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

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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.

1. Introduction

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 [19]. 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 [27]. For nurses, exposure to the medical device alarms present in such soundscapes commonly leads to alarm fatigue [30], posing an indirect but substantial threat to patient safety. Patients, being exposed to cacophony, are directly affected through disrupted sleep [10] and possibly delirium, a confused mental state [39]. These experiences are associated with new problems that patients develop after ICU discharge, such as post-traumatic stress disorder and depression [13]. Considering these challenges, this paper explored the effectiveness of soundscape interventions in facilitating positive listening experiences for ICU patients.

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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 [48]. 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 [6]. 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 [47,51]. 'Quiet time'-protocols, reducing sound levels at night, are implemented to benefit sleep [23]. At the receiver level, earplugs [31] or noise-cancellation headphones [53] offer protection against unwanted sound. At the path level, absorptive materials [37] or new ward layouts with single-patient (i.e., private) ICU rooms and staff room relocations also led to significantly decreased sound levels [44]. Such interventions have demonstrated to improve both patient and staff comfort [8,36,59].

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 [38]. Listening to conversations or procedural sounds of nurses in ICUs can contribute to feelings of safety and reassurance [22]. In a previous investigation, it was found that the removal of these sounds may even contribute to negative experiences [33]. 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 [25]. 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 [46] and offers psychological and physical benefits for patients [20,24,56]. However, such additions should be centered around the dynamic, context-related needs of patients as listeners.

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 [43,58]. 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 [41], 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 [34]. Differences between clusters of need-specific soundscapes were found in the sonic ambiance (the affective connotation of the soundscape), perceived eventfulness ISO [18], and organization and distribution of individual sounds.

Building on the differences between clusters of need-based soundscapes [34], 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 [34] 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 [35]. 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 [34], 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?

2. Methods

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 ($\text{median}_{\text{age}} = 30$, 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.

2.2. Experimental setup

This study was conducted in a single-patient ICU room at the Adult

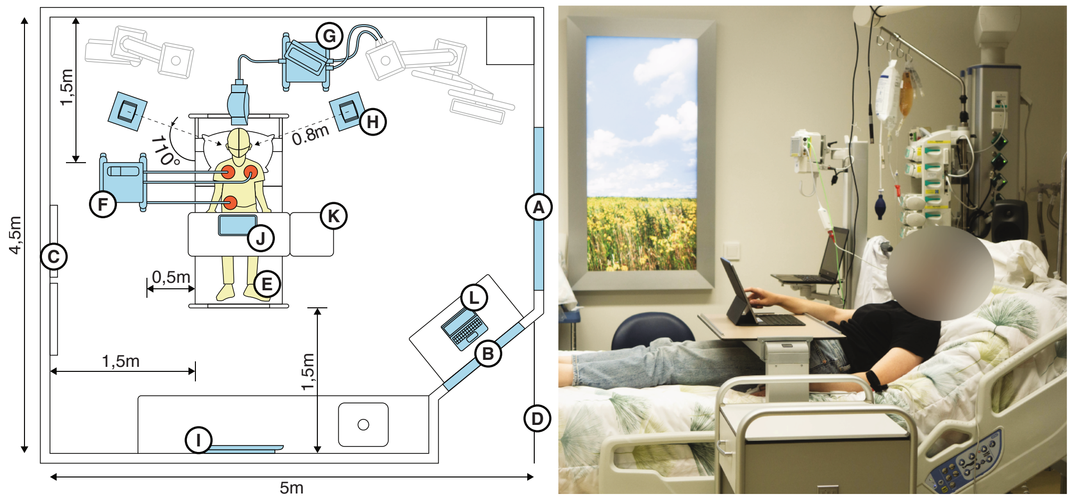

Fig. 1. Floorplan of experimental setup (left) and photograph of participant in the room (right).

ICU department of Erasmus Medical Center, see Fig. 1.

The room included a sound-proof sliding door (Fig. 1, A), nurse-window for observations (Fig. 1, B), and back-lit wall art mimicking an outside window depicting natural scenery (Fig. 1, C). There were no other windows in the room. A researcher (GL) controlled the experiment from outside behind the nurse-window (Fig. 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. 1, E). The bed-head was tilted 30°, resulting in ear-height of approximately 1.2 m. This semi-upright angle repositions the upper body of patients, and is commonly used in ICUs to improve respiration [26]. A patient monitor (Dräger Infinity M540) with laptop (Fig. 1, F) was placed near the bed (h = 1.6 m). Three ECG electrode patches were connected to participants from the patient monitor. A mechanical ventilator (Maquet Servo-i Ventilator System V8.0) (Fig. 1, G) was positioned behind the bed.

Two speakers (Genelec 8020DPM) (Fig. 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 0.8 m distance, as suggested in placement documentation [14]. A 42″ LCD screen (Fig. 1, I) was located on the opposing wall to provide digital timers for the rating tasks. Participants rated on a 13″ iPad Pro (Fig. 1, J) in front of them on a bedside table (Fig. 1, K). The speakers were connected to a MacBook Pro 13″ (Fig. 1, L). Soundscape interventions were played from the sound card of this laptop on a constant gain.

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 [34]. 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 [34]. Full methodological details and rationale for these compositions can be found in Louwers et al. [34]. Each sonic ambiance type relates to a distinct, particular grouping of psychological needs based on a need taxonomy [9], see Table 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).

A sound artist with music conservatory training used the sonic ambiance qualities and perceived eventfulness as input for creating the compositions, see Table 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 [12,29,52]. 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 [57] 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

Table 1
Sonic ambiance types and related psychological needs.

Sonic ambiance type	Psychological needs			
Comfortable	Security	Comfort		
Pleasurable	Autonomy	Beauty	Relatedness	
Stimulating	Fitness	Recognition	Competence	Stimulation

Table 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

process, see the previous study [34].

2.4. ICU room soundscape: ICU-bg1 and ICU-bg2.

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 Fig. 2.

Yellow medium priority alarm sounds ($t \approx 0.8$ s) 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) [7]. Furthermore, since many ICU patients require respiratory support [11], sounds of mechanical ventilation were incorporated. Mechanical ventilation sounds consisted of both an inhalation and an exhalation sound (see Fig. 2), lasting for $t \approx 0.5$ s each. To simulate a real lungs' resistance during inhalation and exhalation, an artificial lung (Dräger SelfTestLung 1000 mL) was attached to the mechanical ventilator [15]. Respiratory rate (RR) was set to standard device setting of 15 breaths/min, within standard variations (RR = 12 – 20) of adult ICU patients [32]. 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.

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 [34]. The measured A-weighted sound level within the single-patient ICU room during the ICU-bg_1 condition was $L_{A,eq185s} = 36.3$ 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 [34]. Acoustical measurements in $L_{A,eq}$ of ICU-bg_2 alone and ICU-bg_2 with each added soundscape intervention are included in the Appendix (Table 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 0.5 m 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.

3. 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 [4]: 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 200 Hz 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 ISO [18]. In line with the circumplex model of affect [49], 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 [3] 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.

The experiment consisted of 13 epochs, see Fig. 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. 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. 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

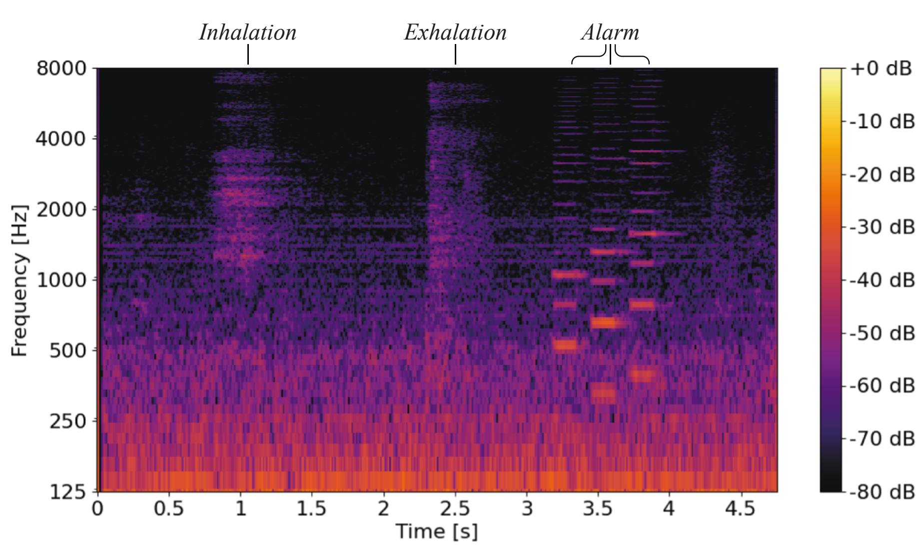

Fig. 2. Spectrogram of ICU-bg_2 over 5 s with a frequency range between 125 – 8000 Hz, featuring air conditioning, inhalation and exhalation by the mechanical ventilator and medium priority (yellow) alarm from the patient monitor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

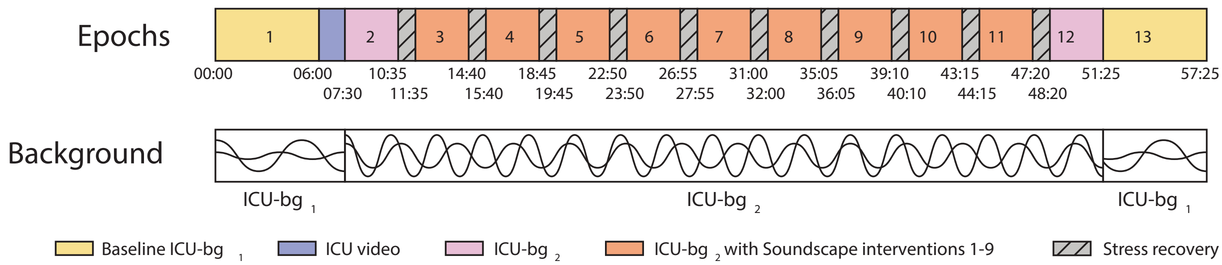

Fig. 3. Experimental procedure showing the epochs, including nine soundscape interventions, ICU-bg$_1$, the simulated ICU-bg$_2$ soundscape, and respective durations.

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 s of listening to ICU-bg$_2$ was included to allow stress recovery.

3.1. *Data analysis*

3.1.1. *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 [17]. 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 [42]. 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 50th percentile kernel density plots [42]. 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 [40].

3.1.2. *Physiological stress indicators*

ECG data was pre-processed using a 40 Hz low-pass filter and a minimum R-peak amplitude cutoff of 50 millivolts using PhysioData Toolbox [54]. 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 [16]. 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:

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

where $\text{HRV}_{\text{epoch}}$ represents the median RMSSD or IBI value for a given epoch, and $\text{HRV}_{\text{ICU-bg1}}$ 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.

4. Results

4.1. *Effects on the perception of the soundscape*

In Fig. 4, boxplots show the dispersion of perceived pleasantness (Fig. 4a) and eventfulness (Fig. 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.

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. 4a), we found a significant main effect ($F(2.7, 68.0) = 27.2$, $p < 0.001$, $\eta^2 = 0.52$). 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. 4b), a significant main effect was also found ($F(3.1, 78.0) = 38.5, p < 0.001, \eta^2 = 0.61$). 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.

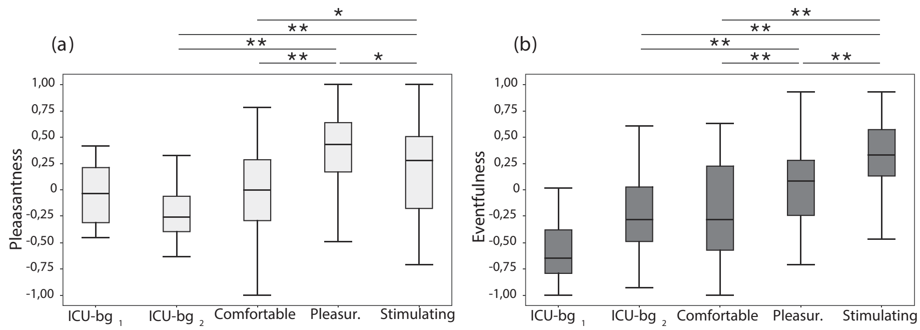

Fig. 4. Dispersion and central tendency of resulting soundscapes across sonic ambiance types of soundscape interventions for pleasantness (a) and eventfulness (b). (*) 0.001 <= p <= 0.01, (**) p < 0.001. To declutter the figure, indications of significant pairings with ICU-bg$_1$ were omitted.

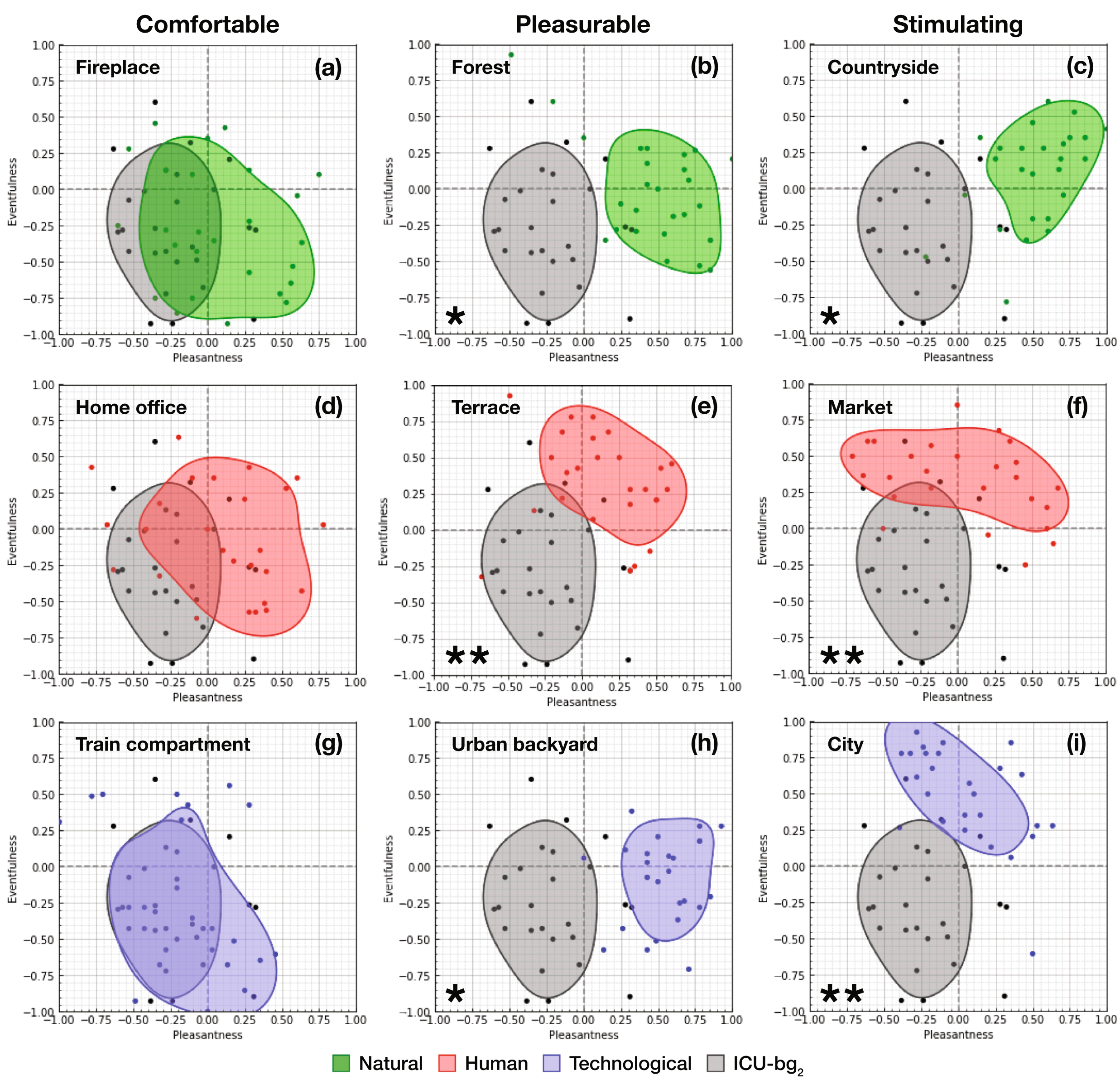

Fig. 5. 50th percentile kernel density plots of ICU-bg$_2$ with soundscape interventions versus ICU-bg$_2$ alone. (*) indicates significant differences in pleasantness, (**) indicates significant differences in eventfulness.

In Fig. 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 ($F(6, 150) = 17.3$, $p < 0.001$, $\eta^2 = 0.41$) and also for eventfulness ($F(5, 135) = 18.2$, $p < 0.001$, $\eta^2 = 0.42$). 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 [2]. A moderate (ICC = 0.53, $CI_{95\%}$ 0.20 – 0.76, $p = 0.002$) consistency was found for pleasantness, and a good (ICC = 0.72, $CI_{95\%}$ 0.52 – 0.86, $p < 0.001$) 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.

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 ($F(4, 100) = 9.6$, $p = 0<.001$, $\eta^2 = 0.28$) and eventfulness ($F(4, 100) = 8.1$, $p = 0<.001$, $\eta^2 = 0.25$) as can be seen in Fig. 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. 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. 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.

4.2. Effects on the listener

4.2.1. 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 Fig. 7.

For experienced pleasure, a significant difference was found between the sonic ambiance types and ICU-bg$_1$ and ICU-bg$_2$ ($F(4.1, 107.3) = 15.8$, $p < 0.001$, $\eta^2 = 0.39$). 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 ($F(4.3, 107.8) = 4.7$, $p = 0.001$, $\eta^2 = 0.16$). 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 ($r = 0.85$, $p < 0.001$) 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 ($F(4, 100) = 11.7$, $p < 0.001$, $\eta^2 = 0.32$). 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.

4.2.2. 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,

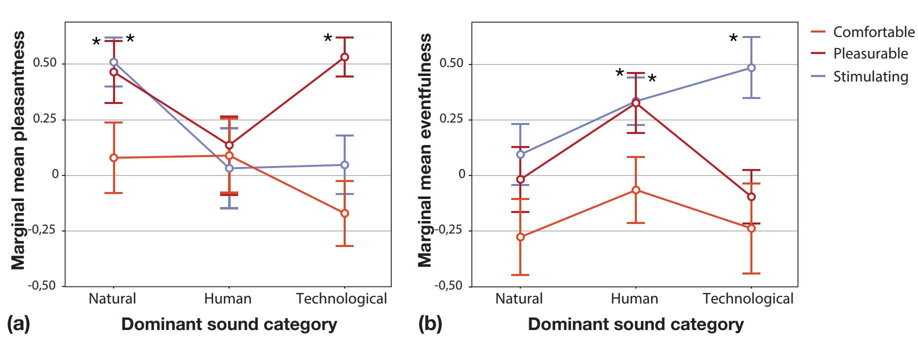

Fig. 6. Interaction plot of estimated marginal mean differences in (a) pleasantness and (b) eventfulness, error bars indicate 95% Confidence Interval, (*) indicates significant pairings within sonic ambiance types for each dominant sound category.

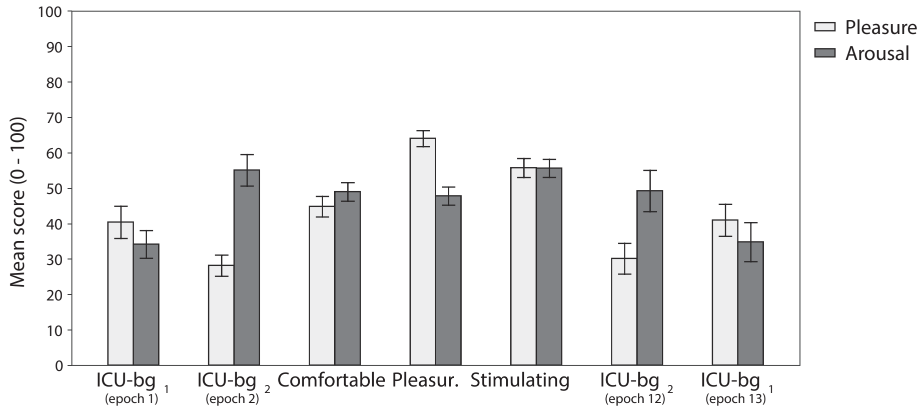

Fig. 7. Bar charts of mean pleasure and arousal scores ranging from 0 to 100 as indicated by participants with sliders, with each error bar constructed using one standard error from the mean.

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.

In Fig. 8, the RMSSD (Fig. 8a) and IBI (Fig. 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 Fig. 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. 8a) and IBI (Fig. 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 ($t(18) = 2.84$, $p = 0.005$) and IBI ($t(18) = 5.46$, $p < 0.001$). This suggested that participants were in a more relaxed state after listening to the soundscape interventions than before.

5. Discussion

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.

5.1. *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

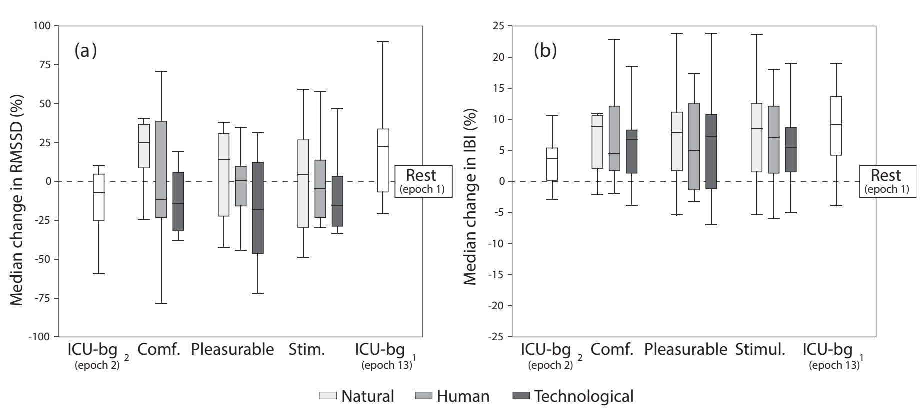

Fig. 8. Boxplots of percentage changes in RMSSD (a) and IBI (b) compared to Baseline ICU-bg_1 of epoch 1, in rest.

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 [5]), 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 [45]. A prerequisite of our need-driven approach presented in an earlier study [34] 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 [34]. 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 [33]. 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 [33]. 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.

5.2. 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 [6]. 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 [9]. 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 [33]. 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 [55].

5.3. 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 [60]. 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 [50] and health benefits related to exposure to nature in general [21]. 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 [28]. 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.

5.4. 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 [33]. 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 [1], 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. 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.

CRediT authorship contribution statement

Gijs Louwers: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sylvia Pont:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Esther M. van der Heide:** Supervision, Data curation, Formal analysis, Writing – review & editing. **Gabriele Papini:** Writing – review & editing, Methodology, Conceptualization. **Rene van Egmond:** Conceptualization, Methodology, Formal analysis. **Diederik Gommers:** Writing – review & editing, Supervision, Resources, Conceptualization. **Elif Özcan:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: GL is employed by Delft University of Technology through the project fund.

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Appendix A

Table 3
Backgrounds and soundscape interventions with measured sound level $L_{Aeq,185s}$ (dBA).

Background	Soundscape intervention	$L_{Aeq,185s}$
ICU-bg_1	–	36.3
ICU-bg_2	–	38.9
ICU-bg_2	Fireplace	41.5
ICU-bg_2	Home office	40.5
ICU-bg_2	Train compartment	39.7
ICU-bg_2	Forest	42.7
ICU-bg_2	Terrace	43.2
ICU-bg_2	Urban backyard	40.0
ICU-bg_2	Countryside	42.1
ICU-bg_2	Market	42.7
ICU-bg_2	City	46.2

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2025.110975.

Data availability

The data supporting the findings of this study are openly available on Zenodo at: https://doi.org/ 10.5281/zenodo.14867355

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