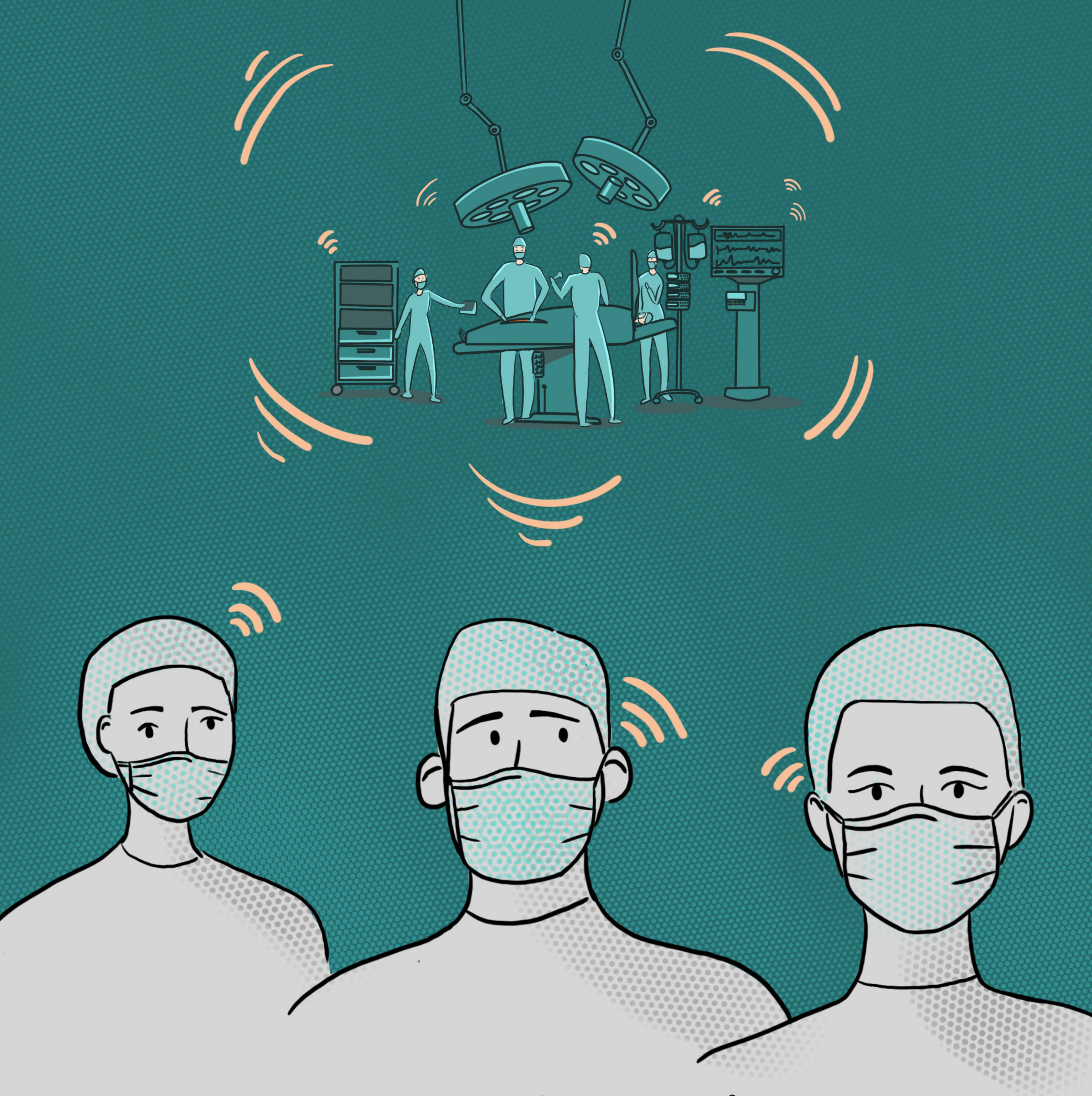

Sounds of **Surgeries**

Design for health behavior change in the soundscape of orthopedic operating theaters

Master thesis by Zoe Luck

Msc Design for Interaction, TU Delft
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& Dr. Jos Kraal

Master thesis (MSc) - Design for Interaction
Delft University of Technology
October, 2020

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Supervisory team
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Mentor: Dr. Jos Kraal

Commissioned by Critical Alarms Lab

"Sound is a nutrient; we can either charge or discharge the nervous system by the sounds we take in through both air and bone conduction."

– Dr. Alfred Tomatis (1920-2001)

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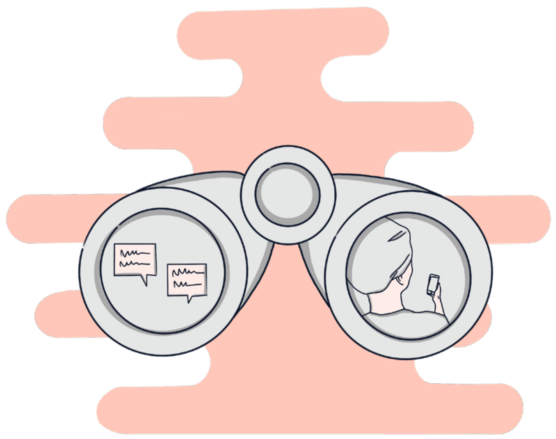
Zoe Luck
Delft, October 2020

Executive summary

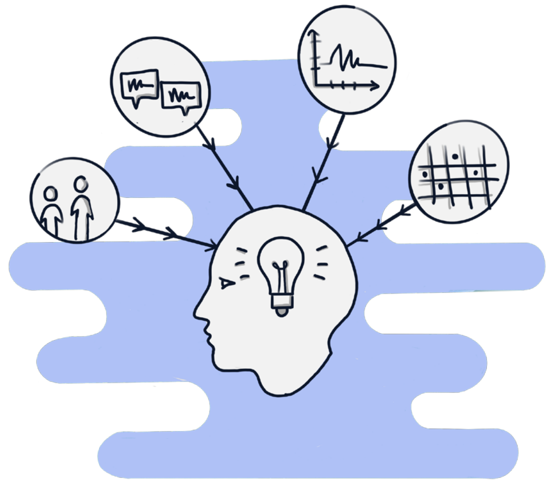
Keywords:
sound | noise | sound perception | operating theater | context mapping | medical staff | health psychology | health behavior | awareness

Noise in orthopedic operating theaters
The medical staff working in orthopedic operating theaters are often exposed to significant noise generated by many simultaneous sound events (e.g. powered tools, alarms) that pose a risk to their health and well-being. This thesis focuses on their health behaviors associated with the sound situation. Existing literature provides evidence that noise in some orthopedic surgeries can cause health issues ranging from increased stress levels to noise-induced hearing loss. Nevertheless, literature research also shows that the field of sound and health assessment has not been widely explored. Consequently, this thesis has two aims:
Firstly, understanding the soundscape, its entailing health risks and the motivations of current health behaviors of the medical staff in relation to the soundscape.
Secondly, contributing to an improved sound situation and reduced health risks for medical staff applying design.

Sound perception and health behavior
Applying the user research method "context mapping" (design method making people reflect on personal experiences) current health behaviors of the medical staff (e.g. surgeons, anesthesiologists) were investigated. In particular psychological consequences of noise are often underestimated. Sound levels in seven orthopedic surgeries (with varying surgical approaches) were assessed. Although the evaluation showed differences in sound levels, average sound levels did not exceed current legislation. Further investigations on sound characteristics (through psychoacoustic analysis) show that sound perceptions (e.g. pleasant or unpleasant sound experiences), causing psychological health impacts, are not sufficiently explained by loudness (i.e. especially average decibel levels).



Based on the research findings, that some sound situations in operating theaters are in parts hazardous and that the behavior of the medical staff is often non-precautionary, a theoretical framework (based on Social-Ecological Model (SEM)) was developed. It showcases the stakeholders directly or indirectly involved in potential behavior change processes towards an improved sound and health situation in operating theaters. This framework formed the core guideline for the consecutive design process, aiming to explore how behavior concerning the soundscape can be improved. The key discovery: There is a lack of awareness and knowledge of health consequences posed by sound within medical staff, as well as on other social-ecological levels (e.g. hospital management).



Design towards sound and health awareness
The final design outcome, a website, targets a wide healthcare audience. The website initiates greater engagement concerning sound improvements through increasing awareness of the current sound situation in operating theaters. It caters to varying awareness levels: General information on sound and health in operating theaters (to increase knowledge and initiate awareness) and concrete action advice to transform awareness into action for sound improvement and risk reduction.

Reflecting on the final outcome and future research
This thesis showed that sound perception in operating theaters is still not sufficiently explored. The initial evaluation with medical and non-medical staff participants indicates that the website successfully improves knowledge, triggers reflection and thereby sparks awareness. By further extending the websites' sphere of activities, it has the potential to contribute to the achievement of better sound quality in operating theaters. This thesis concludes with suggestions on future sound and health behavior research.

Table of contents

Reading guideline

This thesis is structured into eight sections.

The **FIRST SECTION** provides an introduction to the topic, the motivation, the aim, and the relevance of this master thesis project for sound-related health in operating theaters.

The **SECOND SECTION** contains a background and context literature review on the current state of sound in operating theaters, discussing contextual factors, sound-related behavior, and how they can lead to the development of health consequences for the medical staff. It concludes by discussing the findings, forming the aim of the consecutive research activities.

SECTION THREE describes the planning of the research activities, including user research on individual soundscape experiences by medical staff, on-site observations, and sound level measurements in orthopedic operating theaters, as well as a psychoacoustic sound experiment to assess sound characteristics of operating theater-sounds.

The **FOURTH SECTION** consequently describes the research results, featuring overall sound perception, the sound analysis (decibel measurements and sound characteristics), and discussing the medical staffs' sound-related behaviors and attitudes towards precaution measures for sound exposure.

SECTION FIVE reports on the main insights from literature and research activities to reflect on the risks of sound exposure in operating theaters. Subsequently, a theoretical framework is presented. It aims to map the complexity of the topic, showing the stakeholders involved in the sound-related decision-making, to provide a starting point for ideation.

The **SIXTH SECTION** presents the ideation period, starting by explaining the ideation procedure and by presenting the developed concept ideas to tackle sound issues identified in the previous user research. Subsequently, it describes the selection and working out of one final concept, an awareness-website campaign, aiming to create awareness for sound issues in the operating theaters.

SECTION SEVEN outlines the final website-design, explaining the different sections within the concept. It closes with an evaluation of the website developed in this thesis.

SECTION EIGHTH discusses the contribution of this work to the field of sound in healthcare environments, it critically reflects on the process and outcome of this project and lists final suggestions final on how to tackle sound issues in operating theaters in the future.

(+) "NICE-TO-KNOW"-Information

This thesis is written for a wide audience of people with different professional backgrounds. Therefore, you will find boxes that contain additional information to complement the findings with background information throughout this thesis.

Glossary

A.	**Arthroscopic surgery**	A surgical procedure that is usually minimally invasive. The examination of a joint (or sometimes treatment) is performed using a device inserted into the joint only through a small incision.
C.	**Context mapping**	It is a method used in design where designers use people's individual experiences to learn from and to take those as a starting point and inspiration for their project ideation.
D.	**Decibel (dB), and dB(A) and dB(C)**	Sound loudness (pressure) is measured in decibels (dB). The decibel scale is logarithmic. If sound levels increase by 10 dB the sound intensity is doubled. While so-called A-weighted decibels (dB(A)) represent the average sound intensity within a certain period of time (e.g. within one second), the C-weighted decibels (dB(C)) represent the highest peaks within a time period.
H.	**Health behavior and auditory health behavior**	Health behavior describes how people act in relation to maintaining or enhancing their health and well-being, or preventing health problems. In this thesis, auditory health behavior is used to describe all the behavioral aspects of people in relation to their sense of hearing.
	Health beliefs	Health beliefs are what people believe about their health, what they think constitutes their health, what they consider the cause of their illness, and ways to overcome an illness.
	Health psychology	Health psychology is a discipline within psychology that focuses on health and well-being of people and that pursues two main goals: To explain the psychological aspects that influence, shape or cause specific health behaviors and to develop strategies to change or achieve the desired behavior.
I.	**Intra-operative period**	It is a time-period within a surgery. It comprises the timespan when patients are placed on the operating table until the moment when the surgery is completed. In this project it is the most important one with regard to sound, as it entails the most sounds due to tool and monitor use.
M.	**Mallet**	It is a tool (kind of hammer) used in orthopedic surgeries when a manipulation of the bone is required.
	Medical staff	The organized body of individuals that work together in an healthcare environment to provide care. In this thesis, it describes the personnel that work in the operating theater.
	Minimally-invasive	In minimally invasive surgeries the aim is to apply techniques to operate with less damage to the body than with open surgery.
N.	**Noise**	The state in which sound creates a situation that people perceive as loud or unpleasant.
	Noise-induced hearing loss	A hearing impairment resulting from (over-)exposure to noise. Noise-induced hearing loss is non-reversible and often not noticed until the damage has already progressed significantly.
O.	**Operating theater (OR)**	The room within a hospital where the patients' receive their surgery. Within this thesis the two words, operating theater and OR are used interchangeably.
	Orthopedics	The branch of medicine that aims to correct deformities of bones, muscles and ligaments.
	Osteotomy	Is an orthopedic operating technique, where bone is cut and realigned in the desired position.
	Psychoacoustics	It can generally be described as the scientific study of sound perception. By correlating the human sound perception with physical properties of sound, it is possible to determine causal relationships why a certain sound is perceived as it is (Guski & Blauert, 2009).
R.	**Resident**	It describes individuals that are still in training for their medical education, for example to become orthopedic surgeons.
S.	**Situational awareness**	Perception and vigilance to on-going events that are happening around oneself that improve the understanding of the environment and may influence the own mode of action.
	Social-ecological level	Levels of influence of behavior within a social environment (e.g. individual, interpersonal, organizational, community, and public policy) with the idea that the levels are interrelated.
	Sound	Sound is "the sensation perceived by the sense of hearing" (Merriam-Webster's Dictionary, n.d.). Unpleasant or loud sounds are also called "noise".
	Sound cacophony	It describes the incident when different sound sources mix up into a harsh and inharmonious sound situation.
	Sound perception	In this thesis sound perception describes how people experience sounds. For example, whether or not a sound is pleasant to listen to by an individual.
	Soundscape	According to ISO 12913-1 (2014), a soundscape is "an environment of sound (or sonic environment) with emphasis on the way it is perceived and understood by the individual, or by a society".
	Suction device	A tool used during orthopedic surgeries to remove substances (e.g. blood and other fluids) from the operated area.
T.	**Time-Weighted Average (TWA)**	The Time Weighted Average (TWA) describes a worker's daily exposure to occupational noise (usually over an 8-hour working day). Two factors are considered: The decibel levels (loudness) and the duration of exposure.
	Total knee replacement	Surgical intervention to replace a damaged knee joint with an implant.
V.	**VAPR system**	A device used during orthopedic surgeries to control bleedings (e.g. through coagulation).

Section 1

Introduction: Sound in orthopedic operating theaters

01 Introduction: Sound in orthopedic operating theaters

1.1 Motivation for this project

Operating theaters are of utmost importance to ensure the public health of society. These facilities require high levels of performance from the medical staff that treat patients there. While operating theaters often contain advanced specialized technology, they are also a place where high levels of noise can be found. Almost 50 years ago, noise in operating theaters was assessed and described as “third pollution” while the problems of air and water pollution were already solved (Shapiro & Berland, 1972). Nearly 50 years later “the third pollution” is still existent in present-day operating theaters. Some technological developments have even contributed to an increase in noise (Hasfeldt, Laerkner, & Birkelund, 2010). This circumstance and the question of how the “third pollution” affects medical staff today, initiated this thesis project.

1.2 Problem definition

The question arises why the “third pollution” has not been successfully diminished in present-day operating theaters. One of the reasons is certainly that noise has not been widely recognized as a problem. Many individuals working directly (medical staff) or indirectly (health technology developers) in operating theaters have limited knowledge of, or concern for the sound conditions in operating theaters. Some physical dimensions, in particular the loudness (decibels) of operating theaters, have occasionally been assessed and evaluated. However, other sound characteristics and dimensions like sound perception have received little attention in research. This is where the term “soundscape” becomes important. A soundscape is “an environment of sound (or sonic environment) with emphasis on the way it is perceived and understood by the individual, or by a society” (ISO 12913-1:2014).

There are two ways that go hand-in hand to assess sound perception: Analyze the acoustic situation through various sound parameters (not only their loudness) and talk to people about their sound experiences. This soundscape approach has been applied in other healthcare environments, like hospital wards (Busch-Vishniac, 2019; Mackrill, Cain, & Jennings, 2013), but not in operating theaters. It is also important to investigate sound in operating theaters, through examining how people experience and interact with the sound situation (Figure 1), because there is a lack of evidence in current literature on how sound in operating theaters is used, experienced and how it affects the medical staff. It is evident that some orthopedic operating theaters bear high sound levels while at the same time inhabiting sounds that interact with different timbres causing a sound cacophony. Being exposed to loud sounds entails not only physiological risks (e.g. hearing loss, tinnitus) but also risks of psychological discomfort (e.g. stress, fatigue, distraction) (OSHA, n.d.-a). The operating theater is the medical staffs’ workplace and they are therefore exposed to the auditory environment on a regular basis. Patients are only exposed to sounds during their individual surgery; this is why this thesis focuses solely how sound impacts medical staff.

1.3 Research approach

The following research questions guided this thesis:

Literature:
“What is the current state of knowledge on sound, health and sound-related behavior in orthopedic operating theaters?”

Self-conducted research:
“How does the medical staff perceive the current soundscape of orthopedic operating theaters?”

“How do sound characteristics influence sound perception?”

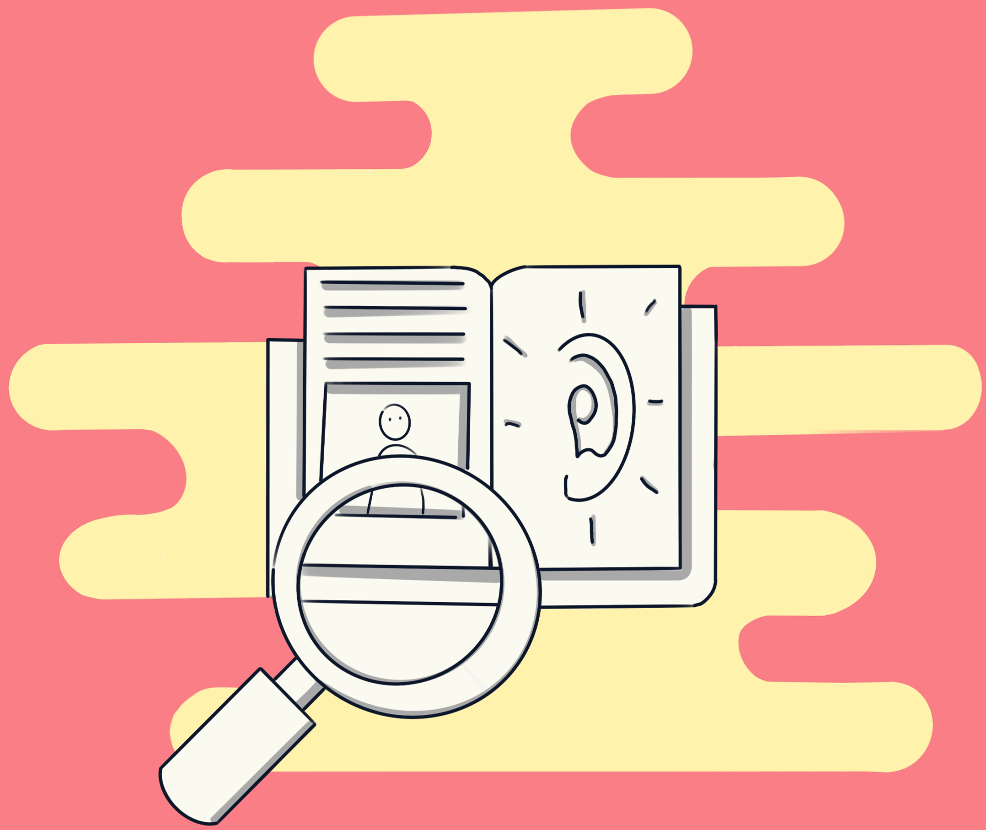
“What are the current sound-related risks of different orthopedic surgeries?”

Idea generation and conceptualization:
“How can behavior in relation to the soundscape be improved?”

Figure 1. During surgery in an operating theater. Retrieved from Unsplash (Gellidon, 2019)

Section 2

Context literature review



02 Context literature review

2.1 Sound as a physical phenomenon

Introduction

Sound is "the sensation perceived by the sense of hearing" (Merriam-Webster, n.d.). This rather simple definition offers an important insight: Sound is a physical phenomenon that is "perceived". From an acoustic point of view, sound and noise originate from the same physical phenomenon. According to the definition of European Standards, noise is a "disagreeable or undesired sound or other disturbance" (IEV, 1994), indicating that sound and noise differ in their subjective perception. Noise cannot be tied to a certain sound pressure level, because there are many other sound parameters that influence the individual human response to a specific sound event. One is the person's sensitivity to sound. For example, while some people may enjoy "noise" at a concert and find the experience pleasant, for others it might be an "unwanted" acoustic phenomenon (Hansen, 1951). However, there are certain sounds that society generally perceives as more pleasant (e.g. the sound of classical music), whereas other sounds are perceived as noisy or unwanted (e.g. industrial noise).

Understanding how sound perception is influenced by the properties of acoustic signals is the aim of the research area "psychoacoustics". Psychoacoustics can be generally described as the scientific study of sound perception. By correlating the human perception of a sound (e.g. a person describes the sound of a fork scratching on a plate as noisy) with physical properties of sound, it is possible to determine causal relationships why a certain sound is perceived as it is (Guski & Blauert, 2009). Next to parameters like loudness, psychoacoustics also investigate other sound parameters (e.g. sharpness, roughness, or regularity of sounds) (Genuit & Fiebig, 2006).

"Measuring noise" is complex. It depends on the one hand on physical properties (e.g. the measurement of the volume of noises) and on the other hand on the respective situation, the attitude of people and their subjective perception as well as on the functionality, the information content and the sound character of the acoustic signals.

(+) NICE-TO-KNOW

Sound represents a vibrational energy, the sound waves. The loudness of sound "is a subjective term describing the strength of the ear's perception of a sound" and is assessed through decibel units (Nave, n.d.). Nevertheless, the characteristics of sound waves can be measured using different physical sound parameters. One parameter is the loudness of sounds (sound pressure levels). It can be assessed through the amplitude of the sound wave and is expressed in decibel units. Decibel measurements follow a logarithmic scale. A sound is judged by humans to be twice as loud if its sound level is about 10 dB higher, meaning that a sound level at 110 dB is twice as loud as 100 dB (Ostdiek & Bord, 2013).

Sound interaction through listening

Hearing consists of the physiological process (outer ear, middle ear and inner ear and transmission of electrical potentials), while listening (i.e. sound perception) is an active mental state, where acoustic signals are analyzed, acoustic patterns are recognized and the information contained is processed to recognize the meaning and consecutively interact with the environment (Tuuri & Eerola, 2012). Hearing and listening, and thereby the perception and the sensation of sounds are especially important for orientation as well as for communication with other individuals. According to Truax (2001), there are different layers of listening and of acoustic attention. In the context of everyday environments, he defined three layers: listening-in-search, listening-in-readiness, and background listening.

The highest level of attention is called "listening-in-search". It means that individuals are intentionally scanning the soundscapes for a sound that is important to them to perform their tasks. By recognizing noise patterns and comparing them with similarities in pattern classes, people can classify their surroundings according to certain sound properties and events. By classifying and interpreting sound sources, humans can understand their surroundings. It is a "fundamental process by which meaning is applied to sensory experience" (Bones, Cox, & Davies, 2018).

"Listening-in-readiness" is the state in which the attention of listeners' is "ready" to receive important information. Since the sense of hearing allows multitasking through pattern recognition and interpretation, listening can be performed while a person is concentrated on something else, for example on a visual task (Polli, 2012). An example from a medical staffs' perspective for "listening-in-readiness": A surgeon listening for the specific sound of a medical device (e.g. saw) to verify that it is performing the desired action. The surgeon requires this acoustic information, whereas the anesthesiologist, for example, requires auditory signals from the patient's monitoring systems and derives no use from the sounds of the saw, meaning that it is rather obstructive for him. Therefore, the anesthesiologist is "listening-in-readiness" for other sounds than the surgeon. Human ears are constantly accumulating and processing sound information approaching from different directions. While recurrent, regular sounds can be masked out easily requiring little cognitive attention, a considerable change in the sound situation will alert the individual and will almost immediately receive their attention (Polli, 2012). Another example from the medical staffs' perspective: An anesthesiologist is responding to the ringing phone, while monitoring patient's signals. In case of the anesthesiologist, it is substantial to mention, that the ringing phone may not include important information. Instead it might even be perceived as disturbing for the anesthesiologist himself, because the "ringing" requires unnecessary attention, might mask or even cover up the important sounds (e.g. patient's signals) and will be undesirable or may even produce unnecessary stress.

The lowest level is "background listening". It means that a person is not at all actively paying attention to what is happening sound-wise. They are not directing their attention to a sound in order to "achieve any practical purpose" (Supper & Bijsterveld, 2015). But still, since they are part of the situation, they might be able to recall the sound later on (Tuuri & Eerola, 2012). An example within the operating theatre is the sound of the ventilation. At this moment none of the medical staff is aware that the sound is there, but they might later be able to recall it, once the ventilation is turned off. However, the hearing of the medical staff members is still receiving the sound, even though it is masked out and subconsciously received. Furthermore, the sound might make it more difficult to receive important soft sounds (e.g. opening of a packaging).

Human hearing impressions

Psychoacoustics is a scientific subfield of acoustics. It aims to explain and objectify the complex processes of human's sound perception by investigating the interrelation between physical sound parameters and subjective hearing impressions (Genuit, 2008). In general, some sounds leave more impression on a human's sound perception than others. This impression on individual's perception is not only related to loudness, but also influenced by other sound characteristics. One study, for example, investigated the recall-memory of sound sources in a traffic sound situation. Their study illustrated that outstanding sound features contribute to sound perception. Many people recalled, for example, the sound of a bird chirping but not loud sounds, like engines (Kuwano, Namba, Kato, & Hellbrück, 2003). This also applies to the soundscape of operating theaters. One example are patients' signals. Continuous and usually high pitched sounds are designed to draw on the attention of the medical staff, even when heard with surrounding noise (Kerr, 1985).

2.2 Sound in operating theaters

Sound plays an important role in everyday life. However, it is unclear how sound per se and sound interactions affect operating theaters' soundscapes. But it is important to understand context-specific sound experiences and the multilayered factors that shape them in order to draw conclusions on current state of sound in operating theaters. There are three overarching factors affecting the soundscape experience: Environment-related, technology-related, and human-related factors.

Environment-related factors

Environment-related factors describe conditions that influence the medical staffs' sound experiences and which set limits on human behavior (e.g. room layout influencing the allocation of staff members). Healthcare facilities usually differ in structural aspects, such as the size and layout of the operating theater or wall properties (see Figure 2), which directly influence the sound qualities within a room. In the Netherlands, orthopedic surgeries are performed by university hospitals, community hospitals, and private healthcare centers (LROI, 2018). They differ in several aspects, such as the applied type of surgical equipment (e.g. protective equipment or tools) or the organizational structure (e.g. number of personal per surgery). For instance, university hospitals have more people present during one surgery due to educational purposes. This may also lead to more sound from increased communication during the surgical procedure due to "knowledge sharing", as indicated in the study by Bleakley, Allard and Hobbs (2013). They reported that almost 25% percent of communication was related to staff training.

Another environment-related factor is the use of anesthetic screens, used to divide and provide a physical and visual barrier between the surgical team and the anesthesia team to minimize infection (Bleakley et al., 2013). When visual communication is restricted, as it is the case with these screens, "the extent of auditory influence grows correspondingly" (Heron, Whitaker, & McGraw, 2004).

Figure 2. Empty operating theater at Erasmus MC.
Retrieved from Dutch Daylight (n.d.)

Technology- and procedure-related factors

Technology-related factors describe sound conditions set by the medical equipment and devices used in different types of orthopedic surgeries (see Figure 3). Sounds related to equipment are defined as any sounds produced by products or machines (e.g. anesthetic monitors signals and alarms, or sounds produced by operating instruments (Hasfeldt et al., 2010).

Figure 3. Stryker surgical power tools.
Retrieved from VIRTUAL EXPO GROUP (n.d.)

Two types of surgical techniques can be distinguished, the "open surgical approach (conventional or open surgical technique)" versus the "arthroscopic approach (minimally invasive techniques)". Open surgical approaches (e.g. total and revision joint replacements for hips and knees) have been investigated in the past due to the high impact noise produced by tools (e.g. mallet, oscillating saw) (Simpson & Hamer, 2017; Love, 2003; Kracht, Busch-Vishniac, & West, 2007). However, there is still a lack of knowledge and literature about sound levels and sound patterns in other orthopedic surgeries, such as in arthroscopic approaches (e.g. soft tissue repair) or in osteotomies (e.g. reshape of bones for better alignment with joint). One study, Kuzmich, Rojas and Phillips (2001) assessed sounds in arthroscopic surgeries and their results suggest that arthroscopic approaches produce less noise than open-surgical procedures.

The previous studies indicate that tools are primarily responsible for high sound levels in operating rooms (e.g. Hasfeldt et al., 2010). Nevertheless, regulations regarding the allowed emitted sounds of tools are vague.

According to the Medical device directive, sounds only need regulation if they are not "part of the

specified performance" (European Parliament and of the Council, 2007). The question arises when "noise" is to be considered as part of the performance. The regulation leaves room for interpretation, which can consecutively cause a lack of consistency in the adherence of sound levels.

The Directive also states that "devices shall be designed and manufactured in such a way as to reduce to the lowest possible level the risks arising from the noise emitted, taking account of technical progress and of the means available to reduce noise, particularly at source, unless the noise emitted is part of the specified performance" (European Parliament and of the Council, 2007).

Human-related factors

Human-related factors are human characteristics and interactions, which influence sound-related behavior in the operating theater. Behavior-related sound sources are described as "any type of sound that is made or initiated by a person" (Hasfeldt et al., 2010), e.g. opening packages and preparing for a surgery, moving trolleys, slamming doors, moving, using and dropping metal tools, performing suction or medical staff communicating loudly (see Figure 4).

Figure 4. Work and communication of medical staff.
Retrieved from Pixabay (n.d.)

2.3 Individual professionals in operating theaters

The complex multidisciplinary working environment of operating theaters requires that each profession performs particular, predetermined tasks. At least three different professions are present in orthopedic operating theaters: surgeons, nurses, and anesthesiologists (Healey, Sevdalis, & Vincent, 2006). A table featuring and explaining the different professional roles in more detail can be found in Appendix B. The role in the team influences the sound situation for the individuals insofar as it determines the distance to the different sound sources within the operating theater. It further determines which sound sources are important for the individual and it influences their listening style (e.g. background-listening or listening-in-search). Besides, each profession produces different sounds, determined by their tasks.

(+) NICE-TO-KNOW

The team is divided into sub-teams: The "sterile" medical staff is responsible to perform the surgery (e.g. surgeon, operating assistant, and resident). They stay in the sterile or aseptic area (marked on the floor) during the entire surgery. The "non-sterile" medical staff consists of those team members who are located outside the sterile area (e.g. circulating nurses and anesthesiologists) (Fox, 1997). They are responsible to take care of the patients' well-being during the surgery (e.g. anesthesiologists) and to support the surgical team (e.g. circulating nurse). Some surgeries also require other professions, such as radiologists (Bott, Dresing, Wagner, Raab, & Teistler, 2011) or other individuals present (e.g. researchers, medical students, etc.).

2.4 Sound, health and well-being in operating theaters

Hearing is an important human sense and contributes to one's overall well-being by allowing effective interpersonal communication as well as social and environmental interaction. In addition, several studies have suggested that sound or music can positively affect people's health (Lippi, Roberti di Sarsina, & D'Elios, 2010; Thoma et al., 2013). Beside the many benefits that hearing and listening entails, sound interactions can also harm human's health.

Negative sound effects for individuals

Several studies have identified negative health effects as consequences from sound exposure for medical staff individuals. Individual physiological consequences can range from higher blood pressures, heart rates, or a rise in stress hormone levels (Basner et al., 2014; Rylander, 2004). Severe, long-term health consequences for medical staff include tinnitus and noise-induced hearing loss (OSHA, n.d.). Willet (1991) indicated in his study that early noise-induced hearing impairment was prevalent in 50% of orthopedic staff. However, Willet's study included only a small sample size (27 senior orthopedic staff). Therefore, it may not be representative for the entire orthopedic staff population. Sound exposure can also lead to individual psychological consequences, such as an increased feeling of stress (Wetzel et al. 2006). It can also lead to decreased attention capability (Szalma & Hancock, 2011).

Negative sound effects for teams

Next to individual health impacts, noise can also have negative work-related consequences. Noise can lead to miscommunication (Hasfeldt et al., 2010). It impairs the transmission of case-relevant information and does more so if the information is complex. Furthermore, noise forces speakers to either raise their voices or to interrupt others' communication (Keller et al., 2016). While more experienced staff may be able to compensate for this impairment, e.g. by blocking out noise (Moorthy, Munz, Dosis, Bann, & Darzi, 2003), one study that included participants with different levels of experience showed that less experienced surgeons were more likely to be distracted by noise (Siu, Suh, Mukherjee, Oleynikov, & Stergiou, 2010). Within one study, the authors investigated the effect of noise on task execution from the medical staffs' perception perspective (Padmakumar et al., 2016). Within this study 83% of participants stated that according their experience, sound contributes to human errors.

2.5 Occupational hearing safety legislations

The World Health Organization (WHO, 1948) defined health as a "state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". To prevent sound-related health consequences at work and consequently in operating theaters, regulations to protect the medical staff from potential health consequences are in place. Occupational work legislation influence sound-related behavior insofar as they set conditions for whether or not hearing preservation programs have to be implemented and followed in the operating theaters. According to the Dutch occupational work legislation (in Dutch "Arbeidsomstandighedenbesluit"= ARBO), noise protection has to be in place when average sound levels exceed 85dB(A) per 8-hour working day or when peak sound levels exceed 140dB(C) (Arbeidsomstandighedenbesluit, Article 6.8, 2020). European occupational work legislations specify further that "first action levels" are set at 80 dB averaged over an 8-hour-working day or peak sound pressure exceeding 135 dB, meaning that employees have to inform their affected staff about potential risks and actions (Health and Safety Authority, Regulation 125, 2007). The WHO (1999) recommends 30dB for wardrooms in hospitals (indoors), the guideline for sound levels in hospital treatment rooms are recommended to be "as low as possible". At the same time, the WHO stated that speech and communication start to be impaired from decibel levels as low as 50 decibels. A clear recommendation, in particular for operating theaters does not exist.

Current safety regulations applicable to operating theaters may decrease health risks, but certainly do not eliminate them. One study by Kracht et al. (2007), for example, demonstrated that the measured peak levels were exceeding 100 dB in the timespan of an orthopedic surgery more than 40% of the time and highest peak levels were frequently exceeding 120 dB. An exposure level of 85 dB(A) per working day within a working career of 40 years increases the risk of noise-induced hearing loss by 35%. Due to the logarithmic scale of decibels, sound levels of 109 dB(A) can only last for 1.9 minutes until posing the same risk of noise-induced hearing loss as 85 dB(A) for eight hours (Love, 2003).

Occupational work legislations may prevent hearing loss to a certain extent, but they neglect the contribution of noise to other health impacts, such as psychological discomfort (e.g. fatigue, stress). Also, as Prasad and Reddy (2003) indicated, there is a large variation among individuals regarding the susceptibility of health and hearing impacts. Depending on individual characteristics (e.g. age, pre-existing conditions) the risks are different and what is regarded as "safe" levels may cause irreversible damage to some. Several studies have indicated that sound interaction in orthopedic surgeries may not reach unbearable loudness, but that there are certainly steps in the surgical procedures that negatively influence sound interactions (Way et al., 2013) and consequently also have an impact on medical staffs' health (Kracht et al., 2007). In one controlled study, "mental efficiency and short-term memory" were already impaired when anesthesiology residents were faced with sound levels at 77 dB(A) (Murthy, Malhotra Mo, Bala, & Raghunathan, 1995). Besides, noise can cause changes in moods or emotions due to disruptions of workflows (due to the experienced disruption) rather than due to the loudness of sounds (Zimmer, Ghani, & Ellermeier, 2008).

2.6 Behavior change in operating theaters

Today's understanding of auditory health risks (i.e. relating to hearing) has evolved into a widely acknowledged societal health concern, especially for leisure activities and behaviors (e.g. listening to music with headphones) (Matheson & Stansfeld, 2003). However, the literature on sound exposure in relation to health behaviors is still scarce. There is still a general lack of knowledge about how medical staff interacts with sound in operating theaters, whether it is precautionary or not. One indication was found by Love (2003) who found no evidence for precautionary behavior. He reported that even though sound periods of some orthopedic surgeries exceeded the threshold of discomfort (set at levels above 110 dB (IQWiG, 2017)) and the threshold of pain (levels above 130 dB) several times, hearing protection was merely used. These sound periods were, for example, related to the use of the mallet in total hip replacement surgeries. He concluded that the short duration of those peak levels "decrease the perceived risk of harm among surgeons."

2.7 Health psychology

To understand why behavioral change for health is difficult to accomplish, a whole discipline has evolved which is called "health psychology". The discipline pursues two main goals: Explaining the underlying psychological processes that influence behavior, and developing effective strategies for behavior change (Leventhal, Weinman, Leventhal, & Phillips, 2008).

This thesis aimed to investigate and explore peoples' behaviors in relation to health and well-being. To do so, the "Intervention Mapping" protocol, a health psychology framework served as a guideline. This protocol empathizes three core components of the Intervention Mapping approach: "searching the literature for empirical findings, accessing and using theory and collecting and using new data" (Kok, Schaalma, Ruiter, Van Empelen, & Brug, 2004). Using and exploring theories to understand and change health behaviors continued in all phases of the thesis project. Therefore, whenever health psychology methodology was used as a guideline in the thesis process it is mentioned within the according section (e.g. in the development of sensitizing tools in Section 3 or in the research synthesis in Section 5).

(+) NICE-TO-KNOW

The first component of the intervention mapping approach, literature assessment took place: Theoretical frameworks, such as the "Theory of Planned Behavior" have been successfully applied to examine sound-related health behaviors (Gopal et al., 2019). Another applied framework is the "Health Belief Model" that has been used to assess adults' attitudes and behaviors towards hearing loss prevention (Saunders, Frederick, Silverman, & Papesh, 2013; Rawool & Colligon-Wayne, 2008).

2.8 Takeaway

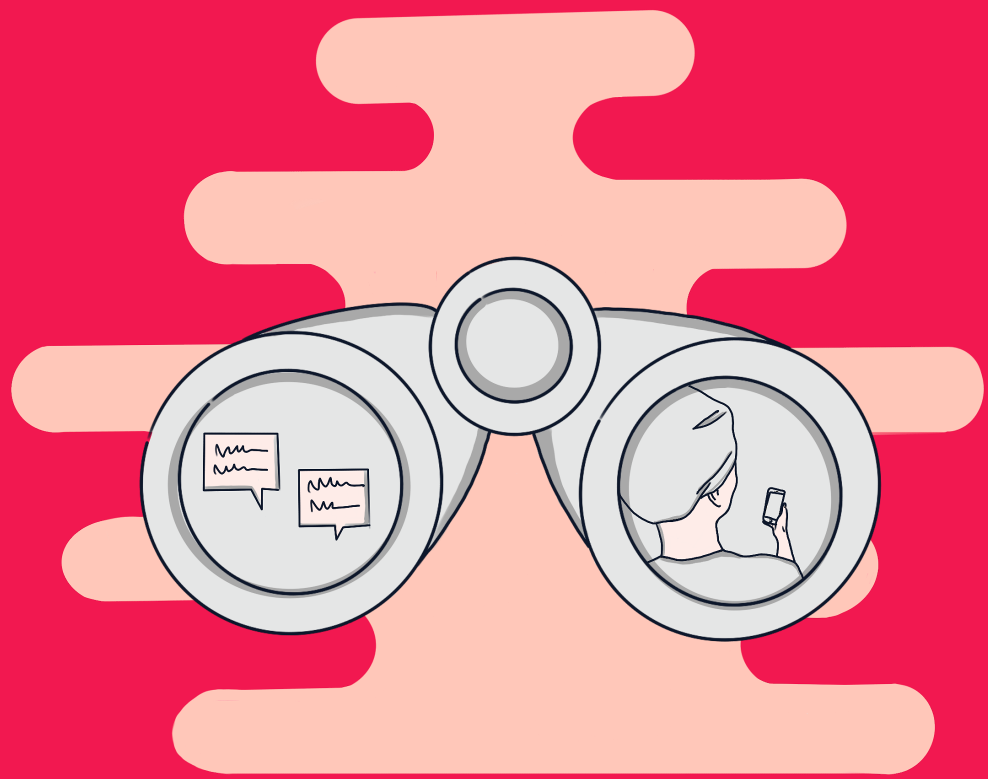
"First action levels" for noise protection on an 8-hour working day were set by legislations at 80dB(A), while sound levels above 85 dB(A) require immediate action (Arbeidsomstandighedenbesluit, 2020; Health and Safety Authority, 2007). These action levels showcase that they aim for absence of illness instead of overall well-being as 85 dB correspond to frequently encountered sound events such as being in a noisy restaurant or close to a vacuum cleaner (Healthwise, 2019). Further, those legislations neglect the fact that sound exposure risks are not limited to the loudness of sounds. Also sounds less loud than 85dB can have sound characteristics that make listening to them demanding.

Overall, there is still a lot that is not known about the soundscape of orthopedic operating theaters. Literature can, for instance, not give sufficient answers to the sound emitted by high impact tools in the different orthopedic surgeries. To my knowledge, only one study to date has measured decibel levels in minimally invasive orthopedic surgeries (Kuzmich et al., 2001). Furthermore, it has not been sufficiently explored how sound affects the workplace interaction of individual medical staff members, and how medical staff perceives the soundscape with regard to health. In the following field research, I build on the existing literature on sole acoustic analysis and extend it by investigating user-centered measures, including individual sound and health perceptions, as well as the behaviors of medical staff in orthopedic operating theaters.

Section 3

Research: Activities

3.1 User research with medical staff
3.2 Observations in operating theaters
3.3 Sound level measurements in operating theaters
3.4 Psychoacoustic experiment on sound perception
3.5 Physical analysis of sound samples



03 Research: Activities

The literature review illustrated the complexity of orthopedic operating theaters soundscapes, yet it has not given sufficient answers on the sound situation in operating theaters. Multiple questions remain, like: "How does medical staff perceive the soundscape themselves? How do they interact with the soundscape? Does it affect their health and well-being? Do they take precautions for their auditory health?" These questions were transformed into three research questions, which to answer was the target for this exploratory phase:

User research:
"How does the medical staff perceive the current soundscape of orthopedic operating theaters?"

Sound level measurements and observations: "What are the current sound-related risks of different orthopedic surgeries?"

Psychoacoustic sound analysis:
"How do sound characteristics influence sound perception?"

I performed a variety of activities, comprising user research with medical staff, field observations, sound level measurements and psychoacoustic sound quality analysis (see Sections 3.1-3.4). The research results are summarized and discussed as a compilation of the three research questions and several sub-themes: The user research includes the findings on sound perception, listening behaviors, health behaviors, and beliefs of the medical staff, while the observations and sound analysis complemented the insights and the sound-risk assessment (see Section 4).

3.1 User research with medical staff

Participants

I collected insights from a diverse group of four professions (orthopedic surgeons, orthopedic residents, OR-nurses, and anesthesiologists). In total 11 staff members participated. A more detailed description of the participant's characteristics is shown in Table 1. Most participants were recruited from the Erasmus Medical Center in Rotterdam, but also from four other Dutch hospitals. For privacy reasons, the specific hospitals are not indicated in the participants' descriptions. Some participants were only partly involved in the user research due to limited availability.

Context mapping

For the subjective evaluation of sound in the operating theaters, I applied the qualitative research method "context mapping". Through active participation, this method allows participants to communicate their experiences while simultaneously supporting participants to reflect and become more aware of their experiences in a specific context (Van Boeijen, Daalhuizen, Zijlstra, & Van der Schoor, 2014). My goal was to explore how people behave and make health-related decisions. Through "sensitizing material" (a booklet), the medical staff was empowered to express their latent sound-related needs, beliefs, and attitudes in the specific context of the orthopedic operating theater soundscape prior to a consecutive user interview.

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Preparing research tools with health psychology
This project focuses on illness prevention rather than on illness treatment. At the same time, it is not yet clear how significant or how hazardous sound in the operating theater is. A theoretical framework has been developed to guide the search for determinants for health problems that are not widely acknowledged yet: The Precaution Adoption Process Model (PAPM) (Weinstein, Sandman, & Blalock, 2002) takes into account that knowledge and behavior change over time. It is, therefore, structured into different stages reflecting the behavior change process and the individual different mental states which people go through; from unawareness to acting. It suggests that there are qualitative differences among people that may cause different characteristics to initiate action or not (Weinstein et al., 2002). The PAPM inspired the structure of the sensitizing booklet and the interview.

Table 1: Participants (medical staff) within qualitative user research

Participants	Hospital type	Years working in operating theater	Orthopedic specialty	Sensitizing booklet	Interview
Surgeon 1 (male)	Academic hospital	25 years	Arthroscopy (shoulder/ knee), trauma	Yes	Yes and observed during surgery
Surgeon 2 (male)	Academic hospital	13 years	Replacement and revision (hip)	Yes	No, but observed during surgery
Surgeon 3 (male)	Community hospital	10 years (8 of which in training)	Arthroscopy (shoulder)	Yes	Yes
Surgeon 4 (male)	Private hospital	21 years	Replacement and revision (knee)	No	Yes
Resident 1 (male)	Academic hospital	2,5 years (in training)	All orthopedic surgery types	Yes	Yes
Resident 2 (male)	Academic hospital	3 years (in training)	All orthopedic surgery types	Yes	Yes
Resident 3 (female)	Academic hospital	6 years (in training)	All orthopedic surgeries (+ trauma and plastic)	Yes	Yes
OR-nurse 1 (female)	Academic hospital	10 years (4 of which in training)	All types of surgeries (not only orthopedics)	Yes	Yes
OR-nurse 2 (female)	Community hospital	20 years	All types of surgeries (not only orthopedics)	Yes	Yes
Anesthesiologist 1 (male)	Academic hospital	8 years (6 of which in training)	All types of surgeries (not only orthopedics)	No	Yes
Anesthesiologist 2 (male)	Academic hospital	25 years	All types of surgeries (not only orthopedics)	No	Yes

Sensitizing Booklet

Being actively engaged with sound in the operating theater was rather uncommon for participants. Sleeswijk Visser et al. (2005) explained that actively reflecting on prior and current experiences helps to form opinions on a topic. Therefore, a sensitizing booklet was used to actively engage participants with their sound experiences in the operating theater. The sensitizing booklet contained small exercises spread over the timespan of one week asking participants to write down their individual sound experiences step by step (see Figure 5). Completing the PDF-booklets was planned for seven days. However, due to the COVID-19 epidemic, it usually took participants longer to complete it.

Interviews

The semi-structured interviews lasted around 30 minutes and were divided into two parts. The first part focused on participants' answers in the sensitizing booklets. The booklet answers were analyzed prior to the interview. This enabled tailoring the interview questions to the already given answers and allowed deeper and more detailed conversations.

The second part of the interview focused on questions related to explaining individual auditory health behaviors. As Galletta, (2013) explained, semi-structured interviews are especially useful for qualitative research because they offer the opportunity to use a structured script for answering the research questions, while also providing the freedom to explore themes that might emerge during the interview as a result of participants' answers. An exemplary interview outline can be found in Appendix C. The individual interviews were audio-recorded and transcribed later. This allowed an in-depth, back, and forth analysis. It also enabled me to reflect on the conversation instead of an immediate interpretation after the interview.

Day 1 introduces the participant to their individual relationship to sound. This information allows to understand a person's attitude towards sound and later on helps interpreting interview statements. Part of Day 2 asks to name sound sources that are experienced in the regular operating theater workdays. This exercise is the preparation for the labeling of sound sources according to their perception.

The exercises of partly Day 2 and Day 3 involve naming the "positive" sound sources in the operating theater, which are perceived as pleasant or useful. Here participants can refer to their previous collection of sound sources that they have previously written down.

On Day 4 and Day 5, "negative" sound experiences in the operating theater are reported. These sound perceptions are further distinguished into unpleasant and harmful sounds.

While the other exercises focus on the present situation in the operating theaters, Day 6 and 7 focus on the "future". Asking participants about their dream environment aims to make people express their latent needs. Otherwise, people are often very practical, and do not mention a need, because they believe it is not possible to be fulfilled.

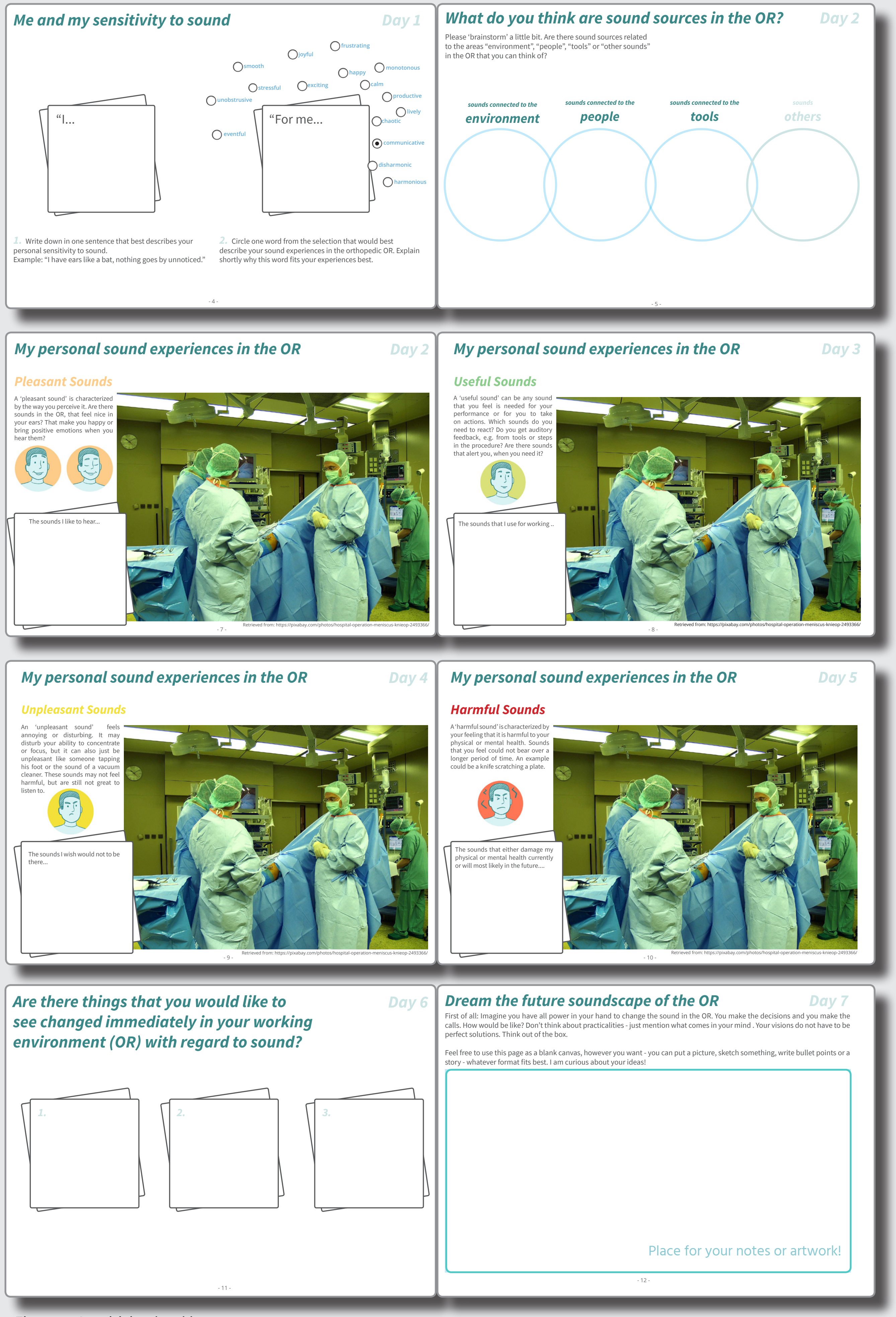

Figure 5. Sensitizing booklet

Data interpretation

As a first step, I selected quotes from the transcripts and captured them in statement cards. Each statement card included the "interesting quote" of the participant and my interpretation. Additionally, each card indicated the owner of the statement, i.e. profession within the operating theaters (see example in Figure 6).

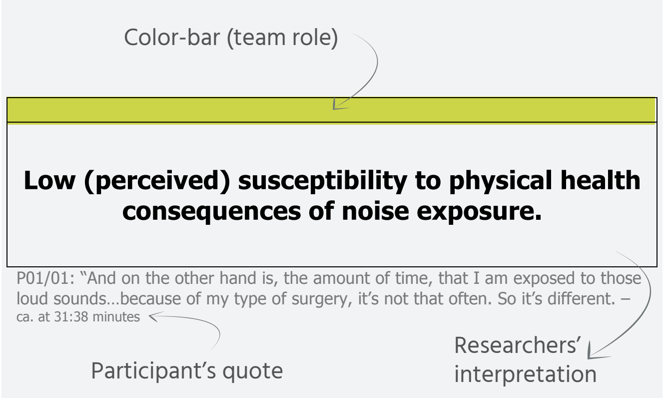

Figure 6. Example of statement card

As a second step, I clustered the statement cards into different themes. The themes were mainly structured along the soundscape perception (e.g. pleasant sounds, unpleasant sounds) and sound-related beliefs, knowledge, and behavior, but also along other context determinants (e.g. professional work performance needs) that emerged during the interviews (see Figure 7). An overview of the compilation of statement cards can be found in Appendix D.

Figure 7. Clustering of statement cards

(+) NICE-TO-KNOW

Personas

I created personas to summarize and showcase the diversity of user insights and personalities. According to the Delft Design Guide, three to five personas are advisable; as the information is "sufficient" for communication, yet still "manageable" (Van Boeijen et al., 2014). Five Personas were created and enabled me to frequently reflect on personal characteristics that shape the sound experiences and behaviors of individuals in the following ideation phase (see examples in Appendix E).

3.2 Observations in operating theaters

I spent one day solely observing the operating theater environment and the human interactions that it entails. During this day, I attended three surgeries (two knee arthroscopies & one total hip replacement). The aim was to understand the interactions between the different medical professions and how the room is set up. It also gave me insights where sound sources are located. Figures 8 and 9 show exemplary sketches. The observations based the basis to refine the "listener types" that have previously been explored in a research project (conducted under supervision of Elif Özcan-Vieira).

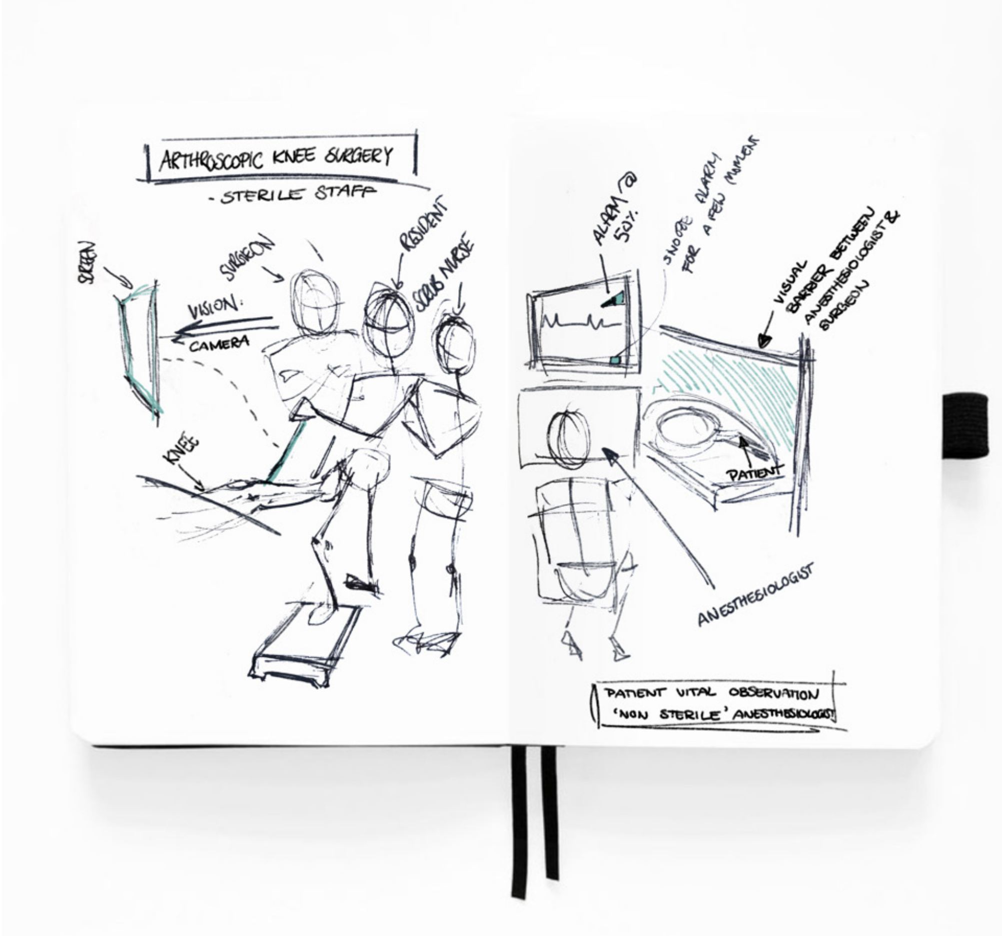

Figure 8. Team-positions within arthroscopic surgery

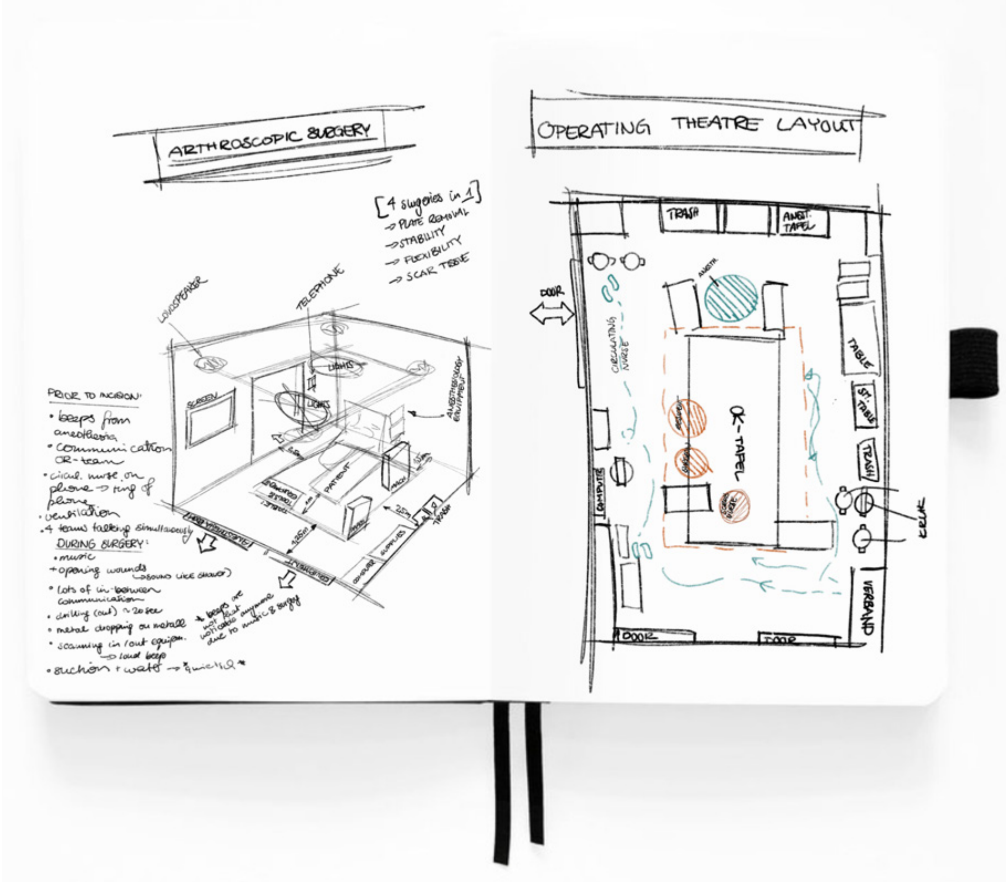

Figure 9. Room layout during an arthroscopic knee surgery

3.3 Sound level measurements in operating theaters

The assessment of sound levels was performed in two different hospitals and in different orthopedic surgery types, all featuring the knee (see Table 2).

Sound pressure levels were assessed with decibel-meters. In each surgery, four devices were distributed among the different professions (surgeon, circulating nurse and, anesthesiologist) and the researcher. The decibel-meter device consisted of an EU-certified smartphone (i.e. Nokia 2.2) with an attached microphone (i.e. iRig Mic Lav). The decibel values (of microphones in combination with the smartphones) were verified with a professional dB-meter (Bedrock SM30).

The smartphones of surgeons were under their gown and the microphones were attached at the side of the neck, approximately 10 cm from the ear. The devices of the non-sterile members were attached similarly, except for the microphones, which were not covered by an extra layer of sterile clothing. Within the less loud surgeries, the devices of the anesthesiologists were placed right next to them on the table, approximately 40 cm from their ears (as the anesthesiologists switched, i.e. a different anesthesiologist took over for the previous anesthesiologist during the procedure).

Linear sound pressure levels (dB) were measured and recorded simultaneously during the intraoperative surgery time with the four devices, while each profession performed their usual tasks. The intraoperative period entails the most sounds due to tool and monitor use: It starts when patients are placed on the operating table and lasts until the moment when they are transferred from the operating room to the recovery room (McGarvey, Chambers, & Boore, 2000). Subsequently, I examined the correlated health risks posed by the sound situation in the operating theater in relation to sound loudness.

Table 2: Measured surgeries within orthopedic operating theaters

Sound base-line	Surgery types "less loud"	Surgery types "loud"
Number of recorded surgery types	3 knee arthroscopies 1 lower leg osteotomy	3 total knee replacements
Location	Erasmus Medical Center Rotterdam	Sint Maartenskliniek Nijmegen

Data processing

For each surgery one dataset per user (surgeon, circulating OR-nurse, anesthesiologist, researcher) was generated by the database. These datasets were transformed from JSON-files into XLSX (Excel-files). Seven surgeries with four datasets each were processed (in total 28 datasets). Each individual dataset included four columns:
- user
- time of recording (hour: minutes: seconds)
- dB value per second
- event (Option in app to label sound events for relating sound levels with sound events)

User

The user-datasets from each individual surgery were time-wise set into relation to compare the different users among one surgery.

Decibel values in app

To understand what decibels stand for are, it is important to understand that they are describing a power ratio between two sound pressure values. Sound pressures are expressed through the unit pascal (PA). While P describes the power that is actually being measured, P_{ref} is the reference value, which is the human threshold of hearing (20 μPa). Because humans can hear from 20 Hz to 20 kHz, a linear calculation would not be suitable to display this very large range. This is why decibel calculations (they are logarithmic) are applied. The following formulas were retrieved from OSHA (2013a) and adapted to the default application values (with Pref= 20 μPa).

(+) NICE-TO-KNOW

The smartphones used an app for measurements, developed together with Deanne Spek from the Critical Alarms Lab of TU Delft. While I decided on the required functions and consecutively created the analog structure and layout (see Appendix F), Deanne coded the entire app and set up the database. This app is suitable for sound measurements in the operating theater, as it is a non-intrusive and personal-data friendly approach, not affecting patient care. Only numbers (dB values) are collected, no audio recordings are taken. The app and the algorithm are still under development. Further research must follow after this thesis project.

Calculating the dB mean within measured surgeries

As decibels cannot be summed arithmetically, the available dB-values first had to be recalculated (power law). To do so, the following formula was used (reference to OSHA, 2013a):

$$P=10^{\frac{dB}{20}}$$

(+) NICE-TO-KNOW

Explanation of formula:
P= actual measured sound pressure
dB= value describing the power ratio between P and P_{ref} (20 μPa)

The actual measured sound pressure levels (P) are summed up applying the following formula (reference to OSHA, 2013a) and recalculated into the dB mean value:

$$L_{mean}=20*\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} P_i\right)$$

(+) NICE-TO-KNOW

Explanation of formula:
L_{mean}= mean value of one surgery
P_i= actual measured sound pressures, but summed in formula: all values within one surgery per user (one per second)

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Linear decibels (dB) assess the loudness of a sound, without adjusting it to the human hearing system. But humans are not sensitive to all levels to the same extent. The loudness of sounds is also influenced by its frequency. Various filters have been developed that are applied to mimic the human hearing (A-weighted) and to assess high peaked noise (C-weighted – mostly applied to evaluate noise like aircraft noise). These filters factor certain frequencies more than others to optimize the assessment to the human hearing (Gracey, n.d.; OSHA, 2013b).

3.4 Psychoacoustic experiment on sound perception

After completing the qualitative user research with the medical staff, it became evident that loudness of sounds (decibels) alone cannot explain the sound perception of sounds that are described as demanding or annoying sound events in operating theaters. For example, the suction device was often mentioned as a very annoying sound. Literature reports suction device sound levels of "85 dB(A)" (Tsiou, Efthymiatos, & Katostaras, 2008) while, for instance, the use of a mallet is reported with sound levels of around "105.6 dB(A)" (Simpson & Hamer, 2017). The focus on sound loudness neglects other sound parameters that additionally influence sound annoyance (e.g. irregularity of a sound). This is why I expanded the acoustic sound research with "psychoacoustics".

Psychoacoustics analyses are useful to detect and explain the cause of sound annoyance. I selected four sound events that were described as rather unpleasant, namely anesthesia signal sounds, suction device sounds, mallet sounds and oscillating saw sounds. As Psychoacoustics aims to understand the relationship between human hearing perception and physical sound parameters, the approach was two-fold: An experiment to obtain a subjective description of sound characteristics (through participants' evaluation) and then a physical analysis of the sound samples (e.g. through sonograms) to see how both analyses are correlated.

Subjective evaluation of soundscape samples

The four soundscape excerpts were selected from sound recordings of operating theater soundscapes. As I did not have my own audio-recordings, I purchased various sound samples. As Axelsson et al. (2010) indicated, soundscapes can have sound situations where different sounds occur simultaneously, but also separately. Therefore, I used sound events similar to those occurring in real-life operating theaters (with background noise) for the analysis. The subjective sound evaluation was initiated and prepared through a self-experiment. I tried to describe the different sound samples with as many attributes as possible. The result was a sound quality description list that was transformed into a polarity profile, consisting of 14 pairs of sound descriptive attributes. This specific list for operating theaters was used for the sound sample evaluation (see Figure 10), but polarity profiles have already been applied in the past for feature detection of environmental sounds (Kotterba, 1983).

In total four people (fellow students at TU Delft with no medical background) participated in the experiment. Each participant listened to each sound sample four times. Each time, they fulfilled another “professional role”. Even though the participants were not familiar with the sound situation, I wanted to see if the sound perception is affected, e.g. when a participant fulfills the listening role of a surgeon. In future studies, it is advised to use medical staff professionals. In the first round, they did not know the origin of the sound and they evaluated the sound based solely on their own sound perception.

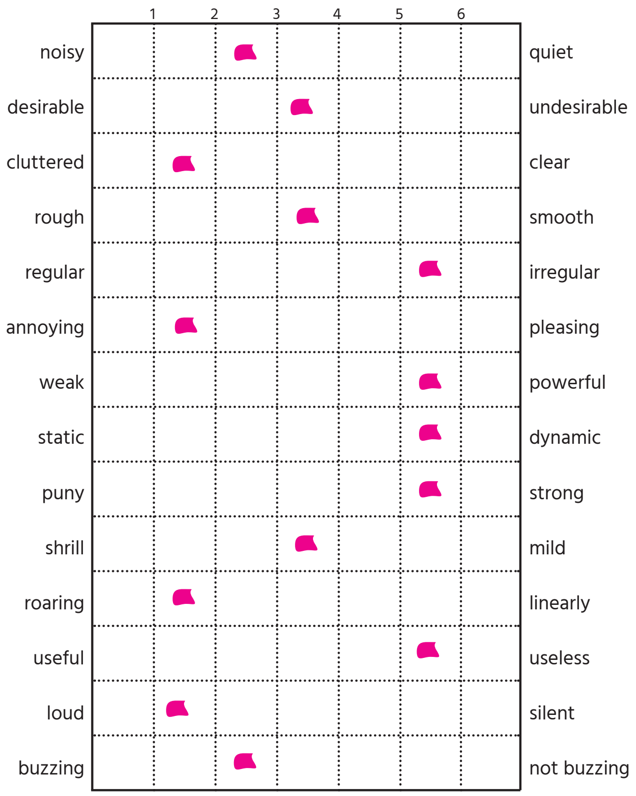


Figure 10. Example of polarity chart

In Round 2-4, they were told about the origin of the sound and they had to evaluate the sound from different “professional roles” (e.g. surgeon, nurse and anesthesiologist). The test-set up included the four sound samples which were listened through earphones (to avoid background sounds). The evaluation was done on paper to assure a dynamic completion of the individual sound quality tables (see Figure 11). The procedure was as follows:

Round 0: Test-round

To get participants acquainted with the sound quality scheme, they practiced in an evaluation of a test sound sample (no sound from operating theater).

Round 1: Not knowing the origin of the sound

The participants listened to the four 25-second sound samples (without knowing the origin of the sounds, i.e. they did not know it was a suction device). While listening to each sample, they completed the sound quality list.

Round 2-4: Listen like a surgeon, OR-nurse and anesthesiologist

An illustration of the sounds’ origin (e.g. a suction device) was shown and its function explained to the participant. Then they were instructed on their role “as a surgeon”. This step was repeated for the role of an OR-nurse and an anesthesiologist.

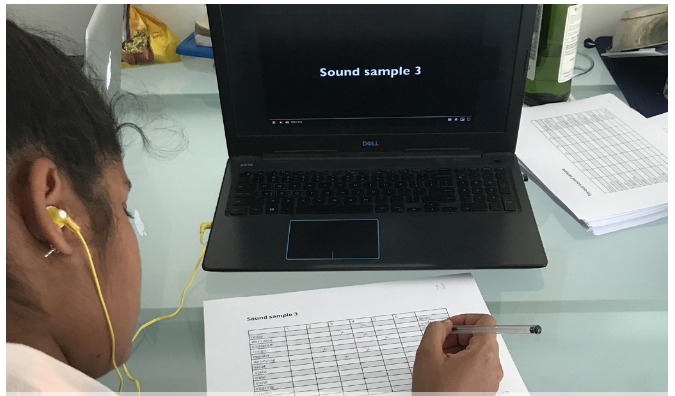


Figure 11. Participant completing polarity chart

Evaluation of subjective evaluation by means of factor analysis

Attributes like “loud” or “quiet” tell us little about sound characteristics. But when someone describes a sound experience as, for instance, “powerful”, it describes more than just powerful, it has the indication that the sound is also loud. With the explorative factor analysis, I wanted to determine which attributes are correlated with each other, i.e. which attributes do we often use to describe similar characteristics of one sound. The explorative factor analysis is a data analysis method that is used when one searches for a correlative in a data set that is yet not determined (Klopp, 2010). The calculation of the explorative factor analysis was performed by Prof. Dr. Benno Kotterba, (president of the “German Society for Acoustic Quality Assurance”, DGAQS e.V.). With my interpretation of the results I aimed to complement the subjective evaluation with an understanding beyond the sound samples at hand and towards a generalization of sound characteristics as described by Kotterba in his dissertation (1983). The factor analysis was exemplarily prepared for the results from role 1 (individual, without knowing the sound source of origin).

Method

The calculated mean values from the subjective evaluation of the sound samples (all four participants) from role 1 were analyzed with regard to their correlation (in the open-source software PSPP, a program for statistic analysis). The correlation was used to determine the dominant factors (highest values of correlation) from the correlation matrix. Based on this evaluation the three dominant factors were the following:

Factor 1

noisy - quiet (Psychoacoustics: loudness)

Factor 2:

rough – smooth (Psychoacoustics: roughness)

Factor 3:

shrill - mild (Psychoacoustics: sharpness, here described through shrill - mild)

Factor 1 describes irritations through sounds, i.e. it is not only determined by the sound pressure level. From the measured orthopedic surgeries and from the four roles and positions in the operating theater (surgeon, OR-nurse, anesthesiologist and researcher), mean decibel levels have been used as a new attribute (called dB-level) to compare sound levels with subjective characteristics. The attribute “dB-level” was retrieved through the conversion of the logarithmic values (ca. 20 seconds) through exponentiation back into linear values (see Section 3.3 for more details on calculation).

Factor 2 corresponds to the subjective perception of the psychoacoustic quantity “roughness”, i.e. the temporal structure of a sound, which is perceived by the ear from uniform to fluctuating to rattling. This factor has originally been determined by Terhard (Vogel, 1975).

Factor 3 corresponds to the subjective perception of “shrillness” (perceived by the ear as bright and sharp) and corresponds to the psychoacoustic quantity sharpness (Fastl & Zwicker, 2007).

Typically, factor analyses can be displayed in a three-dimensional system. For better readability and comprehensibility, each factor plane is displayed separately in a two-dimensional system. The location of the attribute pairs (on the X or Y-axes) determines the correlation to the respective factors.

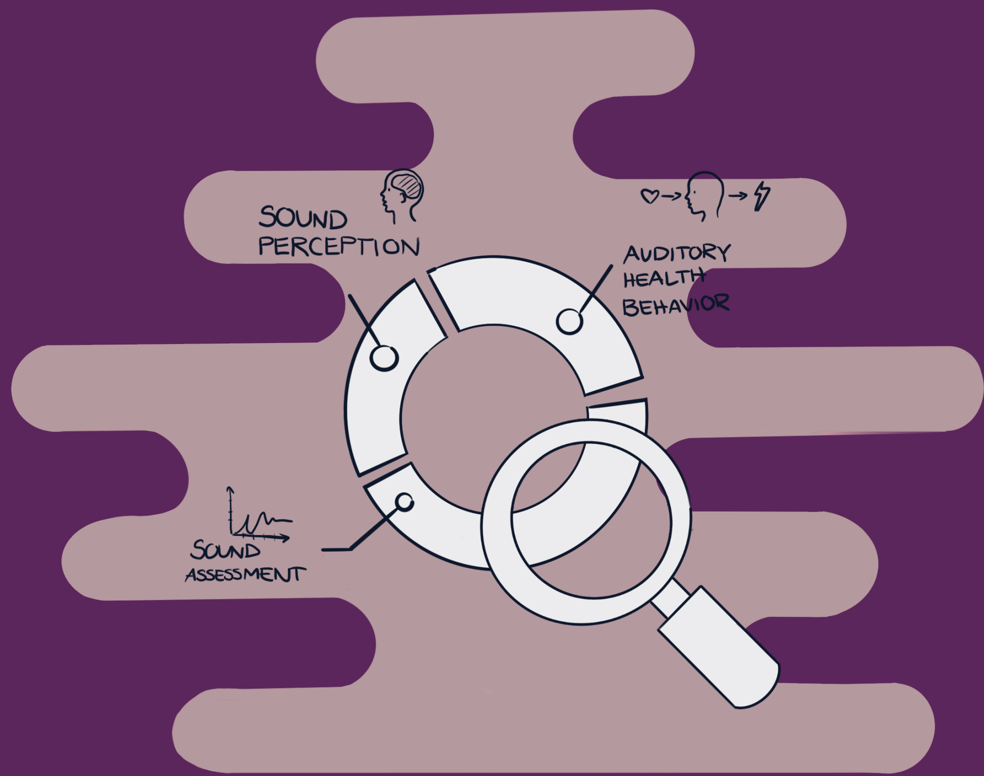
3.5 Physical analysis of sound samples

After completion of the subjective evaluation, the sound samples were analyzed by Lothar Schmidt (co-worker of DGAQS e.V.) according to the following characteristics: time-domain (loudness in relation to time) and frequency division of the sounds (frequency in relation to time). This analysis aimed to determine whether the characteristics used and mentioned in the subjective evaluation (e.g. irregularity, shrillness) are also reflected in the results of the physical parameters (visual representation). Together with the subjective evaluation it was possible to describe the characters of the four sound samples. The interpretation of this analysis was completed in consultation with Prof. Dr. Kotterba.

Section 4

Research: Results

4.1 Sound perception of medical staff
4.2 Listening types in operating theaters
4.3 Sound measurements results of operating theaters
4.4 Psychoacoustic results on sound perception
4.5. Physical results of sound samples
4.6. Patterns and trends recognized through psychoacoustics
4.7 Auditory health behaviors: Precaution adoption attitude



04 Research: Results

This section contains the research results. It is structured according to the chronological sequence of the conducted research activities.

4.1 Sound perception of medical staff

The user research combined with the soundscape observations showed that sound is an important aspect of the work in operating theaters. Most participants reported that sound positively enhances their communication ability when there is no visual access to other team members. Some mentioned that sound and hearing enabled them to multitask.

But participants also expressed that they perceive some sounds as negative and harmful for their work, health, and also for patients' safety. Missing important auditory feedback due to other sounds or noise is prevalent. The following sections illustrate the medical staffs' positive and negative sound experiences for four chosen **sound categories**: **pleasant**, **useful**, **unpleasant** and **harmful sounds**.

Pleasant sounds

Description: Sounds that are pleasant in the participants' ears or sounds that bring up positive emotions (see Figure 12).

Examples for pleasant or desired sounds are conversations with colleagues and music. Participants classified them as an improvement for the atmosphere. Some participants specified that listening to music or conversations is only desirable if the situation "allowed it" (e.g. not during an emergency).

Music was the most frequently mentioned pleasant sound. Most participants enjoy music during their work. It "makes them happier". Therefore, the positive effects of music should not be neglected as long as the music is at a considerate level. Katz (2014) described music as a "special type of noise". Music can have a calming effect in stressful situations, but it also contributes to the overall sound level in the soundscape and can thereby lead to discomfort. Other less frequently mentioned pleasant sounds were those confirming the patients' well-being (e.g. heartbeat), or sounds that participants liked because those underlined an activity they liked doing (e.g. the use of the mallet during a total hip-replacement).

Useful sounds

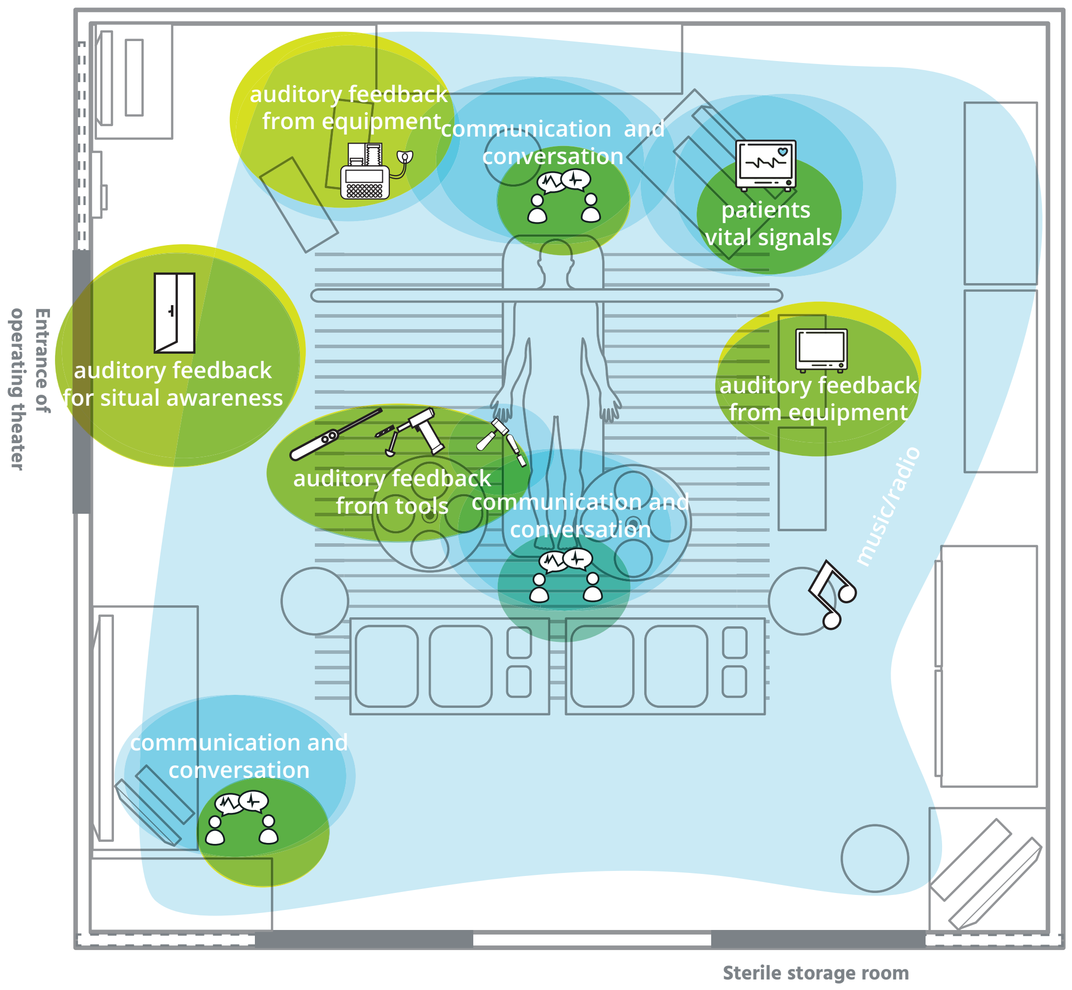
Description: Any sound that is needed for the individual work performance. These sounds give auditory information (functionality) that allows the medical staff to act appropriately to the situations at hand (see Figure 12).

Useful sounds were sub-grouped into three categories: related to equipment, related to communication, and related to situational awareness.

Useful sounds related to equipment were, for example, signals and alarms from equipment. These sounds can also be called "intentional sounds" (Van Egmond, 2008). They are chosen to be part of the product for its functionality. Examples are signals from anesthesia equipment (e.g. oxygen levels) or signals from tools (e.g. signals indicating VAPR is either contouring or cutting). Next to "intentional sounds" there are also "consequential sounds" (Van Egmond, 2008). These sounds result from a products' functioning (e.g. moving of mechanical parts) and user interaction with the product (e.g. the rotation speed of a drill). Participants reported that they applied an analytic listening to know, for instance, where exactly the drill is situated within the bone structure of the patient.

Communication was mentioned as an important useful sound source. Respondents provided examples related to verbal instructions (e.g. supervising surgeon instructing resident) and verbal feedback (e.g. anesthesiologist informing surgeon on the patients' status).

Participants reported that sounds enabled them to be situational aware to ensure an optimal surgical environment. For example, sounds that are unusual or not supposed to happen (e.g. door opening while setting an implant) alert people and trigger them to pay higher attention to the situation at hand.



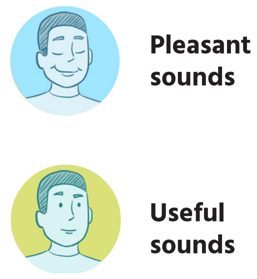


Figure 12. Pleasant and useful sound sources in operating theaters

* The sketch of the operating theater is based on the basis of observations in Erasmus MC.

(+) NICE-TO-KNOW
Participants' quotes

Resident 2

"I think, that yeah, especially the sound of the ***hammer, it can be helpful****. Even if it's loud, it is not bothering me [...] it's kind of* ***an activity that we like****, I think."*

OR-nurse 1

"And then I ***like to listen to music*** *and not to people talking. Not too loud but* ***just like background music****."*

Anesthesiologist 2

"But we always have our ***sixth sense, hearing*** *about: Is there an alarm going on? Or how is the saturation pitch? [...]. So,* ***just by listening****, I know [...] what heart rate my patient has and what saturation, oxygen saturation my patient has, and* ***hearing those sounds on the background continuously*** *tells me that everything goes* ***well or not****."*

"Because if it is just ***simple surgery****, then it can help to chat a little. Because if it is totally quiet in the OR, yeah,* ***I prefer, we can chat a little bit****, but only if the procedure that I am doing is going smooth."*

Resident 2

Unpleasant sounds

Description: Any sound that is perceived as annoying or disturbing. They are unwanted, "situational" sounds that may not be perceived as immediately harmful, but unpleasant or unnecessary (see Figure 13).

The findings show that unpleasant sounds can derive from many different sound sources, but mainly fall in one of the two following categories, "unpleasant sounds related to equipment" and "unpleasant sounds related to people".

The equipment-related sound sources do not necessarily produce unpleasant physical sounds as such, but they can contribute to the general noisiness. Machinery that runs without interruption produces continuous noise (e.g. bear hugger, which is an air warmer for the patient, ventilation within the protective helmet). While they are not necessarily loud, the overlap of multiple sounds results in continuous background noise (e.g. ventilation, music, etc.). The overall noisiness can then cause a distraction itself but also impair communication.

This also applies to other sound sources that produce loud and impulsive noise, for instance, the oscillating saw. Impulsive sounds are very loud, but short in duration. One resident mentioned that the noise from the oscillating saw makes it very difficult or even impossible to follow verbal instructions from the supervisor on how to set the cut. This is in line with Keller et al. (2016), who report that noise peaks can impair case-relevant communication, necessitating speakers to raise their voice or pause their activity to communicate. Within my study, the medical staff often mentioned their annoyance by irregular noise produced by devices like the suction. These findings are also in line with Zimmer et al. (2008), who found that sound interruptions rather than sound loudness cause negative emotions. It is also in line with Fritsch, Chacko and Patterson (2010), who reported that filtering sound gets more difficult when sounds are interrupted. In this case, those sounds are more likely perceived as a distraction. Other non-device sounds can also be perceived as unpleasant as they disrupt the workflow within the operating theaters. Disruptive sounds are, for instance, telephones or non-actionable alarms arriving from anesthesia equipment.

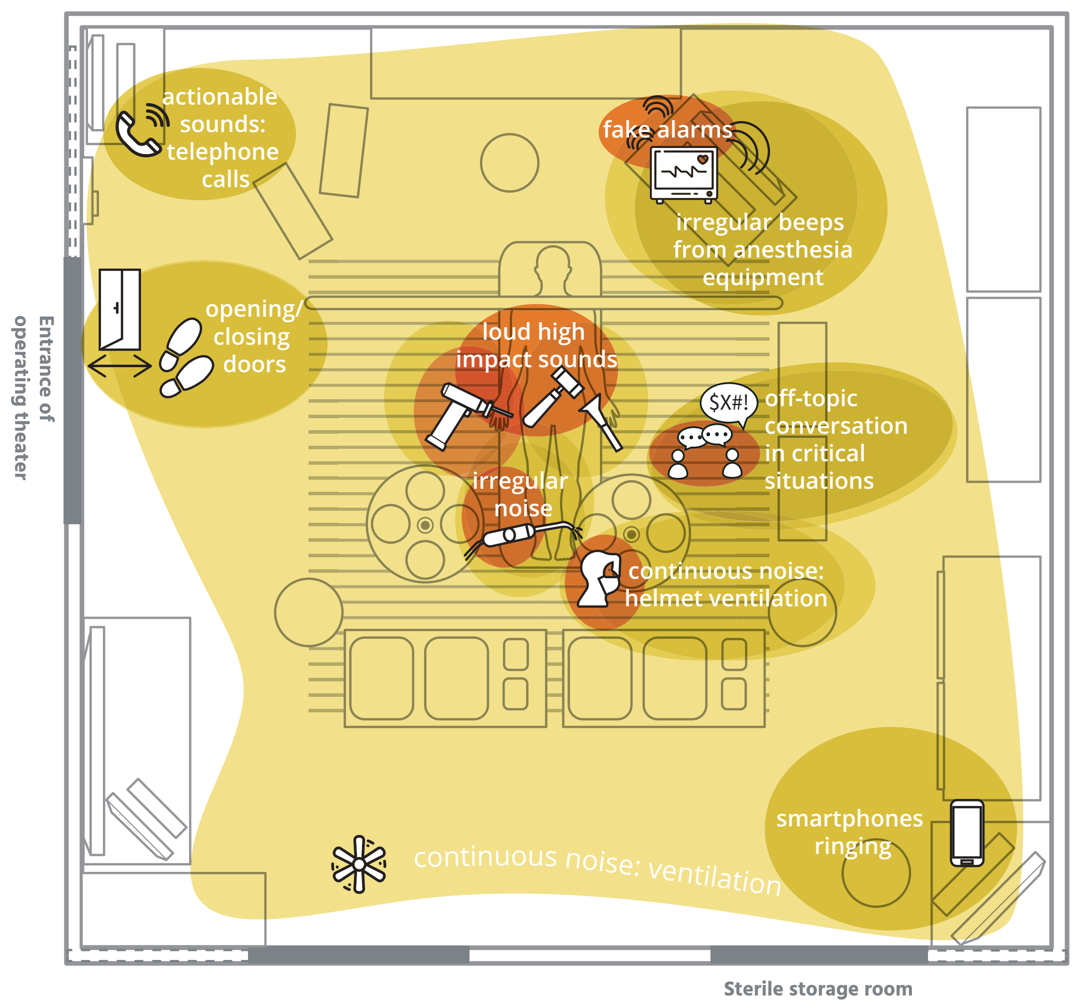
People also cause unpleasant sounds through their individual actions or characteristics. An example mentioned was alarm volumes of the anesthesia equipment being set too loud. However, this may be a vicious circle if alarms have to be upped due to background noise. Another example was that too many people in the room cause extra sounds, for instance, due to moving in the room or continuous conversation. One participant mentioned that it is not unusual to have 12 people in the room during one surgery. Another people-related unpleasant sound was interpersonal communication between colleagues that caused annoyance because of inappropriate timing or case-irrelevant communication. These sounds reduce concentration or create annoyance because the participants felt that sometimes other team-members were not considerate in critical situations. Other examples were unanswered communication attempts (e.g. not listening of an anesthesiologist when contacted by the surgeon due to being occupied with other tasks).

Harmful sounds

Description: Any sound that is perceived as harmful to participants' physical or mental health. Those sounds are perceived as not bearable over a longer period (see Figure 13).

Harmful sounds can be grouped into two categories, "impulsive or high-impact sounds" and "continuous sounds". Sounds such as the oscillating saw, the mallet, or in general the sounds of metal hitting on metal are impulsive sounds. Broom, Capek, Carachi, Akeroyd, and Hilditch (2011) reported that sound sources producing loud noises in the operating theater are mostly associated with technical equipment and its handling. This is in line with the findings of this research. But while some participants perceived impulsive sounds as harmful, others did not.

Continuous noises are an ongoing background distraction. They can also affect one's hearing capability. A rather unexpected finding was that some participants perceived the sound of helmets as harmful. Helmets are used in some orthopedic procedures (mostly involving implants). They include an in-built ventilator that produces continuous noise close to the ear channel. This continuous noise impairs communication and can also lead to annoyance and a strong feeling of distraction.



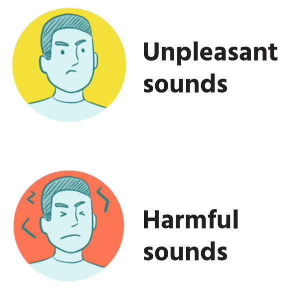


Figure 13. Unpleasant and harmful sound sources in operating theaters

* The sketch of the operating theater is based on the basis of observations in Erasmus MC.

(+) NICE-TO-KNOW
Participants' quotes

Resident 2

*"...Yeah, it's...the sound is not very clear. So if I have to, so if I can choose, I always prefer to operate without the **helmets**. It is not just the communication, for example...[...] **like you are underwater or something**...*

*"But the **oscillating saw** we use...ahhhhh...That makes **such an irritating noise.** It's very loud, it's high pitched. I really don't like it."*

Resident 1

*"There's **a lot of noise in the OR**. There's noise for people speaking, there's noise from devices that the surgeon uses, [...] Then there's the noise from our ventilator, there's the noise from our monitors. **And then, apart from all of that there are alarms**."*

Anesthesiologist 2

Resident 1

*"And in the operation wards sometimes [...] there's in the **ventilator** or something, **like a ticking noise** [...] I think also it's especially **annoying when it's irregular**, because if it is regular, then maybe you get used to it. But if it **sometimes ticks and sometimes does not, then that really distracts me.** [...] mainly has to do with something...**it's like malfunctioning**."*

Surgeon 3

*"There is some fatty tissue, the tip of the **suction gets a little...almost clogged**, then it makes a **very loud noise** and that **happens quite often** [...] it just makes annoying sounds."*

4.2 Listening types in operating theaters

In orthopedic operating theaters, several different professions work side by side. As tasks differ, listeners are prioritizing individually to which degree they pay attention to the auditory information that arrives from different sound sources. Amending and adapting Truax (2001), five listening types were identified: "No-listening" by exposed listeners, "background listening" by passive listeners, "listening-in-readiness" by active listeners, "listening-in-search" by sound users and "listening-and-acting" by sound producers.

Two streams of listener hierarchies were observed (see Figures 14 & 15), depending on the main focus of listening: the perspective of performing the surgery (e.g. surgeon) or the perspective of monitoring the patient (e.g. anesthesiologist). For instance, both the surgeon and the anesthesiologist are sound users focusing on different tasks. The anesthesiologist primarily listens to the patient's signals, while the surgeon primarily listens to the sound situation at the operating table (e.g. feedback from tools). These two listening-attention types sometimes interrupt or cover each other (e.g. if there is a lot of noise from the saw, it may overlay signals from the patient monitor).

Although a general distinction between the listeners can be made, listening types may fluctuate according to the situation within the surgery (indicated in Figure 14 & 15 as arrows). For example, scrub nurses performing a step in the procedure will become sound users themselves, but will most likely switch back into the active listening mode after the step has been completed. The only listener types not fluctuating are the patients, because they are (mostly) sedated. But also when sedated, their ears are still "exposed" to the sounds.

4.3 Sound measurements results of operating theaters

The sound measurements were made with the aforementioned app. As the microphones (iRig Mic) are optimized for voice output, the given results are of similar kind than dB(A) levels. In total, I measured seven surgeries (three total knee replacements, three arthroscopic knee surgeries and one osteotomy of the lower leg). Due to difficulties with the algorithm of the application, peak levels (peak values) were excluded from the results.

Average sound pressure levels

The duration of the intraoperative period within the seven measured surgeries was 81 min on average for total knee replacements, 70 min on average for arthroscopic surgeries and the osteotomy took 135 minutes. The average noise levels of surgeons representing the highest values of the staff ranged between 53 and 71 dB for all surgeries (see Table 3). This shows that the average per different surgeries were both well within allowable limits, for arthroscopic surgeries and total knee replacement and also below the first action limit set at 80dB(A) per 8-hour working day by European legislation (Health and Safety Authority, Regulation 125, 2007).

Decibel level distribution among professions

A comparison between different profession showed that surgeons experienced the highest average decibel levels during the "loud" knee replacement surgeries, while anesthesiologists were exposed to lower sound levels. During the "less loud" surgeries, however, sounds were distributed more equally. Twice the researcher experienced higher mean dB levels than the surgeon. This is probably due to the fact that the researcher was both times situated close to the music loudspeakers during the surgery.

Summary on decibel measurements

None of the measured surgeries exceed averaged allowed decibel levels. But, the risk of physiological health consequences seems higher in open surgeries such as total knee replacements, which often involve powered tools. Arthroscopic surgeries were significantly less noisy as different surgical tools were used compared to the open procedures (total knee replacements and osteotomy). The present results cannot provide any information about the criticality of peak values (dBC), which are assumed to be very high, especially during the use of a mallet. Previous studies showed that those levels exceed 140dBC several times (Love, 2003). The results of total knee replacements suggest that surgeons are at the highest risk for physiological health consequences as they are situated closest to the sound source. However, residents and the scrub nurse are situated right next to the surgeon. Their values are expected to be almost as high.

The decibel values indicated here give an estimation of the physiological consequences of sound exposure,

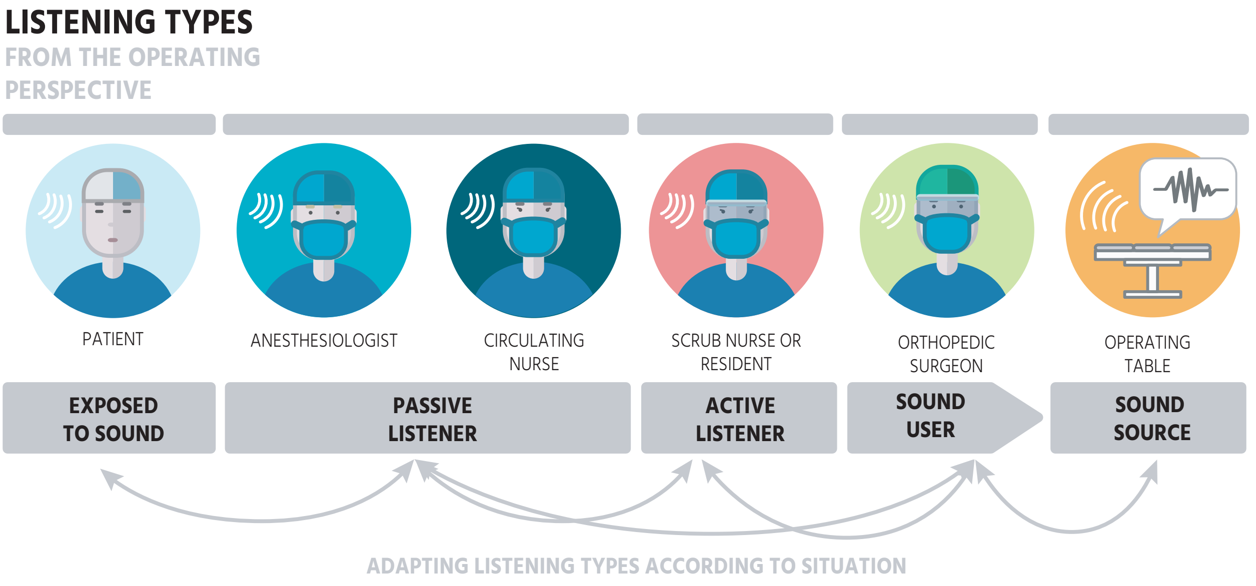


Figure 14. Listening types from the operating perspective

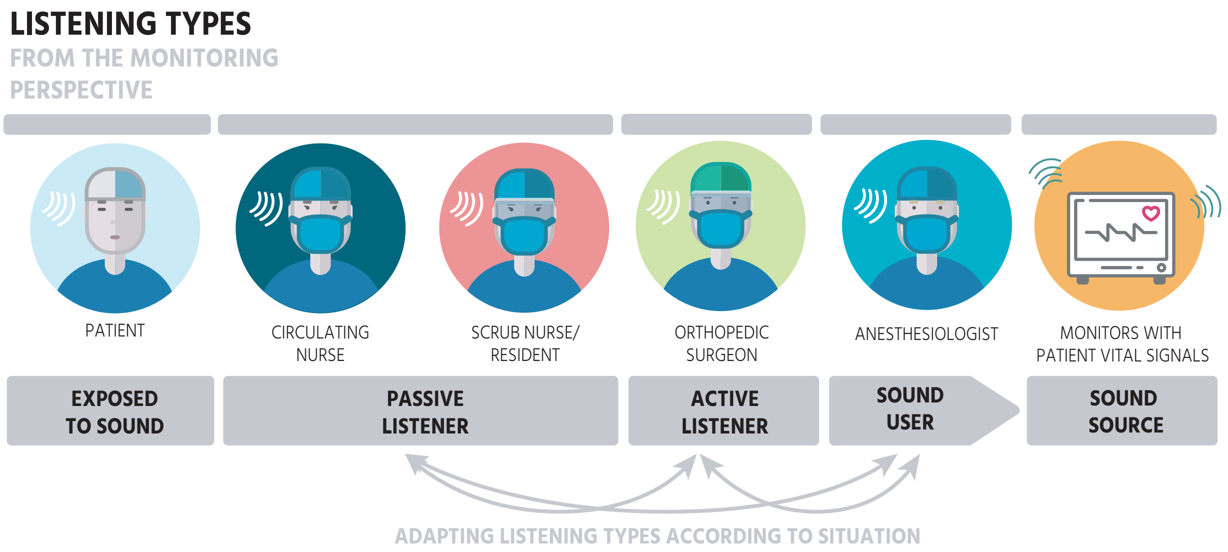


Figure 15. Listening types from the monitoring perspective

Table 3. Mean decibel values per surgery type

	Mean dB (range)			
	Surgeon	Circulating nurse	Anesthesiologist	Researcher
Total knee replacements surgery (3 surgeries)	68 - 71	66 - 68	57 - 61	56 - 60
Arthroscopic knee surgery (3 surgeries)	53 - 57	48 - 53	52 - 54	54 - 58
Osteotomy lower leg (1 surgery)	55	49	53	52

* Not the same number per surgery type were measured. The osteotomy represents one mean dB value, i.e. displays no range.
** The latest starting time and earliest ending time were applied to each user recording to have comparable calculations.

but they cannot give insights on the psychological health impacts associated with sound exposure. Therefore, I complemented the research with an additional psychoacoustic experiment.

4.4 Psychoacoustic results on sound perception

As described in Section 3.4, a psychoacoustic analysis on sound perception took place. Here I will discuss the two steps: The subjective analysis and the explorative factor analysis.

Subjective analysis

The subjective sound analysis was performed with four test-persons (students from TU Delft, with no medical background). Per listening role, average values of the four individuals were calculated and used in the analysis. This experiment is not representative for the medical staff population, but gives an indication for future research. All sound samples evaluations are visualized in Figure 16.

Sound sample 1: Sound of a suction device

At first, all participants (role individual) perceived the suction as noisy. But they adjusted their levels in the next roles after hearing the other sounds in comparison. Annoyance is similarly rated to the oscillating saw and the mallet, even though the suction is significantly less loud. An outstanding sound characteristic was the irregularity.

Sound sample 2: Sound of an oscillating saw

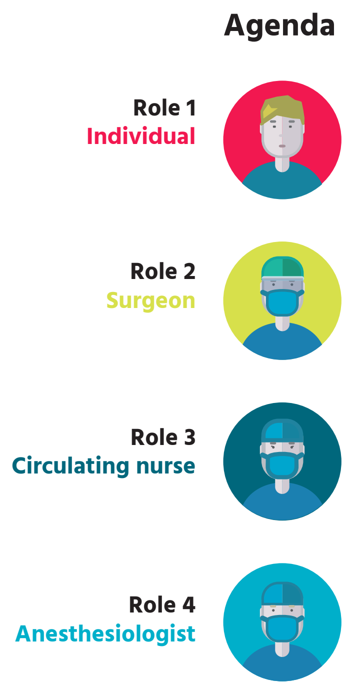
Perceived as the noisiest sound, there is a significant difference in ratings between involved (surgeon, nurse) and uninvolved persons. It is perceived as a very shrill, buzzing and powerful sound. These characteristics may also contribute to the reported high annoyance sensation. The participants seemed indecisive on the usefulness of the sound.

Sound sample 3: Sound of patient's signals

Patient signals were perceived as rather pleasing compared to the other sounds. The participants stated as reasons that it was a continuous, linear and regular sound. The overall sensation of the sound is similar for all roles. Being of comparable loudness to the suction device, it was perceived as significantly less noisy. I cannot explain why for the circulating nurse the sound was perceived as rather buzzing.

Sound sample 4: Sounds of a mallet on a chisel

When the participants rated this sound from the surgeon's perspective, they rated it as a more positive sound, compared to the other roles. This may be because participants assume that the surgeon is the sound producer. Overall, the characteristics of the mallet and the saw were rated similarly.



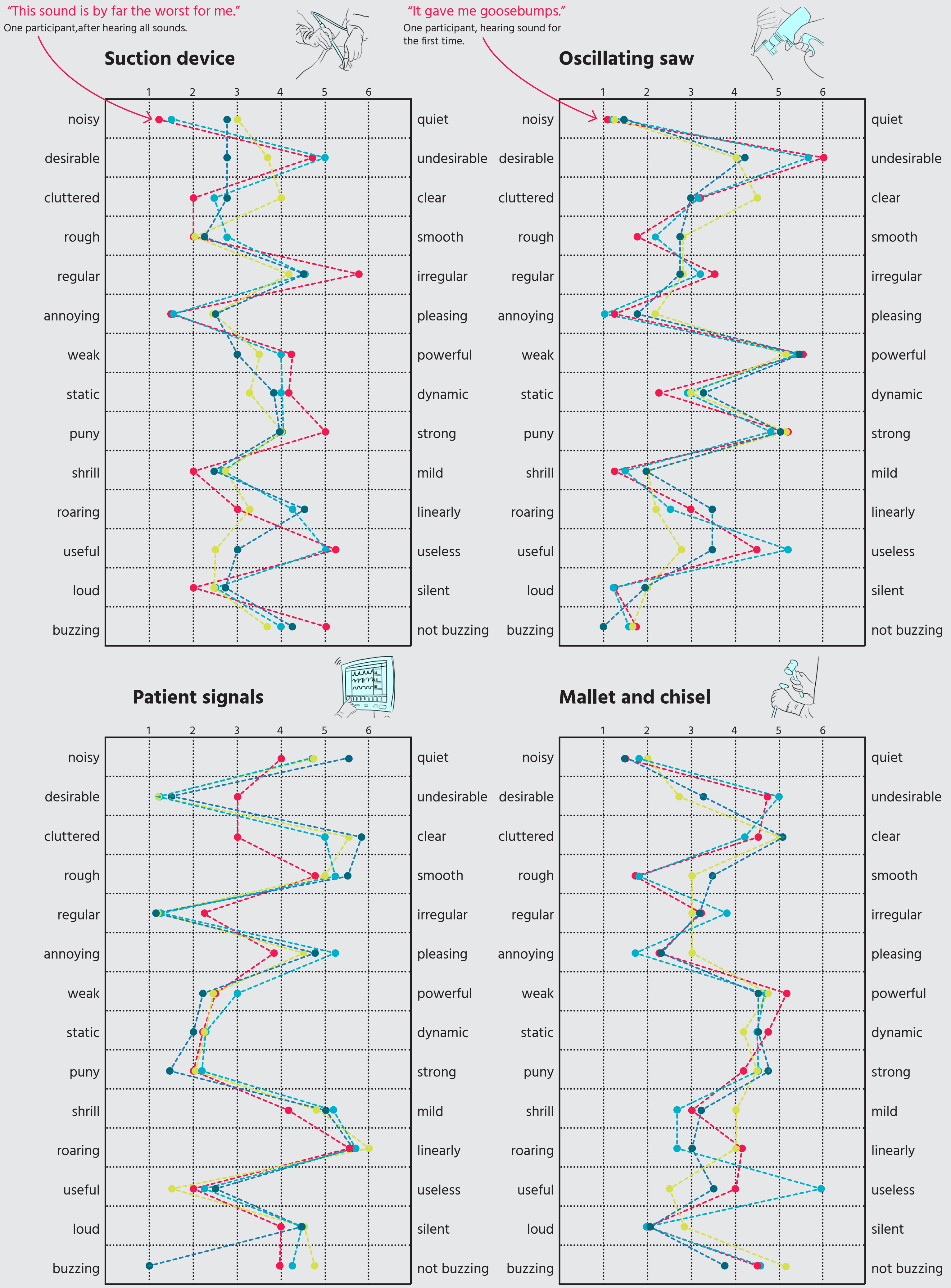


Figure 16. Result of subjective sound perception of sound samples

Explorative factor analysis

An explorative factor analysis was performed in consultation with Prof. Dr. Kotterba. In the following, I discuss the results of role 1 (individual, evaluating the sounds without knowing the origin of sounds). In future studies, it would be necessary to assess whether the attribute correlations change according to the different medical professions (e.g. individual categorization in useful or useless sounds). The closer an attribute is situated in the direction of the factor, the higher is the correlation, i.e. if an attribute is situated at the center of the axes, it is neutral.

Correlation between Factor 1 (noisy vs. quiet) and Factor 2 (rough vs. smooth)

Figure 17 illustrates that the features mild and regular are highly correlated to weak and smooth, corresponding to pleasant sound experiences. Loud and roaring are correlated to noisy and rough, corresponding to unpleasant sound experiences.

Correlation between Factor 1 (noisy vs. quiet) and Factor 3 (shrill vs. mild)

Figure 18 illustrates that the features useful, mild, regular and static are correlated to weak and mild, corresponding to pleasant sound experiences. Annoying, loud and cluttered are correlated to noisy and shrill, corresponding to unpleasant sound experiences. But the feature "shrill" can also be included in quieter sounds (as the location close to zero on the Y-axis indicates).

Correlation between Factor 2 (rough vs. smooth) and Factor 3 (shrill vs. mild)

Figure 19 illustrates that the feature regular is correlated to smooth and mild, corresponding to pleasant sound experiences. Loud is correlated to rough and shrill, corresponding to unpleasant sound experiences.

Correlation between Factors 1 and 2

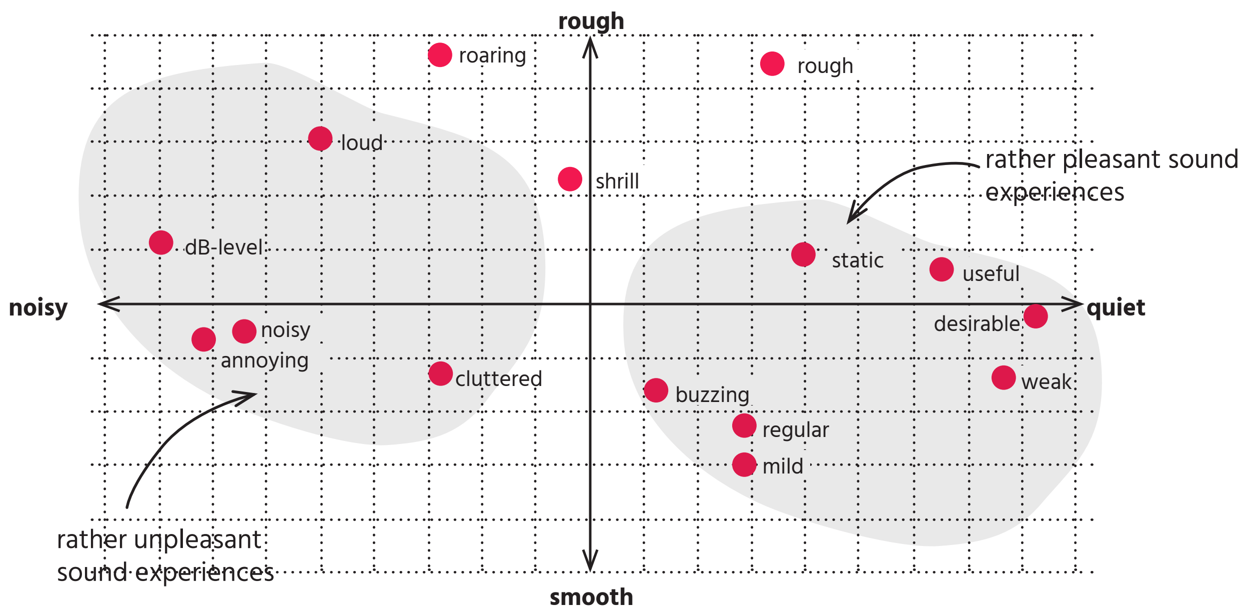


Figure 17. Explorative factor analysis. Correlation between factor 1 (noisy vs. quiet) and factor 2 (rough vs. smooth)
* Own representation adapted from explorative factor analysis performed by Prof. Dr. Benno Kotterba

Correlation between Factors 1 and 3

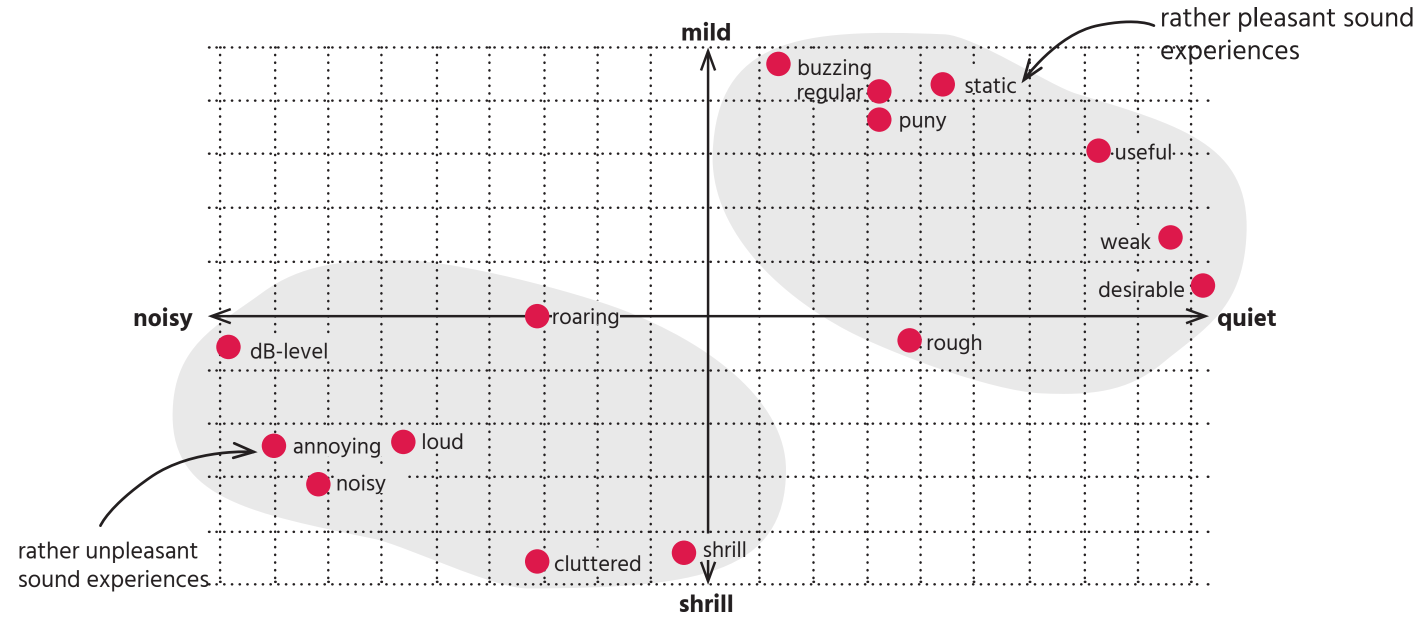


Figure 18. Explorative factor analysis. Correlation between Factor 1 (noisy vs. quiet) and Factor 3 (shrill vs. mild)
* Own representation adapted from explorative factor analysis performed by Prof. Dr. Benno Kotterba

Correlation between Factors 2 and 3

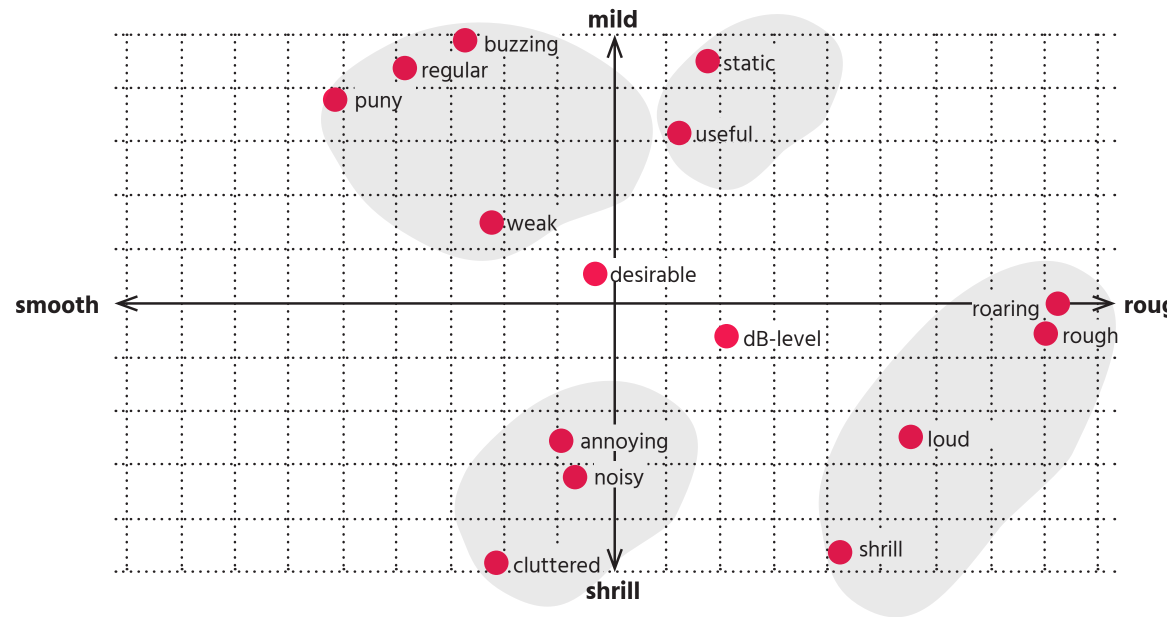


Figure 19. Explorative factor analysis. Correlation between Factor 2 (smooth vs. rough) and Factor 3 (shrill vs. mild)
* Own representation adapted from explorative factor analysis performed by Prof. Dr. Benno Kotterba

4.5 Physical results of sound samples

These graphs and spectrograms (Figure 20 - 31) were generated by Lothar Schmidt and analyzed in consultation with Prof. Dr. Kotterba. Different to the subjective evaluation, the sample lengths were not adapted to 25 seconds, i.e. the graphs represent different lengths of acoustic signals (12 - 14 seconds).

Time-domains

The time domain describes the change of amplitudes of a sound over time. High amplitudes refer to high sound levels. The change over time is an indication of the regularity/irregularity of the sound. Therefore, high amplitudes with sudden appearance and disappearance of signal represent an up and down of sound, low amplitudes without major changes a continuous silent sound.

Sound sample 1: Suction device
Figure 20 illustrates the level characteristic of the suction device in the time domain. The sample length (15 sec) is shown on the X-axis. Within this time period the amplitude of the signal is very irregular. At the beginning (0 sec until 7 sec) unsteady amplitudes are recorded. Between 11 sec and 14 sec there are almost no amplitudes.

Sound sample 2: Oscillating saw
Figure 21 illustrates the oscillating saw. The sound is present all the time with a high intensity and amplitude. The amount of the amplitude indicates that the sound is much louder than, for instance, the patient signal. Even more, the sound was louder than the specific microphone could depict (the curves look “cut off”).

Sound sample 3: Patient signals
Figure 22 illustrates the level characteristic of the patient signals. Within the sample-time, the recorded signal shows a base amplitude with certain irregular ups and downs. This is in contrast to the description of the subjective sound perception by participants (“regular sound”). This is important to notice because the regular beeping is not clearly visible in this curve. The reason could be that its signal is masked by other (background-) sounds (the time-domain cannot reflect the actual sound situation because the sound situation cannot be separated for fore-ground and background sounds). But the delicate structure environment.

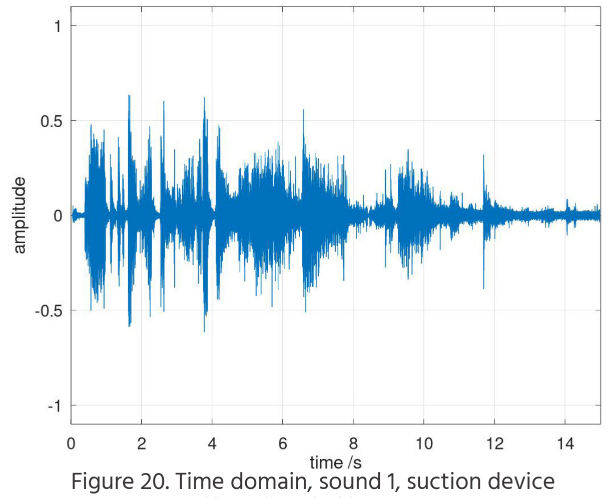


Figure 20. Time domain, sound 1, suction device
* Image prepared by Lothar Schmidt

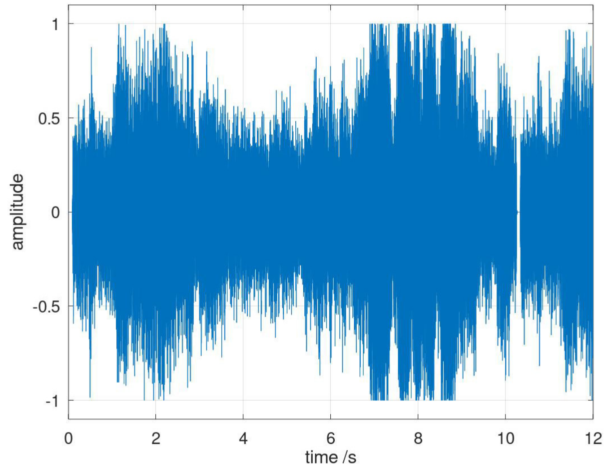


Figure 21. Time domain, sound 2, oscillating saw
* Image prepared by Lothar Schmidt

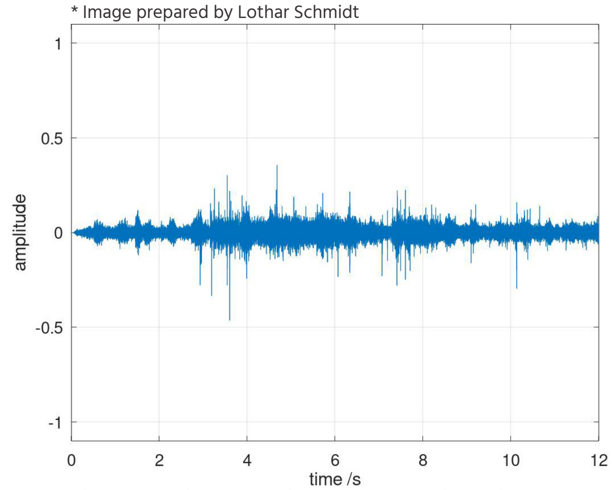


Figure 22. Time domain, sound 3, patient signals
* Image prepared by Lothar Schmidt

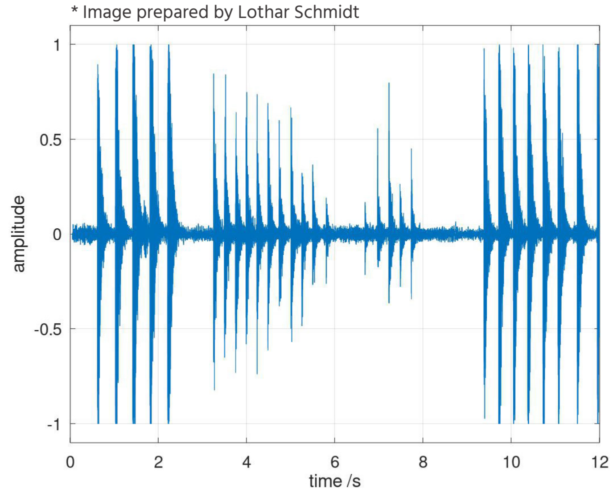


Figure 23. Time domain, sound 3, patient signals
* Image prepared by Lothar Schmidt

of human hearing can detect specific timbres, even though the background sounds are louder than the environment.

Sound sample 4: Mallet and chisel
Figure 23 illustrates the level characteristic of the mallet. This sound is an impulsive sound. It is a noise in which short sequences of high amplitudes are combined with relatively silent phases – each peak represents one blow. Across time, the sequence of the amplitudes shows some regularity.

Sound level curve

The sound level curves represent the loudness of the respective sounds. As the calibration of the microphones, used to perform the recordings are not known (due to purchased samples), the sound levels presented here indicate the fluctuation of decibel levels, not the factual loudness (linear shifting is not possible).

Sound sample 1: Suction device
Figure 24 illustrates the sound level of the suction device in the time domain. The curve shows that the sound levels are irregular. The signals fluctuate by about 30 dB within the time span measured and indicate a quickly changing loudness with an irregular sequence.

Sound sample 2: Oscillating saw
Figure 25 illustrates the sound level of the oscillating saw in the time domain. The curve shows a high level over time with no major changes (the down at 10.5 sec is an artefact due to the measurement). This characterizes a regular noise with high intensity.

Sound sample 3: Patient signals
Figure 26 illustrates the sound level of the patient’s signal in the time domain. The curve shows a somehow regular shape on a relatively low level. The patient’s signals (“beeps”) are not visible, when only looking at this decibel level distribution. That is the reason that looking at the frequencies or spectrograms of sound gets necessary (see Figure 30).

Sound sample 4: Mallet and chisel
Figure 27 illustrates the sound level of the mallet in the time domain. The curve shows a quite regular sequence of ups and downs with high levels (40 dB). This impulsive noise with high peaks is especially important when maximum sound levels are examined.

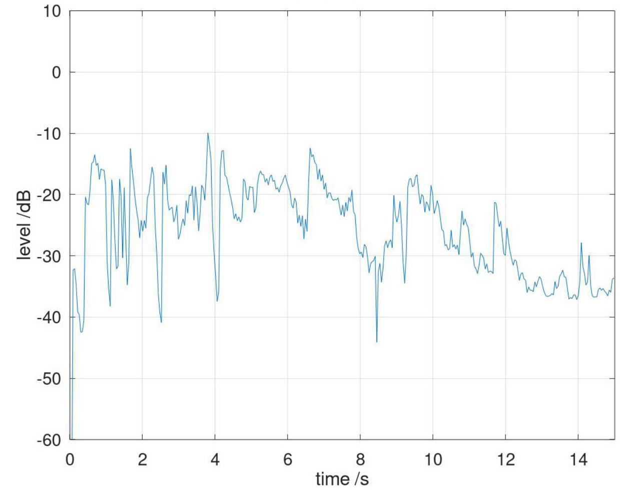


Figure 24. Sound levels sound sample 1, suction device
* Image prepared by Lothar Schmidt (2020)

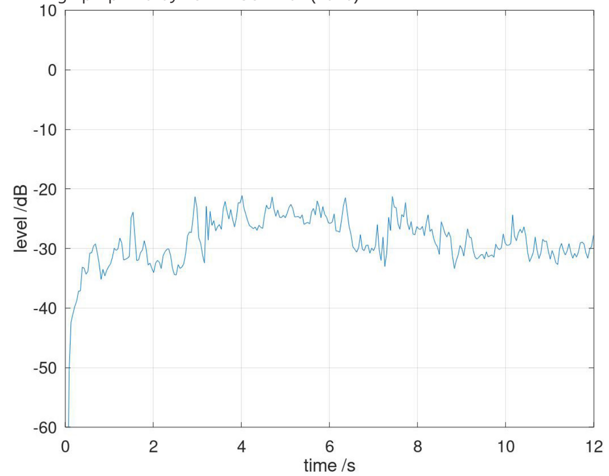


Figure 25. Sound levels, sound 2, oscillating saw
* Image prepared by Lothar Schmidt

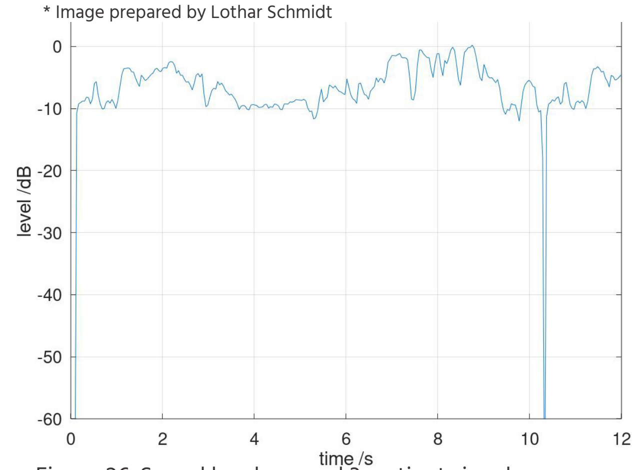


Figure 26. Sound levels, sound 3, patient signals
* Image prepared by Lothar Schmidt

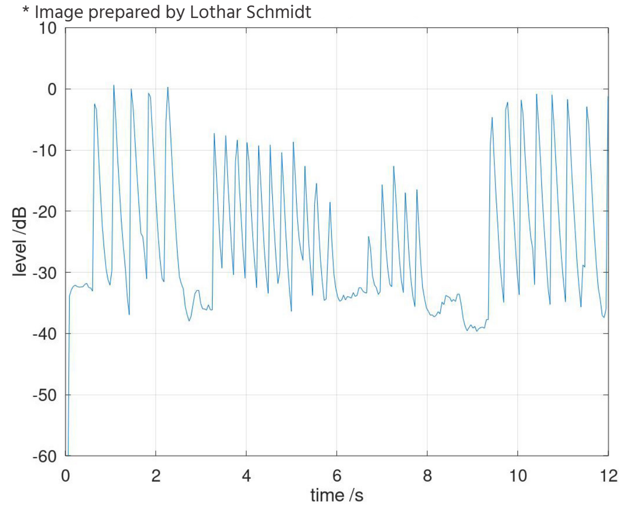


Figure 27. Sound levels ,sound 4, mallet and chisel
* Image prepared by Lothar Schmidt

Frequency division: Spectrogram

The spectrogram visualizes the spectrum of the frequencies of the sound indicated by different colors. The measured range of 0 to 8,000 Hz represents a major part of the frequencies which human hearing is able to detect (20 Hz up to 20,000 Hz).

Sound sample 1: Suction device

Figure 28 illustrates the irregular gurgling sound of the suction. The color coding indicates that the frequencies are rather low (between 0-3000 Hz). These are also the frequencies similar to speech frequencies. Also visible is that the acoustic signals are short and often interrupted with different levels of loudness. The louder a sound is, the brighter it is shown in the spectrogram.

Sound sample 2: Oscillating saw

Figure 29 illustrates the oscillating saw spectrum. The arrows indicate a horizontal bar (ca. 0-2,000Hz) representing the (basic sound of the) engine noise of the oscillating saw. One line represents the base tone, while the combination of base tones form a basic noise. The vertical bar (e.g. 6-10sec.) indicates the moment where the saw cuts the bone. This is where the background noise of the saw is coming together with the sound when hard material is cut. From an acoustic point of view, not everyone will be hear the higher frequencies (e.g. from 4,000- 6,000 Hz), because the older people get, the less they hear high frequencies.

Sound sample 3: Patient signals

Figure 30 illustrates the patients' signals within the soundscape environment (e.g. background noise). The patients' signal (monitor signal) is slightly visible in the spectrogram. The little regular dots (see arrows) indicate the signal within the sound situation. They are visible from around 1800Hz with distances until around 5000 Hz. From that it can be concluded that the tone probably has a frequency of about 600-700 Hz.

Sound sample 4: Mallet and chisel

Figure 31 illustrates the signals of mallet and chisel. Their sound includes a broadband spectrum - all frequencies are covered (0- over 8000 Hz). It is an impulsive noise in which short sequences of noise and relative silence alternate in a fast pace. Similar to the saw, the vibration between material and material (metal on metal) are clearly visible.

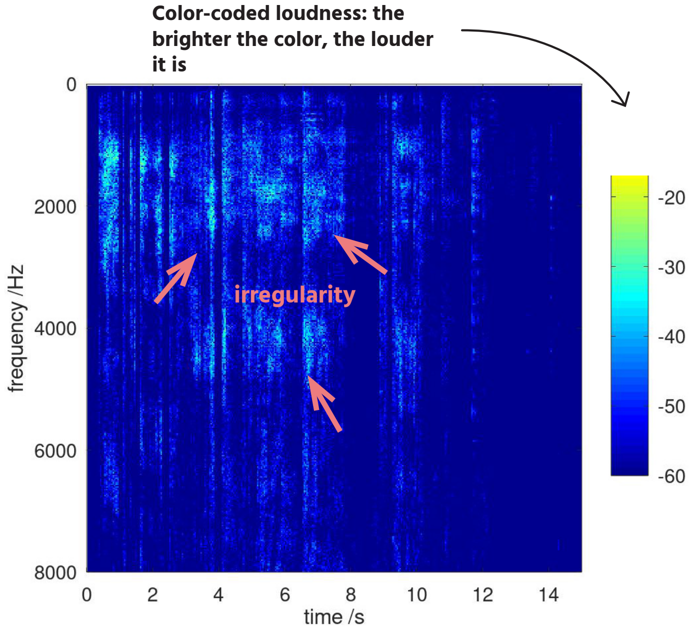


Figure 28. Frequency division, sound 1, suction
* Image prepared by Lothar Schmidt

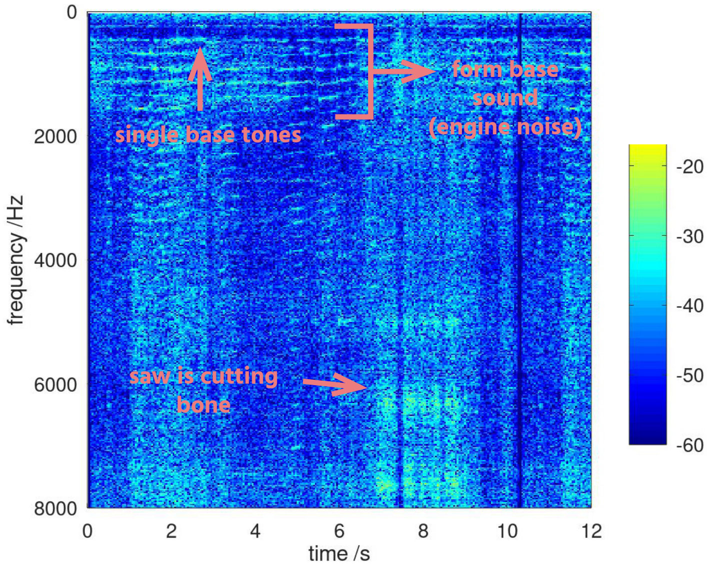


Figure 29. Frequency division, sound 2, oscillating saw
* Image prepared by Lothar Schmidt

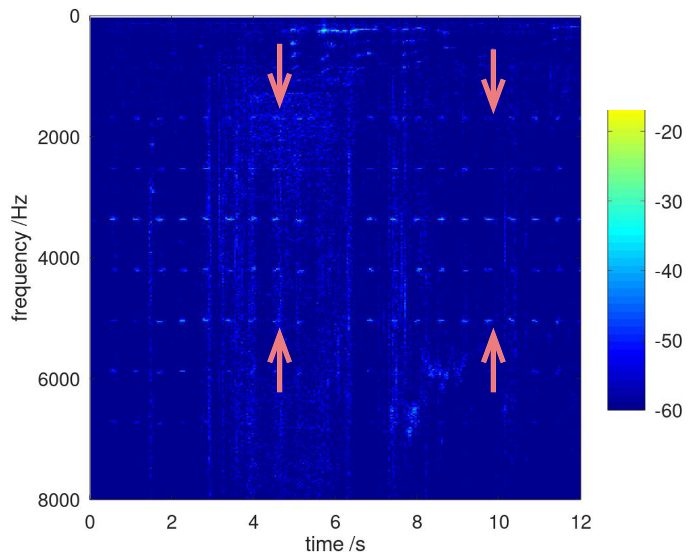


Figure 30. Frequency division, sound 3, patient signals
* Image prepared by Lothar Schmidt

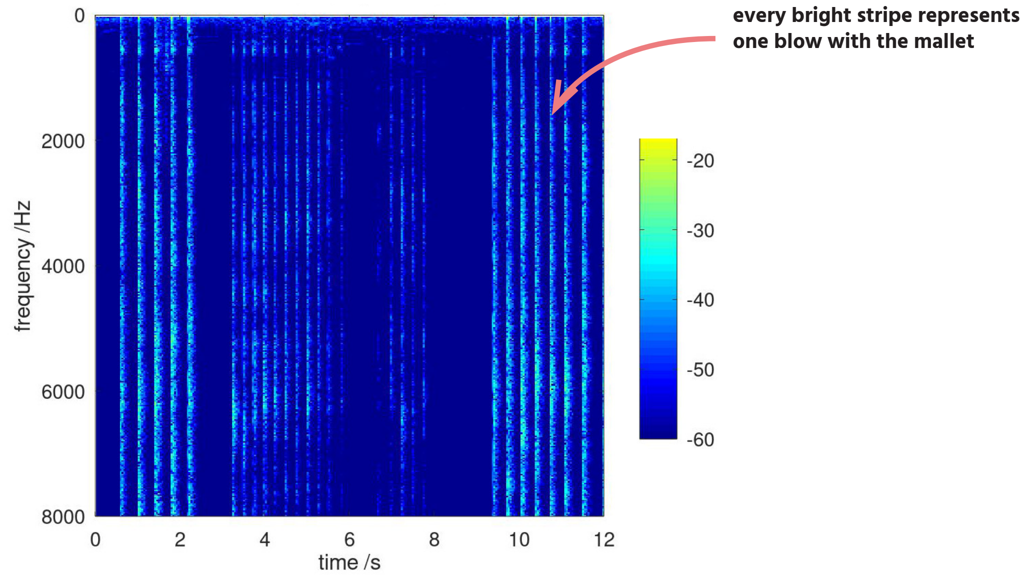


Figure 31. Frequency division, sound 4, mallet and chisel
* Image prepared by Lothar Schmidt

4.6 Patterns and trends recognized through psychoacoustics

Sound sources and their sound characteristics

The subjective evaluation showcased that next to the loudness of sounds, other sound characteristics determine the timbre (sound color) of sound sources. The four examined sound sources exemplary show how sounds can be distinguished into different timbres independent from their loudness.

Sounds marked by irregularity:

In case of the suction, device material is picked up into a tube. This tube rattles and produces a rattling sound (similar to a vacuum cleaner).

Sounds marked by regularity:

Patient signals show that operating theaters inhabit sounds where the auditory signal hardly changes as the distance between distinctive sound signals (beeps) stays similar (as long as there is no alarm).

Sounds marked by impulsiveness:

The mallet in combination with hitting the implant into the bone showcases a sound that has an impulsive character. Nevertheless, a regular impression is created because the sequence of the impulses is nearly constant.

Sounds marked by power and variable intensity:

The oscillating saw showcases that sound changes depend on the processed materials (e.g. metal of the saw blade in relation the bone structure). For instance, when the saw works through the bone, the diversity of the bone structure will alter the sound. This change is perceptible.

One sound source is not necessarily marked by one single characteristic, as the subjective evaluation of sounds showed. Instead, different characteristics can account for one sound impression, for instance influencing the categorizations of sounds in desirable and undesirable. In addition, the interplay of various sound sources into one sound situation creates a unique auditory experience, meaning that within one sound situation one sound source may be dominating and the others act as background (e.g. situational sounds).

Sound perception in relation to the listener

In addition to the findings on sound perception with medical staff, the psychoacoustic analysis gives first indications (through role divisions in sample listening) that the perceived usefulness or functionality of sounds may have an influence on how individual professionals rate their sound experience. For an individual without the intention to "use" sound, the sound perception is purely about the sensation of sounds. As a surgeon, self-produced sounds may be more accepted (e.g. use of oscillating saw during bone-cut), yet some of the sound features (e.g. shrillness) are still not desired. A circulating nurse, not being the producer of either sounds (not patient signals, nor saw or mallet) may not need to detect nuances in sound changes, but needs to be attentive to the entire sound situation. The anesthesiologist must hear the patient signals. Patient signals are regular in pattern, but may be masked by situational or background sounds (e.g. during oscillating saw use).

4.7 Auditory health behaviors: Precaution adoption attitude

As indicated in Section 3.1 , the Precaution Adoption Process Model (PAPM) (Weinstein et al., 2002) was applied, aiming to determine the mental state (or stage) of individuals within the behavior change process (unengaged to maintaining action). In this project, the desired action relates to the initiation of awareness for the need of preventive behavior and for the need to improve the sound situation in operating theaters. During the interviews it became evident that collecting answers on this topic is difficult because there are no universally accepted or advised precaution measures (e.g. reducing sound at the source/applying protective equipment like earplugs). Furthermore, the sample size within this project was small and may therefore not be representative for the entire orthopedic medical staff population. Nevertheless, reflecting on the PAPM framework and the individual interviews allowed me to assess at which stage in the behavior change process participants were (see Figure 32). The majority of participants were either unaware or unengaged with the health risks associated with sound exposure. Only two participants out of eleven actively took action in the operating theater to protect their hearing by using earplugs.

Whether people perceived or were aware of sound as a health risk was also correlated to personal characteristics (sensitivity to sound, current health status). Participants' answers suggest that there was a difference in sound perception with respect to personal preferences, such as whether one likes to work in silence or to work with background music. But it is also influenced by how health consequences through sound exposure express themselves in each individual.

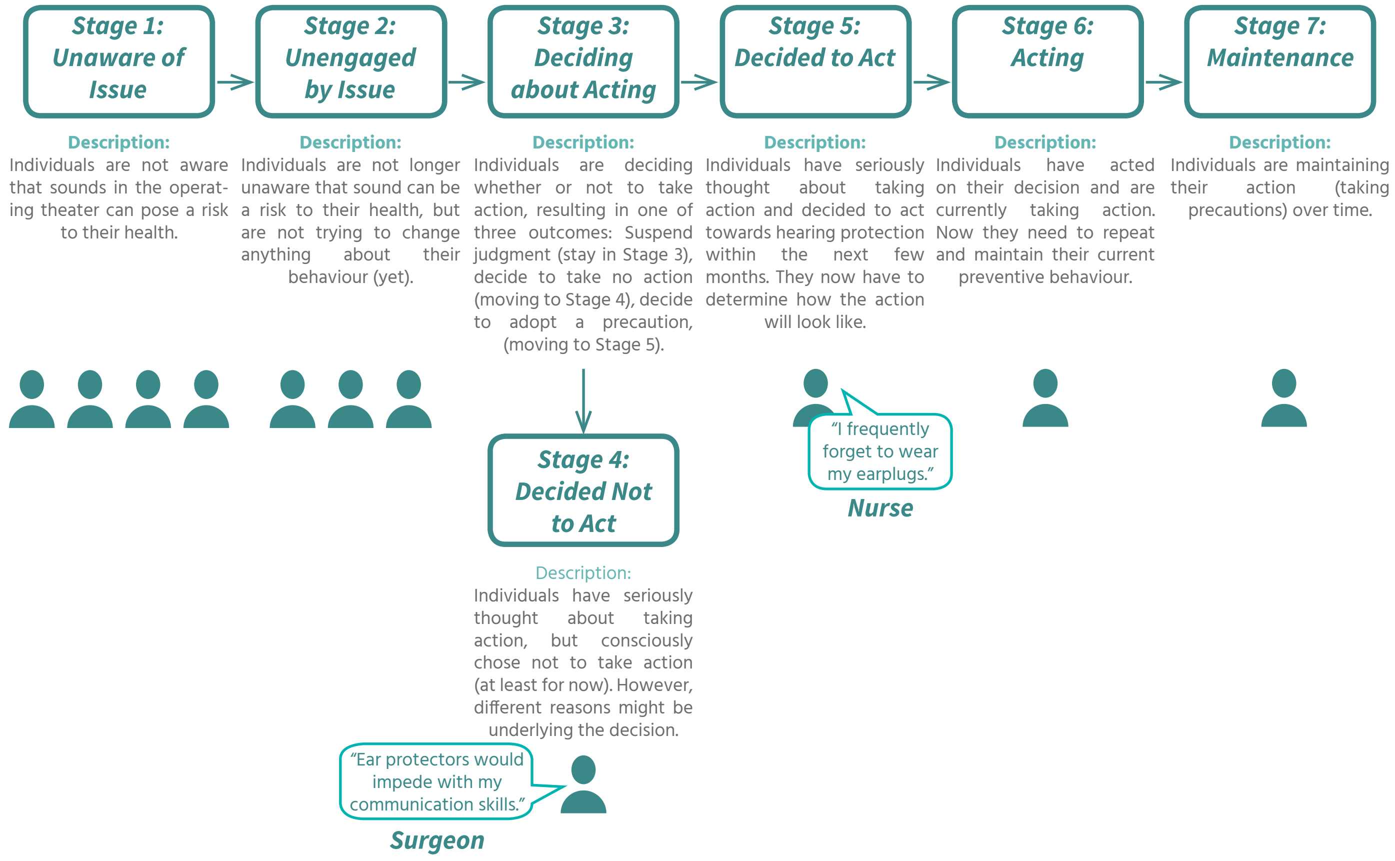


Figure 32. Application of the PAPM on auditory health behaviors in operating theaters. Adapted from Weinstein et al. (2002)

(+) NICE-TO-KNOW
Participants' quotes

"The hammer or the mallet are used, but I don't mind too much about that. I think for a surgeon, it's certainly, it's very... that's also useful. [...] so yeah, that's a bit... but those sounds are very loud...but it's not...It's not that...we don't use it for hours in a row."

Resident, unaware

"Health per se, yeah, it is annoying to work in a very noisy environment. [...] I must say when it starts to annoy me, I leave the OR, I'm a supervisor. I can do that."

Anesthesiologist, unengaged

"Yeah! It's funny, because sounds, they are just there and you don't think about it. They have to be there or something."

Nurse, unaware

"And one of my colleagues in training, I didn't know that before, but he is using earplugs as well, because of tinnitus. [...] Yeah, so for me and for my colleague...yeah, we've started using them, after we got tinnitus, yeah."

Surgeon, acting

5

Section 5

Synthesis

05 Synthesis

This section discusses and synthesizes the insights from the literature research, the sound analysis and the user research (see Section 5.1). Based on my insights, I developed a model to determine the windows of opportunities for the consecutive design process (see Section 5.2) and to formulate my design goal (see Section 5.3).

5.1 Discussion of sound (perception), health and behavior in operating theaters

The research phase (see Section 4) showed that the interplay between the soundscape of orthopedic operating theaters and the medical staff's health is shaped by many factors (e.g. through individual sound perceptions, the influence of team members, the support or non-support of hospitals etc.).

With my research questions (see Section 3), I aimed to investigate the current sound-related risks in orthopedic surgeries, the sound perception of orthopedic operating theaters by medical staff, and the sound characteristics (other than loudness) that determine individual sound perception.

Current sound situation in operating theaters

Noise by context-given circumstances

The sound situation in different orthopedic surgeries is not equally loud. Especially the tool-use (e.g. oscillating saw, mallet) and the resulting high-impact noise influences the sound levels in operating theaters. Also the environment (e.g. wall paneling) may negatively (or positively) impact the overall sound situation. Two medical staffs reported that after the re-building of their operating theaters the perceived loudness of the space significantly increased. But although physiological health-related risks may differ between soundscapes, the user research showed that also relatively "quiet" surgeries contain sound situations that cause psychological discomfort to medical staff (e.g. suction devices, "fake" alarms from anesthesia equipment).

Influence of individuals

Medical staff individuals contribute with their own behavior to the sound levels in the operating theater. Individual sound preferences (e.g. regarding music or conversations during the procedure) together with the patient's status may change the sound medical staff produces. Sound preferences often depend on experience and surgical characteristics (e.g. less concentration needed when steps are known, standard procedure or not). Lower sensitivity to sound might also lead to a lower effort to behave as quiet as possible during the procedure.

Positive noise or "functional" sounds

The reason why sounds are perceived positively can be two-fold: Either because they are pleasing to listen to (e.g. harmonious sounds), or because the listener attributes a certain functionality to the sound. The functionality of a sound may considerably influence its perception (e.g. hammer gives auditory feedback that surgeons wants to hear). If noise is generated by the active involvement of the listener (e.g. hammering), it is less likely perceived as a disturbance. If the listener has no influence, he or she is more likely to be disturbed (e.g. ventilation in helmet).

Adverse noise or "situational" sounds

Background noise (situational sounds) that is not beneficial to pursue one's listening aim (e.g. the sound of saw while focusing on the patient's signals) can negatively impact the individual staff member. Especially in critical moments these sounds are highly undesirable. In the worst case it drowns out important functional auditory signals, while in the best case undesirable background noise may not be noticed due to the ability of people to mask out continuous sounds. However, background noise still contributes to the hearing exertion. Sound characteristics other than loudness influence the desirability of sounds and thereby also determine how much they affect the mind. Characteristics, like irregularity, roughness and shrillness contribute to the overall strain as the psychoacoustic examination illustrated (see Section 4.4).

Physiological versus psychological health impacts

Sound can function as medicine to improve and support emotional wellbeing and it can even be beneficial for someone's physical health. But sound can also have adverse physical and mental health impacts. Adverse physiological consequences (e.g. risk of noise-induced hearing loss) of sound exposure can be assessed through decibel levels. However, the loudness of sounds cannot explain psychological impacts such as annoyance or stress through sounds.

Mental states and beliefs influencing health behaviors

People rarely relate short-term negative health consequences (e.g. annoyance, stress) to sound exposure as the exact source of these consequences is often difficult to determine. Furthermore, medical staff has often not yet experienced long-term negative health consequences from sound exposure. This additionally reduces perceived risk. Reduced perceived risk is also the result of a lack of awareness. Missing knowledge on sound and difficult traceability of auditory health consequences lead to states, where the impact of loud peak periods is often underestimated due to the short duration of those sounds (e.g. hammer or oscillating saw). Judging sound loudness (decibel levels), for example, requires knowledge on sound parameters. Yet, the self-conduced user research showed that only two participants (out of 11) were somewhat able to relate decibel levels to sound exposure risks.

Sound quality and sound perception

The self-conducted user and psychoacoustic research illustrated that reducing loud sounds in the soundscape will not necessarily create a positive sound environment (see Section 4.1 and 4.4). The research also showed that sound in operating theaters is indispensable for the medical staffs' individual work and for communication. As sounds interact with one another (e.g. they amplify, mask or cover one another completely), the soundscape of operating theaters must be approached as a unit rather than tackling sound sources individually. Also looking at the different professions and their individual sound-related needs might be necessary. Depending on the individual professional, the meaning attribution of sounds (e.g. into functional, useful sounds or useless, situational sounds) may differ and this also influences individual sound perceptions.

Outlook to the future and towards sound improvement – is it achievable?

One participant in this projects' user research described the current sound situation as an "unchangeable state of the art", expressing that in his opinion sound improvement is almost impossible. Contrastingly, another participant argued that the implementation of some precautions (e.g. earplugs) was easy. However, in his opinion other team members would not accept precautions like earplugs because they interfere with work performance and communication. But individual team-member behaviors have the potential to positively shape health beliefs and the willingness to take up precautions for hearing. For example, knowing someone who is wearing earplugs during surgeries encourages others to wear them as well (as indicated by one participant). But if the problem is not evident in the circle of colleagues, it is less likely that individuals consider it as an option for themselves.

In the conducted user research, participants were asked about their influence to improve the sound situation in the operating theater (e.g. by addressing concern to stakeholders and decision-makers outside the operating theater). Their perception of influence was diverse. Surgeons generally perceived their influence as high (e.g. discussing their concerns with hospital management). In contrast, OR-nurses and residents perceived their influence as low and stated that they do not even know whom to contact regarding a sound concern. This may be a sign of insufficient (visible) support from hospitals and other stakeholders (e.g. labor associations, policymaker). Active support or promotions by others than the medical staff might increase the chance of appropriate risk perception and action-taking.

5.2 Determinants of sound-related health

The user research illustrated the importance to look beyond the medical staff and highlighted the necessity to evaluate which stakeholders can influence the sound situation within orthopedic operating theaters. The model shown in Figure 9 aims to provide a holistic overview of the relationships between actions and stakeholders involved. It is based on Bronfenbrenner's (1977) social-ecological model (SEM). The SEM hypothesizes that health is affected by the interplay between the characteristics of the individual, the community, and the environment including social, and political components (Kilanowski, 2017).

Implications of the model: Starting points for design interventions

Designers usually aim to create solutions with the user in its center. Applying the SEM to the context of operating theaters shows that the targeted beneficiaries (medical staff) are affected by interactions (or non-action) on many levels (see Figure 33). Their auditory health behaviors as well as their experienced sound environment (in the operating theater) are influenced by the interplay between themselves and others. This multi-layered structure also indicates that one solution or one design intervention might not resolve the problem. Therefore, I assessed each social-ecological level of the SEM separately to identify current characteristics, interactions or situations that may affect the sound situation in operating theaters. In the next step, I defined the design space for each level. The "gain creators" are the starting points solving the sound and health issue in operating theaters. However, this design space is not deterministic but aims to be a source of inspiration and starting point for various initiatives.

Individual professionals

Characteristics:

Sound-related needs and priorities differ by profession. For example, the anesthesiologists focus on patients' signals (i.e. acoustic feedback through monitors), while the surgeons focus on sound related to their tools. Besides fulfilling their role, each professional has specific individual characteristics (e.g. sensitivity to sound) that shape their sound and health needs.

Pain creators:
Lack of sound awareness

Medical staff may currently not actively engage with sound, neither in their daily life, nor at work. As a consequence, they are not (sufficiently) aware of the relationship between sound and/or noise, hearing, and health. But even when knowledge on sound exists, sound levels may not be perceived as harmful due to short exposure times.

Non-precautionary health behaviors

Individual behaviors are often not focused on preventing health impacts. Factors such as the perception that ear protection hampers work performance may prevent individuals from applying precautionary behavior. But precautionary behavior is also related to the sound-producing potential of medical staff individuals. The same action (e.g. turning on the music) can result in very different sound levels depending on the individual who executes it (due to differing preferences for music type and loudness).

Gain creators:

Individuals have the potential to achieve changes by increasing their own and general awareness and by improving their own knowledge. Critical self-reflection equips individuals with the know-how to lower health-related sound exposure risks. Knowledge on sound implications and tools fosters a change of attitude (towards action-taking).

Operating theater teams

Characteristics:

Being part of a team requires balancing out individual and superordinate needs.
Team-related characteristics are influenced by the interplay of individual actions among team members. The shared goal is optimal patient care and teamwork is influenced by circumstances and restrictions related to this care (e.g. need for sterility).

Pain creators:
Care-related restrictions

Team behavior is centered around patients' care. This determines the interaction and the communication within the team. But team dynamics and the type of surgical procedure also influence the sound situation. Another context-specific characteristic is the need for sterility within every aspect of the environment.

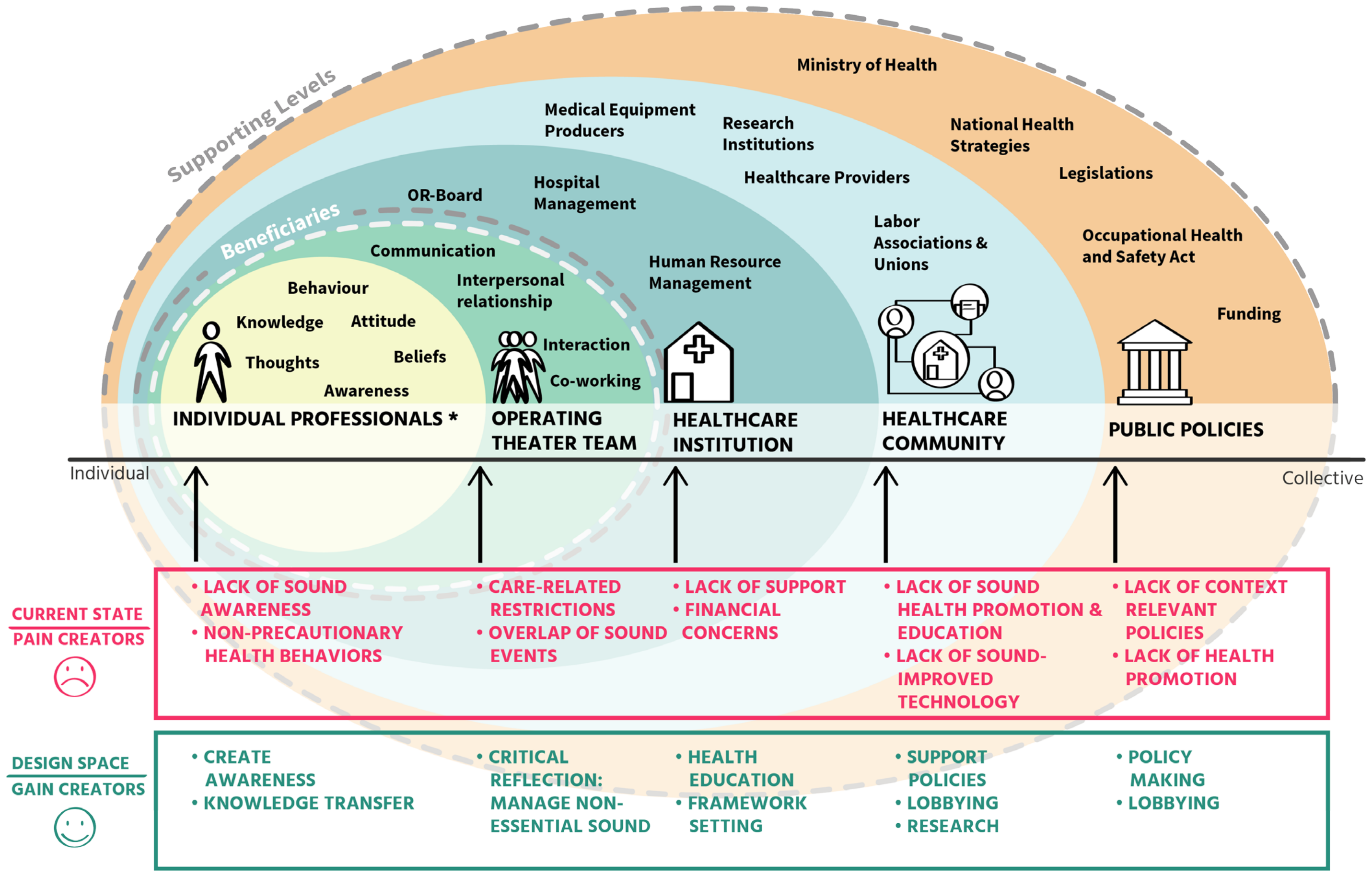


Figure 33: Levels of influence on sound and health in orthopedic operating theaters. Adapted from Bronfenbrenner (1977)
* Individual professionals, i.e. surgeons, anesthesiologists, OR-nurses, residents etc.

This influences the room layout, its surfaces, the tools and equipment used and also protective gear (e.g. ventilation in helmets, see Section 4.1.3 unpleasant sounds).

Overlap of sound events

Simultaneously performed actions and interactions in the operating theater by sub-teams (e.g. anesthesia and operating team) result in sound cacophony. Sound cacophony describes the overlap and mixture of sounds that result in a chaotic auditory experience.

Gain creators:

Critical reflections of teams have the potential to lead to a change in behavior (individual awareness expanded to team awareness). By evaluating the sound situation together, teams can determine whether they themselves produce non-essential sounds (e.g. too loud music, conversations in stressful situations for sub-teams etc.) that could be easily avoided.

Healthcare institutions

Characteristics:

Healthcare institutions (i.e. hospitals) are responsible for the occupational safety and health protection of their employees. They also have responsible bodies (e.g. OR-board) in place to assure compliance with occupational legislations and to prevent sound-related injuries and illnesses.

Pain creators (concerning medical staffs' health):
Lack of support

Healthcare institutions are interested in ensuring the well-being of their staff. Yet, the support for medical staff to improve sound conditions or protect oneself from harm is still scarce and offers room for enhancement. Working towards an optimum sound situation for patients and staff requires research, investments, promotion and facilitation.

Financial concerns
As stated in Klimek, Houdenhoven and Ottens (2008), operating theaters are the places where "the most money is earned and lost." Therefore, all potential sound improvements (e.g. purchase of new tools, environmental changes) further increase the overall costliness of operating theaters, leading to a possible hesitation to invest. But by investing, hospitals might also be able to save money as the medical staff may have less absences and the productivity in the operating theater might increase.

Gain creators (concerning medical staffs' health):
Healthcare institutions can provide health education (e.g. safety trainings) to help their employees recognize the risks associated with sound. With respect to framework setting they can issue regulations for hearing protection to minimize the associated sound consequences. In addition, the purchase of sound-optimized tools could contribute to lower sound situations in their operating theaters.

Healthcare community
Characteristics:
The healthcare community comprises many different organizations which are directly or indirectly involved in the sound situation of operating theaters.

Pain creators (concerning medical staffs' health):
Lack of sound education and promotion
Labor associations are the point of contact when it comes to the representation of collective interests. In the Netherlands, the LVO (Landelijke Vereniging van Operatieassistenten) represents almost 50% of Dutch surgical assistants. One of their statues is to educate its members through training. Yet, the currently displayed pieces of safety training on the website focus merely on the responsibility towards the patient, rather than on the individual health of medical staff. This indicates that there is still a lack of education on precaution behavior to preserve individual health (LVO, 2020).

Lack of awareness and facilitation of sound-improved technology
Noise in operating theaters is the result of single sound sources feeding the overall noisiness. Medical device producers may not be aware of the overall sound levels in operating theaters and how their product as a single component contributes to the sound situation. One participant in the user research (medical staff) indicated that sound seems to be a secondary aspect that often does not have a high priority in the development of equipment. Furthermore, product producers might not have the know-how yet to improve certain sound characteristics (e.g. reducing fake alarms through machine learning for anesthesia alarms, as indicated by a medical staff participant).

Gain creators (concerning medical staffs' health):
The opportunities for improvement within the healthcare community are manifold and their applicability to the different actors may differ. However, there are three key possibilities. First, further sound research (e.g. sound assessments for physical and psychological consequences) would support the development of improved and appropriate legislation. Second, more lobbying for the importance of sound and the health of medical staff can additionally make the issue clear to the medical community itself and to policy makers. Third, education and training at universities and research institutes could spread the knowledge (e.g. education on sound exposure risk). Only students who have been sensitized to the impacts of sound will later be able to use this knowledge when, for instance, developing new tools for operating rooms.

Public policy
Characteristics:
The governing bodies that are in charge of the prevention effort concerning sound exposure in operating theaters are responsible to build alliances and committees to do research and ultimately take action if problems occur (e.g. by establishing laws, regulations and recommendations as well as by providing financial support of initiatives).

Pain creators (concerning medical staffs' health):
Lack of context-relevant policies
The Dutch healthcare system is responsible for the protection of the medical staffs' health, for example through appropriate regulations and legislations. However, as already demonstrated in the literature review (see 2.3.2), there are no explicit regulations on the work in operating theaters. According to the WHO (1999), sound levels in hospital treatment rooms are recommended to be "as low as possible". Moreover, the more general occupational sound regulations that are directed to jobs such as construction, neglect that operating theaters require a high degree of focus and communication.

Lack of health promotion
The current focus of the operating theater environment lies primarily on the patient. This is reflected in the context-relevant policy, enforcing, for instance, sterility in all aspects of the operating theater but neglecting the effect these measures have on the sound experience of the medical staff (i.e. sterility requires easy cleanable surfaces that often hinder sound absorption and instead amplify sounds). But the medical staff is working in the operating theater continuously and they are essential to assure society's and individual patients' well-being. Therefore, health promotion with regard to sound for medical staff individuals has to be improved.

Gain creators (concerning medical staffs' health):
Policy makers have the tools at hand to pass regulations towards sound improvement and health protection. But besides passing (appropriate) legislations, it is important to continuously inform about new developments and evidence in research (e.g. on physical and psychological wellbeing in relation to sound in operating theaters), which for instance requires the adjustment of regulations or governmental investments. That is why a functioning network between the healthcare community, the hospitals including (their employees) and the government is essential.

5.3 Formulation of design goal

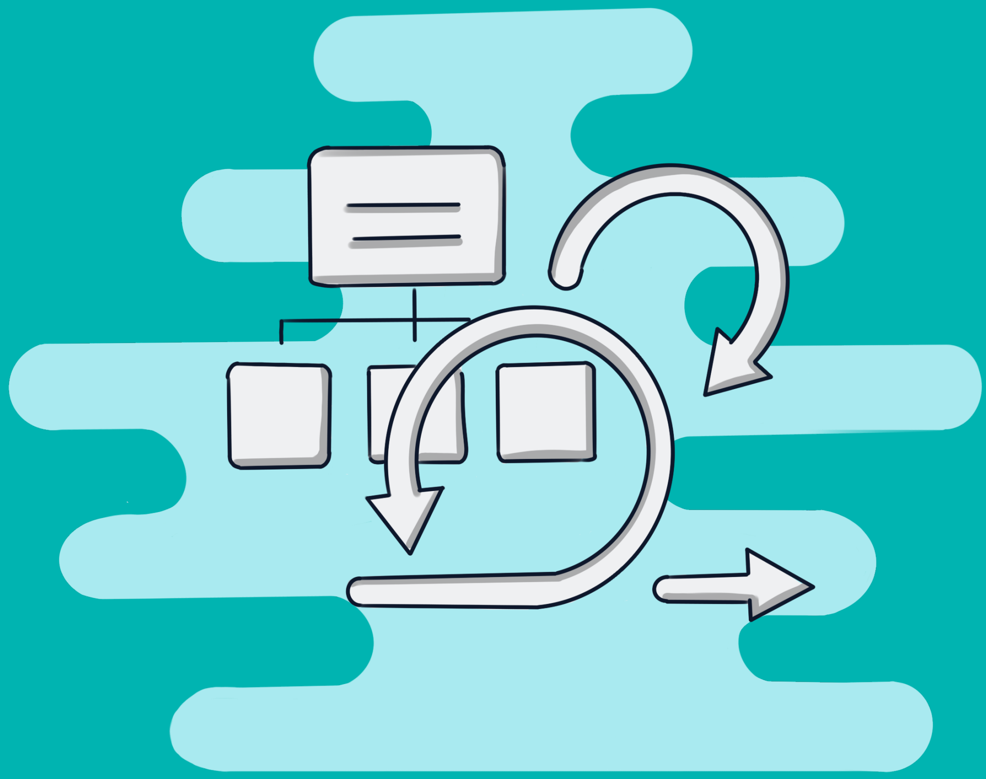
Based on the synthesis of my main insights and the SEM, I formulated a general design goal to identify starting points for sound improvement through behavioral change on various levels:

"My design goal is to address sound issues in operating theaters by improving sound-related behavior on different social-ecological levels."

To allow a broad base to start the initial brainstorming with the utilization of the developed model, the design goal was chosen to be open-ended. After the initial ideation phase, a second, more precise design goal was specified (see Section 6).

Section 6

Ideation and conceptualization



06 Ideation and conceptualization

The insights from the previous research phase formed the basis for the ideation period and the iterative, creative process. The ideation process aimed to develop an intervention that improves the well-being of medical staff in operating theaters.

I started by generating various concept ideas for intervention options through brainstorming sessions. The techniques and methods that were applied during the design phase to create possible solution strategies to the "pain creators" as identified in the research phase are provided below. Subsequently, I report how I brought together the concept ideas into one final concept direction – a website to create sound awareness for the sound situation in operating theaters.

6.1 Ideation

The ideation period was initiated by using the "How-To" method (Van Boeijen et al., 2014) and aiming to develop a repertoire of concept ideas that positively affect the sound-related well-being of medical staff operating theaters. Those built the basis for the following conceptualization of one final concept. The "How-To" method aims to discover the solution space from different stakeholder perspectives, asking questions like: "How to encourage medical staff to be more cautious about their personal sound experiences?". This exemplary question is based on a problem: not being aware of personal sound experiences and exposure, which was discovered in the user research. While identifying problem statements, I applied my knowledge from the preceding user research (context mapping with medical staff), aiming to put myself in the user's situation, before describing the problem and developing solutions. This experience-based approach enabled me to evaluate and reflect on the invisible structures (e.g. attitudes, norms, stakeholder interaction) that shape the decision-making structure in operating theaters.

The problem statements rephrased as "How-to'" questions initiated the brainstorming for (non-judged) concept ideas. The How-to questions started on a more abstract level and got more specific through iteration. The "pain creators" identified in Section 5 were the starting point to formulate the initial How-to questions, which are listed here: "How to initiate sound awareness in medical staff? How to strengthen sound awareness in the operating theater (individual and team-level)? "How to facilitate long-term sound improvements in the operating theater (all levels)? How to promote long-term, sustainable sound engagement in the operating theater (all levels)?"

6.2 Applying behavior change methods

During and after formulating the How-to-questions, I sought inspiration for behavior change methods in "Taxonomy of Behavior change Methods: An Intervention Mapping Approach" (Kok et al., 2015). This compilation of intervention strategies presents evidence-based methods of health behavior change for different socio-economic levels. Additionally, I explored "basic human motivations", a service design strategy that aims to explain the motivations that influence people in their decision-making (Koos Service Design, n.d.). These methods provided me with starting points and ideas on how to tackle the How-to questions and enabled me to sketch the first concept approaches.

6.3 Outcome: Concept cards

The concept approaches were visualized in concept cards. Each concept card includes a short description of the "pain creator" (or problem currently present in the operating theater), the "How-to" question, and the initial intervention strategy, and an initial sketch of how to tackle the problem. In total, 26 concept cards were developed (see Appendix G for all concept cards). In order to determine which concept ideas have the potential for further development, they were each individually evaluated using the vALUe method (Van Boeijen et al., 2014).

Analyzing each idea by its advantages, its limitations and its unique elements, offered the opportunity to find the concepts with highest potential. But it also helped to identify single elements of concepts that

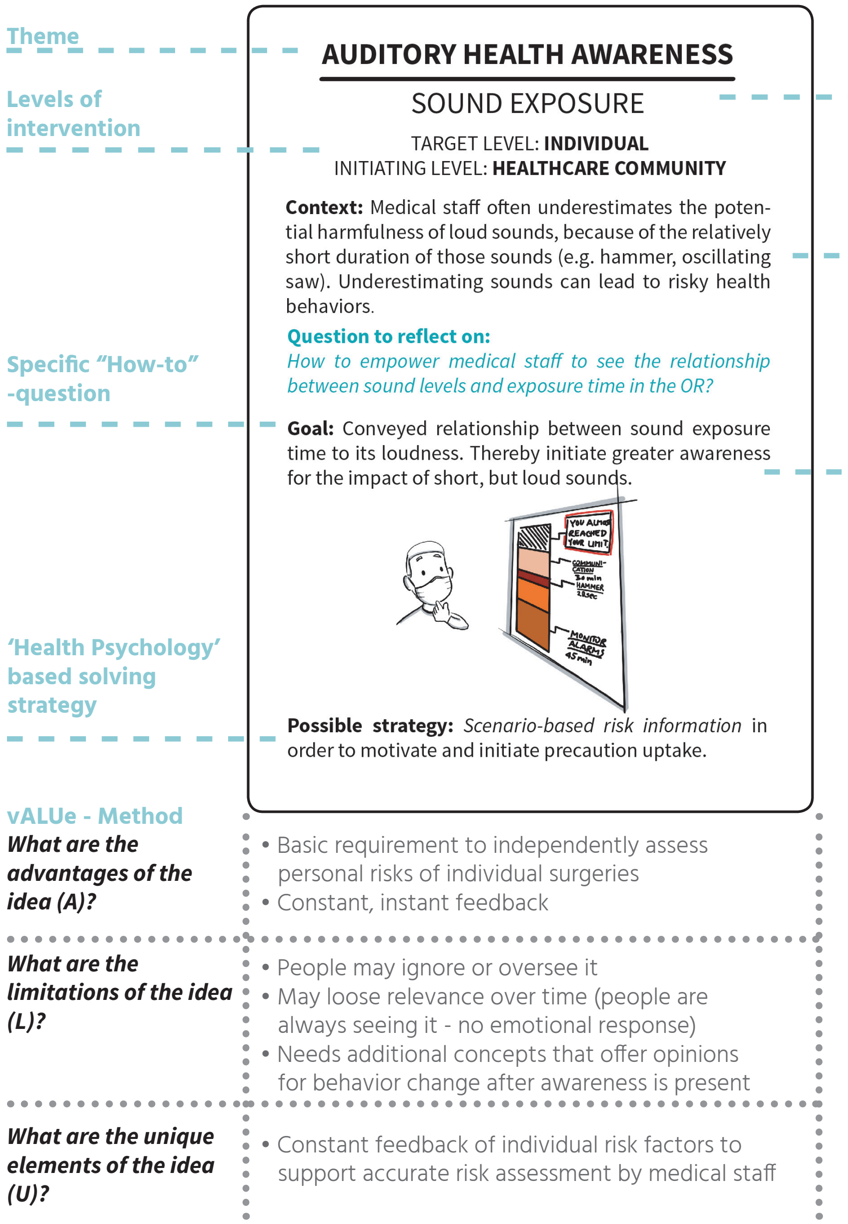


Figure 34: Example of concept card including a "vALUe evaluation"

can be added to an overarching concept. An example of the applied vALUe method is shown in Figure 34.

6.4 Concept evaluation

One of the findings applying the vALUe method was that none of the concepts could solely solve the sound issues in operating theaters. Using the method also triggered reflection, trying to grasp the underlying reason why the different sound issues actually exist. To intensify the reflection, I applied a root-cause analysis (see Appendix H). This method aims to identify underlying problems. Asking the question "why" several times revealed that some of the concept ideas are treating symptoms instead of the root. The underlying problem in all social-ecological layers could be traced back to the fact that there is an overarching lack of awareness. Individual sound issues and sound sources are feeding the overall sound cacophony leading to potential health impacts for medical staff. The final concept, therefore, followed a system approach, combining different ideation elements, to allow raising awareness on different social-ecological layers (see Figure 35).

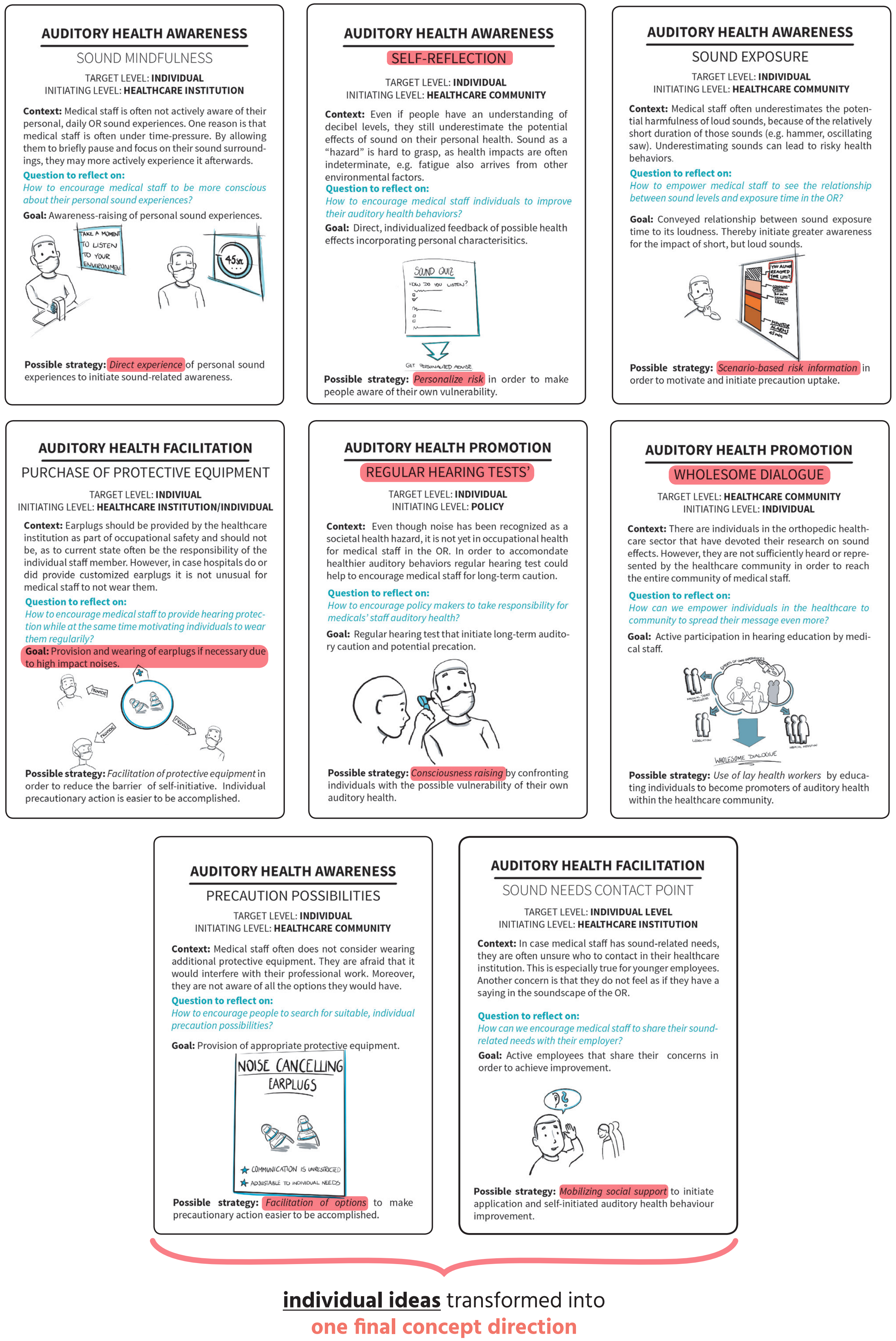


Figure 35: Combination of ideation elements into one final concept

6.5 Design requirements

For the final concept direction, I formulated two design requirements:

1. The concept must have a low access barrier for all social-ecological levels.

2. The concept needs to cater to people with different levels of awareness (completely unaware to aware, but unsure how to act).

Based on the specified approach, the final design goal evolved:

> **"My final design goal is to improve the awareness of medical staff regarding sounds in the operating theater and provide support in changing the current sound situation by raising awareness in all involved social-ecological levels."**

Low access barrier for all social-ecological levels

A prerequisite for the final concept direction was that it does not require any social-ecological level to be the first initiator for auditory behavior change or sound improvement. Instead, it should empower individuals to act independently towards a better sound situation. One strategy to achieve individual awareness is health communication. This strategy aims "to convert scientific findings into actionable, empowering information for the public" (Neuhauser, 2017). For this project, a website deemed the most suitable medium to accumulate information about medical staffs' health (risks) and possible counteractions for an improved sound situation and consequently better auditory-related health conditions. E-health communication increases access to health information, especially when aiming to reach several social-ecological levels without multiple (possibly costly) interventions. Exploring options for a suitable distribution channel, I decided to use the Critical Alarms Lab. The lab is equipped with an already existing network of different stakeholders within the healthcare community and could act as a suitable network builder.

People with different stages of awareness

In order to design for awareness, it was important to understand which mental state is described with the word "awareness". The words awareness and knowledge are often strongly associated and used interchangeably in scientific public health research (Trevethan, 2017). However, there is a distinction between both terms: "Knowledge" is a "specific information that is factual in nature" (e.g. including information about prevalence, risk factors, prevention and precaution of specific health problems), whereas "awareness" contains strong elements of "personalization" (e.g. self-focus and personal familiarity) which are not part of "knowledge" (Trevethan, 2017). The importance of this differentiation was visible during user research. Even when individual professionals had information (e.g. knowledge on decibel levels) they did not necessarily correlate it with their own risk or health status (e.g. self-awareness of experiences).

Based on that understanding three different user-groups in different stages of awareness with different demands have been formulated:

Stage 1. No knowledge – no awareness
Goal: Create knowledge (using learning theories).

Stage 2. Some knowledge – no awareness
Goal: Personalize the knowledge to make people aware.

Stage 3. Awareness – missing knowledge to proceed
Goal: Provide advice for action.

Stage 1. Transferring knowledge

People naturally have certain preferences and ways to accumulate new knowledge. This requires tailoring the sound-related information to different kinds of learners and should also be reflected in the website design. Based on Kolbs' (1984) first introduced learning theory, learning styles can be distinguished into four categories (see Figure 36, next page): Accommodating (Activists), assimilating (Theorists), diverging (Reflectors), or converging (Pragmatists) (Anderson, 2017). Within one study (Engels & De Gara, 2010), research on surgical education indicated that the predominant learning styles among surgeons and surgical residents were accommodating and converging. However, they reported that medical students' predominant learning style was "assimilating". This implicates that learning styles are different and continuously evolve over time. Reflecting on the personal characteristics of medical staff meant that all learning theories needed to be served with the website. To achieve this, the design of the website needed elements providing fact-based technical information (for assimilating), while also allowing shortcuts and interactive elements with little theory, such as summaries of information (e.g. through short explanatory videos).

Stage 2 Transforming knowledge into awareness
In the second stage, it was important to tailor the information on the website, so knowledge is transformed into awareness. This required two steps: First, categorizing the information into social-ecological levels to allow individuals to select the information that is relevant for them. Secondly, triggering the personalization of knowledge. While medical staff knows the sounds in operating rooms and experiences them on a regular level, other stakeholders may not have experienced the sound situation of operating theaters. To let people emerge in the sound situation of operating theaters the website aimed to provide a sound experience, for example through sound samples from the operating theater.

Stage 3 Transforming awareness into action
In the third stage, when people have the necessary level of awareness and would like to transform their awareness into action, it was necessary to provide them with further knowledge to lower potential barriers for action-taking (arriving from lack of knowledge on how to proceed). The importance of further advice or knowledge was found while doing additional user research with two surgeons. These two surgeons already identified the sound in their operating theater as a potential hazard to their health. However, they reported to lack knowledge on how to proceed or change something about the situation. To eliminate possible stagnation of behavior change, directions for action are needed (e.g. giving advice on the first steps that should be taken in order to assess the extent of the sound hazard).

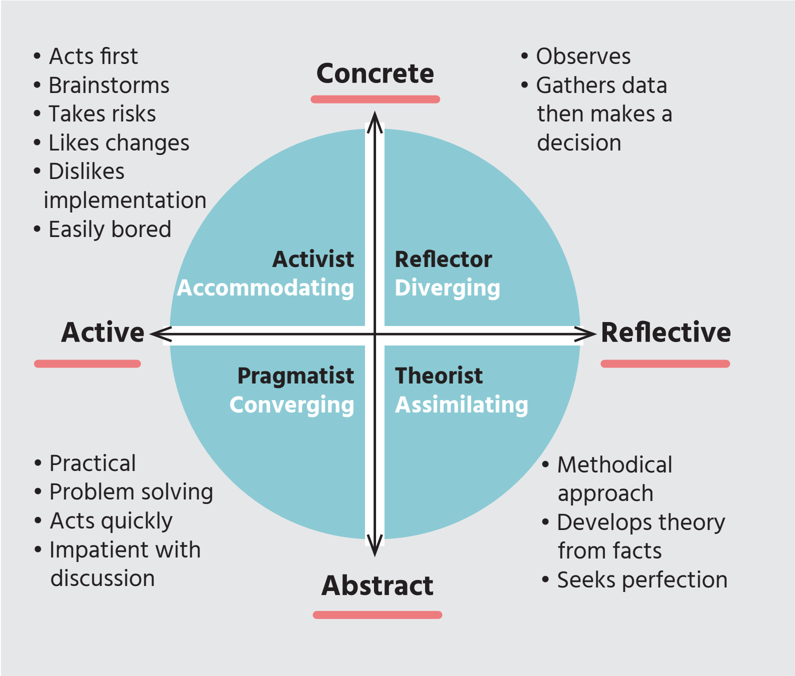


Figure 36: Learning style preferences.
*Own representation based on Anderson (2017)

6.6 Prototyping and iterating

Taking into account the different learning styles and the initial ideas as described in Section 6.3, a first website prototype was established, using a web-application-tool (Readymag). Through quick virtual walkthroughs, participants with various backgrounds assessed the preliminary prototype throughout the development process. They provided feedback on the website-content and the user flow within the website. The four preliminary participants were two fellow peers, a user experience designer, and an OR-nurse. The variety of participants allowed different iteration focuses (e.g. content vs. design).

The assessment primarily applied the thinking aloud method and by asking open-ended questions, as described by Nielsen (2012). The participants expressed their thoughts loudly while I observed or listened to their actions (going through the website, see Figures 37 & 38). Those walkthroughs led to the following insights:

Insights on website content
- Structure the website with different layers (use a tree-structure)
- Reduce the amount of text

- Do not provide too much (detailed) information on the landing page
- See website as "advertisement" the research: landing page needs to be the "seller" of this research

Insights on website design and general usability:
- Demand of a clear navigation
- Structure the website through the design (e.g. through color-coding)
- Interactive elements decrease the feeling of "too" much information

(+) NICE-TO-KNOW

Eye-tracking studies over 13 years by the Nielsen Norman Group (Moran, 2020) has demonstrated that "people rarely read online — they are far more likely to scan than read word for word." There are several strategies that support the scanning process:

Using clear and concise language
This allows people to quickly understand what they've just scanned.

Breaking up the content through distinguishable headings and subheadings
This enables people to scan for information they are most interested in.

"Front-loading" or tree-structure of the structure with subheadings and links
This allows users to understand the content quickly while scanning.

Using formatting techniques (e.g. bullet points, bold text)
This also allows the user to focus on the most important information.

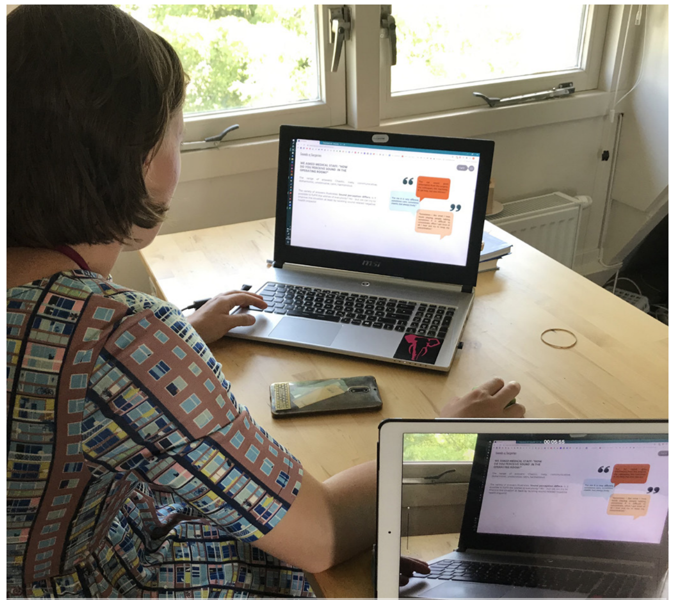


Figure 37: Participant speaking out loud during the website testing (video-recorded on iPad)

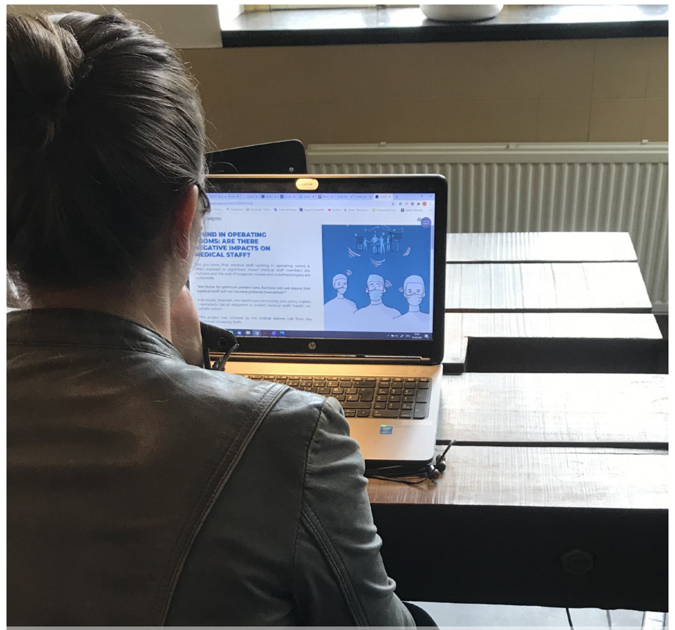


Figure 38: Participant exploring the website

Section 7

Final design: “Sounds of Surgeries”

07 Final design: “Sounds of Surgeries”

Figure 39: “Sounds of Surgeries” in action

7.1. Concept description

The concept aims to reduce harmful sound impacts on medical staff in operating theaters by creating awareness on multiple levels. Design is used as a method to involve medical staff, hospital management, the healthcare community, and policymakers in the development of positive changes in sound-affected healthcare. As a starting point, a website serves as information source on soundscapes in operating theaters. It aims to inform medical staff about sound exposure, health risks, and possible prevention strategies. Simultaneously, it serves as information source for the other social-ecological levels involved in healthcare projects or procedures with touch points to sound (e.g. hospital management or medical device producers).

Overall, the website aims to generate greater consideration for sound in operating theaters, including, for example, greater consideration in equipment legislation. It uses the Critical Alarms Lab and its existing healthcare network as distribution channel. This project should be seen as the first step towards initiating positive sound-related change in operating theaters. Of course, there is a wide room for further exploration (e.g. keynote presentations, health and sound podcasts, or physical designs within the operating theater).

(+) NICE-TO-KNOW

How previous insights inspired the concept:
- Reduce initial access barriers (see Section 6)
- Target not only medical staff, but also other levels of influence (see Section 5)

7.2 Individual website elements

At the beginning, the website structure was based on the three stages of awareness (see Section 6.5). However, the participatory iteration with potential website users showed that in order to improve the websites’ usability it is advisable to restructure and combine the specific website elements designated to users with different stages of awareness. For example: The landing page aims to empathize with all users addressing their different points of view and stages of awareness. Therefore, it explains briefly the overall topic of the website - sound and health in operating theaters - but also triggers awareness on sound issues through an animation.

Landing page: Introduction of the project

The landing page (Figure 40) provides the audience with a primary impression of the sound situation in operating theaters through an introducing text and an animation featuring the sound situation and the

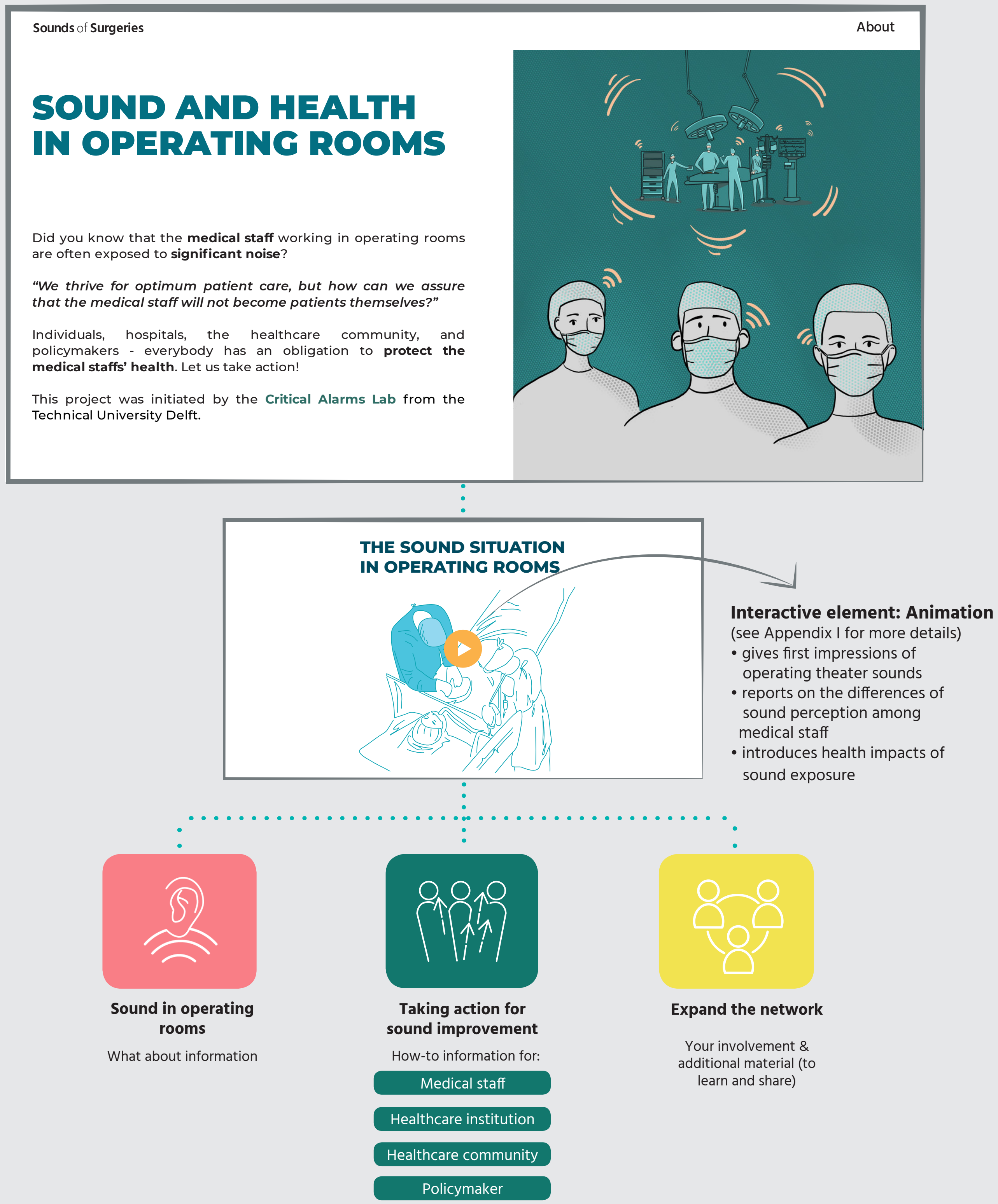


Figure 40: Landing page and website structure of “Sounds of Surgeries”

medical staff’s sound experiences. The animation presents some sound events of the operating theater (e.g. sounds of anesthesia alarms), but it also reports how individuals working in the operating theater are affected by sound. For this I used statements that I collected during user research and presented them in the animation. The animation further gives a brief overview of possible health consequences that the medical staff can face due to the soundscape of operating theaters (see Appendix I for more details). The animation aims to trigger the emotions of medical staff and other stakeholders to become interested to learn more about the project. After the animation, the website “branches out” into three sub-sections, where more information is available. By separating the information, the website user can directly go to the desired section, rather than having to search for the content within one page.

First sub-section: Sound in operating theaters – "What about"- information

The first sub-section (Figure 41) addresses the topic of sound and hearing in operating theaters and provides information on the possible health effects that medical staff faces while working in this soundscape. This sub-section is designed to provide background knowledge and to initiate a first awareness. It is primarily catered to individuals that are unfamiliar with the topic and are in the awareness of stage 1 and also slightly of stage 2.

Sound samples offer the user an auditory experience of the sound situation in operating theaters. This allows people who are less familiar with the sound situation in the operating theater to listen, experience and emphasize with it. The aim is to trigger emotions, reflection and ultimately personalize the gathered knowledge. The end of the first section offers tailored "why should you care" information to achieve that most website users identify oneself with at least one of the presented stakeholders.

(+) NICE-TO-KNOW

How previous insights inspired this concept section:
- Make the information-transfer as simplistic as possible and do not provide too much information (see Section 6)
- Let people choose which information they want to read (see Section 6)
- Make it personal: Address individuals directly "Why should you care about...?" and offer personal (sound) experiences (see Section 6)

Interactive element: Sound samples
- lets the website user listen to sound samples from surgeries separate or together
- makes the operating theater sounds "tangible" for non-medical staff website users
- triggers sound perception reflection outside the usual working environment for medical staff

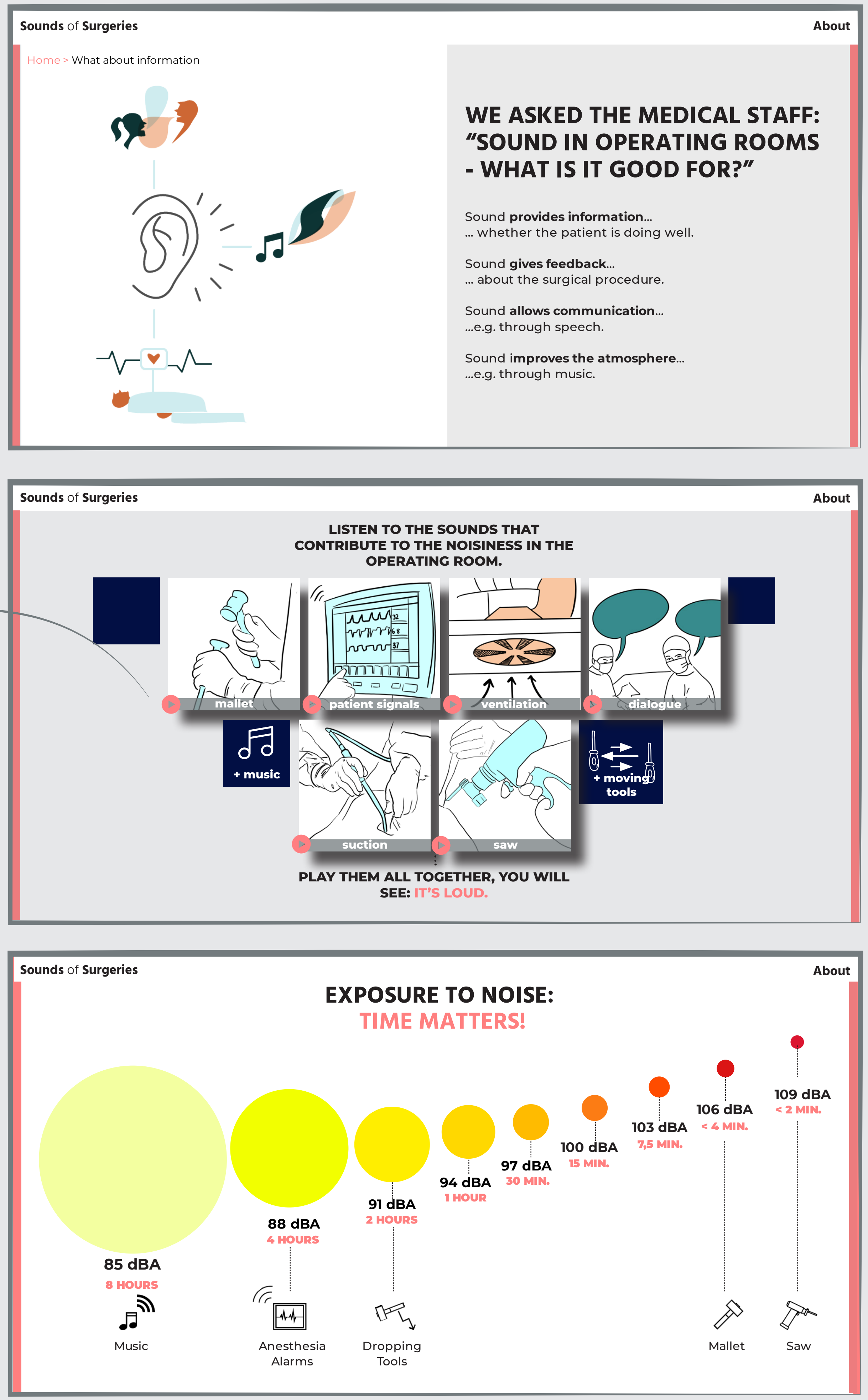
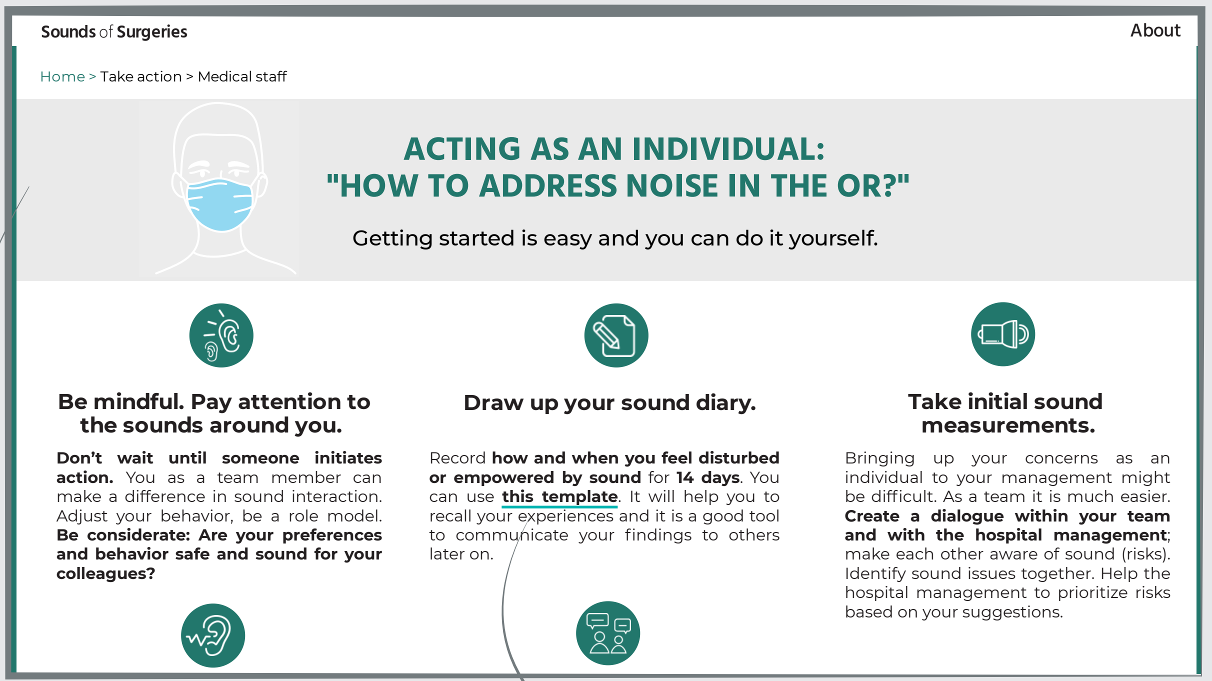
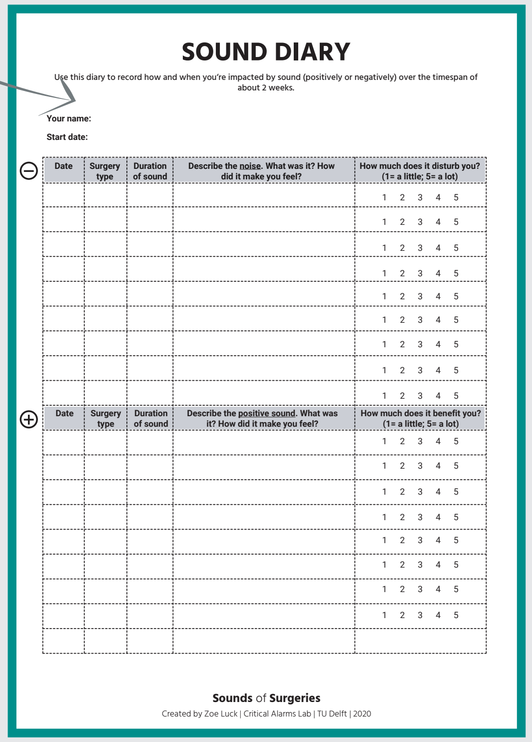


Figure 41: Website content examples, sub-section 'Sound in operating theaters – What about information'





SOUND DIARY

Use this diary to record how and when you're impacted by sound (positively or negatively) over the timespan of about 2 weeks.

Your name:

Start date:

Date	Surgery type	Duration of sound	Describe the noise. What was it? How did it make you feel?	How much does it disturb you? (1= a little; 5= a lot)
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5

Date	Surgery type	Duration of sound	Describe the positive sound. What was it? How did it make you feel?	How much does it benefit you? (1= a little; 5= a lot)
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5
				1 2 3 4 5

Sounds of Surgeries

Created by Zoe Luck | Critical Alarms Lab | TU Delft | 2020

Material: Sound diary template

Levels with own "take-action"-advice sections

Hospitals and healthcare institutions

Healthcare community

Policymaker

Figure 42: Website content examples, sub-section "Taking action for sound improvement – How-to information"

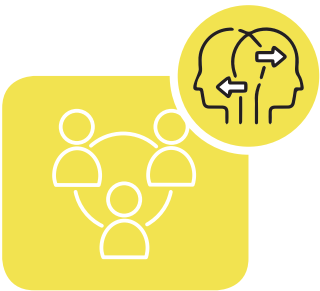
Second sub-section: Taking action for sound improvement – "How-to"- information

The second sub-section (Figure 42) addresses website users who are already aware that a sound issue may exist in operating theaters and provides them with advice for action. Specifically, it provides information on actions individuals themselves can take to assess and protect their individual health (with respect to their role in the operating theater) and information on what others can do to protect medical staffs' health (e.g. risk assessment, development of quieter tools, appropriate legislation).

(+) NICE-TO-KNOW

How previous insights inspired this concept section:

- Offer additional sources of information besides this website (see Section 6)
- Tailor advice to individual groups (see Section 5)
- Provide concrete guidelines and examples to show how behavior change can be implemented (see Section 6)



Third sub-section: Expand the network

The third section (Figure 43) provides the option to obtain more information and also disseminate it within own networks. It offers printout and media-material for download to be used to inform others about the sound situation in operating theaters. It also offers the opportunity to educate oneself further (by offering research papers and extra links to broaden the personal knowledge-base and by providing the opportunity to connect with the Critical Alarms Lab and with other stakeholders to build up a network that interactively works on the improvement of current sound situations within operating theaters). Website users can sign up for virtual events (e.g. via zoom). Every few months, these events present and discuss a different theme featuring sound in operating theaters and its development.

(+) NICE-TO-KNOW

How previous insights inspired this concept section:

- Actively engage people from different social-ecological levels (see Section 5)
- Give medical staff with high-perceived influences (e.g. on hospital management) the opportunity to gather more material to put their influence into practice (see Section 5)

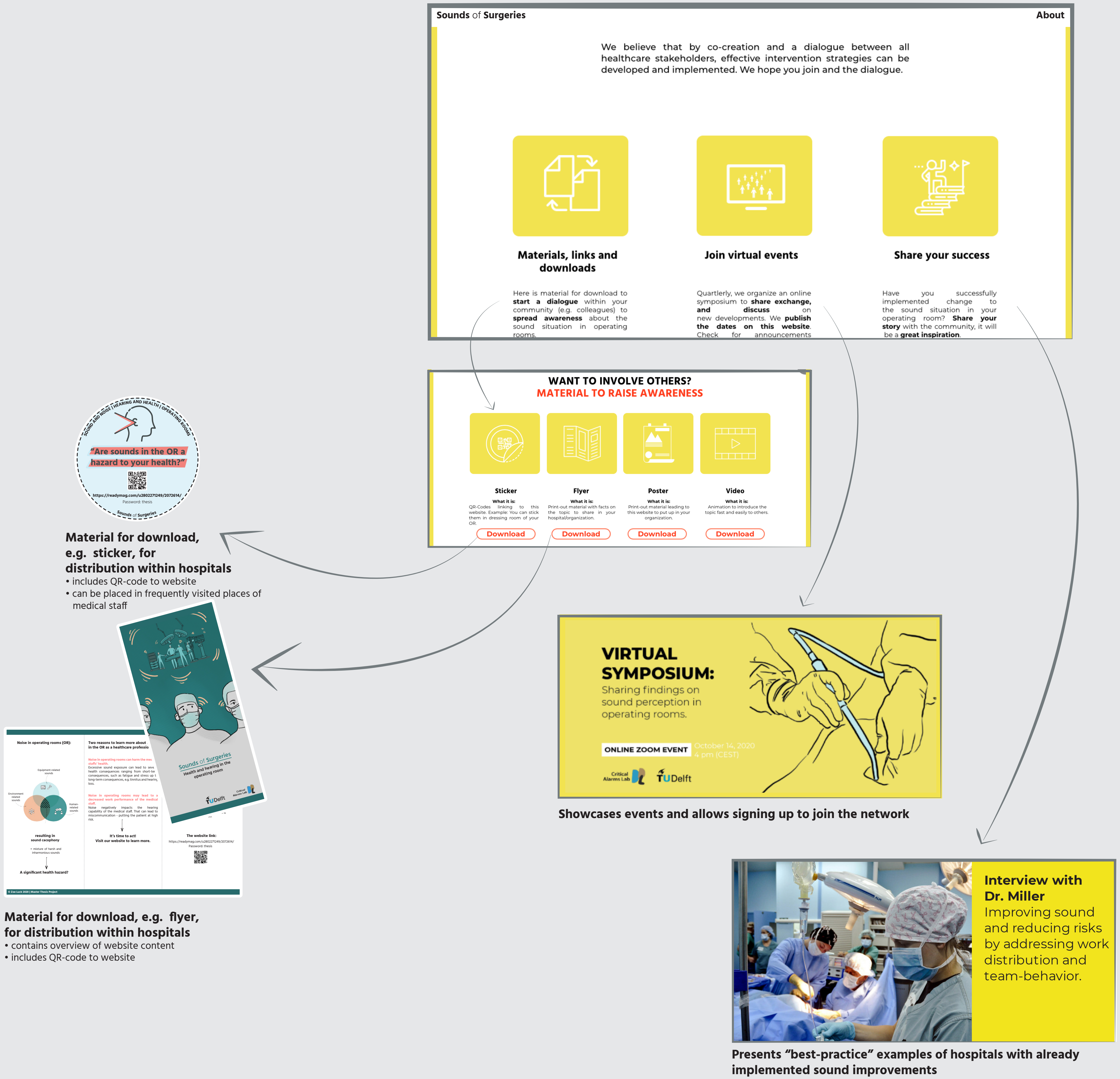


Figure 43: Website content examples, sub-section "Expand the network"

7.3 Concept evaluation

The website was evaluated to assess, whether the website can improve medical or non-medical staffs' awareness regarding sounds in the operating theater.

Participants

In total six people participated in the evaluation of the final concept: three orthopedic surgeons, one OR nurse, one third-year medical student and one PhD student (working in value based healthcare). One of the surgeons already participated in the previous user research, while the other participants had not been involved in the project before. The initial stage of awareness was determined in initial conversations by asking participants how much they agreed to pre-defined statements (e.g. "I have never thought about sounds in the operating theater.").

Limitations

The access, time and resources to find suitable participants for this evaluation were limited. Therefore, the project was only evaluated with a small sample size. The current participants are not equally distributed into the different stages of awareness, nor are they equally distributed among the social-ecological levels. Therefore, these results are not representative for the general healthcare population. But I see this evaluation as a starting point to identify general indications and possible future improvements for the website prototype.

Method

Prior to the website evaluation five questions (adjusted to the stage) were given to the participants. The website prototype was then self-explored by the participants. After the exploration, the questions were answered either in writing or in a call.

Research questions

Stage 1: Unaware & no knowledge (1 participant)
Does the website increase the knowledge of participants, currently unaware of the potential health consequences of sound in the operating theater? Does it spark their awareness and reflection?

Stage 2: Some knowledge & no awareness (1 participant)
Does the website increase awareness among participants with some knowledge on sound? Does it initiate reflection for action-taking?

Stage 3: Awareness & missing knowledge to proceed (4 participants)
Does the website improve knowledge on the topic "Sound in operating theaters and its implications on health" and does it support participants with higher awareness levels to take (further) action?

Results

Comparison stages of awareness
I could not determine significant differences between the different stages of awareness. All participants reported that the website increased their awareness towards sound exposure in the operating theater. One participant (categorized in stage 3) reported that he might use the website to "educate the rest of the team in the operating theater and to start improvements". All participants mentioned that the video on the landing page and the sound samples of surgery sounds helped them to build up awareness. Two surgeons (stage 3) elaborated on the video content and related it to their own experiences: "The video triggers the awareness of the problem correctly", whereas the other surgeon stated that "the video triggers awareness, but I think stress and fatigue are a bit exaggerated to be a result of sound exposure".

The "taking action" content pages were positively perceived by all participants. For example, the medical student reported that she was surprised that action can be more than wearing earplugs. The one major difference that I could determine was that the people categorized in stage 3 considered factual information (like the time-weighted average applied to operating theaters) most valuable, whereas people from other stages considered the "basic information" (why sound is useful in operating theaters or the sound samples) more valuable. The medical student (stage 2) reported that in her current education she has followed a practical course on "self-protection". However, only hygienic safety measures were taught, whereas hearing protection was not mentioned. When asking her "Did the website increase your knowledge on sound in operating rooms?" she reported the following: "The website has not so much improved my knowledge, it has rather improved my awareness of operating theater noise. So far, I have attended and assisted in 50 surgeries myself and was surprised that through the website I realized for the first time how many different sounds there actually are around me. I have always perceived surgeries as tiring and now for the first time I thought that it could actually be due to all the noise."

Comparison among the social ecological levels
There were differences between the different social ecological levels. One surgeon raised concerns that the broad target audience of the website it might not be able to reach each website user equally impactful. The PhD student did not report the same concern, but asked me: "Who exactly is part of the medical staff in operating theaters?". When asking the PhD student how she would use the gathered knowledge, she answered that "if she would work on that topic, she would definitely use it". Besides, two participants reported that they would like the action advices to be more concrete. One medical staff would like to have the advice more specific, so it is easier to put it in practice. One non-medical staff member indicated "to be intrigued" to grasp and learn more on the medical staff's health and actions regarding their health in operating theaters after reading the advices for the different stakeholders.

Discussion of the website experience and suggestions for improvement

Some functions of the website were limited by the tool which was used to built the website, especially the website navigation (as also indicated by participants). On similar account, some of the website elements could be enhanced by providing a website that is suitable for all electronic mediums, like smartphones, tablets, etc.). This is something that can be easily achieved through an IT-professional.

I think the concept would benefit from additional interventions (e.g. physical exhibition at a orthopedic conference, or at the hospital) that advocate the sound issue in operating theaters at the right time and at the right place.

Participants from different social-ecological levels positively received the "interactive elements" (the animation and the sound samples, where people could "play around" with sound samples of operating theaters). Whereas the medical staff reported that it made them reflect on the noise impact they experienced at work, non-medical staff reported that it helped them to get familiar with the sound situation in a playful way. I conclude that it is important to use "real" sound when educating about sound exposure.

The website was one way to showcase the sound situation in operating theaters, but the animation and the sound samples could also find applications separately (e.g. in exhibitions or safety trainings). By using this material in regular safety trainings, people who are not per-se pro-active could be reached. The broad scope of the website was intended to spark a network. But the evaluation showed me that even medical staff is not a homogeneous target group. Maybe even the medical staff must be treated or targeted specifically (e.g. sound sensations and thereby the perceived psychological impacts of sounds might differ on the perception whether or not a sound is useful).

Conclusions

Overall, the website reached its goal to increase awareness (and knowledge) on the sound situation in operating theaters. The participants reported that they perceived the website to be complete and "very accessible". It did initiate and trigger reflection, especially medical staff members (or future medical staff members). The website is a starting point to bring sound awareness into the operating theater and the healthcare community, it is a step towards changing health behaviors to achieve better sound conditions in orthopedic operating theaters that can and should be further elaborated.

Section 8

Conclusions and reflection

08 Conclusions and reflection

The main aim of this master thesis was to contribute to the reduction of auditory health risks in orthopedic operating theaters. The literature research showed that the current focus of sound assessment is mostly on physiological risks in relation to sound loudness (decibels) and whether exposure levels are in compliance with existing legislations. This thesis found that other sound characteristics beyond sound levels many influence medical staffs' sound perception and thereby especially their psychological consequences. The thesis thereby contributes to an understanding of sound beyond sound levels. In particular, it shows that sound perception and the consecutive behavior are highly related to sound awareness. Awareness is often missing among medical staff, but also within other influential social-ecological levels. Therefore, the final design is a website that offers new approaches to tackle the sound situation in orthopedic operating theaters from different perspectives and to raise awareness and educate on many levels (e.g. healthcare community, policy makers).

This chapter outlines how the thesis contributes to the existing research in the field of sound and health psychology (see Section 8.1). Furthermore, the limitations I experienced in this thesis project and its consequences for the final design are discussed. Based on that discussion, I provide suggestions for future research and how my final design can be further developed and put into practice. Finally, this chapter closes with a personal reflection: "How did the project impact me as a designer?"

8.1 Added value to auditory health research in operating theaters

The research conducted in this thesis brings new insights to a field that has received little attention in the existing literature. For this thesis I prepared participatory research tools (i.e. sensitizing booklets, sound quality polarity chart) that can be applied to investigate the sound perception in operating theaters (see Section 3). Section 4 illustrated that describing sound characteristics only by loudness is not sufficient. Since the perception of sound is subjective, the individual behavior with respect to the auditory health protection varies. This necessitates a holistic approach to understand the impact of sound on medical staff. The categorization of common sounds in operating theaters into pleasant, useful ("functional"), unpleasant ("situational") and harmful sounds was the outcome of the sound perception evaluation. The psychoacoustic analysis of sounds with polarity profiles (see Section 4.4) complemented the results with sound descriptions (e.g. shrillness, irregularity, powerfulness) that make the sound experiences of people understandable, giving a clear image which "unpleasant" sound features need to be tackled in order to reach sound improvement. The research further illustrated that auditory health behaviors of the medical staff working in operating theaters is not yet sufficient to protect them from potential health hazards (e.g. physiological and psychological discomfort).

First insights on the potential solutions indicate that behavior change requires the integration and collaboration of several stakeholders. The developed Social-Ecological-Model for sound improvement in operating theaters (see Section 5.2) showcased these stakeholders and illustrated current pain points, but also starting points for improvement and it can be widely applied to the field. The focus of the design goal was the improvement of awareness and knowledge of medical staff with respect to the relation of sound and health. I developed a website as an initial step towards an improved sound situation in operating theaters. By further extending the website's sphere of activities, it can contribute to better sound quality in future operating theaters. Despite the fact that the website is focused on operating theaters, many aspects might also be relevant in other healthcare environments, such as Intensive Care Units (ICU) or Emergency Rooms (ER).

8.2 Limitations faced while working on this thesis

The following section elaborates on the challenges I faced during this thesis project and their impact on the results and the final outcome.

Performing user research during COVID-19

The small sample size and the scattered selection of medical staff participants from different hospitals may limit the generalization to the entire medical staff population and due to COVID-19 the interviews had to be conducted online instead of on-site. Therefore, "soft data" (e.g. emotional expressions) may have gotten lost. These factors may have resulted in less conclusive results. However, the results are in line with similar soundscape investigations in other healthcare environments (Busch-Vishniac, 2019; Mackrill et al., 2013).

Limitations design phase

Challenges of discussions, iterations and collaborations during COVID-19

Design is usually characterized and put forward by collaborative discussions and iterations. I discussed the research results and my interpretations "only" with my supervisors. Nevertheless, given the limited access to hospitals, medical staff and other stakeholders with medical backgrounds during the design phase, the decision to pursue an "awareness"-campaign (e.g. instead for a product solution) might have been influenced by my personal interpretation of the research results in combination with the possibilities at hand (digital work possible, but product development difficult due to COVID-19). Nevertheless, I stand to this decision as the research indicated that there is not one problem to solve, but instead a problem solving and action-taking process to be started.

Impact is only assessable over time

The website is a prototype and the project's timespan is not sufficient to broadly implement or launch the website. Any impact of the website on health behaviors will only be visible over time. As healthcare structures are often lethargic and many stakeholders are involved, a broad distribution of the website combined with a long testing and evaluation period will be necessary. Given that behavior change is a long-term process, an in-depth website evaluation can only be conducted at a later stage in the future. That is why the initial evaluation performed within this thesis cannot answer the question whether enough awareness to the sound issue can be raised and if people are going to take action. It can only give indications and therefore relies on continuation. In addition, the evaluation lacked "new" participants and some participants might have been influenced in their opinion through previous involvement.

8.3 Directions for future research

Evaluating a soundscape is more difficult than evaluating a single sound source. Therefore, also improving the sound situation in orthopedic operating theaters is much more challenging than optimizing the sound emission of one tool. It requires a broad approach that covers the different elements of sound and health research.

Suggestions for future research

Relationship and generality of auditory health beliefs and health behaviors

Testing with medical staff from the same team or hospital is important for assessing sound situations' in a standardized manner (same operating theater with the same conditions) and for the systematic examination of auditory health beliefs and motives. The comparison with results from other hospitals and the incorporation of stakeholders from other social-ecological levels could help to better understand why some medical staff has higher awareness levels or the willingness to take up precautions. This result of the research in my thesis might be interconnected with the technical and organizational differences between hospitals. I believe that team-dynamics and the general attitude of a hospital significantly influence whether or not people want to change the sound situation.

I think it would be worthwhile to further investigate how much influence individuals in the social-ecological system actually have. Moderated discussions and collaboration workshops among teams (different levels of perceived influence), together with people from other social-ecological levels could enhance the understanding of the underlying decision-making processes of all stakeholders.

Need for "training" individuals to participate in soundscape assessment
Describing sounds objectively and in detail is difficult. The sensitizing booklet helped to "train" participants to reflect on their sound experiences. Therefore, I would advise researchers to "practice" sound reporting with their participants (e.g. through a sound diary) and train them to describe their sound experiences through adjectives and attributes.

In the operating theater – categorize sounds into "functional" and "situational"
The medical staff highly relies on auditory feedback and sound is an important "tool" to optimizing patients' care. However, individual professionals may generally categorize sounds differently into "functional" (important auditory feedback) or "situational" (rather unnecessary background sounds). While the sound of a hammer is useful (functional) for a surgeon, it is likely to be "non-functional" for the anesthesiologist. Therefore, I would start any assessment by an examination between the professions – "Which sounds are functional for you?" and "Which sounds are non-functional for you?"

Characterize "functional" sounds
A next step could be to determine whether "functional" sounds are in an accepted shape or whether improvement is needed. I would apply a simple categorization into pleasant, unpleasant, harmful sounds, similar to how it was done in this thesis.

Hearing all the needed sounds without restriction
It has to be assured that important sounds are not masked or covered by situational sounds. To examine whether or not individual staff members are capable of hearing all their "functional" sounds, it would be important to understand how single sound events influence the work performance and the health of the medical staff. This could be achieved through further investigations on how sounds are masked by one another or even covered up during sound events in operating theaters. This was out of the scope for this thesis. One possible method to approach this interaction between sounds is further psychoacoustic analyses, e.g. through the method "Zwicker loudness"(Fastl & Zwicker, 2007b).

Sound characteristics in relation to psychological impact (e.g. stress and annoyance).
Sounds, regardless of their loudness or functionality may cause psychological discomfort. In future research, I would ask medical staff to describe a collection of sound events with their own attributes (e.g. calm, noisy, bright etc.). Then I would suggest to perform a psychoacoustic experiment with polarity charts, similar to the one executed in this thesis (see Section 4.4). As an improvement, I would advise to do this assessment with medical staff members from one hospital (to secure standardized conditions), but also with a non-medical staff control-group. Doing this will make it possible to determine whether the meaning which is attributed to sounds (e.g. is a sound useful) influences the "likability" of sounds.

Suggestions for future design

During the research I realized that the network around the medical staff has a great influence on both – the sound situation in the operating theater as well as the general auditory health attitude of medical staff. A certain commitment and involvement of all stakeholders is thus key for any improvement.

The design development process
For the development of suitable concepts, it would be advisable to organize collaborative brainstorm or scrum sessions with medical staff, policy makers, hospital managements and others involved. As all these stakeholders have limited time and availability it might be a good approach to organize web-based brainstorming sessions, for example by using tools like Miro, a visual collaboration software. The aim should be to change the role of the stakeholders from "affected" to "involved".

The design outcome: Recommendations for the website as it is now
The current design contains a website that offers the possibility to download some "physical" materials. The website could also be seen as a starting point of a movement. For example, European researchers working on sounds in the healthcare domain have recently started a collaboration network (HAVENS). Using this website and complementing it with current research on the European level could further nourish the topic in healthcare and also society. As a starting point some suggestions:

- Use resources to align the navigation to a conventional website and make it also accessible with smartphones and tablets
- Create a holistic campaign package that promotes the website (e.g. leaflets, organized talks, etc.)
- Investigate whether the content is suitable for a broad healthcare audience from different socio-ecological levels by testing it with various user groups
- Complement the current website with more tailored information on psychological consequences of sounds to deepen the information that decibel values will not "replace" a holistic sound assessment (e.g. including sound perception assessments)

Suggestions for future design directions complementing the website
Further action-support for the medical staff would improve the impact of the campaign "improving sounds in operating theaters". One possibility is a more technological approach: To develop an app, which offers the opportunity for the medical staff in the healthcare domain to investigate their specific sound environment. It could act as a first hint of confirmation whether or not individual own sound situation is critical. This should not only include decibel measurements but also provide the opportunity to keep a noise diary, entailing the sound qualities. This in turn could then be the basis for future research and design approaches.

8.4 Epilogue: Personal reflection

Writing this reflection, one statement to describe this thesis process crossed my mind: "When life gives you lemons, make lemonade". I would like to explain why.

Collaborations during a pandemic

The day that I started this project was also the last time for many months that I could be on campus at the Faculty of Industrial Design Engineering at the TU Delft. Due to COVID-19, the Netherlands was in lock-down. That meant I had to change from working on-site, into remote working at home. Of course, many processes and actions could not be performed as planned. I wished I could have conducted user research offline or that I could have worked in the graduation space at the faculty to draw inspiration and motivation from the interaction with fellow students. But this pandemic also showed me that new unexpected circumstances foster creativity and train the ability to be flexible (if you want it or not).

One of the main challenges during this thesis project was to find alternative ways to perform the research since the initial detailed plan was inhibited by COVID-19. I had to find alternative methods of collecting qualitative user data and a way to measure sounds in the operation theatre (without me necessarily being there). Working remotely, I had to explore alternatives to evaluate my concepts on my own and started applying theories and methods to "objectify" and support my design process - a great way to further work against the designers' "gut feeling" and take a step back and evaluate one-self in an organized way.

Personal growth during this project

Working and reaching healthcare workers is generally difficult, even more so in times of COVID-19. At the beginning of this thesis, I was lacking participants and I was afraid not to find enough people for my research, especially because I was performing this thesis in a foreign country and my network in the Netherlands was mostly limited to the university. But I learned during this project and also for my future career – networking is key to a successful project. As long as you value other peoples' time and show them how passionate you are about your project and why it is important, most will be happy to help you. Last but not least, with this project I was able to combine two of my interests; the human body (the human hearing) and the human mind (health psychology). By writing this thesis on sounds in operating theaters, I gained a lot of background knowledge on both aspects and I am sure that it will find application in my future projects and career. But among all things I have learned in this project, the aspect that I am most proud of is that I was able to start a conversation on sound issues in operating theaters – a conversation that is long from being over.

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References (images)

Figure 1. Gellidon, J (2019). [Photograph during surgery in an operating theater]. Retrieved from unsplash.com, September 28, 2020, from https://unsplash.com/photos/9Eb-bpTXglM/info

Figure 2. Rob van Esch (n.d.). [Photograph of empty operating theater at Erasmus MC]. *Dutch Daylight*. Retrieved September 28, 2020, from https://www.dutchdaylight.nl/project/erasmus-mc/

Figure 3. VIRTUAL EXPO GROUP (n.d.). [Photograph of Stryker surgical power tools]. Retrieved September 28, 2020, from http://guide.medicalexpo.com/choosing-the-right-surgical-power-tool/

Figure 4. Pixabay - user:12019 (n.d.). [Photograph of work and communication of medical staff]. Retrieved September 28, 2020, from https://pixabay.com/de/photos/medizin-medizinische-chirurgie-91754/

Appendices

Overview

A Personal project brief

Health Behaviors in the Soundscape of Orthopaedic Operating Theatres — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 16 - 03 - 2020 — 15 - 10 - 2020 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

In general society has developed some sensitivity towards the impacts of occupational sound and noise exposure on people's health and wellbeing. For example, regulations have been implemented for workers being exposed to loud sounds on construction sites or in factories. However, designing "safe" occupational soundscapes is rare. Being exposed to loud sounds is still common in many sound critical working environments. For instance in the specific context, the operating theatres (OR) of orthopaedic surgeries.

According to ISO 12913, a soundscape is described as "an environment of sound (or sonic environment) with emphasis on the way it is perceived and understood by the individual, or by a society." On a daily basis, surgeons, scrub nurses, anaesthetist assistants, and patients present in the soundscape of the orthopaedic OR have to deal with an interplay of different sound sources produced by powered tools, mechanical tools, monitor alarms, by people acting in the environment, speech, and music (see Figure 1). According to the Occupational Safety and Health Administration (OSHA) employers are required to implement a hearing conservation program when noise exposure is at or above 85 decibels (dB) averaged over 8 working hours. As some orthopaedic surgeries (e.g. hip-replacements) are in average at a decibel-level of about 80 dB, it is not legally necessary to provide staff and patients with hearing protection. However, previous studies convey, that within some orthopaedic surgeries (e.g. hip-replacements), measured peak levels exceeded 100 dB in 40 % of the time, while highest peak levels frequently exceeded 120 dB (Kracht et al., 2007). To give reference, the threshold of pain and the risk for noise-induced hearing loss starts at 120 dB (Hyperphysics, 2020).

As legal standards 'only' require the average of a surgery to be below 85 dB, very few sound-related protection is applied. But being in the current soundscape inherits serious physiological and psychological health risks. These risks can range from limitations in work performance due to lack of concentration, stress and fatigue, up to tinnitus and none-reversal hearing loss.

The starting point for my thesis is to understand how the current soundscape is perceived by medical staff. Why do people often not engage in preventive behaviour? Some issues occur due to different sensitivity levels to sound. The medical staff does not perceive the soundscape as a potential hazard to their health. Some issues are caused by the vague legal standards which cause a lack of awareness to the potential risk. In some cases, awareness may be present, but as hearing protection interferes with a persons' listening needs (e.g. they want to hear a monitor signal), they will actively choose not to engage in prevention.

Usually the medical staff in a hip-replacement surgery consist of a team of five to six. In a previous research project the operating theatre of hip-replacement surgeries was observed and five listener types (see Figure 2) were identified: The sedated patient is 'the exposed' with 'no-listening-attention'. The passive listeners are either surgical techs' or circulating nurses with 'background-listening', while active listeners are scrub nurses who are 'listening-in-readiness' waiting inter alia for the surgeon, to give orders. The sound user and sound producer are the surgeons that either use sound as feedback during surgical events, but also produce sounds by using surgical tools or guiding the surgery through speech. Depending on the phases of the surgical procedure, listeners may move between those listening types, but mainly stay in their role. Observing and talking to listeners is the starting point to understand how perception and behavior differs in regard to sound in this complex soundscape. It will show how the medical staff pursues different behaviors, has differing goals, motivations and internal health beliefs that prevent them to engage in health-preventing behaviors.

introduction (continued): space for images

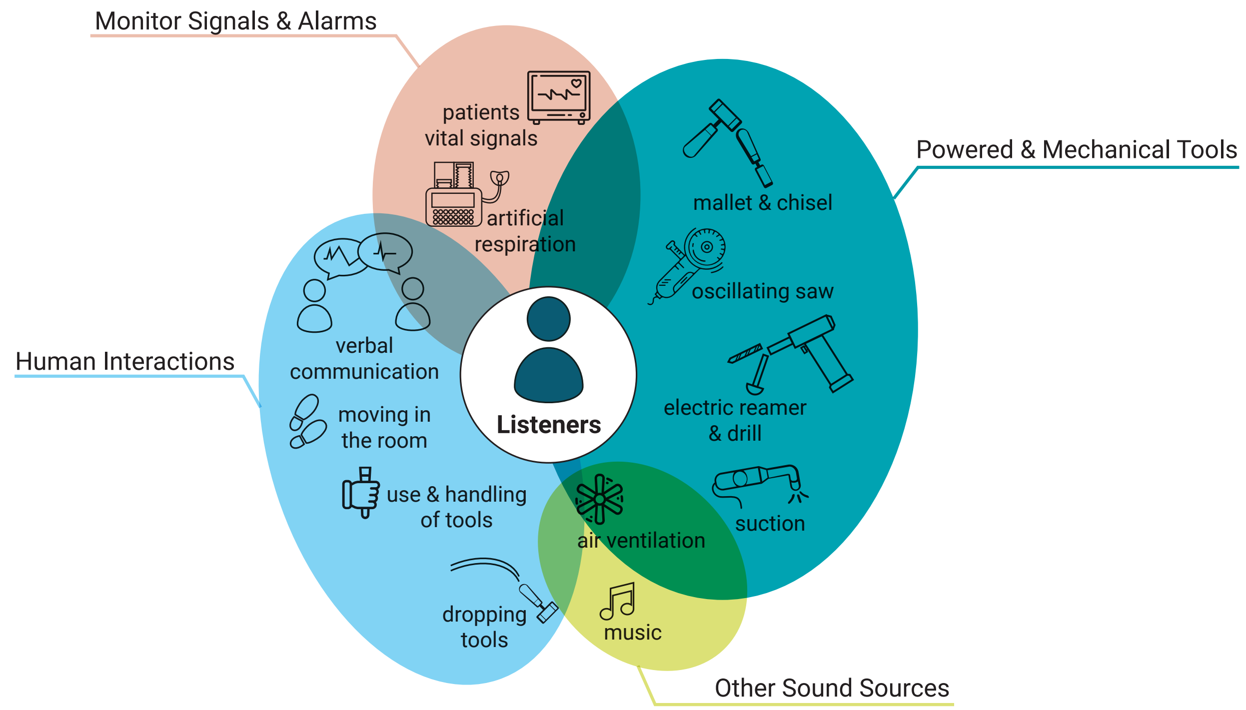


image / figure 1: Interplay of Sound Sources in Orthopaedic Operating Theatres

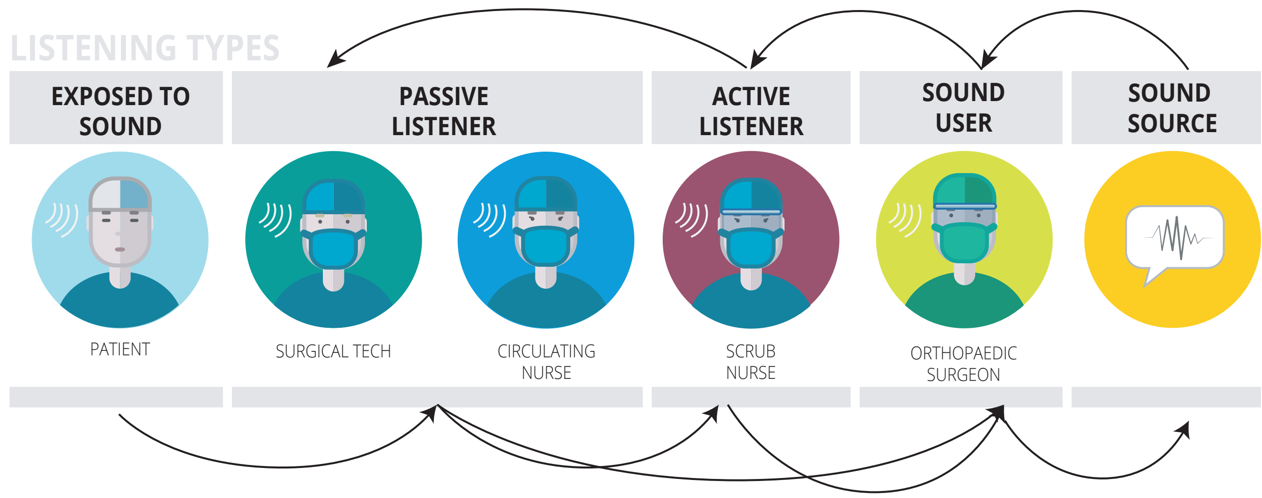


image / figure 2: Listener Types in Hip-Replacement Surgeries

PROBLEM DEFINITION **
Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The focal point for my project lies in gaining an in-depth understanding why the medical staff does not engage in health-protecting behaviors.

Current issues that occur in this soundscape are on one hand the vague legal regulations concerning occupational sound safety. Another factor is, that the criticality has not been fully recognized by people working in this environment as well as by employers (hospitals), medical tool providers and the people creating health and safety work regulations.

The sensitivity to sound as a health hazard may be best achieved by creating awareness to the current criticality sound-situation in the OR. Starting with auditory health behaviours of individuals, it has to be further explored who else influences behaviour to protect the hearing of medical staff in the OR. The structure and hierarchy is important as it also defines where and which actions should be firstly, secondly and thirdly established in order to improve sound and health conditions for all involved persons.

Due to the scope of the project, the focus of will lie on occupational health prevention and will not focus on patients. This is reasoned by the fact, that medical staff is exposed to this critical sound environment on a regular to daily basis, whereas patients are only exposed to this environment for a very short time-period.

ASSIGNMENT **
State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

By conducting in-depth qualitative research, the perception of the current soundscape by the medical staff and their current auditory health behaviours will be investigated. Based on the human-centred research results, I expect to explore different concept directions to improve (auditory) health behaviours of each listener related to the soundscape. The final outcome will be a design approach that contributes to a safer OR with respect to hearing issues.

Road map:
1: A field study will be conducted to analyse current health behaviours and beliefs consisting of two parts:
1A: Observation of the current sound-scape: Observe (if possible) different teams while performing different orthopaedic surgeries (e.g. total hip replacements, trauma-surgery etc.) in the OR. The focus will lie on investigating the soundscape and the people within - how do they behave in interplay with each other with regard to sound use. It also aims to identify the parties ("experts") involved in the decision process of hearing protection.
1B: Sensitizing and interviewing using the context mapping approach: Develop a sensitizing booklet that is the conversation starter for the interviews. It aims to depict general sound-awareness and to unravel current perception of the soundscape in relation to health behaviours. The interviews and booklets will be the foundation of the projects further direction as it will be used to identify problem areas and opportunities within this context.
2: Data analysis and evaluation: Assess and categorize the collected data. Identify the solution space within individual and organisational behaviours, beliefs and perception.
3: Create and design: Create sound-related health prevention strategies, by changing organisational and individual health behaviours without interfering with medical staff needs (e.g. not hindering communication). I expect a promotional design that aims to create 'sound-awareness', motivating every listener type to engage in auditory health prevention, most likely it will be in form of a campaign or speculative design or a product creating awareness to the noise issue.

B Task distribution

Generally speaking, the task distribution in the operating theater can be divided into two teams - the sterile and non-sterile team. In those teams, each profession fulfills their own tasks to contribute to a successful surgery. The tasks listed here arrived from literature research and personal observations. The references can be found on page 115.

Tasks of the **sterile** medical staff:	Tasks of the **non-sterile** medical staff:
Surgeon • Primary person to perform the surgical procedure on the patient (Williams &Williams, 2015) • Knows the important aspects of a patients' health status and the complexities of the procedure itself (WHO, 2009; American Society of General Surgeons, n.d.) • Needs to maintain sight over the timespan of the entire surgical procedure • Delegates tasks across team members and facilitates communication ("The Royal College of Surgeons of England", 2014) • Performs a final wound assessment before closure (WHO, 2009)	**Circulating nurse** (Taylor & Campbell, 1999a, 1999b) • Supports the surgical team (e.g. surgeon) with scrubbing-up and getting into the sterile protective gear • Assists the scrub nurse with the preparation: e.g. instrument trolleys, hooking up devices that require power, deals with patient samples on instruction • Supports the scrub nurse by facilitation of sterile supplies (e.g. implants) • Keeps sight of the sterile zone (around the operating table) to ensure a continuous sterilization chain • Adjusts the lighting for good visual working conditions • Executes a count of goods at the end of the procedure, together with the scrub nurse, to ensure that no equipment remained in the patient (e.g. swabs)
Scrub nurse (Taylor & Campbell, 1999a, 1999b) • Prepares oneself' by carrying out the appropriate scrubbing-up, gowning and gloving • Arranges and provides the appropriate instruments, trolleys and sterile supplies for the surgery • Supports and anticipates the surgeon needs' during the procedure by operating and providing necessary instruments and equipment (e.g. swaps) • Maintains and keeps attention on a sterile environment • Executes a count of goods at the end of the procedure, together with the circulating nurse, to ensure that no equipment remained in the patient's body • Ensures that patient samples' are handled correctly by the circulating nurse	**Anesthesiologist** • Administers anesthesia to the patient (American Society of Anesthesiologists, n.d.) • Provides continual medical assessment of the patient (Colorado Society of Anesthesiologists (CSA, 2011) • Monitors and controls the patient's vital life functions (e.g. heart rate, breathing, blood pressure, body temperature) (CSA, 2011) • Controls the patient's pain and level of unconsciousness throughout the procedure (CSA, 2011) • Establishes and maintains appropriate airway management and provide appropriate ventilatory support (American Society of Anesthesiologists, n.d.)
Resident • Provides assistance the lead surgeon throughout the surgical procedure • Observes the surgical steps for training purposes (Sonnadara et al., 2014)	**Anesthesiologist assistant** • Generally speaking: assists the senior anesthesiologist with their tasks • Collects patients' samples (e.g. blood) to perform laboratory diagnostics as delegated by anesthesiologist (Anesthesist.org, n.d.) • Inserts and interprets data from patient monitors' (e.g. vital functions and anesthesia levels) as delegated by the senior anesthesiologist (Anesthesist.org, n.d.)

C Interview outline

The general interview outline was adjusted to the individual participants. When participant had filled out the sensitizing booklet, their answers in the booklet guided the first part of the interview. The interview was semi-structured. The questions were the guideline, but also allowing to follow up on individual answers in more detail. Here you can see the researcher's script.

1. Introduction: 5 minutes
- Thank you for your time today.
- How are you?
- Is it okay, if I (audio-)record the interview?

2. Sensitizing booklet:
- How was it to fill out the booklet?
- I prepared some questions, were I would like to get to know more about your answers.

Now questions based on the sound perception as answered in the booklet are discussed.
(In case of no prior sensitizing booklet: Extra questions are asked, such as:

Personal sensitivity to sound
- In daily life, what is your relationship to sound? Are you sensitive to sounds? Do you prefer silence?
- How important do you think is your sense of hearing during surgeries? For example compared with visual feedback?

Personal sound experiences in OR:
- Useful sounds: As a surgeon, could you explain me a little bit which kind of sounds are important for you during the intraoperative period?

- Pleasant sounds: During the procedures, are there any sounds you like to hear? (For example music, talking to colleagues?)

- Unpleasant sounds: As a surgeon or for you personally, could you explain me a little bit which kind of sounds are unwanted sounds for you? That are disturbing, annoying or just unpleasant in your ears?

- Harmful sounds: Are there sounds that you perceive as potentially harmful for your mental or physical wellbeing? Can you give examples.

3. Health behaviors, beliefs and knowledge in operating theaters:
Perceived sound pressure levels in OR (dB)
- Usually, the loudness of sounds is measured in decibels. Are you familiar with decibel levels?
- What would you think if a surgery has the decibel average of 75dB?
- Do you think in general that the current sound situation in the OR is acceptable?

- Can you easily name a sound that produces the loudest peak during your surgeries?
- How often and how long does this sound occur per surgery?

Perceived susceptibility & perceived threat:
- Have you ever thought of sound as a potential health issue?
- Does sound in the OR affect your physical or mental health in any way? How?
- Or do you think it could affect you in the future?
- Would you like to change your current auditory behaviors or are you happy with the way things are?

Behavioral intention towards sounds as a hazard
- Which of the following statements describes your thoughts about taking precautions for potential hearing (damage) in the OR best?
- Why does this statement describe you best?

• I am not aware that sound in the OR is a potential hazard to my health.
• I know that sound in the OR can cause health issues, but I have never thought about taking precautions.
• I am aware, but I am undecided about taking precautions in the OR for my hearing.
• I have decided that I want to take action in the OR for my hearing.
• I am taking action for my hearing in the OR.
• I am aware but I've decided that I don't want to take actions in the OR for my hearing (anymore).

Work performance:
- Do you think that you could work efficiently if you would for example wear noise-canceling headphones that filter the loud sounds, but still lets you hear the alarms?

Social conflict: self-efficacy vs. collective efficacy
- Do you think that if you'd decide to take hearing precautions that it would influence your team performance?

Perceived barriers/benefits
- Are their barriers from taking precautions? Which are those?
- Are there benefits of hearing protection in the OR that you could think of?

Enabling Factors:
Social support/peer influence
- Do you mostly perform anesthesia in surgeries where you know the team?
- Do you discuss the sound situation in the OR between other anesthesiologists or with other people?
- Do you think that if most your colleagues would take hearing precautions that this would lead to your decision to take precautions as well?

Facilitation & stakeholder influence
- Who do you think has the power to change the sound situation in the OR?
- Who would be responsible to initiate taking hearing protection in your opinion?
- In what way could change be facilitated?
- Are you part of a labor association?

4. Thank you very much for your time.

D Statement cards

The statement cards were prepared iteratively during user research and comprise insights from sensitizing booklets, interviews and also literature. They were clustered and categorized in order to understand the current sound perception, health beliefs and behaviors in orthopedic operating theaters. As the whole compilation is too big, only excerpts are displayed here.

CAPTURING THE SOUNDSCAPE

IN GENERAL: SOUND PERCEPTION IS COMPLEX

'Loudness' is only one factor of sound experiences. There are many more that influence the soundscape experience.

P01/01: Talking about suction device: "It's more the annoying [nature of the sound], it's not the loudness, but the type of noise that it makes." – ca. at 25 minutes

POSITIVE EFFECTS OF SOUND IN THE OR

USEFUL SOUNDS

GIVEN EXAMPLES BY PARTICIPANTS:

- sound of machines (drill, shaver, VAPR etc.)
- sounds like monitor alarms
- sounds indicating something is different than it should be

Sound is highly important for 'situational awareness'.

Situational awareness

P01/01: - I am not consciously listening to my surroundings, but if something changes, that alerts me, for example when the door of the operating room opens during the surgery, I know that something is wrong, because the door should not open because we have to keep a sterile environment. Another example is, I don't hear the patients monitor, but I hear it if something changes and I know that should not be. – Summarized from initial conversation by reseacher

Auditory feedback of equipment assures a 'safe' and 'time-efficient' surgical procedure. (VAPR)

P01/01: And for the VAPR, it is the feedback of the machine itself, which is similar to the cautery machine. The machine gives a signal, a beep when you have it pressed." – ca. at 7:31 minutes

Auditory feedback of equipment and tools

- on progress (e.g. kind of tissue)
- machine settings (e.g. rotations p. minute)
- signals (on/off)

PLEASANT SOUNDS:

GIVEN EXAMPLES BY PARTICIPANTS:

- communicating with colleagues
- radio/music
- tools due to desired activity
- patients' signals due to confirmation of success

Music may help to reduce overall stress levels in the operating theatre.

Literature: "Our study revealed that 59% of the respondents thought that music helped in reducing their autonomic reactivity in stressful surgeries thus calming them down and allowing them to approach their surgeries in a more thoughtful and relaxed manner." (George, Ahmed, Mammen, & John, 2011)

OR-nurse

Liking the "non-silence".

P03/01: "If it is completely silent, I don't like it that much." ca. at 02:14 minutes

Resident (orthopedic surgeon)

Pleasant sound: Liking the sound of a drill.

P02/01: "Yeah, haha [laughs] Yeah, I like the sound of the drill. I was just thinking about what sounds are annoying, what sounds I am not. [...] But I like the sound of the drill and also, when you use it, you can also use the sounds, it makes the feeling...like what you are doing, but...it's something that I generally like. ca. at 5:09 minutes

- literature insights
- surgeon insights
- OR-nurse insights
- resident insights
- anesthesiologist insights

NEGATIVE EFFECTS OF SOUND IN THE OR

UNPLEASANT SOUNDS

GIVEN EXAMPLES BY PARTICIPANTS:

- telephones
- helmets
- oscillating saw
- not listening of anesthesiologist

Need for unrestrained communication

Restricted communication due to protective gear.

P01/01: "You are less well understood because you're wearing not only the mask, sometimes you are wearing a head protective gear... so that's all... it stops the sound...so it is more muffled. So it's more difficult to understand for the person listening to you and vice versa."– ca. at 10:23 minutes/ "So now the helmets make less noise, but they have a ventilator in it. And the ventilator makes noise. And so that's giving extra noise that you have to, you know, more or less overscream." ca. at 13:14 minutes

Problem: Protective gear

- *reduces ability to communicate*
- *makes disturbing sounds/noise*

(Protective) equipment makes (soft) noise, that is disturbing.

P01/01: "...And it was a very poor sound system. So now the helmets give less noise, but they have a ventilator in it. And the ventilator makes noise. And that's giving extra noise that you have to, you know, more or less overscream."ca. at 13:14 minutes

Anesthesiologist

Details (soft sounds) are missed because of noise.

P04/02: "No, they are interfering. Absolutely, that's why I say that I have to look at the screen rather than listen. Because, I cannot hear the...sometimes I put up the sound, I increase the level of the sound. But sometimes I do not, because I'm busy with something else, I'm typing in some medication that I just gave, I'm working on this, the phone is ringing, I have to talk. And then, you miss all of these details, because of the sound. But I do not know how to address that. It is difficult. Yeah, the sound is there. Yeah, you need to realize that it impacts you. I realized that. But that's why I say, you need to talk to younger people that don't realize that." - ca. at 11:14 minutes

HARMFUL SOUNDS

GIVEN EXAMPLES BY PARTICIPANTS:

- oscillating saw
- hammer of extracting intramedullary nailing
- helmet

Uneven or disruptive sounds may increase stress and result in lower surgical performance.

Literature: Noise peaks can impair case-relevant communication. (Keller et al., 2018)/ Changes in moods or emotions due to disruptions of work flows (rather because of the experience of disruption) rather than the loudness of sounds (Zimmer, Ghani, and Ellermeier, 2008)

High-demanding and important work (outcome).

Disturbance of sound in an already demanding working environment.

P01/01: "...we are all aware now that certain sounds or background noises can be disturbing for certain people. Maybe from many more [sounds], than we are aware of. This is our working environment, but this is also an environment, where let's say the optimum support is important, because the outcome is so important."ca. at 38:35 minutes

Resident (orthopedic surgeon)

Suction is annoying as it adds up to the background noise, while being directly in front of the face.

P02/01: "Yeah, it's the loudness and it creates background noise [...] well in the end they have a very small tube through which they suction. So there's a lot of noise generated through the small opening. So it's pretty loud.[...] And sometimes you just use it [...] for the whole operation [...] a couple of seconds, but it's on al the time. [...] it's not really on the background, because it's right in front of you [...] you really have like [...] a really high decibel level of background noise [...]." ca. at 09:52 minutes

INDIVIDUAL CHARACTERISTICS INFLUENCING THE SOUND PERCEPTION

Task division: Different teams listen to different sounds in the same soundscape.

P01/01: "Or sometimes, they have their own beeps that they're listening to. So I have to be louder than that. Sometimes our own equipment makes noise..." ca. at 10:23 minutes

OR-nurse

Little awareness and engagement with the issue of sound.

P03/01: "Maybe before I made the workbook, I was not aware of sounds. It was just there. But now yeah maybe [...] I know that sound can be a health issue, but I haven't thought about...taking more action or something. – ca. at 18:59 minutes

Work experience improves the ability to 'block out' noise distractions.

Literature: Studies that included participants with different levels of expertise showed that less experienced surgeons were more likely distracted than experienced surgeons (Hsu et al. 2008; Suh et al. 2010)/ Experience levels of surgeons may moderate the impact of noise on performance. (Keller et al., 2018)

Orthopedic surgeon

People's listening preferences influence the sound experience for the rest of the team.

P01/04:"...I know a surgeon who was operating like spine surgery every day, not everyday, but they...He always had like, heavy metal. Music was always, like the metal playlist in the background. It was just...[...] he was just the best surgeon there was for that kind of procedure. ca. at 26:08 minutes

Resident (orthopedic surgeon)

Because of low sensitivity to sound, perceived low susceptibility to hearing damage.

P02/02: "As I said, I am not very sensitive to sound. Maybe if you are, let's say very tired and it is very busy with a lot of different sounds, yeah maybe it can give some stress. But not too much. - ca. at 15:21 minutes

Resident (orthopedic surgeon)

Mental state of the surgeon and stress-level depends on the work experience.

P02/02: "Well it depends on my own experience I think. [...] Even if it is, for the supervisor a quite easy surgery, but for me it can be a difficult one." – ca. at 2:22 minutes

CURRENT AUDITORY HEALTH BELIEFS AND BEHAVIORS

PERCEIVED RISK OF NOISE EXPOSURE:

Resident (orthopedic surgeon)

Low perceived threat by (very) loud sounds due to short duration during surgery.

P02/02: "Yeah, the hammer is loud, but it is short, just a few seconds." - ca. at 18:03 minutes

OR-nurse

Reduced perceived threat of sound levels due to fluctuation of sound levels.

P03/01:"Maybe...in average...Because sometimes it's silence for a while. Maybe 80 (decibel)?" ca. at 15:30 minutes

Resident (orthopedic surgeon)

Mallet not perceived as harmful due to usefulness of sound and it's short duration of use.

P02/01: "The hammer or the mallet are used, but I don't mind too much about that. I think for a surgeon, it's certainly, it's very... that's also useful.[...]" ca. at 15:51 minutes "So yeah, that's a bit... but those sounds are very loud...but it's not...It's not that...we don't use it for hours in a row." ca. at 17:13 minutes

Periods of loud noise may be perceived as not harmful due to short occurrence.

Literature: "These levels mandate the use of hearing protectors but their short duration decreases the perceived risk of harm among surgeons." (Love, 2003)

Short duration of loud noise suggests "no harm"

Resident (orthopedic surgeon)

Knowledge on decibel levels due to playing in band as a teenager. Helps assessing decibel levels. High levels are not perceived too harmful due to short duration.

P02/01: "I know a bit about it. I used to playing in a band for multiple years since I was young, and well, that made a lot of noise and then, you know a bit what kind of decibels...from what level of decibels, it's not nice to your ears anymore. But I couldn't tell like how loud something is. And I could not say well, that's a hundred or that's a 120 or something." - ca. at 19:56 minutes "But it's...so of course...it's very...it's short. Not a constant noise." - ca. at 20:47

Low (perceived) susceptibility to physical health consequences of noise exposure.

P01/01: "And on the other hand is, the amount of time, that I am exposed to those loud sounds...because of my type of surgery, it's not that often. So it's different. – ca. at 31:38 minutes

Unfamiliarity with decibel levels reduces perceived threat through high decibel levels --> difficult to bring across severity of (some) loudness

OR-nurse

Reduced perceived susceptibility because of unfamiliarity with the units of sound (decibels).

Researcher: Also for loudness, if I would say 70dB, would that be something where you have a feeling for? P03/01: "No I wouldn't know." ca. at 14:00 minutes "For the replacement, I think it's the hammer. And that's like 140 decibel, the hammer and the drill." [participant shows no (negative) emotion when choosing 140 decibels from the exemplary scale, she does not seem alarmed]

Orthopedic surgeon

Decibel levels (and their potential meanings) are an abstract number.

P01/04:"Yeah. I don't know exactly what to...Yeah it's true that I am not really aware of the decibel levels. So what's harmful and what's not and what is common in daily life or common in the OR, so I don't know these numbers a lot. So that's difficult to tell for me." ca. at 12:53 minutes

PERCEIVED BARRIERS TO HEALTH BEHAVIOR

Resident (orthopedic surgeon)

Not considering earplugs due to lack of communication ability.

P02/01: "Yeah, I think if I would wear earplugs, I will not be able to do hear and like especially I wouldn't be able to hear people. So that's...I will not do that."- ca. at 22:34

Dislike of protective gear due to reduced physical comfort.

P01/01: "Yeah, I mean [the helmet is] unpleasant, because it's a big thing on your head. So your head is twice the size. [...] You have something around your ears [...] It gives you sort of a closed-in feeling." ca. at 12:15 minutes "I just don't like wearing headphones and having them on. I don't really feel very comfortable with earplugs in, I think the physical wearing it, pressure, is not very pleasant." ca. at 31:38 minutes

Orthopedic surgeon

Until now, taking precautions is not (financially) supported by the hospitals, as it is also difficult to pinpoint the issue of sound.

P01/04:"...Well I bought like not personally made earplugs... ca. at 14:32 minutes Because for an individual healthcare clinic or for a hospital, it's just extra costs. Without it...without a clear benefit at short-term." ca. at 22:13 minutes

Having good hearing conditions (of soft sounds) outweighs possible health consequences.

P01/01: "Well, the point is, at this moment I've never worn and I probably don't dare to wear anything to hear less." – ca. at 28:5 minutes "For the main barriers [of hearing protection would be] that I would hear, let's say the softer sounds. I would hear them probably less or not as good." ca. at 31:38 minutes

PERCEIVED BENEFITS OF HEALTH BEHAVIOR CHANGE (TAKING PRECAUTIONS):

Orthopedic surgeon

Sounds in shoulder surgeries not being needed. Therefore, wearing earplugs is an option.

P01/04:"... Well, actually in our arthroscopic surgeries, where...what we call soft tissue procedures. There's not so much feedback for me [...] But for my arthroscopic procedures, that's very limited, I would say. So for me, that wouldn't be a reason to not use earplugs... ca. at 19:35 minutes

Orthopedic surgeon

Having first signs of hearing damage initiate the will to take precautions, but a damage has already occurred.

P01/04:"...And one of my colleagues in training, I didn't know that before, but he is using earplugs as well, because of tinnitus. [...] Yeah, so for me and for my colleague...yeah, we've started using them, after we got tinnitus, yeah. That's correct. [laughs] ca. at 16:45 minutes

- literature insights
- surgeon insights
- OR-nurse insights
- resident insights
- anesthesiologist insights

Orthopedic surgeon

High perceived susceptibility to harmfulness of sounds, even in "quieter" shoulder surgeries.

Perceived risk dependent on personal health status

P01/04:"I think there are certainly sounds in my OR that are harmful. [...] in the upper extremities it is with less force, but the sound is still metal on metal. When...Yeah, when we implant that prosthesis, so I think that certainly is harmful. - ca. at 08:59 minutes

Orthopedic surgeon

Patients risk of hearing damage risk is acknowledged, compared to own risk.

P01/04:"...what's interesting, like we have...the patient will get an earplug. If you're [operating their] right shoulder, they have an earplug in their right ear. Because we are aware of that...that sound is harmful. Yeah, most of us, ourselves, don't use earplugs."- ca. at 09:47 minutes

Anesthesiologist

Details (soft sounds) are missed because of noise.

P04/02: "No, they are interfering. Absolutely, that's why I say that I have to look at the screen rather than listen. Because, I cannot hear the...sometimes I put up the sound, I increase the level of the sound. But sometimes I do not, because I'm busy with something else, I'm typing in some medication that I just gave, I'm working on this, the phone is ringing, I have to talk. And then, you miss all of these details, because of the sound. But I do not know how to address that. It is difficult. Yeah, the sound is there. Yeah, you need to realize that it impacts you. I realized that. But that's why I say, you need to talk to younger people that don't realize that." - ca. at 11:14 minutes

HIGHER PERCEIVED RISK ON MENTAL HEALTH

Resident (orthopedic surgeon)

Higher required concentration due to blocked communication increases levels of tiredness.

P02/01: "But what I...for like...I don't know if you call it health, but when there's a lot of background noise, and especially when you use a helmet with the ventilator in it, I really have to concentrate on what people are saying who are next to you. Because it's just sometimes a lot of times in you are like "huh, what, huh what did you say" and you reeeeaaaally have to concentrate and I think that...if you do perform such an operation for a couple of hours that also really adds up to getting tired by...just because you have to concentrate on what is said." ca. at 17:13 minutes

Emotional well-being can highly influence the surgical outcome.

P01/01: "I think, ultimately, if I feel better, communicate better...I think the surgery has a better outcome." – ca. at 22:10 minutes/ "Because feeling uncomfortable can be the difference between, putting it bluntly, saving a life or maybe not." ca. at 38:35 minutes

PERCEIVED INFLUENCE TO INITIATE CHANGE OF CURRENT SOUND SITUATION

Who achieves change?

high perceived influence of individual (surgeon)

High perceived power of influence to attain changes on the sound situation in the OR.

P01/01: "No, I think as a let's say as the worker itself and as a surgeon, you are quite influential on what you want in your own operating room. [...] For instance, I am a member of the OR-board. So let's say that would be, let's say the most practical place to do that. You would have to discuss it depending on what kind of investment it would be [...] So yes, I feel that I have an influence." ca. at 34 minutes

Resident (orthopedic surgeon)

Low perceived influence on hospital procedure as a resident.

P02/02: "Well, we are members, but not really influencing I guess."- ca. at 19:40 minutes

little perceived influence of individual

Resident (orthopedic surgeon)

Not knowing where to go when there is a concern with sound.

P02/01: "I have no idea. I would ask like the scrub nurses. [...] They're not the one's who buy the equipment we use., but at least you could ask them something about it. But I do not get the impression that it would be easy [...]." ca. at 23:21

E Personas

Based on the participants Persona's were created to frequently reflect on personal characteristics that shape the sound experiences and behaviors of individuals. By "applying" the different Persona's, I could check whether or not my concept ideas were in line with the different individuals that work in current operating theaters. Here you can find three exemplary Persona's that were used.

Thijs

Orthopedic surgeon since 25 years

Thijs sees the OR as a communicative environment, with an interplay of sounds from equipment and colleagues. In general, he has a very high affinity to sounds: "I am open to sound: what it means, what it provokes, what I produce."

ligament surgery | *arthroscopic surgery (knee, shoulder)* | *trauma surgery*

personal OR-sound experience

"So [...] I don't have to look at the machine to see how many rotations per minute it has [...] it also gives me feedback on what tissue it's cutting."

"It's more the annoying [nature of the sound], it's not the loudness, but the type of noise that it makes."

- *He is a very experienced sound user. Auditory feedback of equipment gives him a lot of information about the surgery.*
- *Sound can be disturbing and distracting. It can have an influence on the work performance, by blocking communication or because unnecessary sounds occur that need a reaction (e.g. telephone).*

personal auditory health beliefs

"Well, the point is, at this moment, I've never worn and I probably don't dare to wear anything to hear less."

"We are all aware now that certain sounds [...] can be disturbing for certain people."

"I think ultimately, if I feel better, communicate better...I think the surgery has a better outcome."

- *The need for good hearing conditions (of soft sounds) would outweigh possible health consequences.*
- *Low perceived susceptibility to hearing impairment with his kind of surgery, but other surgeries are perceived as more "dangerous" for hearing (e.g. hip/knee).*
- *High influence of sound on emotional and mental well-being.*

auditory wishes and needs

"This is our working environment, but this is also an environment, where the optimum support is important, because the outcome is so important."

"My dream for sound: I see a mixing panel that you have for a DJ, which is adding sounds or is taking things away. [...] Why don't we make that, but then for all the systems?"

- *Wish for optimum sound conditions that support the surgical procedure to be more effective and safe.*
- *Need for situational awareness.*
- *Need for unrestrained communication.*
- *Need of autonomy: Desire of customized sound individualization taking into account personal and team preferences.*

"Because feeling uncomfortable can be the difference between -putting it bluntly- saving a life or maybe not."

Lars

Orthopedic resident since 2 years

Lars sees the OR as chaotic sound environment with "a lot of background noise from ventilation and a lot of different beeps in different rhythms."

all kinds of orthopedic surgeries

personal OR-sound experience

"I like the sound of the drill and also, when you use it, that you can use the sound."

"But the oscillating saw we use "ahhh" that makes such an irritating noise. It's very loud, it's high pitched. I really don't like it."

"But if it sometimes ticks and is sometimes not thinking, then that really distracts me."

- *There are some tools that provide him with useful auditory feedback, while there are other sounds, e.g. the saw, which are just really unpleasant.*
- *Lars perceives the OR mainly as chaotic because there is a lot of background noise that makes irregular sounds. If they would be regular, then at least he could get more used to them.*

personal auditory health beliefs

"I think, like the saw is a bit above what still is pleasant for your ears and also the metal of the mallet [...] but it's not...It's not that...we don't use it for hours in a row."

"When you use a helmet with the ventilator in it, [...] a lot of times you are like "huh, what, huh what did you say" and you reeeeaaaally have to concentrate [...] really adds up to getting tired by...just because you have to concentrate on what is said."

- *In general Lars has a feeling for the loudness of sounds, as he used to play in a band. But because in the OR, especially the loud one's do only account for short durations during surgery they seem not so worrisome.*
- *A sound that is constantly distracting is the ventilator in helmets. It reduces his ability to communicate with his team. This influences his fatigue over the day.*

auditory wishes and needs

Well, [...] the person who is sitting behind the machine has to hear it of course, but it is not relevant for me, so...I wouldn't mind if those kind of sounds are, well if they are not there for me."

"No, but I also, what I think, the equipment we use is pretty decent. And so I guess...well, I know, I don't have any other reference for that."

- *Lars would really like to get rid of all the background noise that are not useful for him. These sounds may come from ventilators or the suction device.*
- *He also wishes that sounds that are only relevant for certain people in the room would be directed to the person who needs to hear it (e.g. beeps from anesthesiologist's equipment).*

"The equipment we use now is mainly focused on performance [...] and not on secondary aspects."

Eva

OR-nurse since almost 10 years

For Eva the OR is an environment, with many sound sensations: "For me it is very different, sometimes calm, sometimes chaotic, but always lively. She has good ears, but they are not too sensitive, just to really loud sounds.

orthopedic surgery | *trauma surgery* | *plastic surgery*

personal OR-sound experience

"And then I like to listen to music and not to people talking. Not too loud but just like background music."

"It feels like the sounds, they are just there. They are also necessary and useful."

"So you can listen to the sound of the drill, okay, they are there.[...] I know, that I need to give them the thing to measure."

- *Eva likes having sounds around her. She prefers sound around her rather than silence. But sound is also unpleasant, e.g. the saw or hearing people cursing.*
- *While "listening-in-readiness", waiting for the surgeons' voice or sounds of tools, sounds help her to anticipate further steps in the surgical procedure.*

personal auditory health beliefs

"Maybe before, I made the workbook, I was not aware of sounds. It was just there. Yeah and I was also talking to some colleagues and a few of them they were aware, but others they were also not aware."

"And then the earplugs. [...] Yeah, so I thought, maybe this is something. Because, sometimes, with like the hammer or the drill, it is really loud."

- *Eva is still young and has good ears. Until now she has never thought about taking action in the OR against sounds. She also thinks that even if she would be bothered, she would not know where to go.*
- *But at the same time, she is not averse against earplugs for example, as long as she would still hear what people are saying.*

auditory wishes and needs

"And of course I was thinking about it later, if I could choose, there was like no suction sound or no sound of the warm air, the blower, like all this sounds, they weren't like not there. But yeah, there are there."

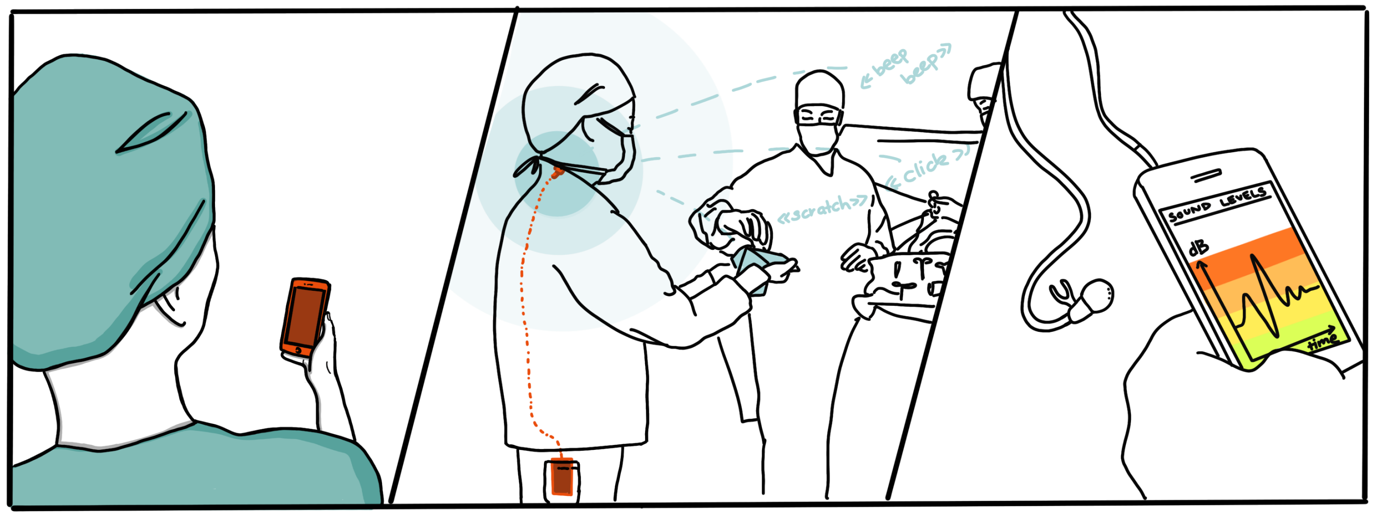
- *Having a harmonic environment with not too many sounds happening at the same time would be ideal for her. But she does not really have the feeling that the sound situation could be changed.*

"It's funny because the sounds, they are just there. You don't think about it. They have to be there or something."

F Sound measurement application

Creating an app to measure sound exposure of individual staff members in the OR arrived out of necessity (Covid19 lock-down). The app, together with a microphone serve as a decibel meter. The features of the app are explained in the following. The app was developed together with Deanne Spek, a member of the Critical Alarms Lab.

The app in practice



Before the surgery

The app is easy to use for the medical staff themselves. It allows the user to enter their details. Then the microphone is attached to the collar, while the phone is stored in a back pocket. The recording is started by the user at the beginning of the surgery.

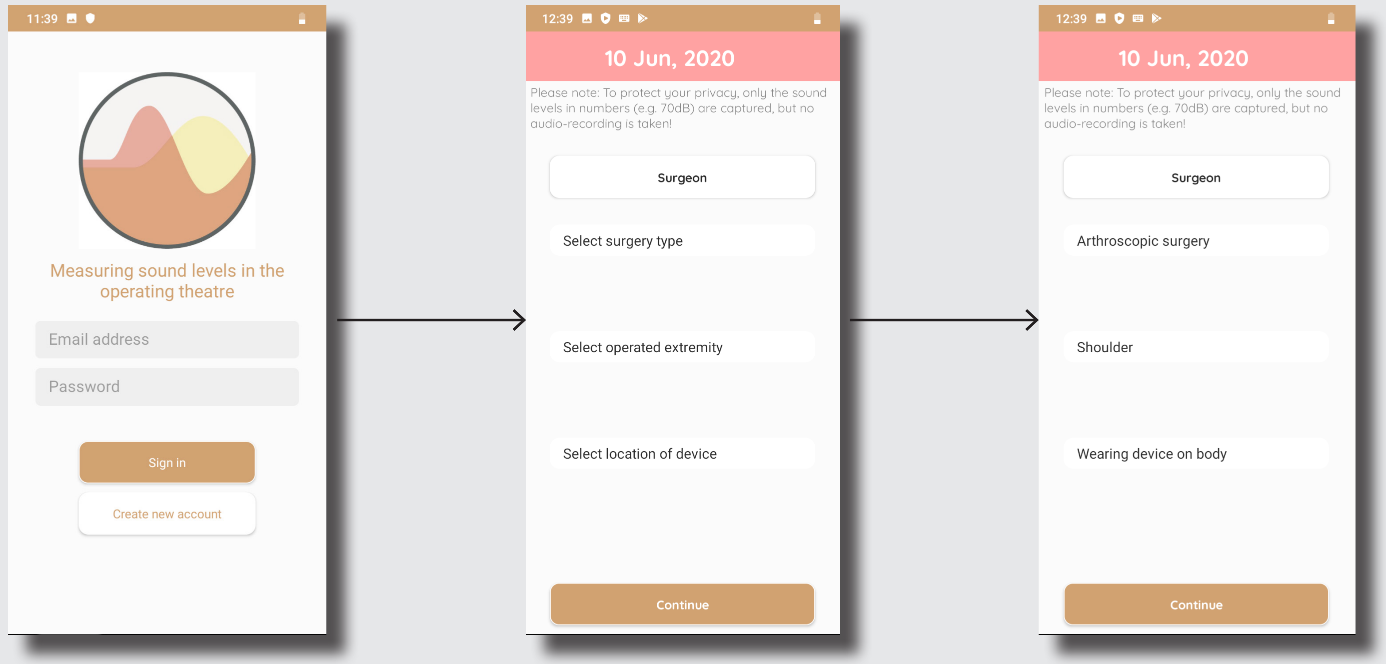
During the surgery

The app collects different decibel values (average levels and maximum peak levels in dB) that are used to assess the general noisiness as well as to identify peak periods of the procedural steps. To further understand which specific sounds pose the highest risks, it is possible to describe sound events directly in the app by selecting pre-set options or by describing a sound event manually.

After the surgery

The app gives direct feedback on sound exposure during the specific procedure to the medical staff after they end the measuring. When multiple people use the app and microphone during one procedure, it allows to compare the collected data on sound exposure (mean and peak values) at the same time among the different professions. From the data it is possible to identify risk periods, or to give feedback to the staff, whether or not the sound exposure is too high.

Before the surgery

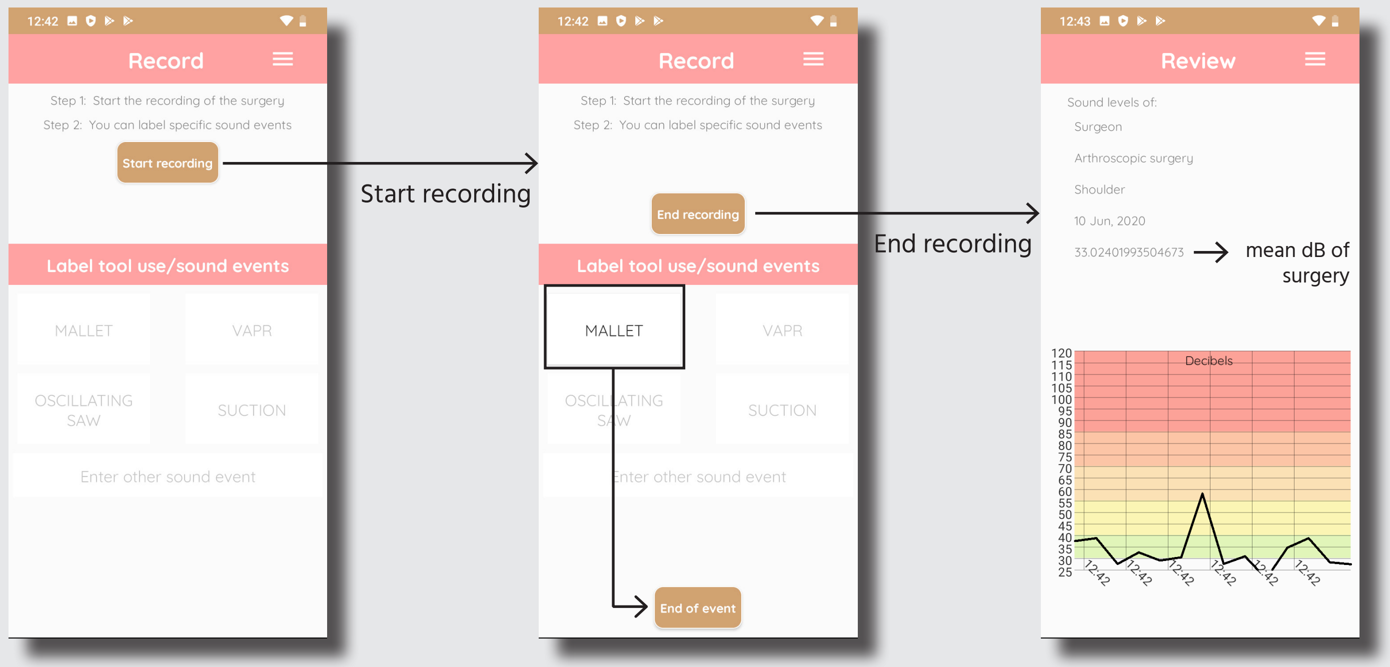


Sign up or create a new account to assure that data collection is assignable.

Enter important background information for consecutive decibel recordings.

During the surgery

After the surgery



After recording is started the device collects dB-values every second, but no sound recordings (privacy issues).

Label individual sound events either through pre-selected options or by "entering other sound event". Start and end the event to indicate the duration.

See the results of the decibel recordings immediately, also indicating the prior selected characteristics (e.g. surgery type).

G Concept cards

The concept cards were developed after the user research was completed. Initially, I brainstormed with three themes: Auditory health awareness, facilitation and framework setting, and auditory health promotion.

Auditory health awareness

It describes a person's ability to perceive and make sense of what's going on around them with regard to sound. This also includes knowledge on sound, for example the ability to draw conclusions how sound impacts and relates to individuals' personal health status.

1

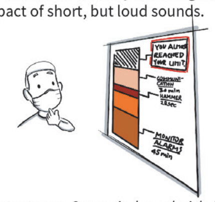
AUDITORY HEALTH AWARENESS
SOUND EXPOSURE

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: Medical staff often underestimates the potential harmfulness of loud sounds, because of the relatively short duration of those sounds (e.g. hammer, oscillating saw). Underestimating sounds can lead to risky health behaviors.

Question to reflect on:
How to empower medical staff to see the relationship between sound levels and exposure time in the OR?

Goal: Conveyed relationship between sound exposure time to its loudness. Thereby initiate greater awareness for the impact of short, but loud sounds.



Possible strategy: *Scenario-based risk information* in order to motivate and initiate precaution uptake.

2

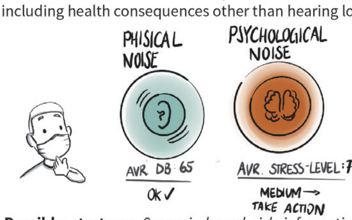
AUDITORY HEALTH AWARENESS
UNEXPECTED HEALTH IMPACTS

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: While hearing loss is a health impact that medical staff easily relate to loud sound exposure, other health consequences, such as fatigue, stress are not directly perceived to be caused by auditory experiences. Therefore, gaining knowledge on other health risks may also motivate greater will towards health protection.

Question to reflect on:
How to encourage medical staff to avoid risky auditory health behaviors?

Goal: Established awareness for potential health hazards, including health consequences other than hearing loss.



Possible strategy: *Scenario-based risk information* in order to convey the criticality of sound exposure.

3

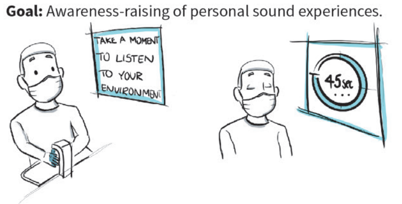
AUDITORY HEALTH AWARENESS
SOUND MINDFULNESS

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE INSTITUTION**

Context: Medical staff is often not actively aware of their personal, daily OR sound experiences. One reason is that medical staff is often under time-pressure. By allowing them to briefly pause and focus on their sound surroundings, they may more actively experience it afterwards.

Question to reflect on:
How to encourage medical staff to be more conscious about their personal sound experiences?

Goal: Awareness-raising of personal sound experiences.



Possible strategy: *Direct experience* of personal sound experiences to initiate sound-related awareness.

4

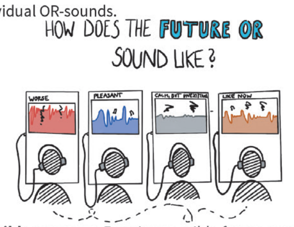
AUDITORY HEALTH AWARENESS
NON-SCRUTINY

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: The OR inhabits many sound sources, e.g. tools, communication, ventilation. Medical staff often perceives those sounds as given and unchangeable. By accepting the sound situation as it is, they also do not try to inform the healthcare institutions about sound related needs.

Question to reflect on:
How to encourage medical staff to expand their sound-related criticality?

Goal: Individual critical reflection of the necessity of individual OR-sounds.



Possible strategy: *Framing* possible future sound experiences in the OR and targeting individual motivations to take action.

5

AUDITORY HEALTH AWARENESS
HABITUAL NOISE EXPOSURE

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: Medical staff often underestimates the potential harmfulness of loud sounds on themselves. As they are used to the sounds in the OR since many years, they aren't alarmed by the already existing sound situation.

Question to reflect on:
How to empower medical staff to critically reflect on their personal auditory health habits?

Goal: Establish a method to convey the individual sound exposure times and the interlinking health impacts.

Possible strategy: *Personalize risk* in order to make people aware of their own vulnerability.

6

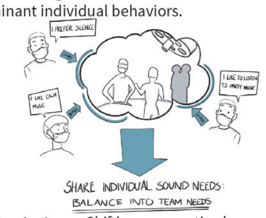
AUDITORY HEALTH AWARENESS
SOUND ATMOSPHERE

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **OPERATING THEATRE TEAM**

Context: Medical staff's individual sound preferences (e.g. listening to music) often differs. Some team-members may not be confident enough to share their personal preferences and dislikes with the team. In addition, they also not always know the team prior to the surgery.

Question to reflect on:
How to encourage medical staff to show consideration for other people's needs?

Goal: Encouragement of a team behavior instead of predominant individual behaviors.



Possible strategy: *Shifting perspective* by encouraging people to empathize with team-members needs.

7

AUDITORY HEALTH AWARENESS
PRECAUTION POSSIBILITIES

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: Medical staff often does not consider wearing additional protective equipment. They are afraid that it would interfere with their professional work. Moreover, they are not aware of all the options they would have.

Question to reflect on:
How to encourage people to search for suitable, individual precaution possibilities?

Goal: Provision of appropriate protective equipment.

Possible strategy: *Facilitation of options* to make precautionary action easier to be accomplished.

8

AUDITORY HEALTH AWARENESS
SOUND TRAINING

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **OPERATING THEATRE TEAM**

Context: Medical staff may sometimes not be aware how important auditory feedback is for their work proficiency. Some medical staff members are however sensitized to the topic and could act as educators for sound use.

Question to reflect on:
How to encourage medical staff to benefit from each others' sound-related knowledge and experiences?

Goal: Mutual assistance for sound-related work proficiency to enhance appreciation of hearing.

Possible strategy: *Mobilizing social support* and *use of peer education* to initiate mutual assistance in sound-related matters.

9

AUDITORY HEALTH AWARENESS
SELF-REFLECTION

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: Even if people have an understanding of decibel levels, they still underestimate the potential effects of sound on their personal health. Sound as a "hazard" is hard to grasp, as health impacts are often indeterminate, e.g. fatigue also arrives from other environmental factors.

Question to reflect on:
How to encourage medical staff individuals to improve their auditory health behaviors?

Goal: Direct, individualized feedback of possible health effects incorporating personal characterisitics.

Possible strategy: *Personalize risk* in order to make people aware of their own vulnerability.

10

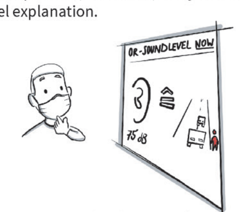
AUDITORY HEALTH AWARENESS
SOUND UNIT

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: Currently sound is mainly displayed through decibel levels. However, most participants are unfamiliar with this unit and cannot relate to it. It causes medical staff not to be alarmed about measured results in the OR.

Question to reflect on:
How to give medical staff an understanding of the current sound levels in the OR?

Goal: A comparative, relatable, easy understandable sound level explanation.



Possible strategy: *Using imagery* (e.g. analogies) in order to make medical staff more familiar with decibel levels.

Facilitation & framework setting

It describes the presence or absence of sound improving measures in place, assuring medical staffs' health in the OR in relation to sound.

11

AUDITORY HEALTH FACILITATION

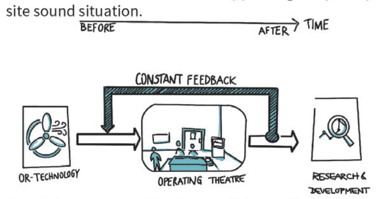
CONTINUOUS NOISE

TARGET LEVEL: **HEALTHCARE INSITUTION**
INITIATING LEVEL: **OPERATING THEATRE TEAM**

Context: There is equipment that adds up to the noisiness of the OR. Those continuous sounds are perceived by the medical staff as tiring, because they make hearing and communicating more difficult. A widely mentioned example of continous sound is the ventilation system in the OR.

Question to reflect on:
How to encourage medical hospital institutions to optimize their OR with regard to sound properties?

Goal: An OR-environment that support a good prerequisite sound situation.



Possible strategy: *Forming coalitions* with healthcare architects in order to initiate joint action to reach the aim of improved auditory health conditions.

12

AUDITORY HEALTH FACILITATION

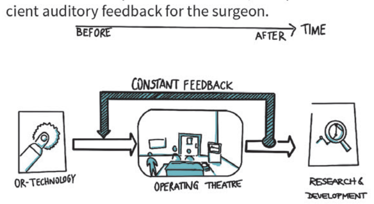
DISRUPTIVE NOISE

TARGET LEVEL: **HEALTHCARE COMMUNITY**
INITIATING LEVEL: **OPERATING THEATRE TEAM**

Context: There are devices in the OR that create a distracting sound experience for the medical staff. Disruptive sounds are perceived as strenuous and also distracting. E.g. a widely mentioned example are saws, e.g. the oscillating saw.

Question to reflect on:
How to encourage medical device producers to optimize their products on sound properties?

Goal: Tools that produce less noise, but provide sufficient auditory feedback for the surgeon.



Possible strategy: *Collaborative learning* by establishing a feedback-loop system to initate product optimization.

13

AUDITORY HEALTH FACILITATION

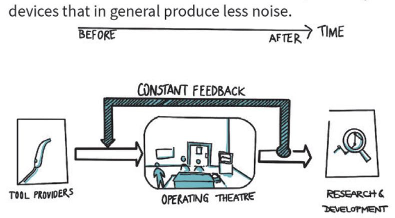
IRREGULAR NOISE

TARGET LEVEL: **HEALTHCARE COMMUNITY**
INITIATING LEVEL: **OPERATING THEATRE TEAM**

Context: There are devices in the OR that create an unpleasant sound experience for the medical staff. Irregular sounds are perceived as annoying and distracting. E.g. a widely mentioned example is the suction device.

Question to reflect on:
How to encourage medical device producers to optimize their products on sound properties?

Goal: Devices that can either be turned on/off easily or devices that in general produce less noise.



Possible strategy: *Collaborative learning* by establishing a feedback-loop system to initate product optimization.

14

AUDITORY HEALTH FACILITATION

PEOPLE IN THE ROOM

TARGET LEVEL: **OPERATING THEATRE TEAM**
INITIATING LEVEL: **HEALTHCARE INSTITUTION**

Context: Especially in university hospitals it is common to have a large number of people in the OR. The more people are in the OR, the more sounds are produced. Therefore, the number of people being in the OR should be critically reflected upon.

Question to reflect on:
How to encourage OR-management to critically reflect the number of people necessary in the OR?

Goal: Critical reflection on methods to reduce personal presence in the OR while assuring proper education.

Possible strategy: *System changes* that initiate adaption of OR-protocols in order to reduce avoidable sounds.

15

AUDITORY HEALTH FACILITATION

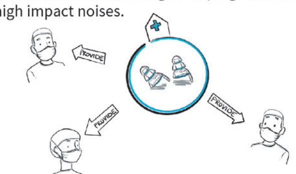
PURCHASE OF PROTECTIVE EQUIPMENT

TARGET LEVEL: **INDIVIUAL**
INITIATING LEVEL: **HEALTHCARE INSTITUTION/INDIVIDUAL**

Context: Earplugs should be provided by the healthcare institution as part of occupational safety and should not be, as to current state often be the responsibility of the individual staff member. However, in case hospitals do or did provide customized earplugs it is not unusual for medical staff to not wear them.

Question to reflect on:
How to encourage medical staff to provide hearing protection while at the same time motivating individuals to wear them regularly?

Goal: Provision and wearing of earplugs if necessary due to high impact noises.



Possible strategy: *Facilitation of protective equipment* in order to reduce the barrier of self-initiative. Individual precautionary action is easier to be accomplished.

16

AUDITORY HEALTH FACILITATION

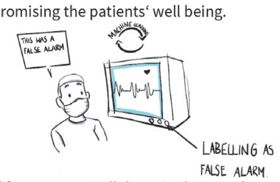
ALARM FATIGUE

TARGET LEVEL: **INDIVIDUAL LEVEL**
INITIATING LEVEL: **HEALTHCARE INSTITUTION**

Context: Current anesthesiology equipment produces many signals and alarms that are later on identified as non-actionable alarms. These alarms causes medical staff to get annoyed, to cause distraction and to lower their threshold to act on alarms (alarm fatigue). It also impedes with communication between the OR-teams. It does not only cause health impacts for medical staff, but it can also endanger the patients' well-being.

Question to reflect on:
How to technically distinguish between relevant and fake alarms?

Goal: Reduce number of non-actionable alarms without compromising the patients' well being.



Possible strategy: *Collaborative learning* by establishing a feedback-loop system to initate product optimization.

17

AUDITORY HEALTH FACILITATION

SOUND NEEDS CONTACT POINT

TARGET LEVEL: **INDIVIDUAL LEVEL**
INITIATING LEVEL: **HEALTHCARE INSTITUTION**

Context: In case medical staff has sound-related needs, they are often unsure who to contact in their healthcare institution. This is especially true for younger employees. Another concern is that they do not feel as if they have a saying in the soundscape of the OR.

Question to reflect on:
How can we encourage medical staff to share their sound-related needs with their employer?

Goal: Active employees that share their concerns in order to achieve improvement.

Possible strategy: *Mobilizing social support* to initiate application and self-initiated auditory health behaviour improvement.

18

AUDITORY HEALTH FACILITATION

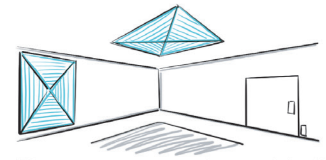
SOUND ABSORPTION

TARGET LEVEL: **OPERATING THEATRE TEAM**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: Tools such as oscillating saws produce high impact noises. Due to hygiene regulations surfaces in operating theatres are often hard and dull, leading to long reverbration times and high noise-levels. This effect has an impact on medical staffs' work performance (e.g. disturbed communication) and auditory health risks.

Question to reflect on:
How to architecturally and technically avoid sound echo's from high impact tools?

Goal: Delvelopment, purchase and use of sound absorbers that meet hygiene and sterilization protocols.



Possible strategy: *Forming coalitions* with healthcare architects in order to initiate joint action to reach the aim of improved auditory health conditions.

19

AUDITORY HEALTH FACILITATION

SPEECH CLARILITY

TARGET LEVEL: **OPERATING THEATRE TEAM**
INITIATING LEVEL: **HEALHTHCARE INSTITUTION**

Context: It is crucial for the team to be able to hear one and other during the surgical procedure. But due to covered mouths and/or sometimes ears, speech clarity and supportive lip reading is affected for the operating team.

Question to reflect on:
How to direct the communication from the source to the desired receiver?

Goal: Improved communication ability through improved innovative protective equipment.

Possible strategy: *Forming coalitions with protective equipment producers* in order to initiate joint action to reach the aim of improved auditory health conditions.

20

AUDITORY HEALTH FACILITATION

TELEPHONES/CELLPHONES

TARGET LEVEL: **OPERATING THEATRE TEAM**
INITIATING LEVEL: **OPERATING THEATRE TEAM**

Context: There are sound situations in the OR that require attention of the medical staff , even though they might not be connected to the surgical procedure. It is not uncommon that telephones ring or doors are opened during a surgical procedure. These sounds require medical staff to shift their attention from the patient to something else and are perceived as distracting.

Question to reflect on:
How can medical staff and the hospital institution be encouraged to avoid surgery-irrelevant sounds?

Goal: Decreased number of surgery-irrelevant sounds.

Possible strategy: *System changes* that initiate adaption of OR-protocols in order to reduce avoidable sounds.

21

AUDITORY HEALTH FACILITATION

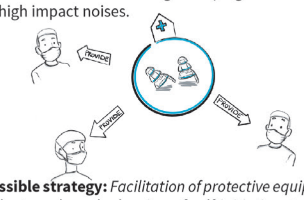
PURCHASE OF PROTECTIVE EQUIPMENT

TARGET LEVEL: **INDIVIUAL**
INITIATING LEVEL: **HEALTHCARE INSTITUTION/INDIVIDUAL**

Context: Earplugs should be provided by the healthcare institution as part of occupational safety and should not be, as to current state often be the responsibility of the individual staff member. However, in case hospitals do or did provide customized earplugs it is not unusual for medical staff to not wear them.

Question to reflect on:
How to encourage medical staff to provide hearing protection while at the same time motivating individuals to wear them regularly?

Goal: Provision and wearing of earplugs if necessary due to high impact noises.



Possible strategy: *Facilitation of protective equipment* in order to reduce the barrier of self-initiative. Individual precautionary action is easier to be accomplished.

Auditory health promotion

It describes the presence or absence of measures in place to keep medical staffs health in relation to sound in place.

22

AUDITORY HEALTH PROMOTION

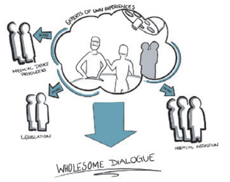
WHOLESOME DIALOGUE

TARGET LEVEL: **HEALTHCARE COMMUNITY**
INITIATING LEVEL: **INDIVIDUAL**

Context: There are individuals in the orthopedic health-care sector that have devoted their research on sound effects. However, they are not sufficiently heard or represented by the healthcare community in order to reach the entire community of medical staff.

Question to reflect on:
How can we empower individuals in the healthcare to community to spread their message even more?

Goal: Active participation in hearing education by medical staff.



Possible strategy: *Use of lay health workers* by educating individuals to become promoters of auditory health within the healthcare community.

23

AUDITORY HEALTH PROMOTION

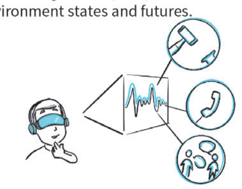
AURALIZATION

TARGET LEVEL: **POLICY**
INITIATING LEVEL: **HEALTHCARE COMMUNITY**

Context: "Auralization" is described as the technology that enables you listen to a room before it's built. Legislations are currently not appropriate to surgical context. This is also reasoned by the fact, that policy makers are not necessarily personally engaged in the OR.

Question to reflect on:
How to give policy makers an understanding of current and future OR-soundscapes?

Goal: Enlightened policy makers with regard to sound environment states and futures.



Possible strategy: *Forming coalitions* in order to initiate joint action to reach the aim of improved auditory health conditions.

24

AUDITORY HEALTH PROMOTION

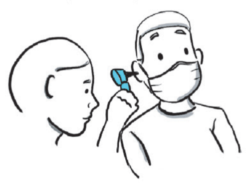
REGULAR HEARING TESTS'

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **POLICY**

Context: Even though noise has been recognized as a societal health hazard, it is not yet in occupational health for medical staff in the OR. In order to accomondate healthier auditory behaviors regular hearing test could help to encourage medical staff for long-term caution.

Question to reflect on:
How to encourage policy makers to take responsibility for medicals' staff auditory health?

Goal: Regular hearing test that initiate long-term auditory caution and potential precation.



Possible strategy: *Consciousness raising* by confronting individuals with the possible vulnerability of their own auditory health.

25

AUDITORY HEALTH PROMOTION

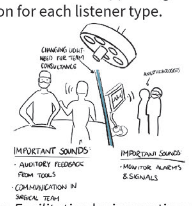
SOUND DIVISION

TARGET LEVEL: **OPERATING THEATRE TEAM**
INITIATING LEVEL: **HEALTHCARE INSTITUTION**

Context: Various OR-teams work side by side during one surgery, e.g. the anesthesia team and the surgical team. Both teams produce sounds that are not necessarily helpful for the opponent team. Those sounds are most of the time perceived as distracting background noise.

Question to reflect on:
How to direct the sound from the source to the desired receiver?

Goal: An OR-environment that support a good prerequisite sound situation for each listener type.



Possible strategy: *Facilitation* by innovating and establishing a sound improving system in the OR.

26

AUDITORY HEALTH PROMOTION

HABIT OF PRECAUTION

TARGET LEVEL: **INDIVIDUAL**
INITIATING LEVEL: **POLICY**

Context: Man is a creature of habit. When someone has been working without hearing protection for a long period of time, it is much more difficult to change his/her attitude towards hearing protection. Therefore, initiating safety sound training already early into the medical career could built up a new precautionary habit.

Question to reflect on:
How to encourage the healthcare community to train medical staff in hearing precautionary practice?

Goal: Occupational safety training early into medical school.

Possible strategy: *Early counterconditioning* to encourage and initiate the learning and habituation of healthy auditory behaviors.

H Root-cause analysis

The root-cause analysis method aims to identify underlying problems within a situation. In this project, the problem on the surface is that the sound situation inhabits health issues. But it is not directly obvious why this problem exists. Asking the question "why" several times showed that instead of treating symptoms of the problem, the final approach should focus on solving the main underlying problem: a lack of awareness.

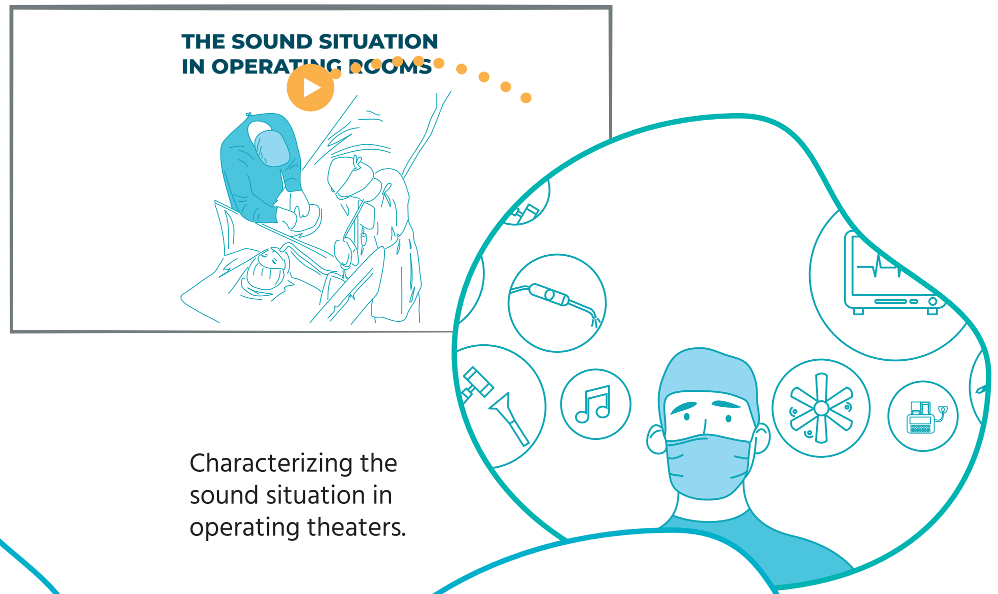
The problem:
Medical staff in the operating theatre soundscape is at risk for auditory health consequences.

INDIVIDUAL LEVEL	OPERATING THEATRE LEVEL	HEALTHCARE INSTITUTION LEVEL	HEALTHCARE COMMUNITY LEVEL (E.G. MEDICAL DEVICE PRODUCERS)	PUBLIC POLICY LEVEL
Why?	Why?	Why?	Why?	Why?
Medical staff's ears are often exposed to too much sound.	Medical staff's ears are often exposed to too much sound.	Some medical staff suffers from sound-induced health consequences.	Sound in the OR is not a priority in the healthcare community.	Surgical procedures treating the patient produce too much sound.
Why?	Why?	Why?	Why?	Why?
Medical staff's ears are not sufficiently protected against sound.	Medical staff is used to the current sound levels within the OR.	Medical staff is exposed to too much sounds in the OR.	Sound is a secondary aspect accompanied by products.	Optimal treatment of the patient is the focus of public policies.
Why?	Why?	Why?	Why?	Why?
Medical staff does not perceive it necessary to protect their ears against sound.	Medical staff is not aware for the sound levels they produce they are responsible for.	Health institutions are not investing sufficiently in sound reducing measures concerning the OR.	Application ergonomics with respect to the patient treatments are prioritized.	Occupational safety legislation lack OR specific adjustments.
Why?	Why?	Why?	Why?	Why?
Medical staff is not sensitized for auditory health risks accompanied with sound exposure.	Medical staff does not see any need to adjust their behaviors in order to reduce sounds.	Healthcare institutions are not prioritizing sound improvement measures in the OR.	Overall sound exposure to medical staff is not payed attention to.	There is not sufficient research about the health consequences for medical staff.
Why?	Why?	Why?	Why?	Why?
Medical staff is not aware of auditory health risks accompanied with sound exposure.	**Medical staff is not aware of auditory health risks accompanied with sound exposure.**	**Healthcare institutions are not aware of the auditory health impacts accompanied with OR-sound exposure.**	**The healthcare community is not aware of the auditory health impacts produced by their products.**	**Public policy makers are not aware of the risks posed at medical staff.**

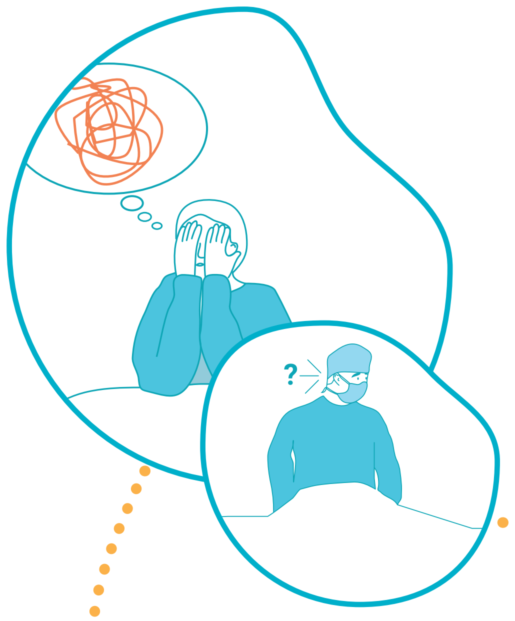
Lack of awareness on multiple levels.

I Animation

This page showcases the different elements that are presented within the animation - from introducing the soundscape, presenting possible health consequences of sound exposure, up to the call for action to the viewer.



Characterizing the sound situation in operating theaters.



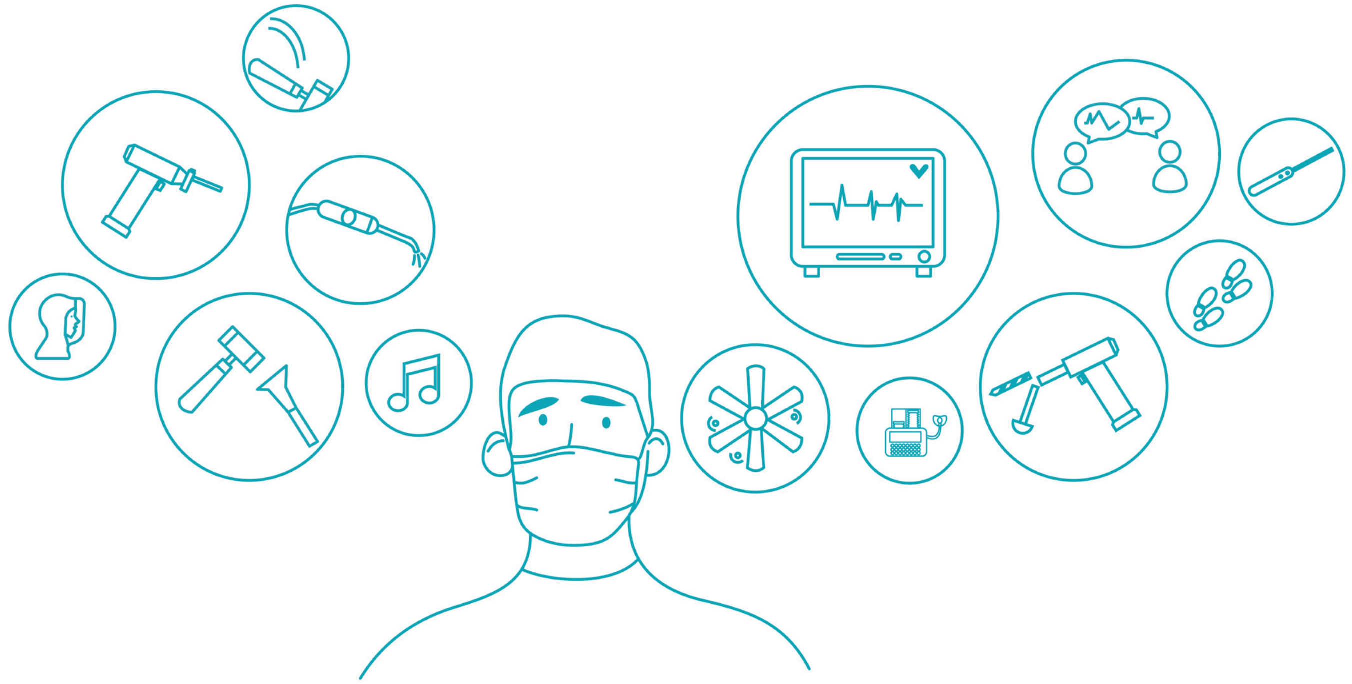
Showcasing possible health consequences of sound exposure.

Introducing the medical staff in the operating theater and their attitude towards sounds.

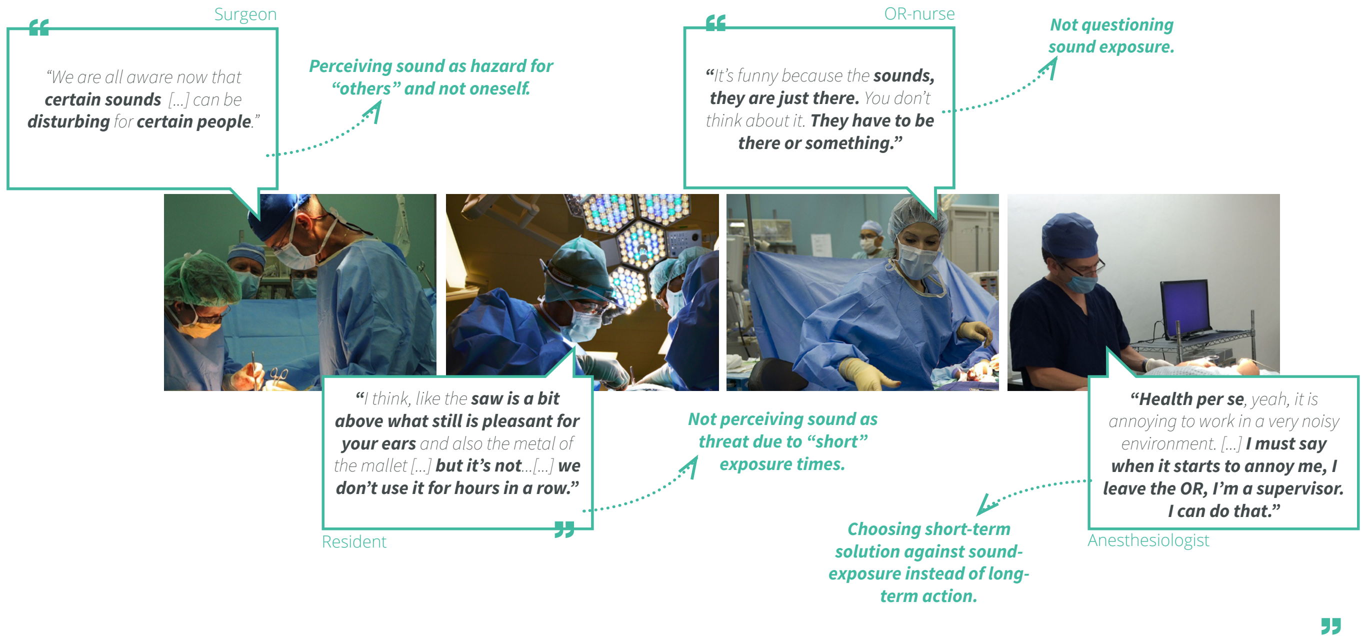
Calls the viewer to action, e.g. to increase the will to explore the website further.

J Additional figures and illustrations

Additional figures and illustrations, which I prepared in the process of the thesis, but were not included in the main body are shown here.

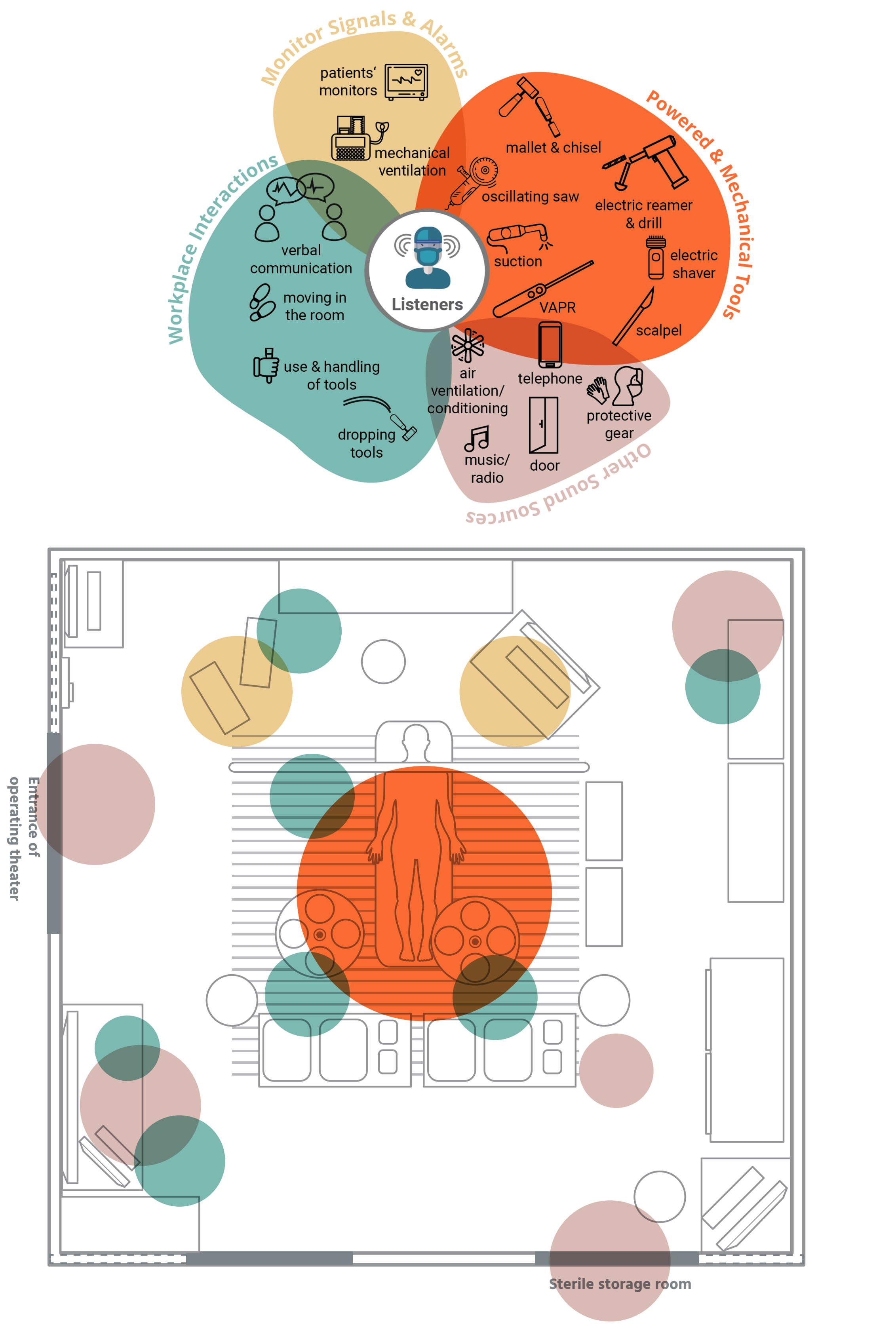


A medical staff member, being exposed to a multitude of sound sources throughout orthopedic surgeries.



Quotes of medical staff, including the researchers interpretation.

* Quotes origin from the user research in this project.
**The images of people shown are representations, not the actual participants. The images were retrieved from Pixabay (free & no attribution required).



Identified sound sources in orthopedic operating theaters and their distribution in the environment.

K References appendix

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