# ICU sound interventions in the time of sars-cov-19: lessons learned from the sounds4coma residency

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*«If I ever hear that Celine Dion album again, I will kill you!»*
One coma patient upon awakening, cited in Owen, 2017.

ABSTRACT

An interesting collaboration has been formed to help one of the world's most vulnerable populations. Sounds4Coma is a cross-disciplinary team tackling the many issues related to sound in the context of the Neurological ICU Ward. The project was initiated by the Neuro ICU team at Paris' Hospital Sainte-Anne, led by Prof. Tarek Sharshar, M.D., in concert with neuroscientists from Parisian sound art institute IRCAM. However, the project found new life and inspiration by bringing in an outside perspective - sound artists from the games industry, Ali Tocher & Joe Acheson. Together, this multidisciplinary team is constructing a dynamic soundscape as a therapy tool to help to manage patient's pain and anxiety.

## THE ICU SOUND ENVIRONMENT

Intensive care units (ICUs) host the most severe of general hospital wards patients who require constant care and life-support equipment to ensure normal bodily functions. Common conditions that are treated within ICUs include traumatic brain injuries, strokes, or acute respiratory distress syndrome, and may involve therapeutically-induced or pathological disorders of consciousness such as coma, vegetative or minimally-conscious states.

Patients under critical care experience a highly stressful environment. In addition to the physical stress of illness, pain, sedation and mechanical ventilation, sound is one of the major psychological stressor of patients of intensive care units (Wenham & Pittard, 2009). As patients and staff battle life-threatening illness, the sonic environment is frenetic, loud and anxious. More than 50,000 alarms per month cry out from cardiac monitors, ventilators and syringe pumps in a typical adult ICU (187 alarms / bed / day in Drew et al. 2014), and many of them are false positives: for instance, as many as 75% of cardiac monitor alarms can be due to patient movement resulting in bad signal detection, and a majority of ventilator alarms are uselessly triggered during interventions like suction or physiotherapy (O'Carroll 1986).

All these alarms, combined with staff conversations, intercoms, closing doors or items falling onto the floor, result in average noise levels of 60–70 dB(A), with peaks over 90 dB(A), an excess of 30-40 dB(A) over World Health Organization recommendations (Venhard et al. 1997). Such levels are highly disruptive of patient sleep, with electronic sounds and conversations above 40dBA having more than 80% probability to arouse patients (Waye et al. 2013), and may also be associated with conditions such as high anxiety and psychosis (Figueroa-Ramos, 2009). A sonic state like this, in a place that intends, and truly needs, to be a therapeutic environment, may in fact be detrimental to the patients it tries to protect.

## TARGETS FOR SOUND INTERVENTIONS IN THE ICU

*"We constantly balance, on one hand, reducing our patient's pain and anxiety, and on the other, trying to keep them alive"* say Paris' Sainte-Anne Hospital Intensivists Aurelien Mazeraud and Tarek Sharshar. Mazeraud, Sharshar and their colleagues recently reported results of a study showing a strong correlation between a patient's anxiety and their prognosis for recovery (Mazeraud et al. 2018). This study led them to reflect on the potential negative impact of the current soundscape in their ICU and, together with cognitive scientists at Paris sound research institute IRCAM, set to form a new team to re-imagine how their hospital can sound. A call was put out to sound artists, composers and sound

designers through European Commission residency program Vertigo Starts (https://vertigo.starts.eu/) in Fall 2018, and British sound artists Ali Tocher and Joe Acheson were selected to join the project.
The team met several times at Hospital Sainte-Anne and Hospital George Pompidou in Paris in Spring 2019 to conduct field visits, and discuss the specific environment of their ICU. We identified a number of possible targets for sound interventions, some of which already tackled by design/art projects.

| Target | Problem | Existing & possible sound interventions |
|---|---|---|
| High sound levels | Average ICU sound levels are 60-80 dB(A). That amount of noise is detrimental to patient sleep, and possibly associated with patient anxiety, demencia, and carer fatigue (Wenham & Pittard, 2009) | **Acoustic modifications** (weather stripping on all doors and drawer fronts, replacement of metal elements with rubber, installation of sound-absorbing panels; e.g. Walsh-Sukys, 2001)<br>**Acoustic guidelines** (Systematic closure of all doors, coordination and limitation of nursing interventions after 11 pm, no use of phone, interphone, television, or radio; e.g. Walder et al. 2000) |
| Sensory deprivation & loss of self | Visual and auditory sensory deprivation, e.g. lack of outside window, lack of interaction, is thought to be linked to the incidence of delirium in ICU patients (Wilson, 1972). There is debate and a lack of experimental evidence whether the opposite, a richer sensory environment, can improve arousal and awareness in vegetative state patients (Wood, 1991). | **Rich auditory environments** (soundscapes and/or music composed or selected for cognitive stimulation or emotional regulation; e.g. Verger et al. 2014)<br>**3D/peripersonal sound** (dynamic 3D sound environment around the patient that emphasize body ownership and sense of self; e.g. Noël et al. 2019)<br>**Familiar sounds / sound walks** (own-name, own-music, and audio environments that mimic the patient's familiar environment and trigger episodic memory; e.g. Demertzi et al. 2013) |
| Social isolation | Interpersonal communication with ICU patients is both rare (5% of nursing time; Baker & Melby 1996) and degraded (e.g. unable to speak with ventilation), and is associated with patient/family dissatisfaction and negative clinical outcomes (Lilly et al. 2003) | **Alternative & Augmentative communication** (interactive systems that sonify/verbalize patient's communicative gestures or physiological state; e.g. Blain-Moraes et al. 2013)<br>**Streaming sounds from family/home** (immersive audio telepresence systems; e.g. Kobayashi, Ueoka & Hirose, 2008) |
| Consciousness evaluation | Behavioral and EEG responses to standardized sound stimuli (e.g. pure tones) are part of clinical coma/consciousness evaluation (André-Obadia et al. 2018). More salient emotionally relevant stimuli, such as recordings of own-name (Perrin et al. 2006) or own-mother's voice (Machado et al. 2007), improve responses. | **Sound design/composition of more efficient stimuli** (stimuli that are more emotionally involving, e.g. Fiacconi & Owen, 2016)<br>**Better audio baselines** (audio environments that stimulate cognitive functions before clinical evaluation; e.g. Verger et al. 2014) |
| Alarms | ICU alarms are too many, often unnecessary (Drew et al. 2014), and the lack of agreement between equipment manufacturers make them redundant or difficult to identify (Meredith & Edworth, 1995). In patients, this contributes to loss of sleep and anxiety. In caregivers, | **Silencing the ICU:** Replacing sound alarms by visual messages or haptic feedback.<br>**Sound design:** making alarm sounds more intuitive with sound icons (heartbeat sound, rattling pill bottle, Schlesinger & Shirley, 2019), or more esthetically pleasing (musical tone relations between co-sounding equipment, Sen & Sen, 2020; sonifying patient physiology with music, Bogers |

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|---|---|---|
| | causes alarm fatigue and medical errors. | 2018) |
| Alteration of circadian rhythms | Patients in the ICU lose track of days/nights and have abnormal sleep/wake patterns (Gazendam et al. 2013). Realigning circadian rhythms may be beneficial for clinical recovery in critically ill patients. | **Cycled sound** (auditory/multimodal environments that cycle through wake/sleep phases to restore circadian rhythms; e.g. Engwall et al. 2013) |
| Pain | Pain is a common and distressing symptom in ICU patients (78% of patients in Gelinas, 2007), often despite pharmacological pain management. Untreated acute pain has negative impact on patient physiology and increase time to recovery (Dunwoody et al. 2008) | **Music therapy** (musical programs composed to emphasize relaxing/deactivating acoustic elements ; e.g., Guétin et al. 2014)<br><br>**Relaxing soundscapes** (immersive environmental sounds constructed as auditory journeys, to reorientate attention; e.g. Nazemi et al. 2017) |
| Anxiety | Anxiety is the most common psychological stressor in ICU patients (52% of patients in Mazeraud et al. 2018) and is predictive of subsequent clinical deterioration irrespectively of a patient's initial severity. | |

## THE SOUNDS4COMA RESIDENCY

Building on the artists' background in game audio design (Ali Tocher) and music composition (Joe Acheson), the sounds4coma project aimed to reduce ICU patient anxiety and pain using a musical/soundscape composition that can be dynamically controlled using non-linear generative audio tools. We describe here the technical aspects of a first prototype, which is now being tested in the context of ICU patients with subarachnoid hemorrhage and, as of April 2020, respiratory failure because of SARS-CoV-2.

### Inspiration

The influence of music listening on affective states is well known (Juslin & Laukka, 2003; Eerola & Vuoskoski, 2013) and a lot of excellent work has been undertaken by music therapists to target pain and anxiety in both clinical and non-clinical contexts (e.g., Guétin et al. 2014.; for recent reviews see Panteleeva et al., 2018 & Howlin & Rooney, 2020). Many of such interventions use a patient's favorite musical genre (Guétin et al. 2014), or even favorite musical items (Verger et al. 2014) to ensure the level of attention and positive affective reactions thought necessary for them to work. However, many factors make such selection problematic in our case: first, the demographics of ICU trauma patients, with diverse age groups and oft-non-western cultures, make it difficult to preselect a genre or type of composition; second, many of our targeted patients are non-responsive or unconscious and thus impossible to involve in music selection; third, with a median ICU stay of 5 days, involvement of family/closed ones to select material is more difficult than e.g. for chronic vegetative or minimally conscious patients in long-stay units (Verger et al. 2014). For all these reasons, we instead turned to use natural sounds such as wind, waves, rain, as these sounds were shown to be no less effective than music in the context of acute pain (Villarreal et al. 2012) and we anticipated that they might be more widely relevant and less subjective than music. A first attempt at purely reproducing these natural sounds performed poorly in a public trial, confirming our intuitions that these sounds did not command enough attention from the listeners (see also Nazemi et al. 2017). We therefore sought a method to move the chosen sounds from unprocessed natural recordings towards a more intentional soundscape composition, in which compositional elements interact with the natural randomness of environmental sounds.

### Sound material

Setting out to find natural rhythms and tones that fit our purpose, we went down a path of looking at eastern cultural music, including those cultures who have sonic healing traditions, such as in Tibet, Kazakhstan or Bali. We looked at the commonality between these diverse traditions and we saw that e.g. singing-bowl practices from Tibet, meditation gongs from Burma or Indonesia, temple bells from China, all used bell-like instruments with long, held tones, with distinct and clean overtones (Crowe & Scovel, 1996). We therefore decided to base our work on wind chimes (a particular type of metallophone in which suspended metal tubes or rods are freely struck by a clapper activated by the blowing wind) because they are relatively culturally neutral, and afford a natural interaction with sounds of wind. Taking a long sample of chimes recorded in The Scottish Borders by Tocher, we identified 10 single hits or rapid clusters, and 3 sequences of multiple hits that had motif properties.

## Using Bells As Impulse

Desiring to extract rhythmic and tonal information from the bells, we first employed spectral analysis to assess the frequency of the fundamental tone and key overtones for each sample. (see figure XXXX ). We also wanted broadband natural sounds to interact with the bells. We built a tool to take the frequency information and use it to colour wind samples so that they would "sing" in unison with each chime sample. The identified frequencies (see table XXX) were then fed into a series of EQs, each bandpassed to one of these frequencies. These EQ channels (Impulse Input Channels) were routed to several channels (Wind Output Channels) that contained a wind sample and had another bandpass EQ, tuned to the corresponding frequency of the EQ on the routed Impulse Input Channel. To incorporate the rhythmic qualities of the bells, we applied a Gate/Expander to each channel of wind. These were set so that they caused audio to output only when signal was received from the input channel. Thus when an individual chime sample played, the Impulse Input Channels with EQs tuned to the key frequencies would trigger the gate/expander on the corresponding Wind Output Channels. Bandpassed wind samples with the same tonal and rhythmic structure as the currently playing bell then "sang out" and was recorded for each sample. As thoroughly demonstrated by the preceding sentences; this technique was relatively ungainly, and a more dynamic and automated process is being sought for future works. We then collected recordings of the ocean in different states of agitation and from different perspectives, and curated samples of these to fit each chime/wind sample.

## Generative framework

These samples are then put into a piece of software used for game audio development called FMOD. This software enables us to control the variables of how the sound is reproduced and gives us an easy path to creating an app in the future. This environment also allows us to apply the U shaped playback method which has been developed by a music therapy hospital project called Music Care. For our composition the U-Shape is created (as shown in table XXX) by initially triggering the wind-chimes at their unity pitch, with active waves to capture the listener's attention. As we proceed down the U the pitch is reduced in octaves, causing the chimes collision impulses to be triggered less often. Tonal content also lowers and the waves become less active and softer. This process is mirrored to bring the listener back "up" at the end of the piece.

Our prototype application interface allows the user to either let the U shape play out as prescribed, each of the 9 stages playing for a fixed duration (eg. 5min. for a total play time of 45 min.), or to "freeze" the playback in its current location in the program. Because the system is generative, it can play pseudo-infinitely, with random variation to the samples.

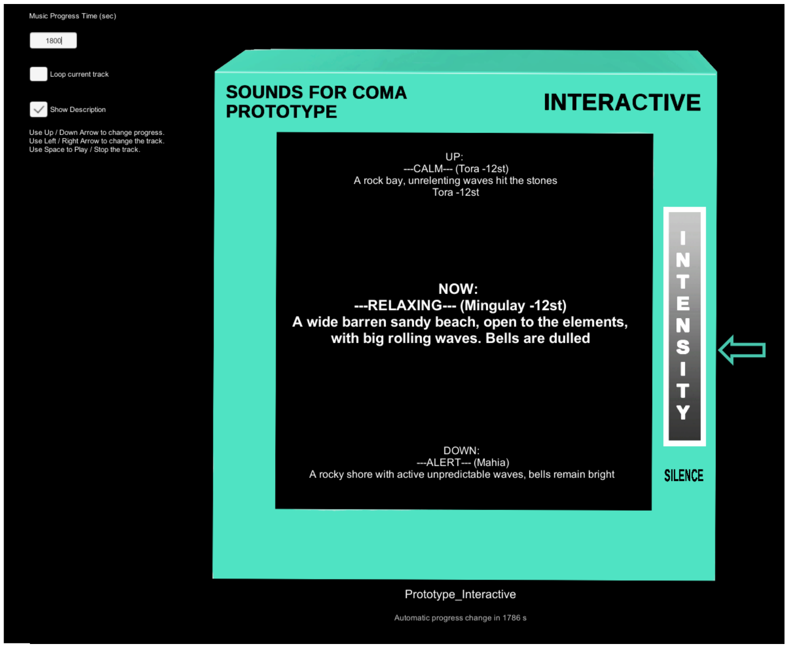


Figure 1- Application user interface.

## Preliminary user testing

The sounds4coma prototype is currently being tested in the Neuro-ICU unit of the Sainte-Anne hospital in Paris, France. It the time of writing, we conducted preliminary user tests on two populations of patients:

- Neurological patients referred to the ICU for a **subarachnoid haemorrhage** (SAH), a life-threatening type of stroke caused by bleeding on the surface of the brain (the area between the *arachnoid* membrane and the pia mater surrounding the brain). SAH patients are typically conscious, but experiencing deep pain which is not easily controlled with analgesics like morphine and which is likely amplified by anxiety (Swope et al., 2014). In addition, one frequent complication of SAH is the occurrence of cerebral vasospasm (narrowing of the blood vessels) and delayed cerebral ischemia 4 to 10 days after admission, which is a major cause of death in these patients. It is believed that both pain and anxiety have a role in the secretion of endothelin-1, which in turn is associated with higher risk of vasospasm (Thampatty et al. 2011). Our hypothesis is that active exposure to the sounds4coma prototype in SAH patients will have a positive effect on perceived pain (measured with a 1-10 numeric scale, heart-rate variability measures and reduction in analgesics), anxiety (measured with the State Trait Anxiety Inventory questionnaire, STAI-Y), and possibly the occurrence of vasospasm and delayed ischemia.
- Patients with **respiratory insufficiency** consequent to infection with SARS-Cov-19 and admitted in critical care for mechanical ventilation (Figure 2). These patients experience stress and anxiety, and may become especially agitated during the process of weaning (the transition from mechanical ventilation support to spontaneous breathing). If such agitation is not managed appropriately, it may lead to traumatic self-extubation, extended duration of sedation, longer length of ICU bed occupancy and prolonged mechanical ventilation (Woods et al. 2004), the latter two factors being particularly critical in periods with scarcity of ICU resources such as the SARS-Cov-19 pandemic. Both music (Jaber et al. 2006) and nature-based sound exposure (Aghaie et al. 2014) have proved useful in the context of weaning. Our hypothesis is that passive exposure to the sounds4coma prototype in Cov-19 patients undergoing weaning will reduce agitation (measured with the Richmond Agitation-Sedation Scale, RASS), increase the rate of successful weaning and decrease ventilation time.

Initial user tests with two conscious ICU patients confirmed that patients could interact with the prototype interface to control their listening, and that they were willing to engage recurrently with the system during their ICU stay. In addition, initial tests with two unresponsive patients confirmed that passive listening for 30 minutes had an effect on monitored vitals such as blood pressure and respiratory rates; anecdotally, one unconscious patient had continuous hiccups which ceased as listening to the prototype unfolded. Based on this proof of feasibility, we started including patients from our two targeted populations into a formal test of the system, to be reported later.

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Figure 2: one mechanically-ventilated patient experiencing passive exposure to the sounds4coma prototype at the Sainte-Anne Hospital Neuro-ICU unit.

## LESSONS LEARNED & FUTURE STEPS

Working in the ICU environment comes with a lot of delicate issues and constraints. We had invaluable access to the neuroscientists and intensivists attached to this project, but in the process we were surprised by a number of facts which led us to correct our misconceptions of how sound art can be deployed in a clinical setting.

1. **Research in music cognition hasn't yet reached the stage of informing musical creation.**

Our first impulse to design music/sounds that can alleviate anxiety was to look at the recent music cognition literature for acoustic or music-structural elements known to affect stress and anxiety. While there is a wealth of research on music and emotion (for a review, Eerola & Vuoskoski, 2013), we found that it was difficult to use it to inform our creative process: first, a lot of work either studies the fine acoustic properties (pitch contour, timbre) of very short stimuli, or the long-term average properties (mode, tempo) of well-known pieces from the repertoire, neither of which can easily translate to compositional practice. When list of features are assembled from meta-studies, they should be understood as statistical co occurrence and not as a cooking recipe (e.g. both happiness and anger are found associated with high tempo, high intensity and high pitch in  Table 11, Juslin & Laukka, 2003); second, emotional reactions to music are generally studied as a perceptive outcome ("is this music happy or sad ?") more than a subjective experience ("does this music make you feel calm ?"), and (perhaps rightfully so) do not construe anxiety and pain as emotional reactions. When studies attempt to link music listening with anxiety (Panteleeva et al., 2018) or pain (Howlin & Rooney, 2020), they mostly focus on the activity of listening to *music* (as opposed to doing something else in a control condition), irrespective of the acoustic elements of the stimuli used for the study. In short, selecting sound material for our work was more a matter of intuition than a fact-based decision.

2. **There is a divide between many general-public claims about music & health, and science**

Perhaps ironically, the most explicit prescriptions on how to create functional music for e.g. health or relaxation come from general-public sources with little if any scientific support: converting pitch tuning to 432hz (14,100,000 results from Google video search for "432Hz music", retrieved 10/04/2020; compare with the limited evidence of Calamassi &

Pomponi, 2019), creating binaural beatings with two close tones (24,100,000 video search results; Garcia-Argibay et al. 2019), or the so-called autonomous sensory meridian response (ASMR, 143,000,000 video search results; Barratt, Spence & Davis, 2017). While such large-scale cultural phenomena command attention, and may be worth studying with the tools of experimental science, we found it surprising that there was so little scientific consensus on these auditory objects, which seem to be construed by researchers as “outside of science”, and it was difficult to bring these up as valid options to use in the ICU.

3. **The clinical environment is not the place to try and test parameters**

In the absence of clear recommendations from the literature, a project like ours entails choices for many parameters that, in an ideal world, we would like to test and fine-tune: are wind-chimes better than other instruments ? should pitch go up or down with increased relaxation ? are sounds from the sea more culturally accepted than sounds from the forest ? etc. We found these parameters very difficult to test in the ICU environment: the cost (ethical, clinical and also financial) of testing on patients is high; patient etiologies are very diverse, making different conditions difficult to compare without very large samples; and it is ethically difficult to have negative controls (i.e. sounds that we suspect will not work as well as others, but for which we would need confirmation; see also Porter et al. 2014). On the other hand, we also found it difficult to create a proxy for ICU-related anxiety with healthy controls in the lab (“imagine you’re in a coma…”), and did not feel we could rely on such prior testing. So, many choices ended up being a leap of faith, for which we could only hope for a confirmation when the complete system is tested.

4. **In deploying the app, it is unclear what belongs to clinical medicine, what belongs to user experience, and who’s in charge of what**

Beyond composition parameters, many design choices concern how the system is presented to patients: how long should one play the music (30minutes, 1 hour, once a day, several times, etc.) ? How should the sounds be presented (in-ear monitors, headphones, loudspeakers, etc.) ? While doctors are typically in charge of such decisions for treatments (posology, in pills or via IV, etc.), we found that standards were lacking for interventions such as ours, and we were no help either. It was unclear who in the patient’s environment is best positioned to make these decisions, and based on what process. One possibility would be to rely on qualitative analysis methods on patient and staff interviews, as done e.g. for the use of augmentative and alternative communication tools in patients unable to speak (Broyles, Tate & Happ, 2012), or on structured observation strategies, as done for e.g. for field research in design (Schokkin, 2019)

5. **Very little is known about patient subjective experience of sound in the ICU**

One question that was raised by hospital staff during informal listening test to the sounds4coma prototype was whether coma patients would really aspire to being cast into a sound universe, made of wind, sea sounds and bells, that are in many cultural representations linked to spirituality and rites of passage to the beyond, or on the contrary would prefer being reconnected to a reassuring world of mundane and familiar sounds. The truth is - nobody seems to know. Very little is known about the cultural representations that are associated with the experience of life-threatening conditions in critical care (Pouchelle, 1996), and how these representations may shape a patient’s experience of sound during their stay. At a lower, perceptive level, it is even unclear how the ICU experience influences auditory processing, e.g. how lying in bed horizontally influences 3D sound localisation, or how the interoception of the sound and vibration of mechanical ventilation conflicts or masks exteroceptive sounds. For such questions, as well as for the previous points raised here, the design and testing of our sound intervention prototype has highlighted the need for a richer comprehension of sound experience in the atypical, but highly critical, situation of coma and intensive care. Progress on this issue is likely to involve practitioners not only of medical science, but also e.g. design and anthropology and, most importantly, patients - survivors and their families.

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## REFERENCES

Aghaie, B., Rejeh, N., Heravi-Karimooi, M., Ebadi, A., Moradian, S. T., Vaismoradi, M., & Jasper, M. (2014). Effect of nature-based sound therapy on agitation and anxiety in coronary artery bypass graft patients during the weaning of mechanical ventilation: A randomised clinical trial. *International journal of nursing studies*, *51*(4), 526-538.

André-Obadia, N., Zyss, J., Gavaret, M., Lefaucheur, J. P., Azabou, E., Boulogne, S., ... & Naccache, L. (2018). Recommendations for the use of electroencephalography and evoked potentials in comatose patients. Neurophysiologie clinique, 48(3), 143-169.

Baker C, Melby V. An investigation into the attitudes and practices of intensive care nurses towards verbal communication with unconscious patients. J Clin Nurs 1996;5(3):185-92

Barratt, E. L., Spence, C., & Davis, N. J. (2017). Sensory determinants of the autonomous sensory meridian response (ASMR): understanding the triggers. *PeerJ*, *5*, e3846.

Blain-Moraes, S., Chesser, S., Kingsnorth, S., McKeever, P., & Biddiss, E. (2013). Biomusic: a novel technology for revealing the personhood of people with profound multiple disabilities. *Augmentative and Alternative Communication*, *29*(2), 159-173.

Bogers, K. 2018. Care Tunes. Master's thesis. Delft University of Technology.

Broyles, L. M., Tate, J. A., & Happ, M. B. (2012). Use of augmentative and alternative communication strategies by family members in the intensive care unit. *American Journal of Critical Care*, *21*(2), e21-e32.

Calamassi, D., & Pomponi, G. P. (2019). Music tuned to 440 Hz versus 432 Hz and the health effects: a double-blind cross-over pilot study. *EXPLORE*.

Crowe, B. J., & Scovel, M. (1996). An overview of sound healing practices: Implications for the profession of music therapy. *Music Therapy Perspectives*, *14*(1), 21-29.

Demertzi, A., Vanhaudenhuyse, A., Brédart, S., Heine, L., Di Perri, C., & Laureys, S. (2013). Looking for the self in pathological unconsciousness. *Frontiers in human neuroscience*, *7*, 538.

Drew, B. J., Harris, P., Zegre-Hemsey, J. K., Mammone, T., Schindler, D., Salas-Boni, R., ... & Hu, X. (2014). Insights into the problem of alarm fatigue with physiologic monitor devices: a comprehensive observational study of consecutive intensive care unit patients. *PloS one*, *9*(10).

Dunwoody, C. J., Krenzischek, D. A., Pasero, C., Rathmell, J. P., & Polomano, R. C. (2008). Assessment, physiological monitoring, and consequences of inadequately treated acute pain. *Pain Management Nursing*, *9*(1), 11-21.

Engwall, M., Fridh, I., Johansson, L., Bergbom, I., & Lindahl, B. (2015). Lighting, sleep and circadian rhythm: An intervention study in the intensive care unit. *Intensive and Critical Care Nursing*, *31*(6), 325-335.

Eerola, T., & Vuoskoski, J. K. (2013). A review of music and emotion studies: Approaches, emotion models, and stimuli. *Music Perception: An Interdisciplinary Journal*, *30*(3), 307-340.

Figueroa-Ramos, M. I., Arroyo-Novoa, C. M., Lee, K. A., Padilla, G., & Puntillo, K. A. (2009). Sleep and delirium in ICU patients: a review of mechanisms and manifestations. *Intensive care medicine*, *35*(5), 781-795.

Garcia-Argibay, M., Santed, M. A., & Reales, J. M. (2019). Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis. *Psychological Research*, *83*(2), 357-372.

Gazendam, J. A., Van Dongen, H. P., Grant, D. A., Freedman, N. S., Zwaveling, J. H., & Schwab, R. J. (2013). Altered circadian rhythmicity in patients in the ICU. *Chest*, *144*(2), 483-489.

Gélinas, C. (2007). Management of pain in cardiac surgery ICU patients: have we improved over time?. *Intensive and Critical Care Nursing*, *23*(5), 298-303.

Guétin, S., Falvay, D., Chanques, G., Jaber, S., de Lattre, S., Souche, B., ... & de Diego, E. (2014). Evaluation of the Standardized MUSIC CARE© App in the Treatment of Pain: The U-Shape Composing Technique. *Music and Medicine (Online)*, *6*(2), 46.

Howlin, C., & Rooney, B. (2020). The Cognitive Mechanisms in Music Listening Interventions for Pain: A Scoping Review. *Journal of Music Therapy*.

Jaber, S., Bahloul, H., Guétin, S., Chanques, G., Sebbane, M., & Eledjam, J. J. (2006, November). Effects of music therapy in intensive care unit without sedation in weaning patients versus non-ventilated patients. In *Annales francaises d'anesthesie et de reanimation* (Vol. 26, No. 1, pp. 30-38).

Juslin, P. N., & Laukka, P. (2003). Communication of emotions in vocal expression and music performance: Different channels, same code?. *Psychological bulletin*, *129*(5), 770.

Kobayashi, H., Ueoka, R., & Hirose, M. (2008, October). Wearable forest-feeling of belonging to nature. In *Proceedings of the 16th ACM international conference on Multimedia* (pp. 1133-1134).

Lilly CM, Sonna LA, Haley KJ, Massaro AF. Intensive communication: four-year follow-up from a clinical practice study. Crit Care Med 2003;31(5 suppl.):S394—9.

Machado, C., Korein, J., Aubert, E., Bosch, J., Alvarez, M. A., Rodríguez, R., ... & Chinchilla, M. (2007). Recognizing a mother's voice in the persistent vegetative state. Clinical EEG and neuroscience, 38(3), 124-126.

Mazeraud, A., Polito, A., Sivanandamoorthy, S., Porcher, R., Heming, N. and Stoclin, A., and Hissem, T., Antona, M., Blot, F., Gaillard, R., Chrétien, F., Annane, D., Bozza, F., Siami, S. & Sharshar, T. (2018) Anxiety Predicts Early Outcome in Critically Ill Patients. SSRN preprints, https://ssrn.com/abstract=3244032

Meredith, C., & Edworthy, J. (1995). Are there too many alarms in the intensive care unit? An overview of the problems. *Journal of advanced nursing*, *21*(1), 15-20.

Nazemi, M., Mobini, M., Gromala, D., Ko, H. H., & Carlson, J. (2017, May). Sonic therapy for anxiety management in clinical settings. In *Proceedings of the 11th EAI International Conference on Pervasive Computing Technologies for Healthcare* (pp. 455-459).

Noel, J. P., Chatelle, C., Perdikis, S., Jöhr, J., Da Silva, M. L., Ryvlin, P., ... & Serino, A. (2019). Peri-personal space encoding in patients with disorders of consciousness and cognitive-motor dissociation. *NeuroImage: Clinical*, *24*, 101940.

O'carroll, T. M. (1986). Survey of alarms in an intensive therapy unit. *Anaesthesia*, *41*(7), 742-744.

Owen, A. (2017). Into the Gray Zone: A Neuroscientist Explores the Border Between Life and Death. Simon and Schuster.

Panteleeva, Y., Ceschi, G., Glowinski, D., Courvoisier, D. S., & Grandjean, D. (2018). Music for anxiety? Meta-analysis of anxiety reduction in non-clinical samples. *Psychology of Music*, *46*(4), 473-487.

Perrin, F., Schnakers, C., Schabus, M., Degueldre, C., Goldman, S., Brédart, S., ... & Maquet, P. (2006). Brain response to one's own name in vegetative state, minimally conscious state, and locked-in syndrome. Archives of neurology, 63(4), 562-569.

Porter, S., McConnell, T., Lynn, F., McLaughlin, K., Cardwell, C., & Holmes, V. (2014). Recruiting participants for randomized controlled trials of music therapy: a practical illustration. *Journal of music therapy*, *51*(4), 355-381.

Pouchelle, M. C. (1996). Réanimation et rites de passage. *Gresclande, M.: En Réanimation: ombres et clartè. Paris: Editions Hospitalières*.

Schlesinger, J. J., & Shirley, S. A. (2019). Alarmed: sensory approaches to improving medical alarm systems. *The Senses and Society*, *14*(1), 81-91.

Schokkin, M. (2019) Sound Cultures of Critical Care - how design could tune sound-related practices of intensive care nurses. Master thesis - Design for Interaction Delft University of Technology.

Sen, Y. K., & Sen, A. (2020). The Future of Hospital Sound: Transforming Healthcare Through Sound Experience. *Music and Medicine*, *12*(1), 60-64.

Swope R, Glover K, Gokun Y, Fraser JF, Cook AM (2014) Evaluation of headache severity after aneurysmal subarachnoid hemorrhage. Interdiscip Neurosurg 1:119–122

Thampatty BP, Sherwood PR, Gallek MJ, et al (2011) Role of endothelin-1 in human aneurysmal subarachnoid hemorrhage: associations with vasospasm and delayed cerebral ischemia. Neurocrit Care 15:19–27

Venhard, J. C., Orrillard, M., Perrotin, D., & Souhet, G. (1997). Étude du bruit dans un service de réanimation. *Réanimation Urgences*, *6*(5), 613-619.

Verger, J., Ruiz, S., Tillmann, B., Ben, M. R., De, M. Q., Castro, M., ... & Perrin, F. (2014). Beneficial effect of preferred music on cognitive functions in minimally conscious state patients. *Revue neurologique*, *170*(11), 693-699.

Villarreal, E. A. G., Brattico, E., Vase, L., Østergaard, L., & Vuust, P. (2012). Superior analgesic effect of an active distraction versus pleasant unfamiliar sounds and music: the influence of emotion and cognitive style. *PLoS One*, *7*(1).

Walder, B., Francioli, D., Meyer, J. J., Lançon, M., & Romand, J. A. (2000). Effects of guidelines implementation in a surgical intensive care unit to control nighttime light and noise levels. *Critical care medicine*, *28*(7), 2242-2247.

Walsh-Sukys, M., Reitenbach, A., Hudson-Barr, D., & DePompei, P. (2001). Reducing light and sound in the neonatal intensive care unit: an evaluation of patient safety, staff satisfaction and costs. *Journal of Perinatology*, *21*(4), 230-235.

Waye, K. P., Elmenhorst, E. M., Croy, I., & Pedersen, E. (2013). Improvement of intensive care unit sound environment and analyses of consequences on sleep: an experimental study. *Sleep medicine*, *14*(12), 1334-1340.

Wenham, T., & Pittard, A. (2009). Intensive care unit environment. *Continuing Education in Anaesthesia, Critical Care & Pain*, *9*(6), 178-183.

Wilson, L. M. (1972). Intensive care delirium: The effect of outside deprivation in a windowless unit. *Archives of Internal Medicine*, *130*(2), 225-226.

Wood, R. L. (1991). Critical analysis of the concept of sensory stimulation for patients in vegetative states. *Brain Injury*, *5*(4), 401-409.

Woods JC, Mion LC, Connor JT, Viray F, Jahan L, Huber C et al. Severe agitation among ventilated medical intensive care unit patients: frequency, characteristics and outcomes. Intensive Care Med 2004; 30:1066-1072.