic, focused, and positive). Keynote sounds are sounds heard by people often enough that they can form the background against which other sounds are perceived, such as a hum, rain or ventilation (Truax, 1999). Sound signals represent sounds in the 'foreground' and are treated in relation to the keynote's context, similar to figure-ground relationships in visual perception. Similarly, the sound artist designed the respective eventfulness with layered keynote and signal sounds from four major sound categories also presented in Study 1: natural, human, musical, and technological sounds. The designed sound distribution was dependent on each of the four sound categories but had one dominant sound category, i.e., a type of sound most prevalent or prominent within the designed sound composition.

Different characterizing locations were chosen for each sound composition based on the sonic ambiance qualities and dominant sound category. The sound artist chose a keynote sound to fit those qualities and the relative eventfulness belonging to the sonic ambiance type. For continuity, the chosen keynote sounds were repeated for each sound composition belonging to that sonic ambiance type, regardless of the dominant sound category. The four keynote sounds (i.e., rain, flowing water, wind, and traffic) formed the basis for the sound compositions. Signal sounds were added in accordance with the characterizing location and sound-producing events, to attain the level of desired eventfulness of the sonic ambiance type.

We relied on the sound artist's creative freedom in terms of narrative structure because experienced sound designers are trained to consider and balance these kinds of relationships in sound design activities (Dunne & Gaver, 1997; Collins, 2008). The narrative characteristics were thus used as tools by the sound artist to organize keynote and signal sounds in time and space to achieve the relative eventfulness and sonic ambiance quality.

5.5.3 Experimental setup

We used a box shaped lab-space with dimensions of 5.3m (length), 3.2m (width), 2.6m (height) at Delft University of Technology (see Fig. 5.7a) with a patient bed (a), bedside table (b) and closed curtain (c) to simulate a clinical setting that approximated the conditions of a single patient ICU room. Participants (d) were in the middle of the bed, at 2m from the opposing wall, and 1.2m from the side wall. Two Genelec 8020DPM studio monitors (e) were placed on stands outside of view. A researcher (f) facilitated the experiment from the other side of the curtain. A 19” LCD monitor (g) was placed next to participants to time the measurements. Participants gave ratings on a 13” iPad Pro (h) in front of them. Sound compositions were played to the speakers from the sound card of a MacBook Pro 13” (i) on a constant level. Together with the sound artist, the sound levels of the designed stimuli were calibrated in the lab-space according to the intended sound levels while designing. In pilot testing, these sound levels were confirmed as being at a comfortable level. Participants did not have control over the sound level. The speakers were positioned at equal distances from the participant. The acoustical axes were positioned at the participants’ ear-height (h = 120 cm). The speakers were rotated to the estimated position of the ears of the participant at approximately 80 centimeters (Fig. 5.7b), as indicated in monitor placement documentation for the respective monitors (Genelec, n.d.). Aside from the sound compositions, no other sounds (e.g., no medical alarms or other ICU sounds) were introduced in the space.

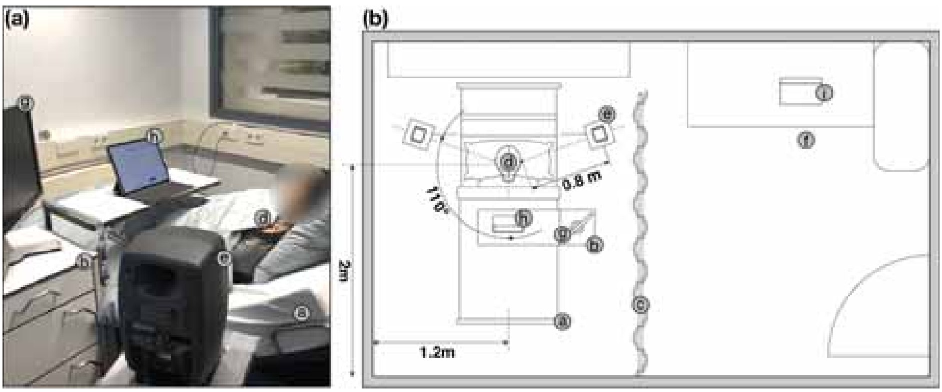

Figure 5.7. (a) Experimental setup of clinical setting in lab-space at Delft University of Technology, with participant in a hospital bed. (b) Schematic illustration of speaker rotation.

5

Acoustical measurements were performed with ½" Microphone Type 4189, on a two-channel Brüel & Kjær Type 2270 Sound Level Meter calibrated at 94 dB SPL 1 kHz with a Brüel & Kjær Type 4231 Acoustical Level Calibrator. We measured the A-weighted equivalent continuous sound pressure level of the background for 30 minutes ($L_{A,eq,30min}$) in the room in the midpoint between the speakers at ear-height on two weekdays, resulting in $L_{A,eq,30min}$ = 30.1/30.3 dB(A). The level ($L_{A,eq,90s}$) of sound compositions measured at the position of the participant ranged between 30 and 45 dB(A) (see appendix Table 5.7). All acoustical measurements are included in the supplementary materials.

5.5.4 Experimental procedure

The study tasks took about 45 minutes to complete and were divided into two parts: rating tasks (1) and forced-choice tasks (2).

In the first part, participants listened and assessed the soundscape of the lab-space at different points in time. At each timepoint, participants evaluated their perception of the soundscape and resulting emotional state. The former was measured by the extent to which eight descriptors (i.e., vibrant, calm, pleasant, annoying, monotonous, chaotic, eventful, uneventful) applied to the soundscape they were listening to with 5-point Likert scales ranging from *Strongly disagree* to *Strongly agree.* This method was based on international standards on how soundscape data should be collected and analyzed (ISO 12913-2, 2018). The latter was measured with affective sliders for pleasure and arousal (Betella & Verschure, 2016). Both were documented on a tablet device using Qualtrics. Participants first heard five seconds of pink noise, thus acting as a cue for the start of a new trial. They then listened to the soundscape for 90 seconds. After 30 seconds of free listening, a 60-second timer showed on the monitor. Participants were instructed to rate the descriptors and affective sliders before the timer ran out. When it ran out, the screen faded to black and pink noise played, indicating the next trial. This cycle was repeated for every trial. The designed sound compositions were played in pseudo-randomized sequences (see supplementary material). Both before and after this sequence, we asked participants to rate their perception and emotional state as a result of the lab-space soundscape without sound compositions (i.e., the baseline), thus resulting in two baseline-measurements. Participants practiced the procedure of rating their soundscape perception and emotional state once while listening to Mozart's Eine Kleine Nachtmusik K. 525: Allegro prior to the first measurement. This first part of the study lasted 30 minutes.

In the second part, we conducted forced-choice tasks to determine whether listeners perceived the design parameters of the sound compositions as intended. We first played groups of four 30-second sound compositions, grouped in pseudo-randomized order in terms of their common sonic ambiance type. After listening, participants were asked to choose which of the four ambiance types (i.e., Comfortable, Pleasurable, Motivating, Stimulating) the grouped sound compositions had in common. This was repeated four times (once for each sonic ambiance type). The same task was employed for the sound compositions now grouped in terms of their dominant sound category (i.e., natural, human, musical, technological). This was also repeated four times (once for each sound category).

5.5.5 Data analysis

As proposed in the standard ISO 12913: part 3 (ISO 12913-3, 2019), we reduced the eight soundscape descriptors into bivariate distributions of primary pleasantness and eventfulness as continuous variables between -1 and 1. This was done using a trigonometric transformation based on the 45° relationship between the diagonal axes (i.e., monotonous- vibrant and chaotic- calm) and horizontal axes (i.e., annoying- pleasant and uneventful-eventful) (Mitchell et al., 2022). Pleasure and arousal scores (measured using sliders with 100 steps) were also normalized between -1 and 1. We first performed one-way repeated measures ANOVAs for pleasantness and eventfulness to assess the main effects of sonic ambiance type and sound category. This was followed by post-hoc tests with a Bonferroni correction for multiple comparisons to determine significant differences. We tested for significant effects of the sound compositions on pleasantness and eventfulness of the lab-space soundscape compared to the baseline with one-way repeated measures ANOVAs and post-hoc tests. These effects were visualized in relation to the baseline in 50th percentile density plots (Mitchell et al., 2022). To further evaluate their effects in terms of eventfulness, we performed an independent two-way repeated measures ANOVA with sonic ambiance type and sound category of sound compositions as within-subjects factors and eventfulness as dependent variable, followed by post-hoc analysis. The accuracy of the forced-choice tasks was calculated by dividing the number of trials with correct judgements by the number of trials. Sound level measurements were imported and processed in Brüel & Kjaer Measurement Partner Suite

BZ -5503. We calculated loudness and sharpness of sound compositions with a MATLAB-based toolbox for quantitative sound quality analysis (Greco et al., 2023).

5.6 EFFECTS OF NEED-BASED SOUND COMPOSITIONS (STUDY 2)

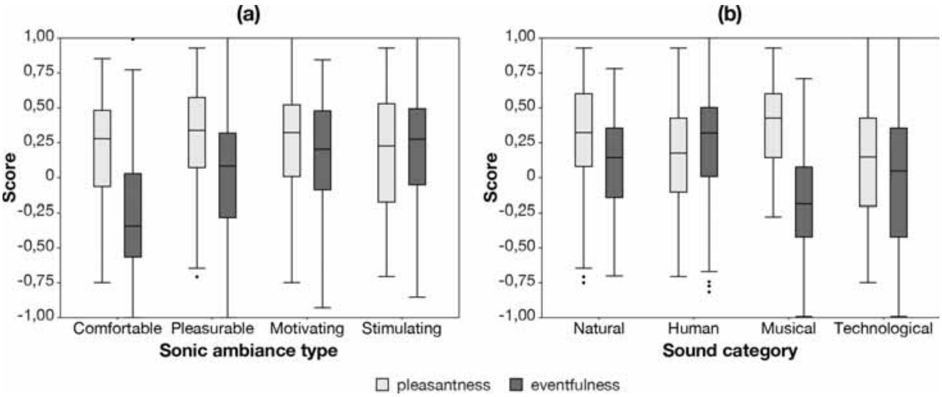

Figure 5.8. Central tendency and dispersion for pleasantness and eventfulness as boxplots for levels of (a) sonic ambiance type and (b) sound category.

5.6.1 Effects of the sound compositions

We calculated the means and dispersion of responses across sonic ambiance types and sound category (i.e., for pleasantness, eventfulness, pleasure and arousal), see Figure 5.8a and 5.8b. For pleasantness, we found no significant main effect between sonic ambiance types ($F(3, 357) = 2.637$, $p = .05$, $\eta^2 = .02$). For eventfulness, we did find a significant main effect ($F(2.8, 335.9) = 53.728$, $p < .001$, $\eta^2 = .31$). Post-hoc analysis (see supplementary materials) showed that eventfulness increased as designed with each sonic ambiance type. These increases were significant except between Motivating and Stimulating sound compositions ($p = .549$).

For pleasantness, we found a significant main effect between sound categories ($F(3, 357) = 15.088$, $p < .001$, $\eta^2 = .11$). In pairwise comparisons (see supplementary materials), we found that pleasantness for the natural sound compositions was significantly higher than for human ($p = .007$)

and technological ($p < .001$) ones. For musical sound compositions, pleasantness was also significantly higher than for human ($p < .001$) and technological ($p < .001$) ones. For eventfulness, we also found a significant main effect ($F(2.8, 333.5) = 26.775$, $p < .001$, $\eta^2 = .18$). In post-hoc analysis we found that eventfulness was significantly higher for the human sound compositions than all others. We also found that eventfulness for natural sound compositions was significantly higher than for musical ones ($p < .001$). Following these analyses, we evaluated the effects of each sound composition by comparing the resulting soundscape's pleasantness and eventfulness scores to those of the baseline soundscape.

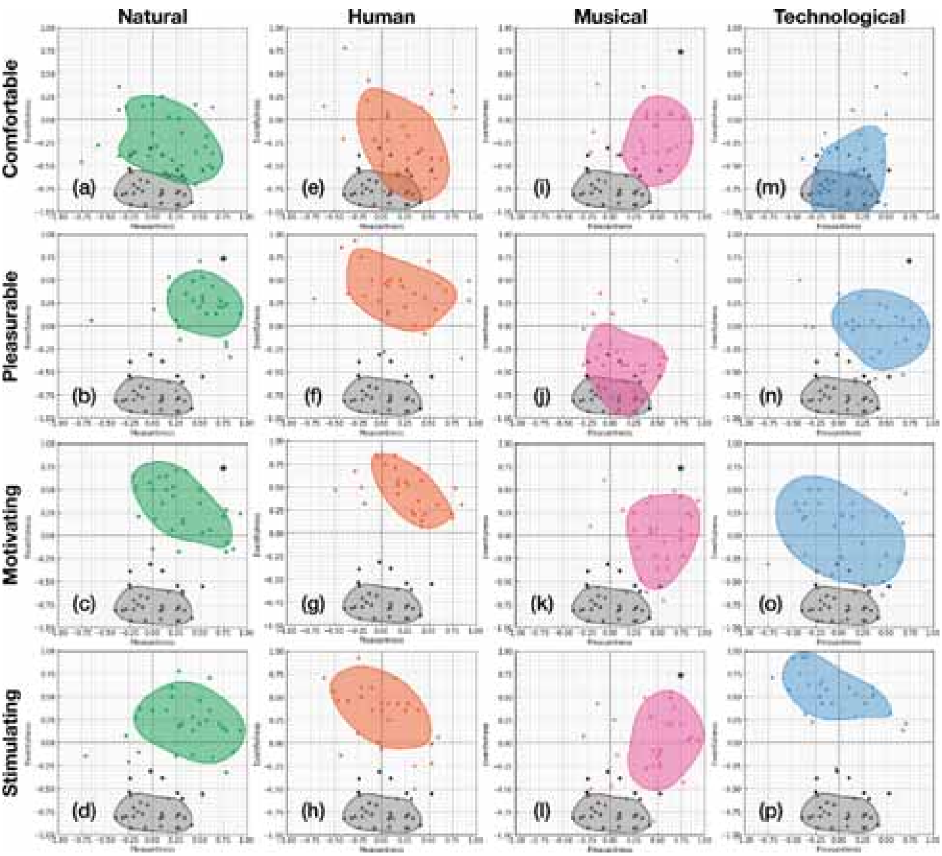

Figure 5.9. 50th percentile contours of sound compositions versus the baseline. (*) Indicates significant differences in pleasantness.

Paired samples t-tests indicated that the two baseline measurements (i.e., before and after the sequence) did not significantly differ in pleasantness (t(29) = 1.595, p = .12) nor in eventfulness (t(29) = 1.397, p = .17). An average baseline score was thus computed for each participant for pleasantness and eventfulness. In Figure 5.9, we plotted the responses of participants in terms of pleasantness and eventfulness per resulting soundscape, and the baseline soundscape. The density of scores is indicated by 50th percentile contours.

Comparing the 16 resulting soundscapes and one baseline soundscape (Fig. 5.9), we found significant main effects for both pleasantness (F(8.7,251.3)= 9.3, $p < .001$, $\eta^2 = .242$) and eventfulness (F(8.5,246.4)= 37.7, $p < .001$, $\eta^2 = .565$). In post-hoc analyses for pleasantness (see supplementary materials), we found that six soundscapes were rated as significantly more pleasant than the baseline (see Fig. 5.9, indicated by asterisk). We also found that all resulting soundscapes were significantly more eventful than the baseline except one (Fig. 5.9m). Most sound compositions moved the soundscape from the 'neutral' (i.e., neither annoying nor pleasant) and uneventful baseline soundscape towards pleasant and eventful (i.e., calm or vibrant) quadrants in the circumplex model of soundscape perception (Axelsson et al., 2010). However, with some human and technological variations (Fig. 5.9h, 5.9o, 5.9p) the average position moved towards negative quadrants.

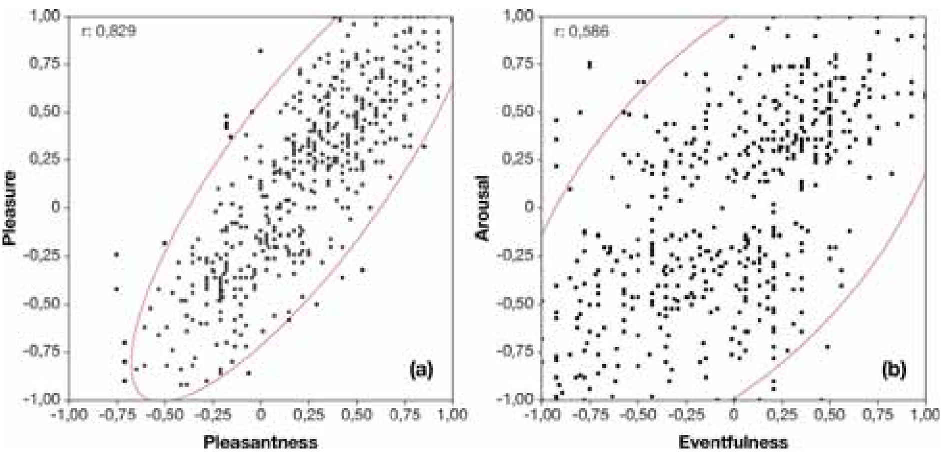

Figure 5.10. Correlation plots for (a) pleasantness and pleasure and (b) eventfulness and arousal, with 95% confidence ellipses.

We evaluated the effects of the soundscapes on emotional state by considering the correlation between soundscape descriptors and experienced pleasure and arousal. We thus conducted a correlation analysis to explore the relationships between soundscape pleasantness and experienced pleasure, and soundscape eventfulness and experienced arousal, see Figure 5.10. We found a strong positive correlation ($r = .829$, $\rho = .827$, $p < .001$) between pleasantness and pleasure (Fig 5.10a). This suggested that the effects of the sound compositions on these two measures were highly congruent with one another. For eventfulness and arousal (Fig. 5.10b), we found a moderate correlation ($r = .586$, $\rho = .594$, $p < .001$), suggesting that in our sample the relationship between these two variables was moderately congruent.

5.6.2 Comparison Study 1 and Study 2

In Study 1, we found that Comfortable, Pleasurable, Motivating, and Stimulating ambiance types ascended in terms of mean eventfulness (see Figure 5.4) which also suggested that eventfulness might be relevant as a design parameter for sound compositions. In Study 2, we found a similar distribution of mean eventfulness for the four sonic ambiance types, as can be visually inspected in Figure 5.11. In order to compare the eventfulness (i.e., as a function of sonic ambiance type) revealed in Study 1 to the measured eventfulness in Study 2, we performed an independent samples Mann-Whitney U test. With this test we assessed the differences between Study 1 and Study 2 in terms of mean-rank ordered eventfulness. This resulted in a non-significant difference between the two studies ($U = 4$, $p = .343$), indicating that the null hypothesis, i.e., that the distribution of mean eventfulness is the same across the different levels of sonic ambiance type between the two studies, could be retained.

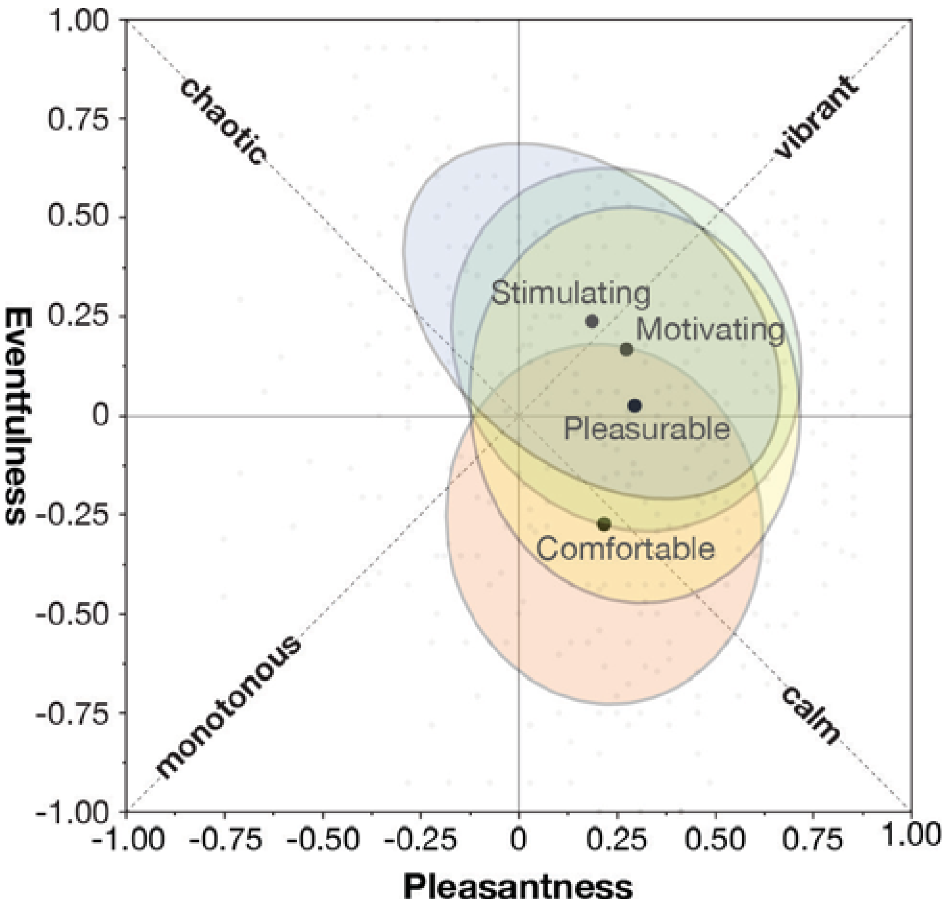

Figure 5.11. Means of measured pleasantness and eventfulness of four sonic ambiance types across sound category variants. Colored ellipses indicate the 50th percentile density contours.

This finding implied that eventfulness could be confirmed as a fitting design parameter to elicit desired effects on the listener. However, the density contours of Figure 5.11 suggested that there were large variations in eventfulness scores within sonic ambiance types. We investigated these variations by comparing the sound category variants per sonic ambiance type in terms of measured eventfulness. To assess the effects of both factors on eventfulness, we conducted an independent two-way repeated measures ANOVA with sound category and sonic ambiance type as within-subjects factors (both with four levels) and eventfulness as the dependent variable. We determined that there was a significant interaction effect between the factors (F(5.8, 168.4) = 13.07, p < .001, η^2 = .31). This suggested that the effects of the sound compositions per sonic ambiance type changed depending on the dominant sound category. We plotted the estimated marginal mean eventfulness for each sound category and sonic ambiance type to visualize this interaction effect (Fig. 5.12).

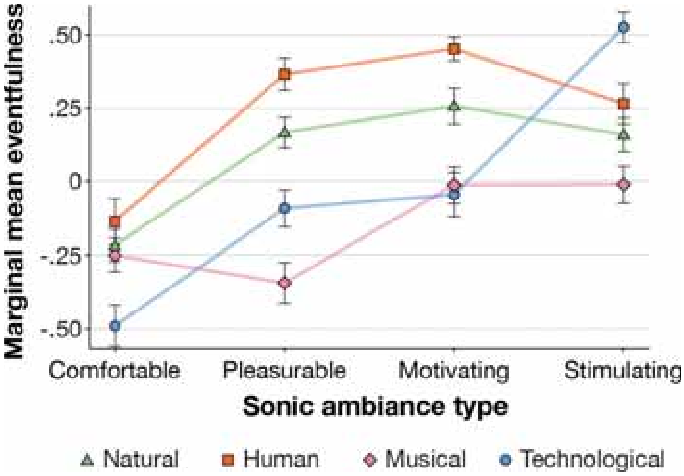

Figure 5.12. Interaction effects between sonic ambiance type and sound category in estimated marginal means of measured eventfulness. For sonic ambiance type, intended eventfulness gradually increases from Comfortable (uneventful) to Stimulating (Eventful). Error bars represent +/– 1 standard error.

Lastly, we assessed whether the sonic ambiance type and dominant sound category were perceived as designed. In Figure 5.13, the accuracy (i.e., correct observations divided by total observations) of the forced-choice tasks is shown for sonic ambiance type (Fig. 5.13a) and sound category (Fig. 5.13b). As indicated by this graphic, accuracy for sonic ambiance type was highest for Comfortable (70%), followed by Stimulating (50%), Pleasurable (33.3%), and Motivating (16.7%) ambiances. This suggested that the sonic ambiance type associated with these sound compositions were roughly perceived as such for Comfortable and Stimulating ambiances, while others were not. Accuracy for sound category was highest for natural (100%), human (93.3%), and musical (83.3%), and a low accuracy for technological (16.7%) were found. This suggested that for the technological category, the dominant sound category was less perceivable.

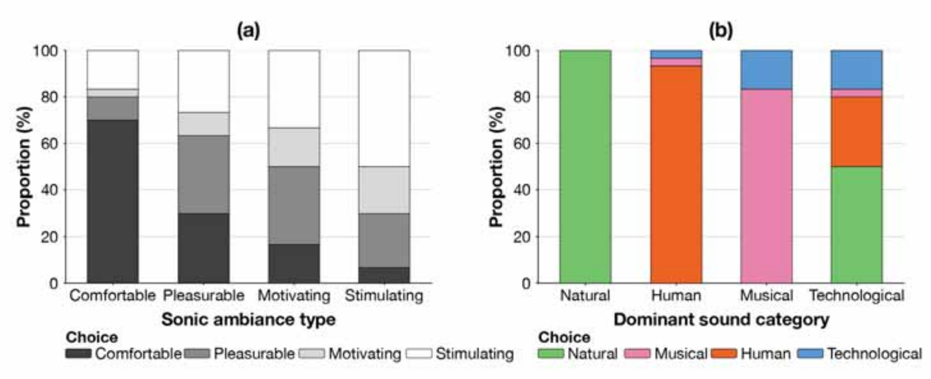

Figure 5.13. Accuracy in terms of proportions of correctly chosen sonic ambiance types (a) and sound categories (b).

5.7 EVALUATION OF A LISTENER-CENTRIC, NEED-BASED APPROACH

In Study 2, we evaluated the effectiveness of designing need-based sound compositions with our framework of four design parameters—eventfulness, sonic ambiance qualities, narrative structure, and sound distribution—in a simulated ICU setting. Sixteen sound compositions were created by a sound artist to evaluate their effects on soundscape pleasantness and eventfulness, and listeners' pleasure and arousal, and to evaluate whether these effects were congruent and as designed for.

Most importantly, we found that designed sound compositions affected the perceived pleasantness and eventfulness of the lab-space soundscape considerably. Achieving pleasant soundscapes was considered a prerequisite to our approach. The data confirm this, as sound compositions resulted in similarly pleasant soundscapes. However, considering pleasantness between dominant sound categories revealed that there were differences in perceived pleasantness. This suggested that not every dominant sound category affected perceived pleasantness of the soundscapes to the same extent. The natural and musical sound compositions led to more pleasantly perceived soundscapes than technological and human ones. The decrease in soundscape's pleasantness with respect to human sound compositions was in line with previous work, where increases in human activity had negative consequences for soundscape's perceived pleasantness (Lenzi et al., 2021). This phenomenon has been accredited to feelings of either safety or vigilance when listening to (un)pleasant sounds in the fore- or background (Andringa & Lanser, 2013). As human and technological sound compositions featured human activity both in the fore- and background this could explain our observed differences in pleasantness. Thus, the choice of individual sounds (i.e., sound distribution) as well as their organization (i.e., narrative structure) could play an important role in moderating pleasantness.

In terms of eventfulness, resulting soundscapes followed the expected ordering of our approach described in Study 1; that is, Comfortable sonic ambiance types were perceived as the least eventful followed by Pleasurable ones. Motivating and Stimulating sonic ambiance types were roughly equally judged to be the most eventful of the four. As auditory order and variation are important indicators of eventfulness (Aletta et al., 2014), it can be said that the density of sound events in time and space (e.g., car sounds, bicycle bells, dogs barking, and an ambulance siren occurring all at the same time) but also the types of sound in the sound compositions contribute to the eventfulness of a soundscape. Our study showed that the human sound compositions added the most to the perceived eventfulness of resulting soundscapes, while musical sound compositions added the least. One possible explanation for the low eventfulness with regards to musical sound compositions could be found in grouping principles in Gestalt, such as streaming (Bregman, 1990). When presented with complex stimuli, such as musical compositions with multiple instruments or musical acts, individuals perceive them as unified wholes rather than as their individual components.

For most individual sound compositions, we found that the soundscape's position was moved from the baseline to vibrant and calm quadrants of the circumplex grid. These shifts were in line with previous research, where it was suggested that deliberate modifications to existing (urban) soundscapes could change their position to more positive quadrants (Cain et al., 2013). In particular, our inspection compared to the baseline soundscape revealed that six sound compositions significantly affected the perceived pleasantness, and nearly all sound compositions significantly affected perceived eventfulness of the soundscape. For Comfortable sound compositions, the effect in eventfulness was consistently mild, whereas for other sonic ambiance types this effect became gradually stronger as designed. Only the perceived eventfulness as a result of musical sound compositions appeared to be inconsistent with this trend between sonic ambiance types.

Furthermore, we confirmed that our design approach for creating pleasant and varyingly eventful soundscapes evoked the desired affective response on listeners. That is, the perceived pleasantness and eventfulness of soundscapes matched the listeners' basic affective experience in terms of pleasure and arousal. Although the correlation between eventfulness and arousal was significant, it was less pronounced than that between pleasantness and pleasure. While pleasantness and pleasure may be more steadily aligned due to common, pre-existing associations regarding pleasant sounds (Andringa & Lanser, 2013), we currently lack a definitive explanation for the difference between the correlations. In previous work regarding such relationships (Fiebig et al., 2020) it was stated that emotional responses to soundscapes not only depended on the stimuli, but also on the individual. The moderate correlation between eventfulness and arousal may thus be related to individual differences between participants. Since listening is a context-dependent, active process of action-based meaning-creation, the degree of arousal could be dependent on the listener's intentionality towards the perceived events (Tuuri & Eerola, 2012). In other words, the extent to which someone will feel activated by listening to a certain soundscape will likely depend on the need(s) of the listener. With our designed sound compositions in a lab-context, these needs may have been latent.

From Study 1 we concluded that need-based sound compositions would inherently be perceived as pleasant, and will differ in terms of eventfulness based on the need(s) of the listener. In Study 2 we confirmed this, as our design approach was effective in achieving equally pleasant soundscapes, which spanned the same range of eventfulness as described in Study 1. Our findings thus indicated that eventfulness was a viable design parameter for creating a varying range of sound compositions. However, as we discovered a significant interaction effect between the sonic ambiance types and dominant sound categories, the effective application of eventfulness as a design parameter needs to be explored further. For example, while human and natural sound compositions overall led to the most eventful soundscapes, perceived eventfulness was significantly less for their Stimulating variant. The musical sound compositions similarly had a negative difference between some sonic ambiance types, while technological sound compositions showed a considerable positive difference in eventfulness for the Stimulating variant. These interaction effects demonstrated that there is no single formula (yet) to describe this interplay, and that a delicate balance is required while choosing and organizing sound events from certain sound categories to create eventfulness.

Finally, we concluded that our choice of four sonic ambiance types may have been ambitious, and that future use of our approach should be conducted with three sonic ambiance types instead: Comfortable, Pleasurable, and Stimulating. In the forced-choice tasks we observed that the identification of dominant sound categories of sound compositions was mostly accurate, except for technological (i.e., 16.7%). This might be attributed to the categorization from existing sound taxonomies (Gaver, 1993). The label 'technological' thus may not reflect the reality of how listeners perceive and label sounds in their daily interactions. Perhaps, a more specific definition of technological sounds should be provided to listeners in future research. In contrast, participants only identified Comfortable and Stimulating sonic ambiance types somewhat accurately (i.e., 70% and 50% respectively). The results of the forced-choice tasks therefore suggested that while participants could distinguish well between dominant sound categories, they were less able to do so for the four sonic ambiance types.

In part, this could be due to the hierarchical agglomerative clustering in Study 1. The elbow diagram (Fig. 5.3b) indicated that a more fitting stopping point may have been at the three-cluster solution. This implied that Motivating and Stimulating sonic ambiance types were perhaps too similar to separate, and should therefore be merged for future considerations. Also, the labels themselves may not have fully captured the meaning of the sonic ambiances. The labels of sonic ambiances might be more meaningful in the presence of the actual related needs that are unfulfilled. Thus, this part of the study should be further investigated in follow-up studies in a functional setting (e.g., a real ICU). Similar to user tests performed with a soundscape augmentation system for dementia patients (De Pessemier et al., 2023), our sound compositions and related sonic ambiances should be tested on their functional role, e.g., to comfort the patient, to provide a pleasurable environment during long stretches of time without visitation, and to stimulate (i.e., distract) them during spontaneous breathing trials or early rehabilitative physiotherapy. For these types of situations in real ICUs, future research should investigate the provision of sound compositions based on our approach, also relative to the existing ICU soundscape.

5.7.1 Limitations and future steps

We can expect that clinical (e.g., severity of illness, pain) and psychological (e.g., stressors) factors impact patients' experiences of real ICUs. Further, ICU patients spend considerable portions of their stay in states of sedation (Pandharipande et al., 2013). These factors are likely of influence on need fulfilment and soundscape perception. However, as a first feasible step to develop our need-based approach, we included healthy people rather than ICU patients. In this light, future studies could include a longitudinal, clinical trial with patients in single-patient ICU rooms with follow-ups after discharge.

Further, the acoustical differences of real single-patient ICUs compared to our lab setting in Study 2 should be considered. In our lab setting, the sound level (without sound compositions) was ± 30 dBA, while in single-patient ICU rooms minima of 37-38 dBA were measured (Özcan et al., 2024). Additionally, actual ICU soundscapes include alarm events, opening doors and other sounds inherent to ICU stays. Thus, we propose that future studies should evaluate whether the insights of this paper can be replicated in acoustic environments of real ICUs.

Also, another limitation of the study was developing our approach for single-patient ICU rooms. Future studies could investigate whether our approach could benefit other ICU formats as well.

Finally, during the design process of the sound compositions the sound artist retained creative freedom over the design parameter of narrative characteristics, such as figure-ground relationships and temporality between individual sounds. This design parameter might be investigated further with relation to soundscape perception and need fulfilment, and with relation to our need-based approach.

5.8 CONCLUSION

While the chances of surviving critical illness have improved drastically due to intensive care units (ICUs), previous studies have shown that patients experience these environments as stressful. The alienating, disruptive, unvaried, and unfamiliar soundscapes that surround patients in single patient ICU rooms harm their fulfilment of basic, psychological needs, such as for pleasure, comfort or purpose. These negative experiences may lead to long-lasting psychological impairments after ICU discharge. In this paper, we studied the soundscape of an ICU room itself as a source of need fulfilment and positive listener experiences by adding sound.

Our results show that adopting a need-driven approach when designing soundscape interventions could form a beneficial new way of providing positive listener experiences for ICU patients. This approach is aimed at developing sound compositions that support nine fundamental human needs, by establishing four distinct types of sonic ambiances (i.e., affective connotations with soundscapes): Comfortable, Pleasurable, Motivating, and Stimulating ambiances. Based on soundscape perception and fundamental need fulfilment, we identified four design parameters that designers could use to create such sound compositions, from the starting point of a (set of) target need(s): eventfulness, sonic ambiance qualities, narrative structure, and sound distribution. The results of the two studies in this paper confirmed that sound compositions developed with our design approach had the desired effects on both the perception of resulting soundscapes, as well as on the emotional responses of listeners. As we set out to provide positive experiences based on the needs of listeners, our findings suggest that with our approach this could indeed become possible. This paper is complementary to previous research regarding the design of supportive soundscapes and environments for vulnerable listeners, adding a novel, need-driven perspective to the field. Provided that the designed sound compositions match the salient needs of patients in different situations, improved experiences with soundscapes of ICUs could contribute to stress reduction and possibly reduce the long-term incidence of PICS-related symptoms, thus forming a promising step in improving ICU stays.

SUPPLEMENTARY MATERIAL

See supplementary material at https://pubs.aip.org/jasa/article-supplement/3316750/zip/2376_1_10.0030470.suppl_material/ for:

1. (Study 1) dataset with qualitative and quantitative data, means and standard deviations of needs, agglomeration table, and contingency tables.
2. (Study 2) spectrograms, (psycho)acoustical measurement dataset; quantitative dataset; 20-second samples of sixteen sound compositions.

APPENDIX

Table 5.6. Ambiance types, qualities and examples from qualitative responses.

Ambiance type	Ambiance quality	Example quote [a]
Comfortable	Familiar	"At home in the garden. A neighbor is mowing his lawn, fountain is spraying. Splashing, lawn mower (...)" (P6)
	Safe	"I'm inside on a cold, stormy night, cocooned in a thick blanket with a cup of tea. Rain on window, jazz (...)" (P24)
	Relaxed	"Sitting in a good chair, closed eyes, listening to music or an audiobook. Burning wood, vinyl player (...)" (P31)
Pleasurable	Harmonious	"A living room with close family. It has harmony, but still with freedom/spontaneity. Voices, whistling (...)" (P28)
	Momentous	"Walking up, looking around, sharing the moment with the person you're walking with. Rustling trees, birds (...)" (P25)
	Engaging	"You are walking in a museum of art. Every few meters displays a new piece of art. Walking, whispering (...)" (P12)
Motivating	Energetic	"I am cycling on a spinning bike. The instructor is talking and playing music. Strong beat, panting. (...)" (P17)

Ambiance type	Ambiance quality	Example quote [a]
	Focused	"I am talking, other people are listening. There is a sense of focus. Quiet, own voice. (...)" (P20)
	Positive	"My supervisor is telling me the doctors are very satisfied with my work. Shifting in chair, laughter (...)" (P21)
Stimulating	Vibrant	"A city center of a world metropolis abroad, with new sounds and cultural experiences. Honking, shouts (...)" (P6)
	Inspirational	"Looking at someone whenever they perform live, a musical, theater show or sport event. Murmur, laughter (...)" (P28)

[a] Summarized descriptions of imagined soundscapes (i.e., *Environment, Events, Sounds*).

Table 5.7. (Psycho)acoustic indicators per sound composition: measured sound level, LAeq,90s; Loudness NR/L (sone), Sharpness SR/L (acum) for right and left channels.

Sound composition	Sound category	Ambiance type	$L_{Aeq,90s}$	N_R	N_L	S_R	S_L
Fireplace	Natural	Comfortable	35.7	5.28	4.46	1.55	1.51
Forest	Natural	Pleasurable	37.8	5.66	5.66	1.68	1.69
Park	Natural	Motivating	41.0	8.31	6.38	1.51	1.42
Countryside	Natural	Stimulating	36.0	3.81	5.64	1.78	1.71
Home office	Human	Comfortable	33.7	3.78	4.57	2.16	2.24
Terrace	Human	Pleasurable	37.8	6.11	5.68	1.63	1.68
Beach	Human	Motivating	37.1	6.04	5.02	1.31	1.70
Market	Human	Stimulating	37.0	5.13	5.64	1.59	1.62
Synthesized	Musical	Comfortable	39.2	5.15	5.22	0.80	0.73
Strings	Musical	Pleasurable	30.5	0.74	0.82	1.05	0.83
Melodic	Musical	Motivating	43.8	5.37	5.57	0.93	0.97
Rhythmic	Musical	Stimulating	45.4	7.12	7.10	0.94	0.92
Train compartment	Technological	Comfortable	33.9	2.75	2.69	0.49	0.59
Urban backyard	Technological	Pleasurable	33.3	2.55	3.27	2.03	1.92
Boats	Technological	Motivating	31.5	2.41	2.46	1.53	1.52
City	Technological	Stimulating	42.0	6.71	6.59	1.15	1.19

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Chapter 6

Listener-centric soundscape interventions for intensive care units: creating positive sonic ambiances in single-patient rooms

To assess the feasibility of implementing soundscape interventions in actual ICUs, this chapter tests the interventions of Chapter 5 in a real-world ICU setting. Conducted in a single-patient ICU room, the study evaluates the effects of soundscape interventions on emotional state, stress, and sound perception. The findings demonstrate the potential of the soundscape interventions to enhance patient well-being.

This chapter is based on:
Louwers, G., Pont, S., Van der Heide, E., Van Egmond, R., Gommers, D., & Özcan, E. (in press). Listener-centric soundscape interventions for intensive care units: creating positive sonic ambiances in single-patient rooms. Applied Acoustics.

ABSTRACT

Perceived acoustic environments, or soundscapes, of intensive care units (ICUs) can be stressful for patients. We developed an approach to enhance ICU soundscapes with soundscape interventions. Compositions of Natural, Human, or Technological sounds were designed to establish three types of sonic ambiances: Comfortable, Pleasurable, or Stimulating. The objective was to investigate the approach's effectiveness in a real-world ICU environment. In a controlled experiment conducted in a single-patient, sound-proofed ICU room, 26 healthy participants were exposed to simulated ICU soundscapes, including patient monitor alarm sounds and mechanical ventilator sounds. Nine soundscape interventions were played via speakers. Perceived pleasantness and eventfulness of resulting soundscapes and experienced pleasure and arousal of listeners were evaluated with questionnaires. Physiological indicators of stress were measured using electrocardiograms (ECGs). Pleasurable and Stimulating interventions significantly increased perceived pleasantness and eventfulness when introduced to the simulated ICU soundscape. Comfortable interventions had no significant effect, suggesting that Pleasurable and Stimulating ambiances better aligned with participants' needs relative to the simulated soundscape. It emphasized the need to tailor ICU interventions to the preexisting acoustic environment and sound-related needs of listeners, such as comfort, distraction or reassurance. Participants reported positive emotional states while listening to the soundscape interventions, indicative of positive listener experiences. Preliminary insights regarding changes in heartrate variability hinted that soundscape interventions could potentially contribute to reduced stress levels. The effectiveness of interventions depended on their featured sound categories, highlighting the importance of personalization. Overall, our approach was found effective, showing promise for creating listener-centric, restorative soundscapes during ICU stays.

6.1 EXPANDING UPON CURRENT INTERVENTIONS WITH A NEED-BASED APPROACH

In intensive care units (ICUs), sound plays a decisive role in shaping patient experiences and outcomes. Caregivers and patients alike consider ICU soundscapes to be noticeably stressful. A soundscape is defined as an acoustic environment as perceived by a person or people in context (ISO 12913-1, 2014). It can thus be seen as the perceptual representation of the entire collection of sounds in an environment. A study on the perceived severity of environmental stressors in ICUs found that sounds of alarms, medical devices, or other patients were considered stressful (Krampe et al., 2021). For nurses, exposure to the medical device alarms present in such soundscapes commonly leads to alarm fatigue (Lewandowska et al., 2020), posing an indirect but substantial threat to patient safety. Patients, being exposed to cacophony, are directly affected through disrupted sleep (Elbaz et al., 2017) and possibly delirium, a confused mental state (Mart et al., 2021). These experiences are associated with new problems that patients develop after ICU discharge, such as post-traumatic stress disorder and depression (Geense et al., 2021). Considering these challenges, this paper explored the effectiveness of soundscape interventions in facilitating positive listening experiences for ICU patients.

6.1.1 Current hospital soundscape interventions

Hospitals aim to mitigate negative effects of sound on patients by providing more human-centered care environments in ICUs (Rodriguez-Ruiz et al., 2025). For this reason, different hospital soundscape interventions are studied to reduce unwanted sound at the source, at the receiver, or along the path (i.e., between the source and receiver) of the sound (Bush-Vishniac & Ryherd, 2023). At the source level, medical device manufacturers work towards a new interoperability standard enabling new alarm solutions and directing alarm sounds outside the patient room (Philips, 2024; SASICU Project, 2023). 'Quiet time'-protocols, reducing sound levels at night, are implemented to benefit sleep (Jun et al., 2021). At the receiver level, earplugs (Litton et al., 2016) or noise-cancellation headphones (Schlesinger et al., 2017) offer protection against unwanted sound. At the path level, absorptive materials (Luetz et al., 2016) or new ward layouts with single-patient (i.e., private) ICU rooms and staff room relocations also led to significantly decreased sound levels (Özcan et al., 2024). Such interventions have demonstrated to improve both patient and staff comfort (Delaney et al., 2019; Luetz et al., 2019; Vreman et al., 2023).

Nevertheless, removing unwanted sound from ICU soundscapes may not necessarily lead to more positive listening experiences. How patients interact with sounds is complex. Loud, intrusive sounds caused by caregivers may be tolerated or appreciated if their purpose is understood (Mackrill et al., 2013). Listening to conversations or procedural sounds of nurses in ICUs can contribute to feelings of safety and reassurance (Johansson et al., 2012). In a previous investigation, it was found that the removal of these sounds may even contribute to negative experiences (Louwers et al., 2025). The study examined how ICU patients experienced the soundscape of sound-proofed, single-patient ICU rooms. Patients were found to be deprived of both negative (e.g., other patients) as well as positive (e.g., nurse activity) aspects of the soundscape. Furthermore, patients experienced the diversity of sounds in ICU rooms as limited: without visits of relatives or nurses, just medical device sounds, alarms, mechanical ventilation, and air conditioning remained. The resulting soundscapes were often described as empty, too quiet, and frightening.

As a complementary approach to noise reduction, soundscape interventions that add sound at the receiver level —such as music, birdsong, or other sounds— may help restore positive aspects to single-patient room soundscapes. Within soundscape approaches, environmental sounds are considered as a resource rather than a waste (Kang et al., 2016). Consistent with this view, sound additions could evoke more positive listening experiences with ICU soundscapes. Studies found that adding music or birdsong can improve the perceived pleasantness of pediatric ICU soundscapes (Özcan et al., 2023) and offers psychological and physical benefits for patients (Iyendo, 2016; Kakar et al., 2023; Tekin et al., 2023). However, such additions should be centered around the dynamic, context-related needs of patients as listeners.

6.1.2 Listener-centric approaches to soundscape design

Designing effective soundscape interventions for ICU patients requires a listener-centric, need-based approach that recognizes patients as listeners with the same basic, psychological needs as healthy people. To fulfil their needs, patients listen with intent for auditory cues (Özcan et al., 2022; Tuuri & Eerola, 2012). Positive listening experiences (e.g., listening to personal music playlists or family chatting) are likely to be characterized by the fulfillment of such needs. Since psychological needs fluctuate over time (Milyavskaya & Koestner, 2011), it can be assumed that with regards to ICU soundscapes the needs of patients are context-dependent. ICU soundscape interventions should therefore be need-specific. For example, a patient may prefer birdsong during periods without visits of relatives and caregivers, but may prefer the distraction of music during endotracheal suctioning (airway clearance). In a previous study, we found that soundscapes which healthy individuals associated with the ideal fulfillment of psychological needs were indeed perceptually and qualitatively distinctive (Louwers et al., 2024a). Differences between clusters of need-specific soundscapes were found in the sonic ambiance (the affective connotation of the soundscape), perceived eventfulness (ISO 12913-2, 2018), and organization and distribution of individual sounds.

Building on the differences between clusters of need-based soundscapes (Louwers et al., 2024a), we derived an approach for achieving three key sonic ambiances within single-patient ICU rooms: Comfortable, Pleasurable, and Stimulating ambiances. With this approach, a sound artist designed sound compositions as soundscape interventions to achieve these ambiances. The effects of these soundscape interventions were examined in a controlled lab-experiment (Louwers et al., 2024a) with healthy volunteers in a hospital bed and without the presence of any other sound events. The effects of these stimuli on perceived pleasantness and eventfulness of soundscapes and experienced pleasure and arousal of listeners confirmed that sound compositions developed with our design approach indeed had the desired effects. However, the stress inherent to real-world ICU rooms, including its physical surroundings and clinical acoustic environment, should be considered when developing effective ICU soundscape interventions (Louwers et al., 2024b). Their effects therefore need to be evaluated in the physical context of a real ICU patient room. Furthermore, expanding upon subjective assessments –such as perceived pleasantness and eventfulness, experienced pleasure and arousal– with physiological indicators of stress or relaxation could offer a deeper understanding of how soundscape design could influence patient well-being in ICU rooms.

In the present paper, we tested the effectiveness of our need-driven approach to soundscape interventions on healthy volunteers in a single-patient ICU room with a simulated ICU soundscape. The experimental procedure was similar to our previous investigation (Louwers et al., 2024a), with the addition of heart rate as a physiological indicator for stress. The research questions addressed in this paper were as follows:

i. To what extent do the soundscape interventions have an effect on perceived pleasantness and eventfulness of single-patient ICU room soundscapes?
ii. To what extent do the soundscape interventions have an effect on experienced pleasure and arousal and physiological indicators of stress of listeners in single-patient ICU room soundscapes?

6.2 LISTENING EXPERIMENTS IN A REAL-WORLD, SINGLE-PATIENT ICU ROOM

6.2.1 Participants

Twenty-six healthy volunteers were recruited to participate in the study through social media posts, mailing lists and recruitment posters at the academic hospital and university buildings. Purposive sampling was used to recruit adult participants with a diverse age range ($median_{age}$ = 30, IQR = [26 – 61]; 14 females, 12 males) and without prior experiences of staying or working in a critical care environment. This was done to avoid prior exposure bias and negative associations related to previous ICU-related experiences and to approximate the wide demographic variation of patients admitted to the Erasmus MC's Adult ICU department. Specifically, people were considered ineligible for participation if they (1) had hearing impairments, (2) were admitted to an ICU ward, (3) had relatives (i.e., partner, sibling, parent, child) who had been admitted to an ICU ward, (4) work(ed) in a hospital, (5) studied medicine/nursing, (6) had (work) experience in acute care/emergency care/intensive care. All participants gave written informed consent before participation and were financially compensated for their time with a fixed-amount voucher. The study ran from the 14th of May until the 7th of July 2024. The protocol for this study was approved by the Medical Ethics Committee of Erasmus Medical Center (MEC-2023-0611) and of Delft University of Technology on 13th of July 2023 (ID#3342). Responses were anonymized by assigning random numbers to each participant. Participants could withdraw consent at any time. All procedures were in accordance with the ethical standards of the Erasmus MC research committee, the TU Delft Human Rights Ethics Committee, and with the 1964 Helsinki Declaration and its later amendments.

6.2.2 Experimental setup

This study was conducted in a single-patient ICU room at the Adult ICU department of Erasmus Medical Center, see Figure 6.1.

Figure 6.1. Floorplan of experimental setup (left) and photograph of participant in the room (right)

The room included a sound-proof sliding door (Fig. 6.1, A), nurse-window for observations (Fig. 6.1, B), and back-lit wall art mimicking an outside window depicting natural scenery (Fig. 6.1, C). There were no other windows in the room. A researcher (GL) controlled the experiment from outside behind the nurse-window (Fig. 6.1, D), while the door was kept shut. Participants remained alone in the room throughout the study procedures to mimic conditions of single-patient ICU rooms. The blinds on the door were lowered to prevent visual distraction due to unrelated clinical events in the corridors. The blinds of the nurse-window allowed observation by researchers (but not vice versa). Participants were in a hospital bed (Fig. 6.1, E). The bed-head was tilted 30°, resulting in ear-height of approximately 1.2m. This semi-upright angle repositions the upper body of patients, and is commonly used in ICUs to improve respiration (Klompas et al., 2014). A patient monitor (Dräger Infinity M540) with laptop (Fig. 6.1, F) was placed near the bed (h = 1.6m). Three ECG electrode patches were connected to participants from the patient monitor. A mechanical ventilator (Maquet Servo-i Ventilator System V8.0) (Fig. 6.1, G) was positioned behind the bed.

Two speakers (Genelec 8020DPM) (Fig. 6.1, H) were placed on speaker stands behind the participant on either side. Their acoustical axes were placed at ear-height. The speakers were rotated 110° to the estimated position of the ears from approximately 0.8m distance, as suggested in placement documentation (Genelec, 2017). A 42" LCD screen (Fig. 6.1, I) was located on the opposing wall to provide digital timers for the rating tasks. Participants rated on a 13" iPad Pro (Fig. 6.1, J) in front of them on a bedside table (Fig. 6.1, K). The speakers were connected to a MacBook Pro 13" (Fig. 6.1, L). Soundscape interventions were played from the sound card of this laptop on a constant gain.

Table 6.1. Sonic ambiance types and related psychological needs

Sonic ambiance type	**Needs**			
Comfortable	Security	Comfort		
Pleasurable	Autonomy	Relatedness	Beauty	
Stimulating	Fitness	Recognition	Competence	Stimulation

6.2.3 Soundscape interventions

Soundscape interventions consisted of compositions of sounds, designed to establish three sonic ambiance types (Comfortable, Pleasurable, and Stimulating). Sonic ambiances are defined here as affective evaluations of the soundscape, which may support psychological need fulfillment (Louwers et al., 2024a). Sound compositions were designed using a framework of design parameters. These parameters were derived from hierarchical clustering analyses and qualitative modeling of each ambiance type in two preceding empirical studies (Louwers et al., 2024a). Full methodological details and rationale for these compositions can be found in Louwers et al. (2024a). Each sonic ambiance type relates to a distinct, particular grouping of psychological needs based on a need taxonomy (Desmet & Fokkinga, 2020), see Table 6.1. The ambiance types were found to differ in terms of the respective qualities of sonic ambiance—affective connotations with soundscapes. For example, Comfortable ambiances (for supporting needs for Comfort and Security) were found to be associated with familiarity, safety, and relaxation. In addition to qualitative differences, sonic ambiance types were shown to differ in terms of perceived eventfulness of their related soundscapes, following an ascending gradient from Comfortable (uneventful), to Pleasurable (moderately eventful), to Stimulating (eventful).

Table 6.2. Nine sound compositions created to establish three sonic ambiance types with three dominant sound categories

Sonic ambiance type	Natural	Human	Technological
Comfortable	Fireplace	Home office	Train compartment
Pleasurable	Forest	Terrace	Urban backyard
Stimulating	Countryside	Market	City

A sound artist with music conservatory training used the sonic ambiance qualities and perceived eventfulness as input for creating the compositions, see Table 6.2. Nine sound compositions were designed accordingly in Ableton Live (44.1 kHz, stereo, 16-bit). To obtain a balanced test-matrix, for each sonic ambiance there were three sound compositions. Each highlighted one of three major, dominant categories of sound (natural, human, or technological). This grouping was inspired by preceding taxonomies (Gaver, 1993; Lenzi et al., 2021; Schafer, 1977). With sonic ambiance qualities, perceived eventfulness, and dominant sound category as input, different narratives (e.g., in the forest, on a train) were created for each sound composition. This process revolved around layering sound events, balancing figure-background relationships with keynote sounds as the ambient background, and signal sounds as characteristic events in the foreground (Truax, 1999) to attain the level of desired eventfulness and sonic ambiance quality. The labels given to the sound compositions (e.g., Countryside) are used as a design reference, and were not created as an expected perceptual cue for participants. For full details on the design process, see the previous study (Louwers et al., 2024a).

6.2.4 ICU room soundscape: ICU-bg_1 and ICU-bg_2

Specific sound events, typical for most ICU stays, were simulated to assess the effects of the soundscape interventions relative to a realistic acoustic environment. Within each single-patient ICU room, a low hum is present from air conditioning. This background soundscape was referred to as 'ICU-bg_1'. Two recurring sound events were introduced: (1) a common alarm sound from the patient monitor, and (2) sounds of the mechanical ventilator. The resulting background of ICU-bg_1 with alarm sounds and mechanical ventilation was referred to as 'ICU-bg_2', see Figure 6.2.

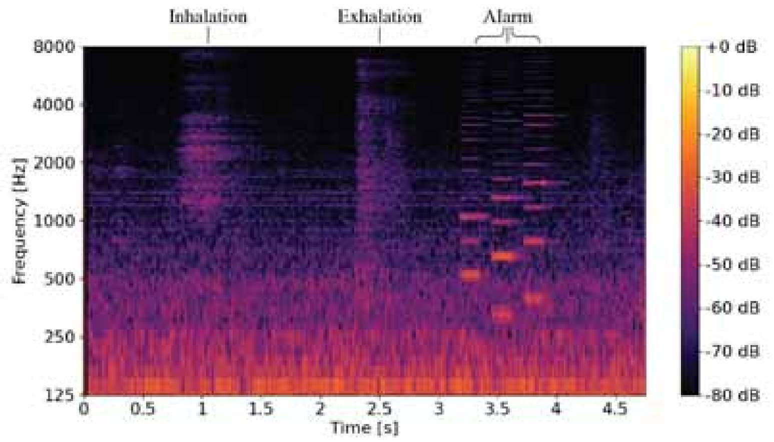

Figure 6.2. Spectrogram of ICU-bg_2 over 5 seconds with a frequency range between 125 – 8000 Hz, featuring air conditioning, inhalation and exhalation by the mechanical ventilator and medium priority (yellow) alarm from the patient monitor

Yellow medium priority alarm sounds ($t \approx 0.8s$) were generated by the Dräger Infinity M540 patient monitor at a rate of four times per minute. Medium priority alarms occur frequently during ICU stays and are often non-actionable (e.g., due to movement of the patient) (Cvach, 2012). Furthermore, since many ICU patients require respiratory support (Esteban et al., 2008), sounds of mechanical ventilation were incorporated. Mechanical ventilation sounds consisted of both an inhalation and an exhalation sound (see Fig. 6.2), lasting for $t \approx 0.5s$ each. To simulate a real lungs' resistance during inhalation and exhalation, an artificial lung (Dräger SelfTestLung 1000 mL) was attached to the mechanical ventilator (Getinge, 2018). Respiratory rate (RR) was set to standard device setting of 15 breaths/min, within standard variations (RR = 12 – 20) of adult ICU patients (Loughlin et al., 2018). The patient monitor and mechanical ventilator were operated using the default sound settings as configured by the ICU department. Audio recordings of ICU-bg_1 and ICU-bg_2 are available in the supplementary materials.

6.2.5 Sound levels of soundscape interventions

The soundscape interventions were presented inside the patient room at sound levels intended by the involved sound artist. For the relative sound levels and psychoacoustical indicators of the interventions, see the previous paper (Louwers et al., 2024a). The measured A-weighted sound level within the single-patient ICU room during the ICU-bg1 condition was LA,eq185s = 36.3 dBA. The sound level of the soundscape interventions was adjusted relative to this measurement so the interventions could be played at the level intended by the sound artist during their original design process (Louwers et al., 2024a). Acoustical measurements in LA,eq of ICU-bg2 alone and ICU-bg2 with each added soundscape intervention are included in the appendix (Table 6.3). Additional sound level descriptors are included in the supplementary material. Audio recordings and spectrograms for each different resulting soundscape are available in supplementary material as well. All sound measurements were conducted at 0.5m from the listening position of the participant with a suspended ½" Microphone Type 4189, on a two-channel Brüel & Kjær Type 2270 Sound Level Meter calibrated at 94 dB SPL 1 kHz with a Brüel & Kjær Type 4231 Acoustical Level Calibrator.

6.2.6 Experimental procedure

Participants laid down in the hospital bed and were asked to restrict their movements. Three electrocardiograms (ECG) electrodes were attached according to the Einthoven triangle (Booth & O'Brien, 2019): under the left- and right clavicle bone and on the right hip. A pulse oximeter was placed on the index finger of the non-dominant hand. ECG data was recorded at a sampling rate of 200Hz during the entire experiment.

Participants made subjective assessments during 13 rating tasks at set points in time. Participants were prompted by a digital timer fading in on the LCD screen, counting down from 60 to zero seconds. Participants rated both their perception of the soundscape and their emotional state. Soundscape perception was measured by the extent to which eight descriptors (i.e., pleasant, annoying, calm, monotonous, vibrant, chaotic, eventful, uneventful) applied to soundscapes with five-point scales from *Strongly disagree* to *Strongly agree* in line with ISO12913-2 (2018). In line with the circumplex model of affect (Russell, 1980), the emotional state of participants was assessed using its two core affective dimensions: pleasure and arousal. A digital self-reporting tool composed of two slider controls (Betella & Verschure, 2016) was used to operationalize both dimensions of emotional state. Questionnaires were administered in English without any observed language-related issues. Scores were documented in Qualtrics using an iPad.

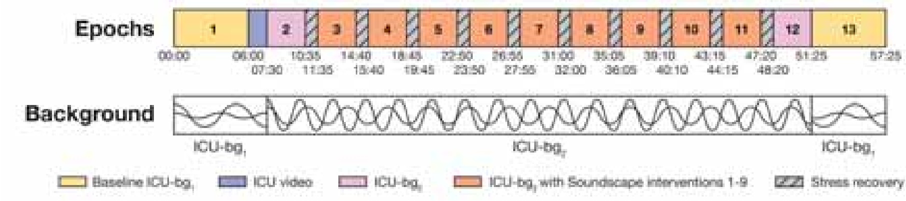

Figure 6.3. Experimental procedure showing the epochs, including nine soundscape interventions, ICU-bg_1, the simulated ICU-bg_2 soundscape, and respective durations

The experiment consisted of 13 epochs, see Figure 3. During every epoch, participants rated soundscape perception and emotional state. At the start and end of the experiment a baseline ECG was made with only ICU-bg_1 (Fig. 6.3, Baseline ICU-bg_1). Next, a 90-second video (see supplementary material) played on the LCD screen, depicting common ICU events such as intubations, consults with clinicians, and comatose patients. Participants did not give ratings during the video. Next, ICU-bg_2 started playing. During epoch 2 and 12 (Fig.6.3, ICU-bg_2), participants listened to and rated ICU-bg_2 without added soundscape interventions. Lastly, in epoch 3 – 11, participants listened to and rated the resulting soundscapes of ICU-bg_2 with added soundscape interventions. The nine interventions were featured in pseudo-randomized order to account for habituation and response fatigue. Each intervention was preceded by five seconds of pink noise to separate the trials. After epochs 2 – 11, 60 seconds of listening to ICU-bg_2 was included to allow stress recovery.

6.2.7 Data analysis

Soundscape descriptors and emotional state

The scores for the eight soundscape descriptors were reduced into distributions of pleasantness and eventfulness as continuous variables between -1 and 1 (ISO 12913-3, 2019). This was done with a trigonometric transformation based on the 45° relationship between diagonal (monotonous-vibrant and chaotic-calm) and horizontal (annoying-pleasant and uneventful-eventful) axes (Mitchell et al., 2022). To assess main effects of soundscape interventions compared to ICU-bg_1 and ICU-bg_2, one-way repeated measures ANOVAs were performed for pleasantness and eventfulness with the three sonic ambiance types, ICU-bg_1, and ICU-

bg_2 as within-subjects factor with five levels, representing the acoustic stimuli the participants were exposed to. Also, the effects of soundscape interventions were visualized with 50^{th} percentile kernel density plots (Mitchell et al., 2022). One-way repeated measures ANOVAs with ten levels compared the interventions to ICU-bg_2 in pleasantness and eventfulness. Intraclass correlation coefficients (ICC) were also computed to assess the consistency of ratings given for pleasantness and eventfulness across soundscape interventions, to determine the degree to which participants agreed in their evaluations. For comparative differences in interaction between sonic ambiance type and sound category of the interventions, a two-way repeated measures ANOVA (nine levels) was performed for pleasantness and eventfulness with post-hoc testing. One-way repeated measures ANOVAs were ran with sonic ambiance types, ICU-bg_1 (epoch 1 and 13) and ICU-bg_2 (epoch 2 and 12) as within-subjects factor with seven levels in terms of pleasure and arousal. All tests were conducted with Bonferroni corrections for multiple comparisons. Sound level measurements were processed in Brüel & Kjaer Measurement Partner Suite BZ -5503. Spectrograms were generated with librosa, a python package for music and audio analysis (McFee et al., 2015).

Physiological stress indicators

ECG data was pre-processed using a 40Hz low-pass filter and a minimum R-peak amplitude cutoff of 50 millivolts using PhysioData Toolbox (Sjak-Shie, 2022). ECGs were visually inspected by trained physicians; ECG data from participants showing arrythmia or other irregularities were removed from the dataset. If advised by the physician, the participant was referred to a general practitioner.

Heart rate variability (HRV) was derived from ECGs for each epoch by first deriving interbeat intervals (IBIs) from the signals. IBI is the time interval between successive heartbeats. Shorter IBIs imply a faster heart rate, suggestive of stress or arousal. From the normal beats (NN) intervals, HRV metrics were then calculated over the epoch, including the root mean square of successive differences (RMSSD) and mean IBI. RMSSD is the most reported measure of short-term HRV fluctuations (Immanuel et al., 2023). It indicates changes in parasympathetic activity and is associated with stress level fluctuations over time. Decreases in RMSSD may indicate states of stress. For each epoch, HRV estimations were calculated using 60-second moving windows with a five-second step interval, resulting in multiple overlapping measurements (with a 55-second overlap between consecutive windows). The median of these values was then computed to represent the overall HRV change for that specific epoch (in IBI and RMSSD). Only windows which were fully contained in the epochs were included. To account for interpersonal differences in baseline HRV, the percentages of change in median RMSSD and IBI were subsequently calculated for each epoch compared to the baseline ICU-bg_1 measurement during epoch 1. This was done using the following formula:

$$\text{Percentage Change} = \left(\frac{HRV_{epoch} - HRV_{ICU\text{-}bg1}}{HRV_{ICU\text{-}bg1}} \right) \times 100$$

where HRV_{epoch} represents the median RMSSD or IBI value for a given epoch, and $HRV_{ICU\text{-}bg1}$ denotes the corresponding baseline measurement from epoch 1.

Extreme outliers were also identified and excluded based on visual inspections of the percentage change in RMSSD over time per participant; outliers may be artifacts related to motion during the experimental procedures. To assess whether there were any significant differences between the HRV baseline ICU-bg_1 measurements at the start and end of the experiment, one-sample t-tests were performed on IBI and RMSSD percentage changes of epoch 13.

6.3 EFFECTS ON SOUNDSCAPE PERCEPTION, EMOTIONS, AND STRESS

6.3.1 Effects on the perception of the soundscape

In Figure 6.4, boxplots show the dispersion of perceived pleasantness (Fig. 6.4a) and eventfulness (Fig. 6.4b) of the resulting soundscapes, including ICU-bg_1 (i.e., the background soundscape), ICU-bg_2 (i.e., background of ICU-bg_1 with alarm sounds and mechanical ventilation), and ICU-bg_2 with added soundscape interventions. The soundscapes with interventions are grouped into sonic ambiance types.

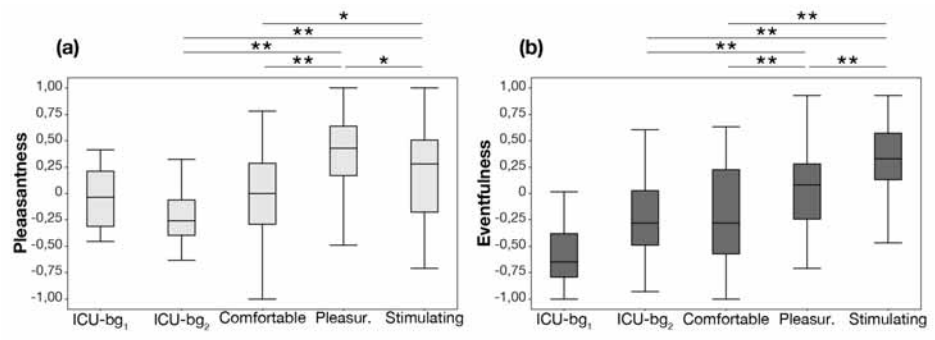

Figure 6.4. Dispersion and central tendency of resulting soundscapes across sonic ambiance types of soundscape interventions for pleasantness (a) and eventfulness (b). (*) .001 <= *p* <= .01, (**) *p* < .001. To declutter the figure, indications of significant pairings with ICU-bg$_1$ were omitted.

Differences in pleasantness and eventfulness were neither significant between epochs 1 and 13 (ICU-bg$_1$) nor between 2 and 12 (ICU-bg$_2$); hence, in this figure, only the scores measured during epochs 1 and 2 are shown for clarity. Significant pairwise comparisons between the sonic ambiance types and ICU-bg$_2$ are denoted in both figures. Denotations of comparisons with ICU-bg$_1$ were omitted, because all comparisons with ICU-bg$_1$ were significant for pleasantness and eventfulness – except for Comfortable soundscapes, which showed no significant differences from either ICU-bg$_1$ or ICU-bg$_2$.

For pleasantness (Fig 6.4a), we found a significant main effect (F(2.7, 68.0) = 27.2, *p* <.001, η^2 = .52). Post-hoc tests showed that ICU-bg$_1$ was rated as significantly more pleasant than ICU-bg$_2$. Both Stimulating and Pleasurable soundscapes were rated significantly more pleasant than ICU-bg$_1$ and ICU-bg$_2$. Pleasurable soundscapes rated significantly higher in perceived pleasantness than Stimulating ones. Both Pleasurable and Stimulating soundscapes were rated significantly more pleasant than Comfortable soundscapes. For eventfulness (Fig 6.4b), a significant main effect was also found (F(3.1, 78.0) = 38.5, *p* <.001, η^2 = .61). Post-hoc testing showed that the soundscapes of all three ambiance types, as well as ICU-bg$_2$, were significantly more eventful than ICU-bg$_1$. Pleasurable and Stimulating soundscapes were significantly more eventful than ICU-bg$_2$. Soundscapes of Pleasurable and Stimulating ambiance types were also rated significantly more eventful than Comfortable soundscapes, with

Stimulating soundscapes in turn scoring more eventful than Pleasurable ones.

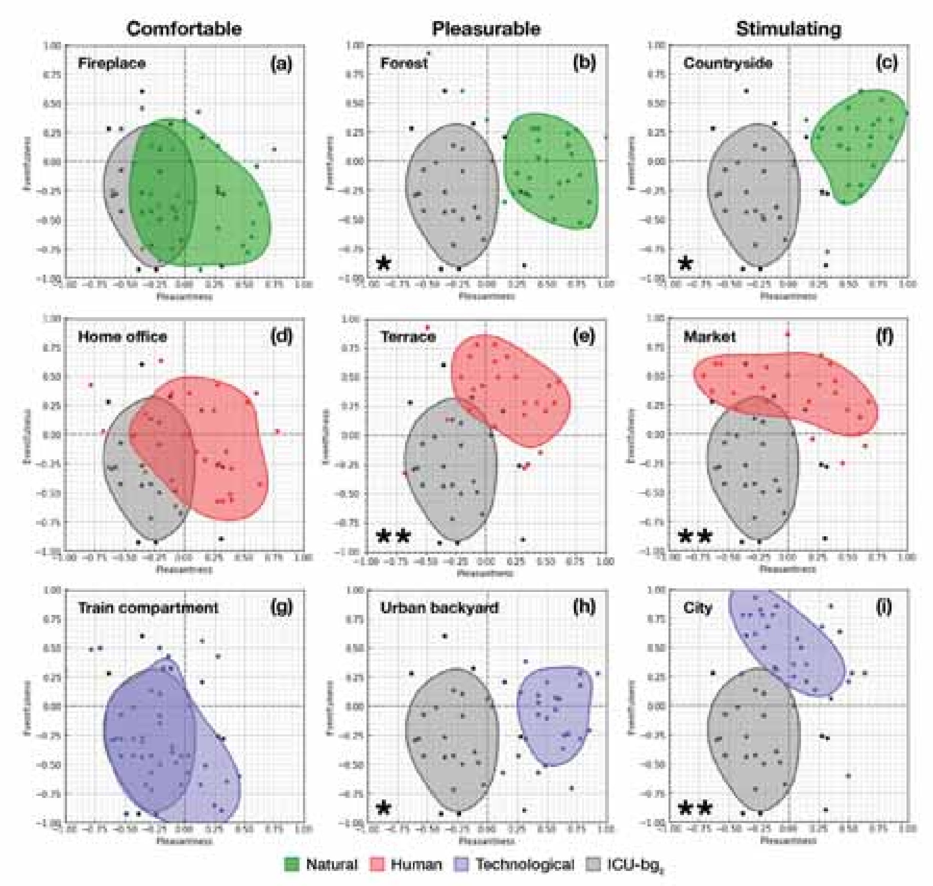

Figure 6.5. 50^{th} percentile kernel density plots of ICU-bg$_2$ with soundscape interventions versus ICU-bg$_2$ alone. (*) indicates significant differences in pleasantness, (**) indicates significant differences in eventfulness

In Figure 6.5, the perceived pleasantness and eventfulness for soundscapes resulting from adding soundscape interventions were plotted to show the relative shifts compared to ICU-bg$_2$. They are ordered by the interventions' respective sonic ambiance types (vertical) and dominant sound categories (horizontal). Evaluating the effects on perceived pleasantness and eventfulness, a significant main effect was found for pleasantness ($F(6, 150) = 17.3$, $p < .001$, $\eta^2 = .41$) and also for eventfulness ($F(5, 135) = 18.2$, $p < .001$, $\eta^2 = .42$). For pleasantness, post-hoc testing showed that four soundscapes were rated as significantly more pleasant compared to ICU-bg_2, (indicated with single asterisk). For eventfulness, three soundscapes were significantly more eventful than ICU-bg_2 (indicated with double asterisks).

Most Pleasurable and Stimulating soundscapes moved to more positive pleasantness and eventfulness (calm or vibrant) quadrants than ICU-bg_2 (monotonous) in the circumplex model of soundscape perception (Axelsson et al., 2010). A moderate (ICC = .53, $CI_{95\%}$ .20 – 0.76, p = .002) consistency was found for pleasantness, and a good (ICC = .72, $CI_{95\%}$ .52 – 0.86, p < .001) consistency for eventfulness when comparing responses across interventions. This suggested that there was more agreement between participants regarding scores for eventfulness than for pleasantness across soundscape interventions.

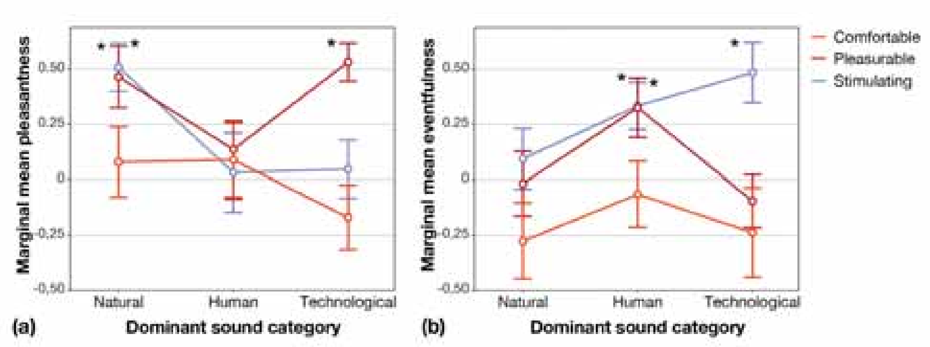

Figure 6.6. Interaction plot of estimated marginal mean differences in (a) pleasantness and (b) eventfulness, error bars indicate 95% Confidence Interval, (*) indicates significant pairings within sonic ambiance types for each dominant sound category

Within the set of soundscape interventions, the interaction between sonic ambiance type and sound category was analyzed for perceived pleasantness and eventfulness as separate dependent variables. A significant interaction was found between the two factors for both perceived pleasantness ($F(4, 100) = 9.6$, p = <.001, η^2 = .28) and eventfulness ($F(4, 100) = 8.1$, p = <.001, η^2 = .25) as can be seen in Figure 6.6. These interaction effects indicated that the extent to which soundscape interventions with Comfortable, Pleasurable, or Stimulating ambiance types influenced perceived pleasantness and eventfulness of resulting soundscapes depended on their dominant sound category. In terms of pleasantness (Fig. 6.6a), no significant differences were found between Comfortable soundscapes. For Pleasurable soundscapes, Natural and Technological interventions resulted in significantly more pleasant soundscapes than the Human ones. For Stimulating soundscapes, the Natural intervention led to significantly more pleasant soundscapes than both Human and Technological ones. For eventfulness (Fig 6.6b), there were also no significant differences between pairings of Comfortable soundscapes. For Pleasurable soundscapes, the Human intervention was significantly more eventful than the Natural and Technological. Finally, for Stimulating soundscapes, both the Human and Technological interventions led to significantly more eventful soundscapes than the Natural ones.

6.3.2 Effects on the listener

Emotional state: pleasure and arousal

The effects of the soundscape interventions on participants were assessed by analyzing the degree of pleasure and arousal they experienced throughout the experiment. The pleasure and arousal experienced by participants while listening to ICU-bg_1, ICU-bg_2, and ICU-bg_2 with the soundscape interventions (grouped by sonic ambiance type) are shown in Figure 6.7.

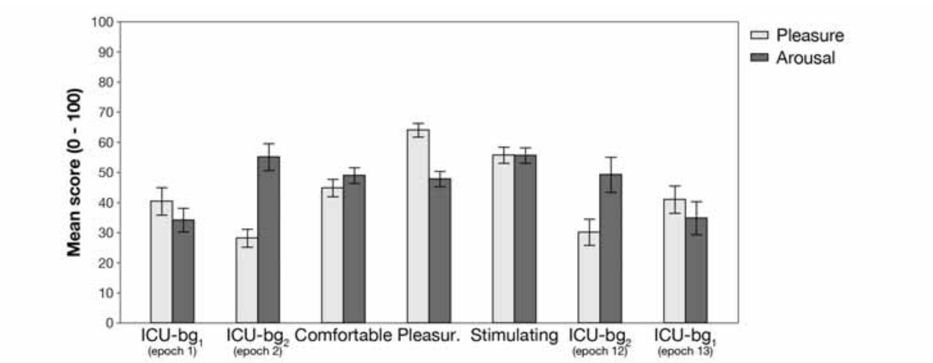

Figure 6.7. Bar charts of mean pleasure and arousal scores ranging from 0 – 100 as indicated by participants with sliders, with each error bar constructed using one standard error from the mean

For experienced pleasure, a significant difference was found between the sonic ambiance types and ICU-bg_1 and ICU-bg_2 ($F(4.1, 107.3) = 15.8$, $p < .001$, $\eta^2 = .39$). Pairwise comparisons showed that pleasure scores before listening to the soundscape interventions (i.e., ICU-bg_1, epoch 1) did not significantly differ from those after listening (i.e., ICU-bg_1, epoch 13); likewise, no significant differences were found for ICU-bg_2 between epochs 2 and 12. Pleasure scores were significantly higher for each ambiance type than ICU-bg_2; this implied that while listening to the soundscape interventions participants experienced significantly more pleasure than while listening ICU-bg_2 alone. Pleasure scores were also significantly higher for Pleasurable and Stimulating (but not Comfortable) ambiance types compared to ICU-bg_1. Finally, significantly higher pleasure scores were found for Pleasurable and Stimulating ambiance types compared to Comfortable ones.

For experienced arousal, a significant main effect was also observed ($F(4.3, 107.8) = 4.7$, $p = .001$, $\eta^2 = .16$). Participants experienced significantly more arousal during ICU-bg_2 (epoch 2) than ICU-bg_1 (epoch 1), but no significant differences were found in post-hoc testing for arousal between the pairings of epoch 12 and 13. Furthermore, arousal scores for Stimulating ambiances were significantly higher than ICU-bg_1 (epoch 1). No significant differences were observed between pairings of the sonic ambiance types and ICU-bg_2, implying that the degree of arousal of participants did not change significantly with the addition of the soundscape interventions compared to just ICU-bg_2.

The pleasure score results were in line with the relative differences we found in terms of the perceived pleasantness of the soundscapes, possibly due to the strong positive linear correlation ($r = .85$, $p < .001$) between perceived pleasantness and experienced pleasure. This analogous result also showed in a significant interaction effect in terms of sonic ambiance type and sound category for experienced pleasure ($F(4, 100) = 11.7$, $p < .001$, $\eta^2 = .32$). This suggested that, like perceived pleasantness, the extent of pleasure experienced by participants as a result of soundscape interventions with the sonic ambiance types depended on the sound category of the interventions.

Physiological indicators of stress

Due to a systematic problem with data buffering, four epochs (i.e., 9, 10, 11, 12) were lost for every participant, leaving only ECG data of six (of nine) soundscape intervention epochs for each participant. Yet enough datapoints remained for each of the nine soundscape interventions due to pseudo-randomization. See supplementary material for a distribution of the soundscape interventions per epoch.

One participant (P22) was excluded due to missing data. Three participants were excluded for whom physicians identified arrhythmias or ECG irregularities (P13, P24, and P25). None of these irregularities warranted referral by reviewing physicians. Another three participants (P1, P8, P23) were excluded due to extreme values in terms of RMSSD, possibly owing to excessive motion. For the remaining 19 participants ($median_{age}$ = 29, IQR = [25 - 60]; 10 females, 9 males), percentage changes of the median RMSSD and IBI values for epoch HRV windows were calculated as outlined in the methods.

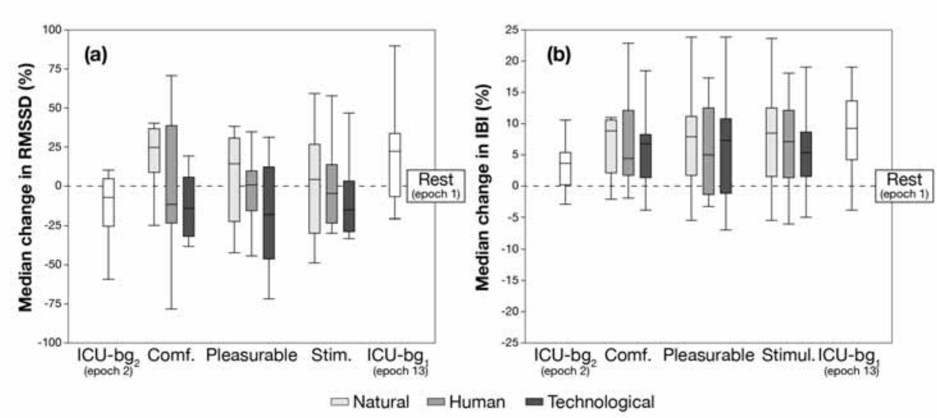

Figure 6.8. Boxplots of median changes in RMSSD (a) and IBI (b) compared to Baseline ICU-bg_1 of epoch 1, in rest

In Figure 6.8, the RMSSD (Fig. 6.8a) and IBI (Fig. 6.8b) changes are plotted with Baseline ICU-bg_1 of epoch 1 represented by zero (Rest). Descriptive statistics of the median percentage change in RMSSD and IBI are available in the supplementary materials. Percentage changes during epochs with soundscape interventions are shown grouped by sonic ambiance type. Changes in RMSSD indicate lower or greater variability in successive heartbeats (respectively, negative and positive changes relative to the rest state of Baseline ICU-bg_1 of epoch 1) and changes in IBI indicate a shorter or longer interval (and thus a faster or slower heart rate). Hence, positive shifts in RMSSD and/or IBI while listening to the soundscape interventions compared to ICU-bg_2 suggest that participants were in a more relaxed and calm state.

As can be observed in Figure 6.8, percentage changes in RMSSD decreased when participants listened to just ICU-bg_2 (epoch 2), implying that participants experienced higher states of stress during this period than during Baseline ICU-bg_1 of epoch 1. Within the sonic ambiance types, both the percentage changes in RMSSD (Fig 6.8a) and IBI (Fig. 6.8b) increased while listening to Natural soundscape interventions, but results were not systematic for other sound categories. With regards to Natural interventions with Comfortable, Pleasurable, and Stimulating ambiance types, increased percentage changes in RMSSD and IBI were observed compared to rest, indicating a more relaxed state. Comparing rest at the start of the experiment (epoch 1) and at the end after listening to the soundscape interventions (epoch 13), the Baseline ICU-bg_1 of epoch 13 showed a significantly higher RMSSD ($t(18) = 2.84$, $p = .005$) and IBI ($t(18) = 5.46$, $p < .001$). This suggested that participants were in a more relaxed state after listening to the soundscape interventions than before.

6.4 POTENTIAL BENEFITS OF ICU SOUNDSCAPE INTERVENTIONS

Listening to soundscapes of single-patient ICU rooms can be a stressful experience for patients. We developed an approach to improve experiences with ICU room soundscapes by introducing designed compositions of sound with three sonic ambiance types: Comfortable, Pleasurable, or Stimulating ambiances. This study's objective was to investigate the effectiveness of this approach in a real-world setting. We investigated to what extent these soundscape interventions impacted soundscape perception and emotional state, and physiological stress levels of healthy volunteers in a real-world ICU patient room. The findings demonstrate the potential benefits of providing our structured approach of designed soundscape interventions to patients in single-patient ICU rooms, indicated by significant improvements in the perception of the soundscape and the emotional state of listeners, along with preliminary indications of decreased stress levels.

6.4.1 Perception of the soundscape

The sound compositions improved the perceived quality of the soundscape relative to realistic ICU acoustic environments. The alarms emitted by the patient monitor and the inhalation/exhalation sound of the mechanical ventilator –together forming ICU-bg_2– negatively impacted the soundscape (perceived as chaotic). This was indicated by the significantly decreased perceived pleasantness and increased perceived eventfulness compared to ICU-bg_1, where only room ventilation was present. Introducing soundscape interventions to ICU-bg_2 with Pleasurable and Stimulating sonic ambiance types shifted the soundscape towards more pleasant and eventful quadrants (perceived as vibrant). This may be explained by phenomena of auditory stream segregation (Bregman, 2006), such as masking – where one sound obscures competing sounds – or auditory salience (i.e., redirecting attention to a more salient sound), with more pleasantly perceived soundscapes as the result. It could also be that past experiences played a role, evoking personal, positive associations with the sounds in the compositions (Özcan & Van Egmond, 2007). A prerequisite of our need-driven approach presented in an earlier study (Louwers et al., 2024a) was that designed sound compositions should yield pleasantly perceived soundscapes. The interventions with Pleasurable and Stimulating sonic ambiance types presented stronger effects in terms of perceived pleasantness; the interventions of the Comfortable sonic ambiance type only marginally increased the perceived pleasantness of the soundscape.

The acoustic environment inside the patient room played a critical role in shaping to what extent Comfortable, Pleasurable, and Stimulating soundscape interventions affected perceived quality. All interventions were designed to gradually increase the perceived eventfulness from Comfortable to Pleasurable to Stimulating ambiance types (Louwers et al., 2024a). Also, they were designed to address different groupings of needs, dependent on their sonic ambiance type. While previous findings showed all soundscape interventions (including Comfortable ones) significantly enhanced perceived eventfulness, this study found that only Pleasurable and Stimulating soundscape interventions produced significant results compared to ICU-bg_2. Unlike that former study, in the present study heavy room ventilation, alarm sounds and sounds of mechanical ventilation were present (i.e., around 8 dBA difference compared to the former study). This could indicate that interventions with Pleasurable and Stimulating ambiance types fit the needs of participants better during simulated ICU sounds (i.e., ICU-bg_2) than Comfortable. This highlighted the importance of tailoring soundscape interventions to the auditory needs of ICU patients with relation to their acoustic environment. These findings are consistent with earlier insights regarding the sound-related needs of patients (Louwers et al., 2025). It implied that soundscape interventions in ICUs should be listener-centric and acoustically adaptive. They should dynamically change, or change on demand, in terms of content based on the acoustical conditions in ICUs. With increased sound-related stressors, Pleasurable and Stimulating soundscape interventions may be desirable, introducing Comfortable soundscape interventions during quiet periods (e.g., periods without visitation). In future research, the interplay between the situational needs, psychoacoustics, and soundscape descriptors could be further investigated with patient cohorts to better inform context-relevant soundscape interventions.

Also, participants' sound-related preferences strongly influenced the effectiveness of soundscape interventions. A significant interaction between sonic ambiance type and sound category indicated that the sound distribution (featured in the sound compositions) affected perceived pleasantness and eventfulness of the soundscapes they were added to. Natural soundscape interventions with Pleasurable and Stimulating ambiances yielded more pleasant soundscapes than Human and Technological ones. Human and Technological interventions showed wide variations in perceived pleasantness, reflected in the moderate intraclass coefficient (ICC) consistency for perceived pleasantness. The wide variations in pleasantness regarding Human and Technological soundscape interventions could be explained by the lack of sound diversity inherent to single-patient ICU rooms. In previous research regarding such patient rooms, ICU patients indicated a preference for hearing commonplace sounds, such as conversation or footsteps, over the monotony inside their rooms (Louwers et al., 2025). In absence of ambient sounds of people and the outside world due to sound-proofing, it may be that the soundscape interventions that included such sounds offered a welcome source of variety for some participants. However, individual preferences can vary, especially given the diversity of ICU patient populations. Documenting patients' auditory preferences before ICU stays could guide musical therapists, sound artists, or automated systems in tailoring soundscape interventions to better suit individual needs. Future research could explore further how differences in sound-related preferences influence soundscape perception in ICU rooms.

6.4.2 Emotional state of listeners

Listening to the soundscape interventions improved the emotional states of participants. The low ratings of experienced pleasure during ICU-bg_2 reflected the negative impact of alarms and mechanical ventilation on emotional state. This aligns with previous research on adverse psychological effects of ICU sound-related stressors (Bush-Vishniac and Ryherd, 2023). Notably, emotional states of participants while listening to ICU-bg_1 and ICU-bg_2 before the soundscape interventions were introduced did not differ significantly from after. This suggested that the effects of the interventions on emotional state of participants did not last beyond their overall duration. However, they consistently provided more positive experiences than the background soundscapes. These positive experiences implied that listening to the added soundscape interventions may have contributed to psychological need fulfillment. Previous research has shown that positive user experiences stem from the fulfillment of psychological needs (Desmet & Fokkinga, 2020). The sonic ambiance types of the soundscape interventions were based upon psychological needs such as Security and Comfort (i.e., for Comfortable). The ability to contribute to positive listening experiences in different situations with these need-based sonic ambiance types may provide the support for individual patient needs that current single-patient ICU rooms seem to lack (Louwers et al., 2025). Further research could investigate whether sonic ambiances in clinical scenarios (e.g., a Stimulating ambiance during physiotherapy sessions with patients) contribute to positive experiences and psychological need fulfillment. Interestingly, experienced arousal did not change significantly due to the sound compositions, indicating that they did not heighten arousal relative to ICU-bg_2. – an important insight, since elevated states of activation can be clinically undesirable (Tate et al., 2012).

6.4.3 Physiological indicators of stress

Changes in heart rate variability provided preliminary evidence that soundscape interventions may help alleviate stress during ICU stays. During ICU-bg_2, the relative RMSSD of participants decreased compared to the other epochs, which may indicate increased stress levels. This supports findings that short-term exposure to auditory stressors like patient monitoring alarms can induce physiological stress responses (Walker et al., 2016). While distinctions between different soundscape interventions were limited, the interventions showed positive IBI changes compared to ICU-bg_2. This may suggest that the addition of the soundscape interventions lowered the heart rate of participants and evoked more restful states. After listening to the soundscape interventions, participants showed higher percentage changes in IBI and RMSSD compared to before (epoch 1 vs 13), further suggesting that the soundscape interventions may have contributed to the stress reduction of participants. It should be noted, however, that part of these observed indications of stress reduction could also reflect an initial stress response to the ICU environment at the start of the experiment, which may have naturally decreased over time due to habituation. Nonetheless, the physiological changes following the introduction of the soundscape interventions suggest that these interventions played a role in facilitating relaxation beyond mere habituation effects.

Primarily, differences were observed between interventions with regard to dominant sound category. Natural soundscape interventions with Comfortable and Pleasurable ambiance types led to consistently positive RMSSD changes, aligning with literature on the relaxing effects of nature in ICUs (Saadatmand et al., 2013) and health benefits related to exposure to nature in general (Jimenez et al., 2021). Technological soundscape interventions across sonic ambiance types resulted in decreased RMSSD, while Human soundscape interventions showed varied results. This variation possibly reflected the personal preferences of participants, as Human sounds may have relaxed participants who preferred them. Stressful ICU experiences are associated with long-term psychological impairments such as anxiety, depression, or post-traumatic stress disorder (Lee et al., 2020). Therefore, these preliminary findings highlight the need for further research into the effectiveness of soundscape interventions for stress reduction during ICU stays. Future studies could also explore how soundscape interventions may impact long-term health outcomes after discharge.

6.3.4 Limitations

Participants in this study were healthy volunteers, not ICU patients. As such, their needs and responses to soundscapes may differ from those of actual ICU patients, whose experiences are shaped by critical illness, medical treatments, and prolonged exposure to ICU stressors. To address this limitation, we actively simulated sound-related themes inherent to single-patient room ICU stays –such as monotony, isolation, unfamiliarity, and wakefulness (Louwers et al., 2025). These themes were incorporated into the study protocol with specific recruitment criteria and experimental procedures (e.g., ICU procedures video, being isolated in a real ICU room). However, the intense psychological and physiological stressors faced by ICU patients related to critical illness, medical procedures, or delirious episodes could not be transferred onto participants during the study. Future studies should thus prioritize clinical trials with patient cohorts to evaluate the efficacy of soundscape interventions in addressing specific clinical needs. This includes determining whether such soundscape interventions can aggravate delirium or other unintended negative consequences for patients' physical and psychological well-being during typical lengths of ICU stays. We observed no language-related issues in this study. However, given the complex interplay of language and meaning in perceiving environmental sounds and ongoing work on translating English descriptors (Aletta et al., 2024), future studies should consider using validated translations to optimize the accuracy of perceptual dimensions.

We used RMSSD and IBI as time-domain indicators for short-term HRV assessment, as they are well-established and widely applied in research. While these metrics provided valuable insights, future studies could expand upon this by incorporating frequency-domain measures for a more comprehensive evaluation of HRV. The observed effects of soundscape interventions on physiological stress indicators may have been partially influenced by habituation over the duration of the experiment. To minimize this, we presented the interventions in a pseudo-randomized order; also, we limited participants' ability to fully acclimate due to their unfamiliarity –ensured through the exclusion criteria– with the ICU environment. This further mitigated potential habituation effects. While these preliminary findings highlight the potential of soundscape interventions for ICU stress reduction, further research with larger sample sizes and patient populations is necessary to assess their effects on stress reduction and patient recovery.

6.5 CONCLUSION

ICU patients in single-patient, sound-proofed rooms often experience stress from sounds like alarms or when few sounds are present. We aimed to contribute to restorative patient experiences with a structured approach involving the addition of designed compositions of sounds to ICU patient rooms as soundscape interventions. These interventions were designed with Natural, Human, or Technological sounds to establish three sonic ambiances: Comfortable, Pleasurable, or Stimulating ambiances. This study's objective was to investigate the effectiveness of this approach in a real-world ICU setting. With healthy volunteers, the impact of these soundscape interventions in the presence of a simulated soundscape, consisting of alarm sounds and mechanical ventilation sounds, was evaluated on soundscape perception, emotional state, and stress levels.

The soundscape interventions enhanced the soundscape's perceived quality, led to more positive emotional states of participants, and provided preliminary evidence of physiological stress reduction. With increased perceived pleasantness and eventfulness of the soundscape, these interventions promoted positive user experiences and, although indirectly, possibly contributed to psychological need fulfillment. Interestingly, soundscape interventions with more eventful content (i.e., Pleasurable and Stimulating ambiances) appeared to be more effective in the presence of the simulated soundscape, further emphasizing the need to tailor interventions to the preexisting acoustic environment and sound-related needs of listeners. Furthermore, the extent to which interventions affected the study parameters depended on the categories of sounds in the compositions, indicating that sound category preferences should be considered in future implementations. The results confirmed the effectiveness of our approach in establishing more positive listener experiences with ICU soundscapes. These promising insights call for further research with ICU patients to examine short-term benefits during ICU stays, and effects on long-term clinical outcomes such as PTSD and depression. Overall, this study lays a foundation for redesigning ICU soundscapes from a listener-centric, context-relevant, and need-based perspective that prioritizes both the psychological and physical recovery of patients.

APPENDIX

Table 6.3 Backgrounds and soundscape interventions with measured sound level LAeq,185s (dBA).

Background	Soundscape intervention	LAeq,185s
ICU-bg1	–	36.3
ICU-bg2	–	38.9
ICU-bg2	Fireplace	41.5
ICU-bg2	Home office	40.5
ICU-bg2	Train compartment	39.7
ICU-bg2	Forest	42.7
ICU-bg2	Terrace	43.2
ICU-bg2	Urban backyard	40.0
ICU-bg2	Countryside	42.1
ICU-bg2	Market	42.7
ICU-bg2	City	46.2

SUPPLEMENTARY MATERIAL

See supplementary material at https://doi.org/10.5281/zenodo.14867355 for:

1. Subjective evaluations of soundscape descriptors and emotional state
2. Acoustical measurements
3. Physiological measurements

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Chapter 7

Conclusions

7.1 MAIN FINDINGS

For this dissertation, my objectives were to (1) investigate how human-centered design could contribute to positive listener experiences for ICU patients with a need-based, listener-centric soundscape approach, and (2) to evaluate to what extent soundscape interventions designed using this approach could enhance ICU patients' listening experiences, specifically the perception of ICU soundscapes, emotional states, and stress.

7.1.1 A soundscape approach based on user needs: contextualized sound compositions with sonic ambiances as supportive functions

The first objective was achieved by developing an approach that integrates contextual factors as foundational elements of soundscape design. Specifically, I showed how compositions of sounds could be designed to promote more positive listening experiences inside single-patient ICU rooms by establishing sonic ambiances—affective connotations associated with soundscapes—that are supportive of fundamental need fulfilment.

In Chapter 2, I formed an understanding of the context of ICU soundscapes and patients as its listeners, laying the groundwork for later explorations. A mixed-methods study was conducted to investigate what characterized listening experiences during current intensive care stays (Chapter 2). Modern, single-patient ICU departments were found to be overly reductive of sounds originating from outside patient rooms, and lacking in variation. These insights were derived from sound-related experiences, needs and emotions recalled by ICU survivors. Six themes recurred in these experiences: *Orientation through sound*; *Coping with disruptions*; *Human auditory presence*; *Monotony and variation*; *Associations and hallucinations*; and *Communication behind closed doors*. Thematic findings indicated that single-patient room layouts not only eliminate the negative aspects of sounds but also the positive qualities of ICU soundscapes, such as reassurance of listening to nurses. As a result, at Erasmus MC's Adult ICU, patients experienced soundscapes as too quiet and monotonous, leading to lack of fulfilment of fundamental psychological needs, such as Autonomy and Stimulation, and negative emotions, such as fear and annoyance. To provide more patient-centered ICU stays, we proposed that departments balance the mitigation of unwanted sound by preserving access to wanted sounds and diversifying the soundscape with new sounds.

Building on the problems defined in Chapter 2, I explored whether fundamental needs could form a basis for ICU soundscape design. I explored whether individuals associated the fulfilment of distinct psychological needs with different soundscapes, to investigate if introducing sounds based on patient needs could be central to ICU soundscape design (Chapter 3). Results of an online study into recalled or imagined soundscapes showed that the distributions of sound categories that people associated with the ideal fulfilment of nine fundamental needs were distinctive. For example, sounds associated with the fulfilment of the fundamental need for Beauty mostly belonged to Natural sound categories. However, for each fundamental need except Beauty, Human sound categories were most commonly mentioned, consistent with the importance of Human sounds reported in Chapter 2. These insights suggested that to provide support for different fundamental needs of patients, profoundly different sounds would be required than the ones currently on offer in ICUs. It also implied that one-size-fits-all ICU soundscape interventions are insufficient to support the needs of patients, but should rather be distinctive and need-based.

Having established that ICU soundscapes should be tailored to fundamental patient needs (Chapter 3), I investigated how this could be achieved. A workshop was conducted with ICU stakeholders to generate ideas and determine which design characteristics would need to be considered when designing ICU soundscape interventions (Chapter 4), given the insights gained in Chapter 2. The workshop concluded with three concept directions: a Smart Environmental Assistant for control over the soundscape, a Patient Soundscape Dashboard for delivering contextualized and personalized soundscapes, and a system for Familiar Wake-ups after sedation. Five design characteristics were found by analyzing these concepts, demonstrating that soundscape interventions should be:

- *User-friendly*, offering access for all end-users;
- *Personalized*, providing tailored listener experiences through pre-defined preferences and real-time feedback;
- *Humanized*, enhancing rather than replacing moments of human interaction;
- *Integrated*, respectful of critical care workflows and emergencies; and
- *Familiar*, promoting recognizable associations with the environment.

Based on these findings, it was determined that soundscape interventions created for ICUs should incorporate these design characteristics to effectively establish positive listener experiences.

Given the potential benefits of reintroducing sounds to ICU patient rooms (Chapter 2), the understanding that ICU soundscapes should support fundamental patient needs (Chapter 3), and the concepts and characteristics for ICU soundscape interventions, I investigated how designing such interventions could be approached (Chapter 5, Study 1). A design process was outlined for conceptualizing pleasant, need-based compositions of sounds, based on four design parameters: *intended eventfulness*, *sonic ambiance quality*, *narrative structure*, and *sound categorization*. Whereas Chapter 3 revealed initial differences in how sound category distributions differed per need-specific soundscape, Chapter 5, Study 1 included a more in-depth analysis of quantitative (i.e., ratings) and qualitative (i.e., soundscape descriptions) results of that study. Results indicated that designed compositions of sounds, organized into specific, familiar narratives, established four sonic ambiance types related to the fulfilment of different fundamental needs: *Comfortable*, *Pleasurable*, *Motivating*, and *Stimulating* ambiances. The sonic ambiance types and design parameters were synthesized into a need-based approach to soundscape design aimed at promoting positive listener experiences with ICU patient room soundscapes. This approach comprised of introducing designed compositions of sounds to ICU patient rooms as soundscape interventions from the starting point of a (set of) target need(s).

Together, the sound-related experiences of patients with current ICUs (Chapter 2), perceived need-based distinctions in sound distribution of soundscapes by healthy participants (Chapter 3), concepts and design characteristics provided by multi-disciplinary teams of experts (Chapter 4), and design parameters derived from imagined soundscapes (Chapter 5, Study 1) contributed to the establishment of a listener-centric, need-based approach on designing supportive soundscape interventions for ICU patients. By adding compositions of sounds to ICU rooms based on individual patients' contextual factors, soundscapes and their sonic ambiances can provide the psychological support that current ICU stays may lack.

7.1.2 Pleasant soundscapes, positive listening experiences, and stress reduction

I attained the second objective by demonstrating that need-based soundscape interventions, designed using our listener-centric approach, positively influenced soundscape perception and emotional responses in healthy volunteers under controlled experimental conditions. These positive effects were successfully replicated in a real-world ICU patient room, with the added observation of preliminary indications of reduced physiological stress.

The effectiveness of soundscape interventions designed with the approach of Chapter 5, Study 1 was first evaluated in absence of the physical ICU context. In Chapter 5, Study 2, the designed sound compositions were tested in a simulated ICU environment. The results showed that perceived pleasantness and eventfulness of soundscapes were affected considerably by the soundscape interventions, eliciting positive listening experiences. I collaborated with a sound artist who designed sixteen sound compositions as soundscape interventions following the process outlined in Chapter 5, Study 1. The soundscape interventions, played through speakers to healthy participants in a lab-space, resulted in significantly more pleasant (vibrant or calm) soundscapes. Perceived eventfulness of resulting soundscapes increased in alignment with the anticipated relative ordering of eventfulness between sonic ambiance types outlined in Chapter 5, Study 1. Furthermore, higher levels of experienced pleasure were observed, confirming the positive impact of the designed interventions on listening experiences. Evaluating the approach, it was found that intended eventfulness was a viable design parameter for creating a varying range of need-based soundscape interventions. Based on the lack of perceived differences between Motivating and Stimulating compositions, only sound compositions with Comfortable, Pleasurable, and Stimulating sonic ambiance types were recommended for future application of the approach. Sound categorization and narrative structure were highlighted to merit further investigation. Overall, the need-driven approach was found promising for enhancing ICU patient experiences through soundscape interventions.

Finally, it was evaluated whether the effects of the soundscape interventions, observed in absence of the ICU context (Chapter 5, Study 2), could be replicated in a real-world single-patient ICU setting (Chapter 6). The overall results of this study were in line with the findings of

Chapter 5, Study 2. The interventions developed in Chapter 5 improved the perceived quality of an ICU room soundscape and promoted positive emotional states. Moreover, we found preliminary evidence hinting that listening to the interventions could contribute to physiological stress reduction. Amidst a simulated ICU soundscape of patient monitoring alarms and sounds of a mechanical ventilator, Pleasurable and Stimulating interventions significantly increased the perceived pleasantness and eventfulness of the soundscape, while Comfortable ones were less effective. Since in Chapter 5, Study 2, in absence of other sounds such sound compositions were effective, this suggested that with increased sound-related stressors, more eventful (i.e., distracting) interventions were preferred. Additionally, interaction effects in perceived pleasantness and eventfulness, also observed in Chapter 5: Study 2, demonstrated that the extent to which interventions affected the study parameters depended on the categories of sounds included in compositions. This suggested that sound-related preferences of participants differed and influenced how these sounds were perceived. Experienced pleasure ratings showed that the soundscape interventions contributed to positive listening experiences. Increased heartrate variability indicated that soundscape interventions showed promise for stress reduction. Natural soundscape interventions led to more consistent indications of relaxation than Human or Technological soundscape interventions. Based on the results, it was concluded that the approach was effective and promising for creating more listener-centric, restorative soundscapes during ICU stays, but that further investigations are warranted regarding the effects of the interventions on stress.

7.2 CONTRIBUTIONS

The findings of this dissertation contribute to the fields of soundscape research and humanization in intensive care. In this section, I provide practical contributions for designers in the form of an iteration on the need-based, listener-centric approach for setting sonic ambiances presented in Chapter 5. Also, I present insight cards summarizing three sonic ambiance types and the six themes of sound-related patient experiences (Chapter 2). I then discuss how this dissertation contributes to an ongoing paradigm shift from physics-based design towards human-centered, perception-based design in the acoustic domain. Finally, I explain how this approach adds to trends of humanization of intensive care.

7.2.1 Practical contributions for designers: An iterated listener-centric, need based approach, three sonic ambiance types, and six themes of patient experiences

In Figure 7.1, a version of the developed approach is shown iterated with findings of Chapter 5 and Chapter 6. These findings resulted in three changes.

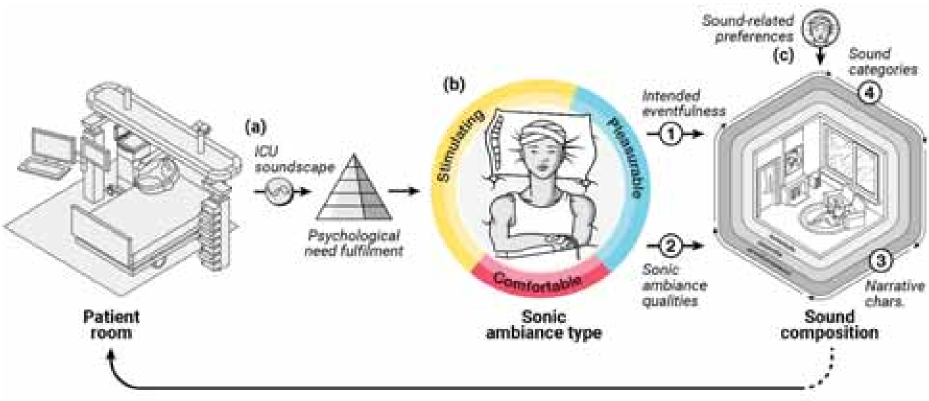

Figure 7.1. Workflow iterated from Chapter 5, Study 1, for setting sonic ambiance types through sound compositions

First, the preceding version of this approach consisted of four sonic ambiance types. This selection was reduced to three after the findings of Chapter 5, Study 2 indicated that Motivating and Stimulating ambiance types were too similar to separate. In this figure, we thus incorporated only Comfortable, Pleasurable, and Stimulating sonic ambiances (Fig. 7.1b). Second, there were differences between Chapter 5 (no simulated ICU soundscape), and Chapter 6 (simulated ICU soundscape of patient monitoring alarms and mechanical ventilation sounds) in effectiveness of the soundscape interventions in terms of perceived pleasantness and eventfulness. This suggested that the preexisting acoustical environment impacted the effectiveness of soundscape interventions; this factor was therefore incorporated into the model (Fig. 7.1a). Third, there was a significant interaction between sonic ambiance types and Natural, Human, or Technological sound categories for perceived pleasantness and eventfulness in Chapter 5 and Chapter 6. This showed that preferences of listeners also affected the effectiveness of the interventions. These preferences were thus assigned as a secondary contextual factor for designing the soundscape interventions (Fig. 7.1c).

The sonic ambiance types developed in this dissertation introduce a novel, need-based perspective to designing soundscape interventions. To provide a practical reference for designers, three insight cards were created (see Fig. 7.2). Each card presents a descriptive statement of a sonic ambiance type, including its sonic ambiance qualities, associated needs profile, and intended eventfulness. A QR code linking to an audio file accompanies each insight card, offering an impression of how these sonic ambiances might sound and feel. Within the scope of this thesis and the studied ICU context, these cards and audio examples serve as a concise tool for stakeholders to understand how soundscape interventions can be designed to support ICU patients. The three-mode approach demonstrated an effective balance between accommodating individual needs and maintaining the simplicity required for practical implementation. Moreover, the associated audio examples (selected from the designed and evaluated soundscape interventions) proved to be effective in shaping listener experiences. As such, these cards and their corresponding audio can be considered as basic modes, which can be translated into more context-specific interventions in both practical and research applications.

Figure 7.2. Cards for Comfortable, Pleasurable, and Stimulating ambiance types

In Chapter 2, six recurring themes were identified in the sound-related experiences of patients. Within the objectives of this dissertation, the developed approach to designing ICU soundscape interventions represented just one possible solution among many. Given the rich contextual insights these themes provide into the lived experiences of ICU patients, they could serve as an inspiring basis for future improvements of ICU soundscapes. Beyond the soundscape domain, these themes could also inform broader aspects of critical care. For instance, insights from patient experiences with sound may contribute to optimizing nurse workflows, adjusting visitation protocols for medical staff, or refining communication strategies between healthcare professionals and patients. By integrating these themes into the ICU environment more holistically, hospitals could create patient-centered care experiences that extend beyond auditory interventions alone.

To provide a practical overview of the themes, insight cards are presented on the next page that summarize the themes in terms of the theme title, an illustration, and a representative quote (see Fig. 7.3). These cards are intended to expand the design space, offering healthcare professionals and designers an informative and inspirational basis for developing new approaches to improving experiences of ICU stays.

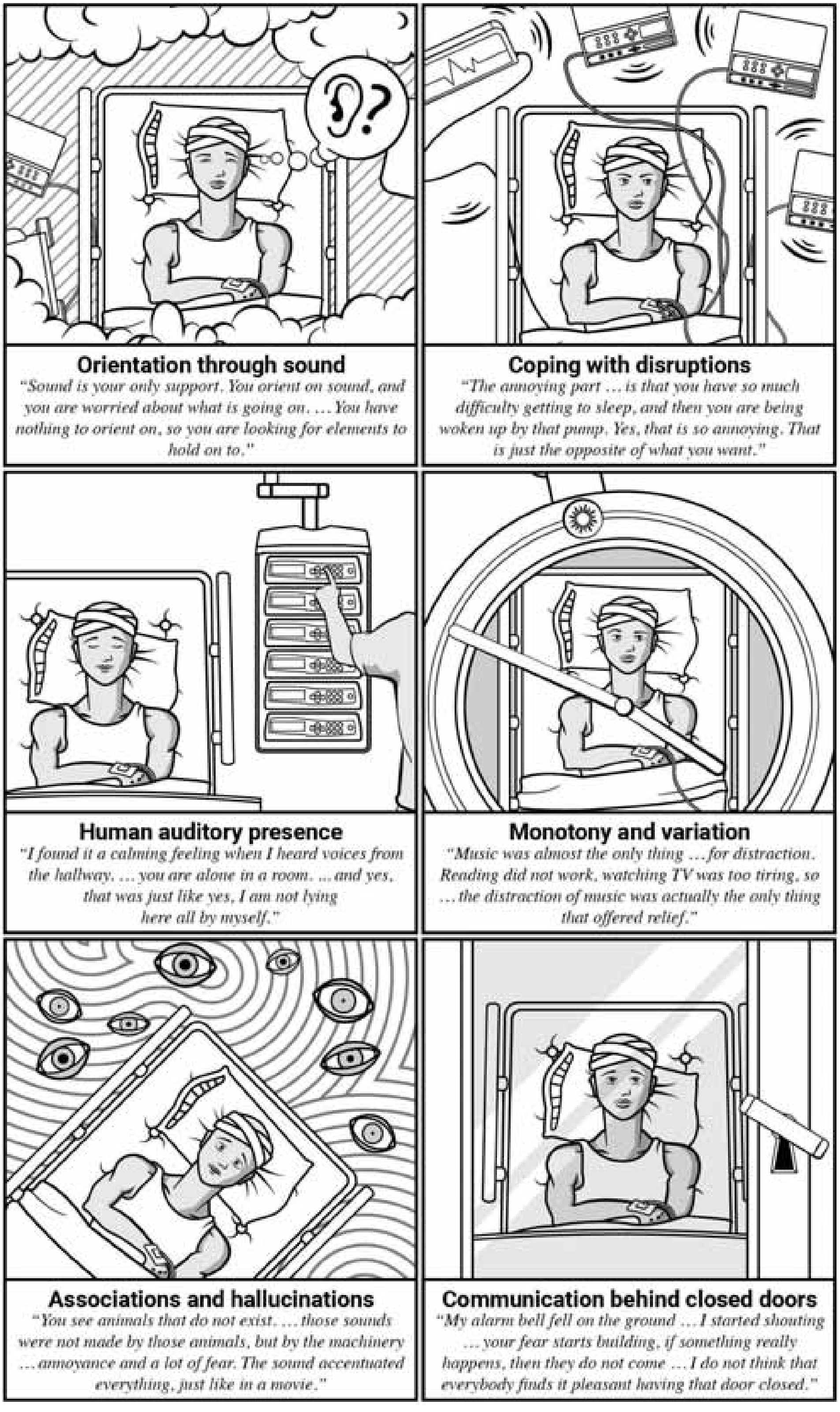

Figure 7.3. Insight cards of themes with quotes of patient experiences

7.2.2 From sound-centric to listener-centric

The listener-centric, need-based approach to soundscape design presented in this dissertation contributes to an ongoing paradigm shift within the acoustic domain (Kang et al., 2016), moving from a sound-centric focus to one about the whole sonic ambiance surrounding the listener. Integrating the psychological needs of listeners as contextual factors into evaluation and design phases represents a promising next step in promoting positive listening experiences in healthcare.

During evaluation phases that precede soundscape design, adopting a need-based, listener-centered perspective can help bridging the gap between soundscape evaluation and designing personalized interventions. As was explained in Chapter 1, soundscape studies inherently consider the context of listening (ISO 12913-1, 2014). The methods employed in the studies of this dissertation built on this approach, evaluating the psychological impact of soundscapes with consideration of fundamental needs as underlying characteristics of listening experiences. Integrating need evaluations into standardized methods of soundscape assessment, such as soundwalks, questionnaires, or guided interviews (ISO 12913-2, 2018), could enhance the utility of soundscape analysis for personalized design. Huang et al. (2025) have recently developed a new diagnostic tool to measure need fulfilment and frustration, the Fundamental Need Scales (Huang et al., 2025). These scales could be incorporated into standardized soundscape evaluations to provide a structured and rich understanding of how existing soundscapes (i.e., before design interventions) fulfil—or fail to fulfil—listener needs. Reframed into design challenges, such findings can act as a bridge between analysis and design, sparking ideation and conceptualization processes to design soundscape interventions tailored to specific listener experiences and need profiles. As standards for designing soundscape interventions are currently being developed (ISO 12913-4, n.d.), the incorporation of need-based approaches could provide designers (i.e., interior designers, sound artists, urban planners, architects) with a framework for iteratively designing soundscape interventions that effectively enhance listener's experiences in a human-centered manner.

During design phases, the developed approach prioritizes the listening experience before the intervention itself. That experiential perspective, with listener's needs at its core, forms a systematic, creative basis for designing hospital soundscape interventions at source, path (i.e., between source and receiver), and receiver levels (Bush-Vishniac & Ryherd, 2023).

In Chapter 5: Study 1, it was proposed that listening experiences are defined by psychological need fulfilment and corresponding sonic ambiance qualities, among other design parameters. Grounding idea generation and conceptualization in a desired listening experience allows a broad range of solutions to be generated for the same design challenge. The interventions presented in this dissertation—sound compositions introduced at the receiver level—exemplified one, perception-based way of achieving the identified sonic ambiance qualities within our specific context. However, other soundscape interventions—such as reducing noise through private ICU rooms (path level), enhancing aesthetic pleasure by redesigning alarms of medical machinery (source level), or fostering reassurance by access to sounds of caregivers in corridors (receiver level)—could also provide positive listening experiences that align with Comfortable, Pleasurable, or Stimulating ambiance types. Importantly, rooting such interventions in desired, need-based listening experiences ensures that they are meaningful to individuals and that critical contextual aspects, such as the lack of variety experienced by patients regarding private ICU room soundscapes (Chapter 2), are not overlooked (Delle Monache et al., 2022). The prioritization of listening experiences thus provides a perspective to hospital soundscape design that offers a novel, promising way of designing humanized future care environments.

7.2.3 Humanization of ICUs through need- and preference-based personalization

This dissertation also contributed to knowledge for humanization of critical care. As described in Chapter 1, ICU departments increasingly recognize the importance of providing holistic, patient-centered care during ICU stays (Rodriguez-Ruiz et al., 2025). Soundscape experiences could become a supportive asset during ICU stays by adopting the comprehensive perspective on fundamental needs included in the approach in this dissertation.

The developed approach does not differentiate between the intentionality of patients and healthy individuals. Instead, it recognizes patients as human beings who seek to fulfil fundamental needs that extend beyond safety or comfort. Standardized, one-size-fits-all soundscape interventions, such as sound-proofed doors in single-patient ICU rooms, ignore this diversity of ICU patients. This dissertation advocates for personalized care environments tailored to the individual needs and preferences of patients in a feasible, desirable, and viable way. This novel perspective on patients' needs during ICU stays is critical for promoting more positive experiences with ICU soundscapes as it respects the complexity of those experiences. The study described in Chapter 2 was the first of its kind, offering an in-depth understanding of how patients experience the soundscapes of single-patient ICU rooms. It not only identified shortcomings in current ICU soundscapes but also contextualized them in relation to patients' needs and emotional responses. This approach revealed complex, latent aspects of sound-related problems that might otherwise remain unrecognized. For example, the findings highlighted that ICU soundscapes lacked variety, but they also underscored the supportive role of sounds of care staff in hallways and the functional contribution of alarms to patients' feelings of reassurance. By adopting such a perspective, ICU design could continue its important shift towards humanization—not only in how patient rooms are structured, but also in shaping the broader social environment and enhancing the overall ICU experience from the patient's perspective.

7.3 LIMITATIONS

The outcomes presented in this dissertation form a promising first step towards providing positive listening experiences during ICU stays. Nevertheless, these outcomes need to be viewed in light of four limitations:

1. **ICU patients and healthy volunteers:** Chapter 2 presented an in-depth understanding from former ICU patients which formed the foundation for all processes of developing our listener-centric approach; nevertheless, the other studies described in the chapters were conducted with healthy volunteers. While this allowed for accurate, controlled experimental assessments to be made, the perception of soundscapes and experienced emotions may differ substantially between healthy individuals and patients experiencing stress, illness, or altered cognitive states. A pilot with a cohort of patients in non-critical conditions, following a similar experimental design as Chapter 6 (but perhaps with a between-subjects design resulting in less stimuli and demand on participants) could thus form a reasonable next step in testing the effectiveness and feasibility of the developed approach.

2. **The effects on and of delirium:** The acoustical environment of ICUs is known to influence sensory processing and orientation of patients, suggesting a link with delirium, a confused mental state associated with negative patient health outcomes (Tronstad et al., 2023). Given that delirium affects a substantial proportion of ICU patients, it is an important factor to consider when introducing any form of environmental adaptation (e.g., lighting, sound). Delirium was not specifically accounted for in this dissertation. However, given the prevalence and impact of delirium, future studies should investigate whether tailored soundscapes could help prevent or mitigate delirium-related distress or unintentionally exacerbate symptoms. This is essential to ensuring safe and effective implementation of such interventions in ICU environments.
3. **Need fulfilment measurement:** The measurement of need fulfilment in this dissertation provided invaluable insights critical to the development of our approach. The need fulfilment questionnaire used during patient interviews in Chapter 2 systematically captured how ICU soundscapes related to fundamental psychological needs, aligning closely with the recently validated framework for measuring fundamental needs by Huang, Desmet, and Mugge (2025). This standardized framework offers an opportunity for future studies to further refine the assessment of need fulfilment and frustration in relation to soundscapes. Incorporating the Fundamental Need Scales into experiential evaluations of ICU soundscapes could enhance the robustness of future studies, allowing for an even more comprehensive understanding of how soundscapes support or impede patient well-being.
4. **Other factors of personalization:** This dissertation primarily focused on need-based personalization of ICU soundscapes but did not explicitly examine other relevant personalization factors such as aesthetic preferences, auditory sensitivity, or cognitive and neurodiversity. These individual differences could influence how patients perceive and respond to soundscape interventions. Future studies should explore these aspects to further ensure that a broader range of patient needs and preferences are accommodated.
5. **Effects on stress:** Preliminary indications of physiological stress reduction were found in Chapter 6; nevertheless, practical complications during the experiments impaired our ability to derive conclusive evidence of the physiological benefits of establishing Comfortable, Pleasurable, and Stimulating ambiance types in the patient rooms. In future research, these potential physical health-related advantages could be investigated with a more extensive experimental protocol and with patients as participants.

7.4 NEXT STEPS

The environmental preferences of patients need to be documented and given a central role in care workflows of hospitals. Documenting these preferences, such as those concerning lighting or door policies, forms a prerequisite of not only the approach developed in this dissertation, but for providing more patient-centered care in general. As part of a wider system change in healthcare concerning the importance of sleep and other 'soft' factors during ICU stays, this can form the next step on the road towards humanization in critical care by personalizing patient rooms to the preferences of patients. It should therefore become common practice that hospitals, and ICU departments in particular, account for these preferences during patient intakes and care workflows. As part of such practices, documenting patients' sound category related preferences (mentioned as a secondary contextual factor in the iterated approach to ICU soundscape design) would allow environmental personalization to become common practice and even automated. To develop such automated systems, designers could draw inspiration from the three concept directions presented in Chapter 4.

Figure 7.4. User interfaces for Amadé, a conceptual system for recording patients' sound category preferences

Digital applications should be developed that facilitate the documentation of preferences of patients and provide personalized, contextualized soundscapes as part of an automated, supportive system. I supervised the graduation project of industrial designer Lindy Kok, who developed user interfaces and a system design for such a conceptual system (see

Fig. 7.4) for emergency or planned patient admissions, usable by patients, relatives, and healthcare professionals (Kok et al., 2024). This system was designed to facilitate personalization of soundscapes inside single-patient ICU rooms at Erasmus MC through interactions before planned ICU admissions by patients themselves (web and mobile application), and during ICU stays (tablet application) by patients, relatives, and care staff. Built upon the insights gained in my PhD project, this system was conceptualized to provide an automated way of documenting the sound-related preferences of patients for Natural, Human, or Technological sound categories, and using them in unison with sonic ambiance qualities to create personalized sound compositions for Comfortable, Pleasurable and Stimulating ambiances. Ambiances can then be actively called upon by caregivers to change the ambiance type in patient rooms during care activities (e.g., providing a Stimulating sonic ambiance during physiotherapy), or configured into routine patterns.

An important next step is to evaluate such systems in real ICU scenarios with patient populations. In Chapter 4, one conceptual direction generated in the workshop (i.e., Patient Soundscape Dashboard) included the notion that different soundscape interventions could support the care activities of caregivers and the situational needs of patients. Many possible scenarios can be explored for this purpose, for example, such as patients being alone in their room without the presence of relatives or visiting caregivers, waiting for nurses during alarm sounds, or undergoing medical procedures performed by care staff. As a transitional step, testing these interventions with non-critically ill patients in private rooms on general care wards could serve as a bridge between healthy volunteers and ICU patients. This approach would allow for a pilot feasibility study on whether the effects observed in controlled environments with healthy volunteers translate to real-world care settings with patients. Additionally, since completing soundscape and emotion questionnaires can be demanding, this setting may provide a more practical context for gathering initial insights. This would provide valuable feedback for refining and iterating the approach and interventions before introducing them to ICUs. Evaluating the effects of the soundscape interventions on patient outcomes in randomized clinical trials with ICU patients would require further iterations of the listener-centric, need-based approach. This includes developing a working soundscape system prototype and ensuring integration with nurse workflows. With such a prototype in place, researchers could assess both short- and long-term effects of soundscape interventions on stress, patient behavior, and recovery.

The effects of the sound compositions relative to different sound-related scenarios need to be investigated. The influence of the pre-existing acoustical environment was found to be impactful in Chapter 6. The findings suggested that compositions with a Comfortable sonic ambiance type were less suitable when there were more ICU sound-related stressors present, such as medical device alarms or mechanical ventilation. While this implied that sound compositions with a Comfortable sonic ambiance were more suitable during periods with less sound-related stressors, we did not specifically investigate the impact of the sound compositions in real-world ICU rooms with no stressors present. Future studies should therefore investigate this phenomenon further to confirm these hypothesized interactions between sonic ambiance types and the preexisting acoustical environment.

And finally, future innovations should extend our findings beyond sound to the multisensory domain. This dissertation was closely linked to the development of the Philips VitalSky, a therapeutic lighting system designed to support circadian rhythms of ICU patients as part of a broader delirium prevention strategy (Royal Philips, 2019). Integrating personalized soundscapes with such a lighting system could potentially further enhance patient experiences. Kim (2024) investigated providing digital, visual elements of natural scenes to stimulate relaxation in ICUs and contribute to well-being and healing environments (Kim, 2024). They designed a visual intervention entitled 'Digital Nature', consisting of a projected continuous stream of virtual natural scenes designed to promote relaxation in ICUs (Kim et al., 2024). As an extension of this visual intervention, sound compositions could be synchronized with projected visual content to create immersive, audiovisual ambiances through integrated speakers.

An example of how this could take shape is Eva van Houwelingen's work on providing audiovisual stimulation in ICU patient rooms (see Fig. 7.5a) (Van Houwelingen et al., 2022). She demonstrated how adaptive audiovisual stimuli could respond to real-time room activity, for example, decreasing (Fig. 7.5b) or increasing (Fig. 7.5c) the level of turbulence of wave visualizations and sounds in accordance with sound pressure levels in the room. Beyond nature-based visuals, future research could explore whether personalized audiovisual environments—such as urban parks or home-like settings—could be employed to further tailor patient experiences. Furthermore, beyond real-world visuals, abstract patterns of light (Louwers et al., 2019) congruent with ambient music (Beardow et al., 2021) could be explored as an alternative source of multi-sensory stimulation. Investigating how affective connotations of acoustic environments (i.e., sonic ambiances), might interact with those of visual (i.e., lighting atmospheres), or even haptic interactive environments presents an interesting direction for future research.

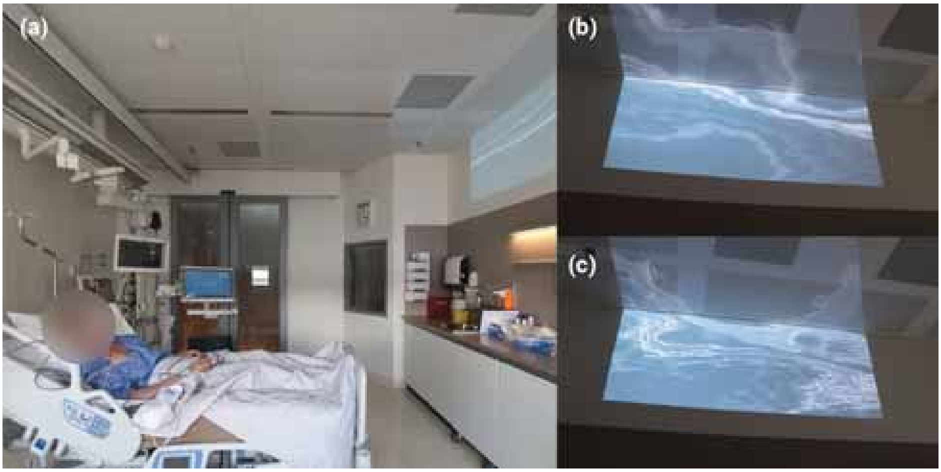

Figure 7.5. User tests conducted by graduation student Eva van Houwelingen on providing adaptive audiovisual stimulation inside ICU patient rooms

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I have been fortunate to grow up in a protected and nurturing environment, a luxury in life that not everyone is granted. As you grow older, you begin to understand how much is sacrificed to provide that foundation. I want to acknowledge my **parents** and **siblings** for giving me exactly that. Without you, I could not have done this. Your opinion matters more to me than I can express, though I understand if your opinion of this dissertation begins and ends with the summary.

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the tree when it comes to having a bèta-mindset, I am proud to be your son.

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ABOUT THE AUTHOR

Gijs Louwers was born on December 6th, 1992, in The Hague, and raised in Vught, where he completed his secondary education at Gymnasium Beekvliet in Sint-Michielsgestel. After an unsuccessful attempt to pursue a career in medicine early in his academic journey, he volunteered as a nurse at Mwananyamala Regional Referral Hospital in Dar-es-Salaam, Tanzania. That same year he successfully ascended Mt. Kilimanjaro at age 19.

He went on to study Industrial Design Engineering at TU Delft, driven by an interest in design, fine arts, human well-being, and technology. During his bachelor's degree, Gijs worked as a UX designer at Vidacle, where he developed an interest into human-centered design. He continued this focus during his master's degree Design for Interaction at TU Delft, supplementing his studies with international experience at Universitat Politècnica de València and a product designer position at UpReach GmbH in Berlin, where he developed photobooth products.

Towards the end of his studies, Gijs became fascinated with the perceptual and experiential potential of light. His graduation project, supervised by prof. dr. Sylvia Pont and Martin Havranek, explored how dynamic light textures, inspired by natural patterns, could transform the perceived atmosphere of interior spaces. This led to a traineeship in lighting design at Atelier LEK in Rotterdam, where he contributed to various public space lighting projects. Given the opportunity to combine his passion for research with his early interest in medicine and love for music as an alto/tenor saxophonist, Gijs returned to Delft to pursue a PhD focused on patient sound experiences in intensive care units. This dissertation reflects the culmination of those interests and a commitment to improving user experiences through design and research.

Today, Gijs continues this mission as a User Researcher at Sanoma Learning, a leading K12 European learning company. In this role, he collaborates with UX designers, teachers, students, and innovators to design and improve digital learning and teaching technology for primary, secondary, and vocational education of schools in the Netherlands and Belgium.

CURRICULUM VITAE

GIJS LOUWERS

6th of December, 1992 Born in The Hague, The Netherlands

EDUCATION

2020 – 2024 PhD | Industrial Design Engineering
Delft University of Technology, Delft, The Netherlands

2017 – 2019 MSc Design for Interaction | Industrial Design Engineering
Delft University of Technology, Delft, The Netherlands

2018 – 2019 MSc | Ingeniería en Diseño Industrial
Universidad de Politecnica de Valencia, Valencia, Spain

2012 – 2016 BSc Industrial Design | Industrial Design Engineering
Delft University of Technology, Delft, The Netherlands

EXPERIENCE

2025 – present User Researcher
Sanoma Learning, the Netherlands

2020 – 2024 PhD Candidate | Industrial Design Engineering
Delft University of Technology, Delft, The Netherlands

2020 Trainee lighting designer
Atelier Licht en Kleur, Rotterdam, The Netherlands

2018 Product designer
UpReach GmbH & Co. KG, Berlin, Germany

2016 – 2017 Product design intern
Happybooth GmbH & Co. KG, Berlin, Germany

2015 – 2016	UX designer Vidacle/Bitnomica, Delft, The Netherlands
2012 – present	Visual designer Freelance, The Hague, The Netherlands

DESIGN TEACHING

2023 – 2024	Mentor | MSc graduation project Delft University of Technology, Delft, The Netherlands
2023 – 2024	Coach | Usability and User eXperience in Design Delft University of Technology, Delft, The Netherlands
2022 – 2024	Coach | Context and Conceptualization Delft University of Technology, Delft, The Netherlands
2021 – 2023	Coach | Form and Senses Delft University of Technology, Delft, The Netherlands
2021 – 2022	Mentor | MSc graduation project Delft University of Technology, Delft, The Netherlands
2020 – 2021	Coach | Research and Design Delft University of Technology, Delft, The Netherlands

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