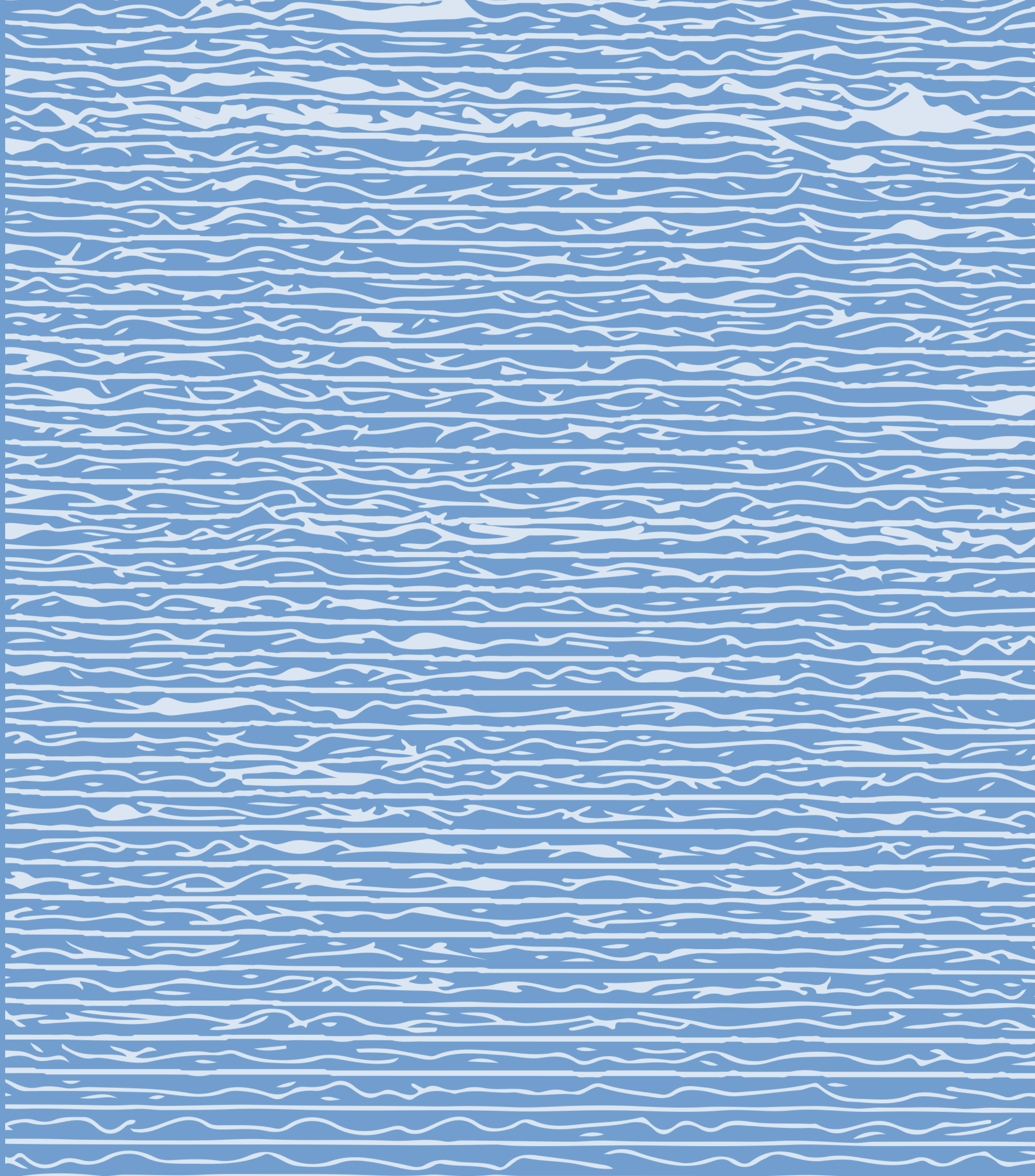
Les_Sons

Product Sound Sketching for Design Education



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Preface

Unlike our eyes, we cannot close our ears. As a result, it is difficult to ignore sound. Secondly, whenever sound is displayed in one room, it can be heard in another room. This means that sound is a sensitive issue and should be taken into account when designing a product. However, based on my personal experience with products and my experience in product design education, it seems that sound is rarely considered in product design.

In addition to my studies, I have always enjoyed making music, which perhaps makes me more aware or sensitive when it comes to sound. In the last few years I have also started to combine this interest in music and sound with design by designing new musical instruments. Before I started my thesis, I knew that I wanted it to include this combination of design and sound. So I started to include sound in some course projects and took electives in sound design, product acoustics, psychoacoustics and musicology. This led me to conclude that product designers can have a great influence on the sound of a product and that the knowledge to do so already exists. However, a clear translation into design implications is often lacking. Secondly, the methods and tools provided seemed more suited to music making than design.

Based on this, I came to the conclusion that it would be useful to develop an instrument, or rather a tool, that could be used by product designers to design product sounds. In doing so, I hope to introduce others to this field. Either to enable them to design good product sounds, or to start making them in order to contribute additional knowledge or tools to improve the current design process.

Acknowledgements

First of all I would like to thank my supervisors Elif Özcan, Dave Murray-Rust and Stefano Delle Monache for their interest and enthusiasm during this project. I cannot thank you enough for the discussions we had during the meetings. Having three supervisors sometimes felt a bit demanding, as it meant extra considerations and recommendations. However, it also allowed us to keep a broad overview of the possibilities with the thesis, reflecting the interdisciplinary field that sound is.

To all the experts, thank you for your enthusiasm and your professional insights. The interviews with you made me aware that methods and tools for product sound design are being developed, but are still in their infancy. They showed the need for good product sounds, what could be improved in this area and gave suggestions on how this could be done. This adds further substance to this thesis.

To all the participants in the user studies, your time and insights are greatly appreciated. The critical feedback improved the usability of the final design. And your enthusiasm showed that there is a general interest in learning how to incorporate sound into product design, if they are made aware of how.

Family and friends for their support or sharing personal experiences of products with poorly designed sound. But for providing good times when it was time to relax. And of course Paula, danke, thank you, for just being there and acting as a sounding board to test whether my thoughts and findings made sense to non-designers or experts in the field of sound design.

Abstract

Despite the fact that product sounds have been shown to have a significant impact on the experience of products, product sounds are rarely considered in design projects and design education at the Faculty of Industrial Design Engineering.

Research through literature review and expert interviews revealed that product sound design requires an interdisciplinary approach. A framework was created from different areas of product sound design. This framework separates that product sounds are influenced on three levels. The first is the product features, i.e. the components that act as a sound source. At this level, it is most important to consider how acoustic and engineering decisions can influence the perception of sound as derived from psychoacoustics.

The second level, the object level, is about factors that influence the composition of the product and is mostly based on knowledge from subfields of musicology. The third level, the scene level, considers the sound of the product together with its use and location. This makes it possible to assess whether the external influences still result in the desired sound.

Based on this framework, a digital audio design tool was developed. The purpose of this tool was to give practical examples of how sounds can be changed. This is achieved by providing parameters that have an impact on the engineering of a product, such as the choice of components and materials, and by allowing a composition of all the features to create the sound of the whole product.

Finally, external factors such as the user's interaction with the product and the influence of the context in which the product's sound is heard can also be modelled.

User testing has shown that this tool allows creative exploration of possible product sounds, while being concrete enough to gather initial design objectives. As an ideation tool, it provides direction for the further development of the product, taking into account its sound.

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1.Project introduction

This chapter introduces the goal, scope of the project, and what research was done and how it integrates with the design of a framework and audio tool. The initial project brief of the thesis is explained in the problem statement. In the scope a definition is given to explain for what type of sound, products, and for whom exactly it is designed. After that, the research questions that were found as relevant starting questions for this thesis are given. In the last section of this chapter the research and design activities are introduced and summarized in an overview.

1.1 Problem statement

When designing products, several qualities are taken into account to ensure good design. These qualities include aesthetics and ergonomics. Visual qualities such as shape and colour are likely to come to mind.

Sound can also have a big influence on the experience of products (Özcan et al., 2014). And since most products in the same category are made using the same production methods and materials, sound is one of the main factors that can differentiate brands (Keiper, 1997). In addition, well-designed product sounds can also be useful (Lemaitre & Suzini, 2019), for example to know if a product is working properly.

From my own experience with products and during my education at the Faculty of Industrial Design Engineering, sound is rarely considered in most product categories. The exception is a few product categories such as cars and motorcycles. In most other products, if sound is addressed, it is only to reduce sound intensity.

Furthermore, if a designer wants to learn more about product sounds and how to design them, the problem is that currently available sound design tools are difficult for product designers to understand. This is because these tools are aimed at sound designers, such as the Sound Design Tool (Baldan et al., 2016), and/or music producers, such as a digital audio workstation. As a result, using current tools requires an advanced understanding of concepts from acoustics or musicology.

1.2 Scope

Product Sounds
Throughout this thesis, "product sounds" will be a recurring concept, with the definition of product sound: "all the sounds that a product makes". As this thesis is part of my Masters in Integrated Product Design, the word "product" is defined as: "an industrially manufactured good designed by industrial engineers".

Consequential sounds
To further specify this description, most of the focus has been on the design of consequential sounds. These are sounds that result from the way a product works.

This is in contrast to intentional sounds, which are sounds that are intentionally added to a product. This decision was made deliberately because the two categories of sound are fundamentally different and their design could benefit from two different approaches. However, several products may contain both accidental and intentional sounds.

Intended user
The intended users of this thesis are Industrial Design Engineering (IDE) students. This was chosen because design students are still exploring the world of design. Presumably they are not focused on a specific design task, which makes them more open to new knowledge. And if knowledge about product sound design is taught during education, it is likely to end up in professional use.

As consequential sounds are likely to be addressed by industrial designers who have studied a similar discipline to the Master's degree in Integrated Product Design (IPD) at the IDE, an additional focus was placed on students who are, or are likely to be, studying the Master's degree in IPD.

Culture
Culture was identified as one of the factors that can influence the experience of sound. Since the intended users, students at the Faculty of Industrial Design in Delft and the author of this thesis, are Dutch, the reader is warned that some statements may only be true within the Dutch culture. However, there was no explicit focus on designing for this specific culture.

1.3 Initial research questions

After a preliminary literature research combined with other preliminary knowledge within the field of sound, the following research questions were ought to be relevant to be answered to come up with a solution that can be used to introduce students to product sound design.

1. What are product sounds?
    - 1a. Why are product sounds generated?
    - 1b. How are product sounds experienced?

2. How are product sounds considered in current design projects?
    - 2a. What process can be followed to design product sounds?
    - 2b. What tools can be used to intentionally design product sounds?

3. How to introduce students to product sound design?
    - 3a. What extra knowledge is required?
    - 3b. In which context can this extra knowledge be introduced?

4. How can this knowledge be gathered to provide a platform to introduce students to product sound design?

1.4 Overview of research and Design

In this thesis, a combination of research activities were used as input for design activities. This section explains the type of research studies conducted and how they influenced the design activities.

A literature review was carried out to collect various methods and activities suggested by researchers for good product sound design, in order to explore the relevant knowledge that a product designer needs to learn before designing product sounds.

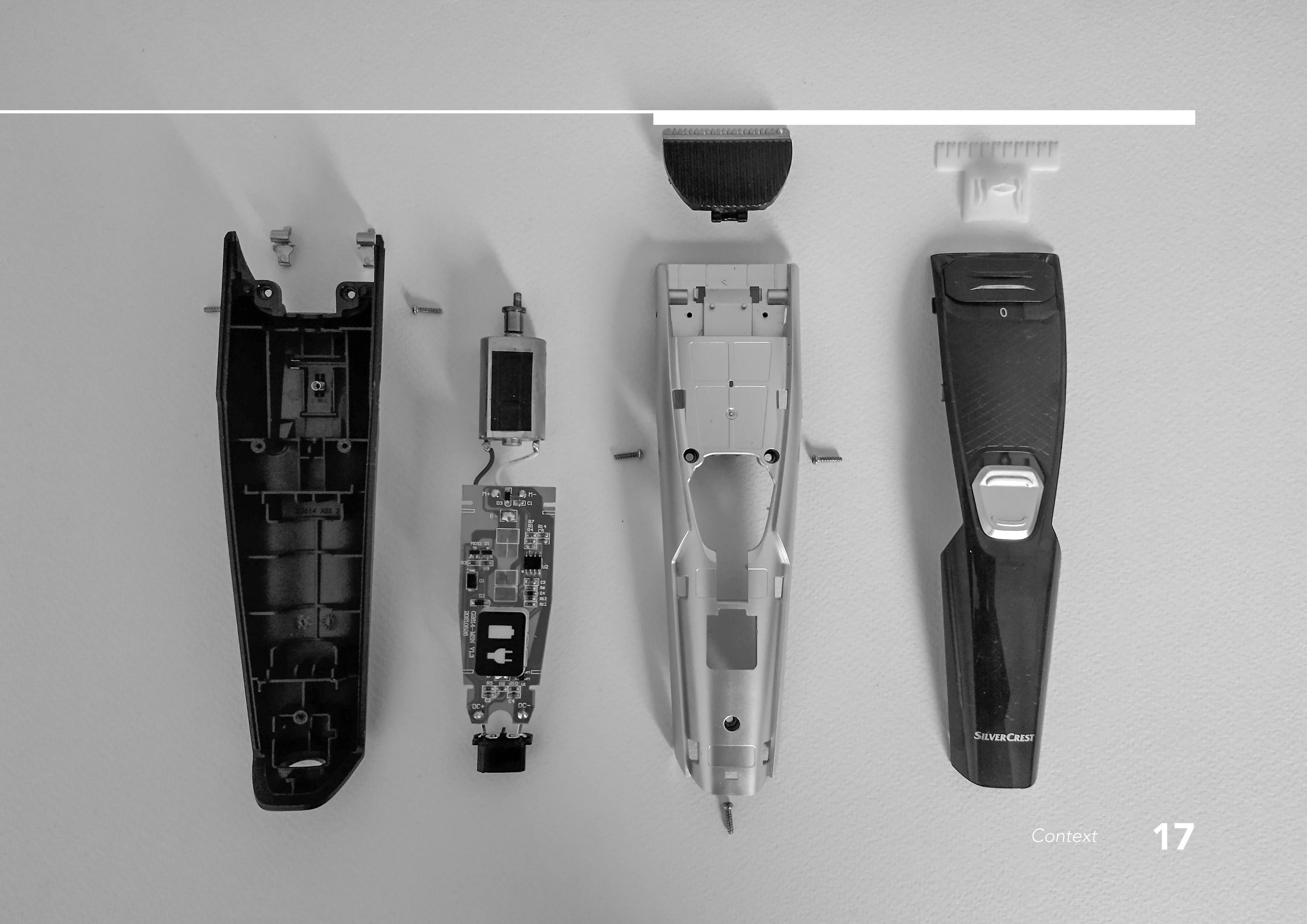
Experts in several relevant fields, including product sound design, sound design tool development and teaching acoustics, were consulted through semi-structured interviews. The purpose of these interviews was to verify whether the findings from the literature review were valid in a professional setting, and to generate additional insights.

This required knowledge was summarised in a framework which served as a basis for how to approach the design of product sounds. Feedback on this framework was gathered through user interviews with IDE students.

This framework was used in the design of a sound conceptualisation tool. A user research study was conducted to evaluate the effectiveness of the tool. The results were then implemented in a design iteration. This iteration was again evaluated through a user study to assess the usability of the tool in a team.

2.Context

In this chapter answers to the initial research questions are given. This was done by means of a literature study. The first section explores what product sounds are and how they emerge. The second and third section explore how sound can be included in a design process. The fourth section defines what general competences a designer requires to take sound into account in such a process. And at last, in the fifth section, an overview of specific tools that can be used in a product design process id given.


SilverCrest

2.1 Introduction to product sounds

Within product sounds two types of sounds can be differentiated, consequential- and intentional sounds.

Consequential sounds

Consequential sounds are sounds that are a consequence of the functioning of a product (Özcan & van Egmond, 2012). Often these sounds are produced by friction that occurs between moving objects (Flipsen, 2022). Due to this, consequential sounds are often experienced as noisy.

The quality of this sound can be influenced by changing product properties such as: geometry, material and replacing components or sub-assemblies. The difficulty for the designer in designing consequential sounds is finding a good solution with a limited set of properties, while keeping other requirements such as the functioning or cost of the product at the same level.

Intentional sounds

Intentional sounds are sounds that are intentionally added to the product. The foremost function of these types of sounds is to inform the user.

Examples are the alarm sounds on your phone or the beep of your microwave when food is ready. Intentional sounds are mostly produced by a speaker and as a result completely designable.

The product designer can take multiple musical concepts into account such as harmony and timbre to design a sound that fits the product in its environment. This results however in large creative freedom making it difficult to define one solution that fulfills all requirements (Langeveld et al., 2013).

How do products sounds originate?

Music instruments are an interesting example to look into why some products generate sound, since in a sense it is a product where one of its main functions is to produce sound (Nykänen, 2008).

Fletcher & Rossing, (1991) gave an overview of the physics of music instruments and in general it can be concluded that sound is the result of a vibration in the product. These vibrations are on itself the result of a physical interaction of spring like characteristics with inertia. In which the spring like characteristics result in a urge to restore to the initial position and inertia resulting in the force to overshoot for example due to its mass or by newly added energy to the system, shown in Figure 2.1.

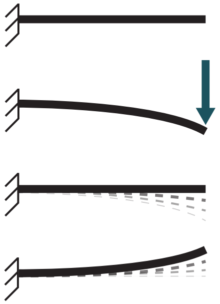


Figure 2.1: Graphical overview of the fundamentals of vibrations

The Product sound model

Langeveld et al. (2013) proposed the model for product sound. This model (Figure 2.2) explains how a source starts a vibration and states the routes these vibrations will follow through the product, essentially pointing out parts that can be engineered to change the

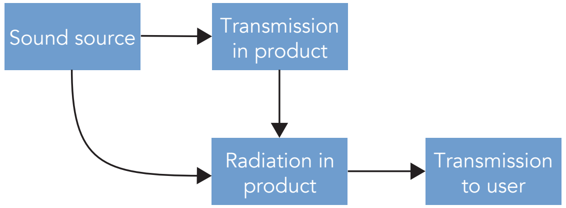


Figure 2.2: Model for product sounds (Langeveld et al., 2013)

acoustics qualities of the product. The source is a component in a product which brings the vibration into the product, like a motor. Multiple categories of sources exist and are given in Table 2.1.

When the source initiates a vibration, both surfaces can be excited, resulting in the radiation of air borne sound, and vibrations are transmitted inside materials, possibly exciting other features (Langeveld et al., 2013). According to Fletcher and & Rossing (1991) radiation is mostly significant for larger surfaces, explaining why the sound from guitar strings are clearly heard when its amplified by the body of the guitar, while hardly producing any sound when the string would be plucked in free air.

In the analogy of the guitar, transmission is significant in the connection between the string and the body. The amount of energy transmitted from the string to the body is dependent on the similarity of acoustic impedance between two materials. If the acoustic impedance is very similar almost all energy will be transmitted from the string through the body. If the difference in impedance is too large most energy will be reflected back into the string (Fletcher and & Rossing, 1991).

From this it can be assumed that radiation is mostly significant for the product's housing, while internal construction such as the connection of the source component to the housing is significant for the transmitted sound.

The radiated sound from the housing is eventually heard by the user (Langeveld, 2013). A part of the radiated sound of an object in a room is directly entering the ear of the user. But also properties of the room acoustics can influence the experienced sound. The walls of a room reflects parts of the radiated sound which might end up at the user as well. However, with a slight delay causing an echo like experience named reverberation (Dejonckere, 2001).

Table 2.1: Sound sources (Langeveld et al., 2013)

Sources	Primary excited medium	Type of excitation	Example
Air borne sounds	Air or another gas	Mechanical	Compressor Refrigerator
		Aero dynamical	Fan Turbulent flow
		Combustion	Exhaust gasses in the exhaust pipe Autogenous welding Gas burner
Liquid borne sound	Liquid	Mechanical	Plunger pump Gear pump
		Hydro dynamical	Turbulence in flow Cavitation
Structure borne sound	Construction	Mechanical	Inertia: unbalanced
		Aero dynamical	Collide: hammering, rolling, stamping, sawing Turbulence gas flow Air spray
		Hydro dynamical	Releasing of whirls Air jet on surface Water heating
		Electro mechanical	Pole attraction Magnetostriction in transformer

The design process

To understand how to integrate the sound of a product into the design of the product it is interesting to know what steps are taken in the completion of a design project. Most often a product is designed following a structured process. During Bachelor education at IDE already multiple design processes incorporating multiples processes are given (van Boeijen et al., 2013).

Pahl & Beitz (1986) described a general process consisting of four phases that can be used to describe most product design projects. The process consists of the following phases: 1. Problem analysis, 2. Conceptual design, 3. Embodiment design and 4. Detail design.

The book “Productontwerpen, structuur en methoden” (Roozenburg & Eekels, 2016) is used at the Faculty of Industrial Design Engineering to introduce students to design methodologies. This book clarifies the goals of each phase in Pahl & Beitz’ model as following;

1. Problem analysis.

In the problem analysis phase, the global goal of the design project is defined. Based on market and technological analysis, the product’s desired functions are put in relation to the market segment for which is designed.

The derived constraints are gathered in a program of requirements and wishes, which then could be transformed into product ideas. A product idea gives a vague representation of what the final product should be and is mostly concludes the analysis phase.

2. Conceptualisation design phase.

In the conceptualisation design phase product ideas are developed into product concepts. A product concept consists of a sketch or diagram that explains the main and subsidiary functions of the product. Next to that approximates of the cost, overall dimensions, and feasibility of producing the product are defined.

3. Embodiment design phase.

A select number of concepts are further refined in the embodiment design phase. For this the dimensions, materials and means of manufacturing are considered together. In the later phases, physical prototypes can be built to clarify the functioning, reliability, usability, aesthetics and producibility of the design. This phase concludes with a composition drawing including the established of the general dimensions and preliminary list of parts.

4. Detail design phase.

The last phase is the detail design phase. During detail design the exact product properties such as dimensions, tolerances and surface roughness are established in technical drawings. At the very end, requirements and manuals on manufacturing, assembly, transport, installation, use, etc. are defined and written.

2.2 The product sound design process

In regard to product sounds, multiple scholars already proposed design processes as well. Most of these methods also contain different design stages, like the general design cycle.

In Figure 2.3 these proposed sound design processes were put into context with the product design process as described by Özcan & van Egmond (2006). This, as their proposed sound design process follows the same phases as Pahl & Beitz' (1986) method, making the comparison of multiple product sound design processes to the product design process easier.

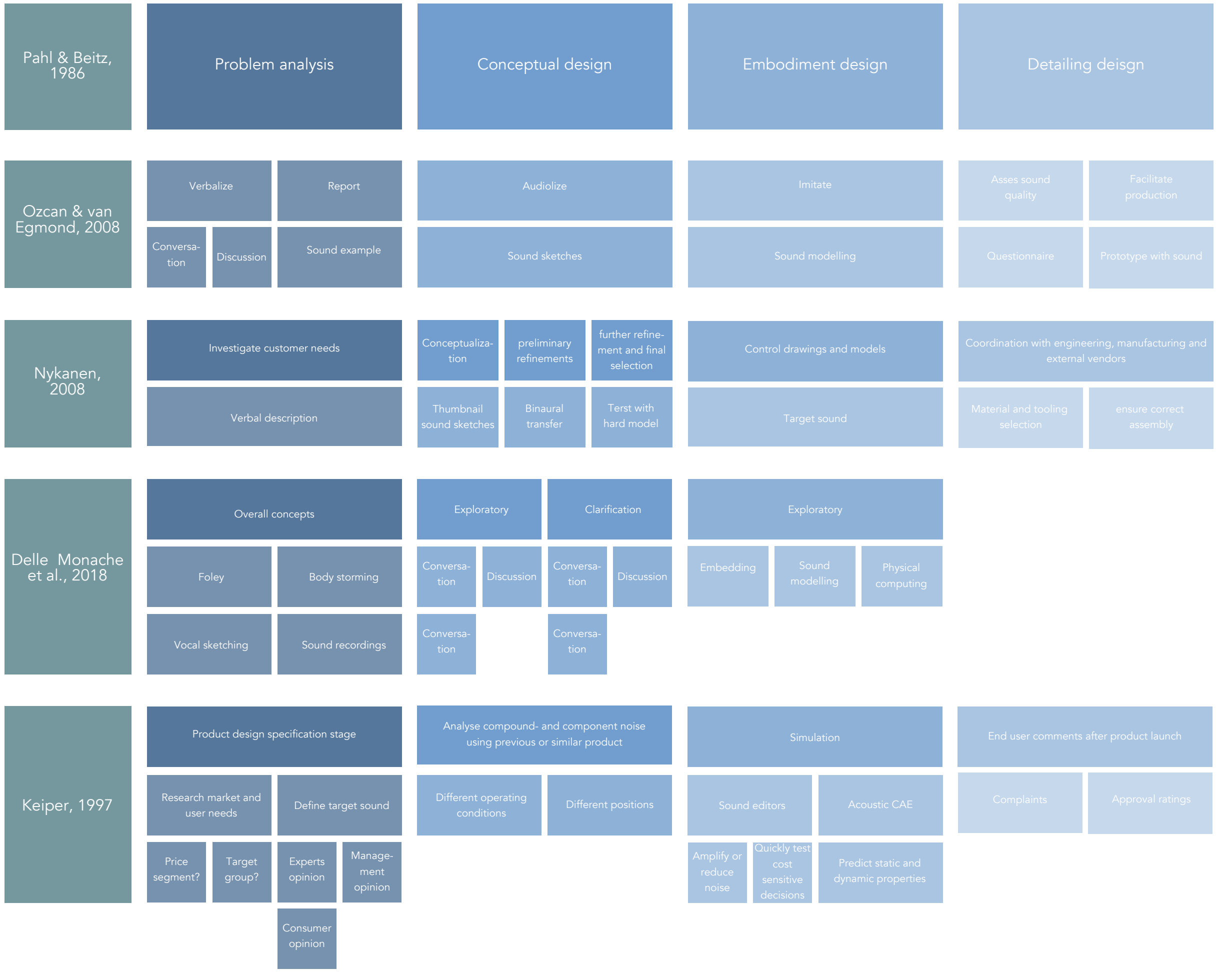


Figure 2.3: Summary of multiple product sound design processes.

Analysis phase
Like in the normal design process, the product sound design process could start with a problem analysis phase. Instead of asking questions for whom the design is intended for, the question is what function the sound should fulfil, or how should the sound is experienced by the intended user.

Second to that, since a product is always used in a context i.e. a location of a house, workplace, etc. defining the context is another step that should be included in this phase. For product sounds this means that all other sounds that can be heard in this location, the soundscape, should be identified. In this phase, the designer could use sounding examples to exemplify the sound related problem (Özcan & van Egmond, 2006).

Some design actions in this phase could be a sounding mood board, similar to currently used visual mood boards. Interviews can be held to gather expert opinions on the desired sound (Keiper, 1997) which could be used in a list of requirements.

Conceptualisation design phase
Analog to the conceptual phase in the general design process, the goal of conceptualisation in a product sound design process could be to create multiple ideas. These ideas can be given in the form of sounding sketches.

It must be noted that sketching in this case this is not drawing sound. But it is "a reflective activity occurring while being engaged in representing the sonic concept under scrutiny." (Delle Monache & Rocchesso, 2019, p. 82).

According to Özcan & van Egmond (2006), sounding sketches can be recordings of any object that has the potential to represent the sound desired. Or, these sketches can be collections of materials and objects that would exemplify the desired features of the product sound or the product itself. These sound examples might be ambiguous and do not aim to represent the original sounds, but rather represent concepts.

Embodiment design phase
During the embodiment phase, ideas about the sound in the concept design phase are transformed to a physical solution. This is done by producing models which can produce the sound. Such models can either be hard model prototypes (Özcan & van Egmond, 2006) or in digital twins, in which the product is modelled in Computer Aided Engineering software with which sound can be simulated (Keiper, 1997).

Detailing phase
As the embodiment of the product is almost entirely clear, the sources of the sound are well known and can be evaluated in audio quality tests (Özcan & van Egmond, 2006).

The final step in this phase is tackling product sound issues dependent on the production or assembly (Özcan & van Egmond, 2006). This includes reviewing tolerances and design changes with little influence on the rest of the design or preferable implementable in assembly without the need of iterating on the manufacturing (Nykänen, 2008).

2.3 Areas of expertise in product sound design

Mostly when issues on product sounds are tackled, this is done by experts from different areas of expertise. Such as experts on acoustics, psychoacoustics, electronics, or mechanics (Lematire & Suzini, 2019). However, due to the iterative process of product design, the delegation of tasks to external parties can delay the design cycle (Özcan & van Egmond, 2008). Secondly, if these tasks are delegated, it is still helpful for a designer to have a basic knowledge in this field to be able to give comments whenever the designer is not content with the delivered result.

Özcan & van Egmond (2008) proposed the responsibilities and the role of a product sound designer and state that the product sound design cycle could profit from product designers taking an interdisciplinary role and gaining knowledge in the fields of acoustics, engineering, and psychology with musicology, and psychoacoustics as hybrid disciplines playing on the background.
A short motivation why a product designer has competence in the respective fields to design product sounds is included in Table 2.2.

Next to the product designer's individual understanding of basic concepts within these disciplines, it should enhance the communication between the product designer and others involved in a design project. This interdisciplinary role would not only improve the communication with experts within these fields, but also in communication with non-experts. For example, when a product designer runs user tests on product sounds with customers.

Table 2.2: The professional domain of a sound designer (Özcan & van Egmond, 2008)

Field	Competence
Engineering	Ability to manipulate the structural aspects of a product and predict the consequences for the sound output
Musicology	Ability to compose musical sounds
Acoustics	Ability to interpret the physics of sound and relate them to products and mechanism
Psychoacoustics	Able to predict user reactions and limitations to perceived sound
Psychology	Able to interpret semantic associations users would with sound and the product

Engineering

At IDE, knowledge from engineering is used in the embodiment of a product. Some aspects from engineering that are relevant for sound are the products' mechanisms (Özcan & van Egmond, 2008), material selection (Fipsen, 2022), geometry (Fletcher & Rossing, 1991) and assembly (Sanz Segura & Manchado Perez, 2018). In the case of consequential product sounds it is mostly the decision made on such aspects (Langeveld et al., 2013)

However, with engineering alone changes can only be made by trying. It would be more effective if iterations could be based on knowledge that explains why certain mechanisms generate sound or how other factors like how materials influence the sound.

Acoustics

Acoustics is the field of physics that studies and describes the way sound waves work. This entails how sound travels vibrating through different materials, but can also be reflected like light. With this knowledge sound can be modelled with mathematical formulae. But it also provides the basis of objective sound analysis, so that measurements of sound pressure and frequency spectrum can be done in an objective way.

Psychology

In product design psychology, mostly cognitive psychology, is used to understand the cognition of senses in relation to the product experience. For sounds this would mean, speculating what is the resulting reaction of the user after hearing a sound.

This can be helpful to bring intent into the design and addresses user needs by for example introducing sounds as use cues (Jansen et al., 2010; Lemaitre & Suzini, 2019).

Psychoacoustics

Psychoacoustic is a field using knowledge from psychology and acoustics is used. This field mainly entails how sound is be perceived by humans.

Within this field, psycho-acoustic analysis is highly relevant in relation to product sound design. Such analysis entails measurements which clarify how sound is likely to be perceived. In psychoacoustic analysis metrics like loudness (perceived sound intensity), pitch, brightness, fluctuation, roughness are used (Fastl, 1997).

Such analysis can be helpful in the prediction of the cognition of product sounds in an objective manner and can thus provide the translation between acoustics and psychology.

Musicology

Musicology is the study of music and mostly entails the analysis of musical compositions. Özcan and van Egmond (2008) consider it most useful in the design of intentional sounds such as alarm sounds, since the design of intentional sounds is similar to musical composition.

In relation to consequential product sounds, a helpful sub-discipline could be cognitive musicology. This field investigates for example why certain aspects in musical compositions such as melodies, rhythm and/or chords evoke certain emotions (Haumann, 2015). And thus knowledge from this field can be used in subjective analysis or descriptions of sound.

2.4 Product sound design methods and tools

As it is clear now how a product sound design process could look like, it is interesting to know what tools or equipment are used in these processes.

Sound gathering tools

One of the earliest steps to design product sounds is to gather sounds. This can be done by gathering the sound of current products but also any sound in general. Tools to gather sound could be categorised in the following types: vocal sketches/Foley, recording sounds and sound simulations. Each type has its own advantages and disadvantages. But since a design is becoming more concrete in later phases, these disadvantages can become an advantage in a different state and vice versa.

Recording sounds

Sound recordings are used during the whole design process. One of the earliest actions an acoustic engineer would do in a design process is to record the sound of the current product. This recording can be used to analyse the current sound, and if a well calibrated recording is done, this recording can be compared to a new recording of the sound of the redesigned product (van Egmond, 2022).

An array of multiple microphones, also called acoustic cameras, can be used to localise the source of sound, especially if the source of sound is to be found without disassembling a device. Acoustic cameras consist of an array of microphones. An algorithm can calculate the direction of the sound by taking the relative position of these microphones and the delay sound arrives at the microphones.

Binaural microphones are commonly used to get a recording of how a real person would experience the sound. This is done by making a stereo recording with the microphones at the location of human ears. Incorporating two microphones in an artificial head, as seen in Figure 2.4, could be used to get a recording more true to the human hearing (Nykänen, 2008).

Figure 2.4: Artificial head for binaural recordings (HEAD Acoustics, n.d.)

With a sound intensity probe the sound intensity can be measured. This is more accurate in measuring sound radiation than using a microphone, at least if an anechoic chamber is not present. Since a sound intensity probe uses two microphone diaphragms, sound can also be localised (Brüel & Kjær, 2021).
By superimposing the sound intensity over an area on the image of a visual camera, a visual representation of the sound of a product can be made, see Figure 2.6.

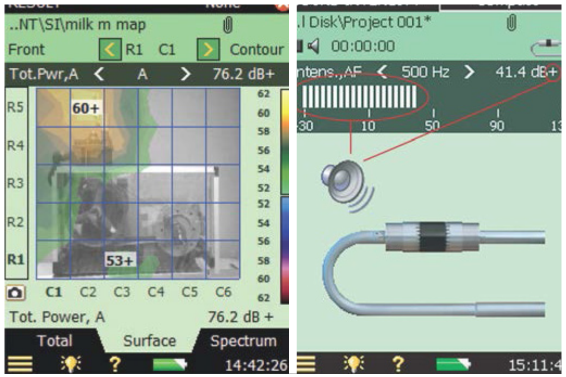


Figure 2.6: Visualising sound with acoustic sensors (Brüel & Kjær, 2021).

Source separation

To know how individual components of a product influence the sound character, a separate recording of each component is needed.

One manner to do this is to make separate recordings of the product with certain components removed or disabled, see Figure 2.5. Separate recordings of components require time and precise recording setup. On top of that, an anechoic chamber is preferred as the reflection of sounds in a room

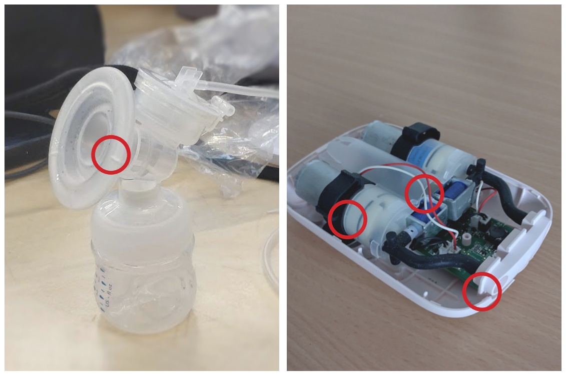


Figure 2.5: Identification of multiple sound sources in a breast pump before recording. (Timmerman et al., 2022).

are also captured in a recording making the recording dependent of the room (van Egmond, 2022).

Another way is to do this separation with software. In this case one integral recording of the compound sound of the product can be used as input and the software gives the sound of different components as output. Multiple ways exist in which this separation can be done.

Inverse wave mask

For this method a compound recording and a recording of one component is required. Then the recording of the component should be aligned to the recording of the compound sound. The recording of the component is. This inversed sound is subtracted from the compound sound, leaving the compound sound without the sound of the component.

Non-negative matrix factorisation

In this technique small portions of recordings of an isolated sound are stored in a reference library called a dictionary. By decomposing a compound recording into two matrices and performing a non-negative factorisation on them, other parts which have similar spectral and temporal characteristics to the isolated recording can be recognised from a compound recording (Févotte et al., 2018).

Machine learning

Most machine learning (ML) algorithms for sound source separation are intended for separating instruments in music. As (popular) music is clearly tonal and contains instruments with a variety of timbre and distinct percussive sound, it might be harder to separate multiple sounding sources from a recording of a product sound. An example of an ML sound separation tool usable in product sound is SiTraNo. This tool intended to separate sound in sine (tonal), transient (percussive) and noise components from a compound sound (Fierro & Välimäki, 2021).

Sound analysis tools

Two important metrics in acoustic analysis are loudness and sound spectrum. Loudness is given as the mean sound level of the whole recording and is given in dB(A) (Milan, 2022). And the spectrum is the presence of multiple frequencies in a sound

Sound analysis in a digital audio workstation

Digital audio work stations, like Audacity (Audacity Team, 2023), are more accessible software with which some sound analysis could be done. A spectrum graph gives a graph of the energy of frequencies bands from a given length of time, see Figure 2.7.

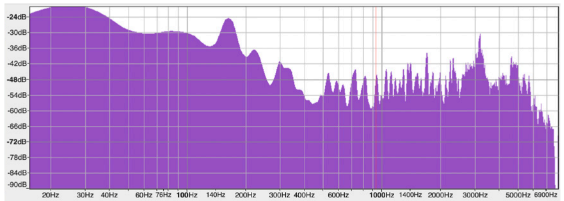


Figure 2.7: Sound spectrum of a shaver retrieved with Audacity.

A spectrogram, Figure 2.8, gives an overview of the energy of frequency bands as well. However, at exact points in time (Smith, 2024). In a spectrogram the energy of the present frequency bands is given by differences in colour.
From these graphs an assumption could be made of what parts of the sounds must be changed to increase the sound quality. For example, multiple narrow peaks give an indication for a harmonic sound and broader peaks indicate noise in that band.

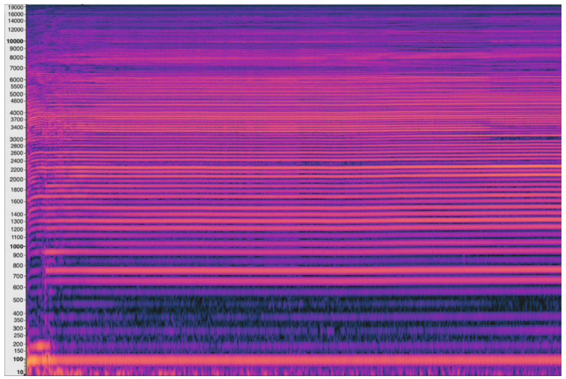


Figure 2.8: Spectrogram of a shaver retrieved with Audacity.

NVH suites

ANSYS, HEAD Acoustics and Siemens provide integral Noise Vibration Harshness analysis suites. Such suites consist of sound analysis software which, next to acoustics measurements, also provide psychoacoustic analysis. Enabling subjective measurements on sound (Ansys, n.d.; HEAD Acoustics, n.d.; & Siemens, n.d.).

Second to that, hardware is most often also a part of the suite such as binaural recording devices but also sensors for vibration and sound pressure measurements. Such suites are however expensive and have a high focus on automotive industry only.

Sound ideation

After the analysis mostly some ideas are generated to quickly explore different solutions.

Vocalisation

In Sketching Sonic Interactions (Delle Monache & Rocchesso, 2019) it is described how sketching can be done with the human voice to convey ideas about auditory concepts. An example of a vocalisation can be the imitation of an existing sound which results often in an onomatopoeia, such as “tick tock” to describe the sound of a clock. Vocal sketches are often used to quickly bring over the intended sound to others as no other equipment than your voice is needed to make a vocal sketch. A vocal sketch can be used in discussions to make clear which sound of what part of a sound you are talking about. On top of that, they could also be used to create and impression of   how the final sound should be. As some practise is required before more advanced sounds can be reproduced, Delle Monache & Rocchesso proposed some exercises.

However, even after practice, a dis-advantage of vocal sketching is the limitation of the human voice. It is almost impossible to create a sound that consists of more than noise or one pitched tone.

Sound editing in a digital audio workstation

To make changes to a recording of a product sound a digital audio work-station (DAW) can be used. Although some useful features are provided, it is not presented in an intuitive way for product design. This is the result as most DAWs are intended for music recording and creation, see Figure 2.9. They provide a user experience that is based on mimicking physical music recording studios. Emulating large mixing panels and providing digital audio effects in a similar way as found in studio effect racks or pedals. Next to the visual element, also the descrip-tion of parameters is given in a way that it is relevant for music and not for acoustics or psychoacoustics.

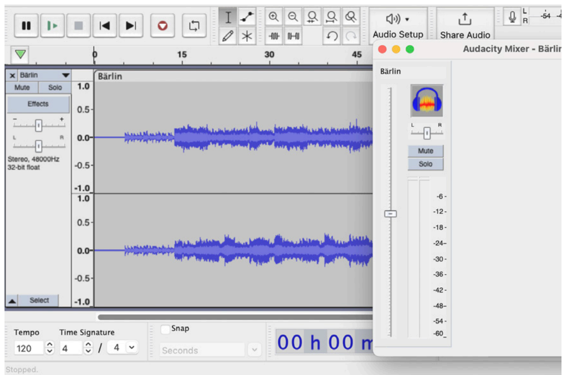


Figure 2.9: Editing sound in Audacity.

Sound synthesis

Sound synthesis techniques such as subtractive synthesis can provide quick exploration of different sounds. This is done by filtering, read subtracting content, from a sound source like an oscillator (Hermann & Hunt, 2011). Most synthesisers incorporating this technique are focused on quickly exploring musical sounds, this makes them less suitable in the creation of more realistic sounds.
Physical modelling synthesis can provide a more realistic sound of a product. This is due that the synthesis system is based on the mathematical model of an acoustic system (Smith, 2023). It thus requires the product to be fully embodied already and thus not ideal to create reference material, or as concepts in ideation.

Generative AI

Like artificially generated images, sound can be generated using Artificial Intelligence (AI). In a design process AI could be used to quickly create reference material for ideation, early prototyping and sketching (Tholander & Jonsson, 2023). However, very few examples of an AI that can generated sound exist yet. Donahue et al. (2019) and learning to synthesize audio requires capturing structure across a range of time-scales. Generative adversarial networks (GANs) used a Generative adversarial network, a concept in AI mostly used in image generation algorithms, to generate a spectrogram of percussive sounds. Using an inverse Fourier transform such a spectrogram can be made audible. Due to limitations with the use of an image generating algorithm, the length of the sound samples was limited to around one second.

Sound conceptualisation

Hard prototypes

If a hard prototype of a product is made in the conceptualisation phase, the sound of the product can be made audible (Özcan & van Egmond, 2006). In a similar way, this hard prototype, or an existing product, could be used to test multiple concepts by switching components or adding or removing material and change the acoustic properties of the product, see Figure 2.10.

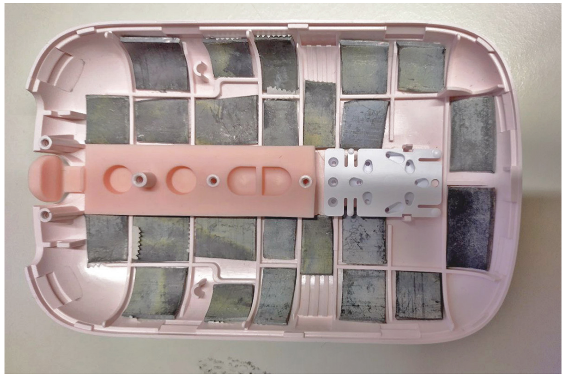


Figure 2.10: Adding weights to a physical model to change acoustics (Timmerman et al., 2022).

Acoustic simulation

Similar to stress simulation already used in design education, finite element method (FEM) and boundary element method (BEM) can also be used to simulate acoustics (Siemens, n.d.).

Most acoustic simulation software can only give a visual representation of which parts will make sound, see Figure 2.11. For specific fields like the automotive industry it is possible to listen to this simulation (Ansys Sound, n.d).

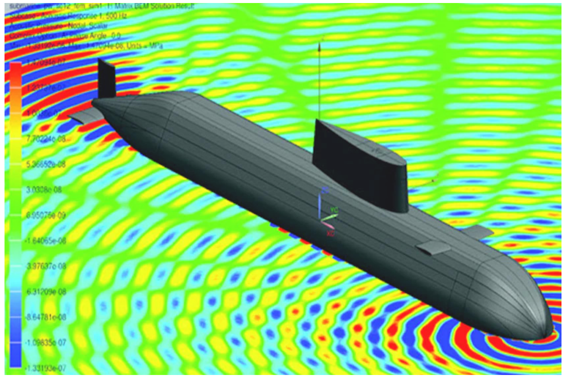


Figure 2.11: Acoustic simulation (Siemens, n.d.)

Sound evaluation

Jury testing

To gain insights on the subjective evaluation of a sound, jury testing can be used. In a jury test possible consumers participate in a survey where sounds of the product is provided and are asked to rate these sounds. Fastl (2005) gives an overview of research techniques that can be used to perform such tests like: semantic differentials, category scaling and magnitude estimation. If enough participants are questioned, such tests can give a statistical indication of how the product sound is likely experienced by consumers.

Sound evaluation with machine learning

The results of sound evaluation can be used as input in prediction algorithms. In the python tool Soundscapy (Mitchell et al., 2022) a recording of a soundscape and its rating of descriptors from a user test on that soundscape can be loaded. A machine learning algorithm analyses which factors in the soundscape were likely to result in this user evaluation. After this a variant of a new soundscape can be loaded. Based on the earlier analysis Soundscapy can now predict how the new soundscape is likely to be rated, without the need of a new user test.

2.5 Conclusion on context

In product design two types of sounds are distinguished: consequential and intentional sounds. Consequential sounds are sounds resulting from the functioning of the product, often due to friction between moving parts. Resulting in the product experienced as noisy.

Designers can influence the quality of these sounds by altering product properties like geometry and materials. However, the challenge is to balance requirements on the product sound with other requirements.

The Product Sound Model provides a general flow of acoustics of products a designer can consider when designing the product sound. It also shows that the sound of a product is dependent on the sound source, but also by how the sound is transmitted and radiated inside the product, and how it is radiated to the listener.

Intentional sounds, deliberately added to products, serve informational purposes like alarm tones or microwave alerts. In contrast to consequential sounds, intentional sounds can be designed with large creative freedom. This results in a need in separate design processes and task between the design of these two types of sound.

Incorporating sound in a design process

If consequential sounds are designed and not considered as an afterthought it is important to include product sounds as early in the design process as possible. Such a sound design process can consist of the same phases as a normal product design cycle. In such a process sound is considered from abstract to more concrete.

Areas of expertise in product sound design

In a product design cycle knowledge from the following disciplines are required to integrally design sounds:

Engineering, to consider the embodiment of the product that is required for its functioning.

Acoustics, to understand and predict the physical behaviour of sound.

Psychology, to understand user needs and design a product experience.

Psychoacoustics, to describe and measure the objective experience of sound.

Musicology, to describe musical and compositional components in a product sound.

Currently used tools and methods in product sound design

Some tools for the analysis and ideation phase in the design of product sound exist, such as vocalization providing a quick but abstract idea on a sound, similar to a sketch on paper.

Also recordings of currently existing products can be made with the intention to analysis and ideation tasks with them. Multiple types of recording devices exist as well as methods and tools to provide a recording of both the whole product or single components.

These recordings can be processed in software for both sound analysis and ideation such as Ansys Sound, and HEAD Acoustics. These are examples expensive suites and less accessible for students if not provided by the university.

Some other software which provides audio analysis and processing, like Audacity, is more accessible for students. However, most of such software is intended for music production. Creating a difficult translation of analysis and ideas to direction for later conceptualization stages.

In the later phases such as conceptualization and embodiment phase, methods similar to methods and tools already used in Industrial Design Engineering education can be used, such as hard prototypes and simulation. The creation of such prototypes and simulations require a good translation from idea to concept.

3.Expert interviews

In this chapter interviews with experts are discussed. These interviews were done with experts from different domains within product sound design. These interviews were held to gather new insights but also verify insights found from the literature study.

3.1 Method

This chapter summarises expert interviews which were done with multiple experts in the field of product sound design. The aim of this research was to verify whether findings from research are also valid in a professional setting.

Participants
Experts from different fields within product sound design were interviewed to gain knowledge of the state of art of product sound design and the future of this field. The areas of expertise were:
A Sound Analysis- and Design software, to gain knowledge on the design of tools that can be used in a product sound design process.

Two lead engineers at a company that design white goods products, to gain knowledge how products acoustics and sound design is incorporated in real design projects.
And lastly, a professor in Acoustics and Haptics, to gain knowledge how students can be introduced to the fields of acoustics, psychoacoustics and sound design.

Table 3.1:Overview of participants in expert interviews

Participant	Role	Affiliation
Expert 1	Director	Ansys Sound
Expert 2	Senior lead engineer acoustics	Arçelik Global
Expert 3	Lead engineer acoustics	Arçelik Global
Expert 4	Professor in Acoustics and Haptics	TU Dresden

Stimuli
The interviews were done using a semi structured interview. Before each interview list of questions was gathered, included in Appendix II - IV. The interviewee was free to omit any questions or keep expanding on the original question. This was done to explore whether unexpected information or tensions within fields of product sound design would show up. Informed consent was gathered by means of Informed Consent. Results were gathered by means of digital audio recordings and written notes.

3.2 Results

After the interviews it was found that participants confirmed similar principles or added the view from their own perspective/profession on the same principles/states. Therefore, in the next section outcomes from the three interviews are presented together by thematically gathering the results of each interview.

Communication between departments

In most design teams every department/member focuses on one expertise. An expert on psychoacoustics might have no clue how the desired metric can be achieved based on acoustical engineering. In the same way professional software like Ansys Sound does not focus on its accessibility level to be understandable for all team members within a project, but to be most useful for the respective expert (Expert 1).

A similar example was given by Expert 2 & Expert 3. They mentioned they need to use, for their field relatively simple to understand graphs, like a sound spectrum, to communicate issues to other design engineers with expertise in different fields. With the result, communication between departments happens in a low detailed manner.

Teaching product sound design

Students should be introduced with the basics of acoustics by using examples of mundane situations. If the interest is there, their expertise will follow automatically. It is recommended to begin with less abstract tools/software first. For example, if one wants to write their own digital sound processing software but does not know any programming language software like pure data is a good introduction instead of directly begin writing in C++ (Expert 4).

This was also backed by Expert 1, who recommended before learning a more advanced sound analysis and simulation tool like Ansys Sound it is useful to start using more accessible tools like Adobe Audition, Audacity or MAX/MSP. These tools are a good introduction to the same concepts that are used in Ansys Sound as well.

Role of ANC in the future

Active noise cancelling (ANC) systems are implemented more and more and are getting better. However, it is difficult to incorporate ANC if the position of the listener is unknown. ANC is used more and more in headphones and cars and works well because in these cases the head position of the listener in relation to the sound source is well known. Some experiments exist to perform ANC without the need of a headphone, but results are not as good yet. On top of that, it requires extra electronics to be implemented in the products, making it currently an expensive option. Therefore, it is likely that physical adaptations to the product design like material and geometry that influence the sound are still the most relevant properties to change in the next 20 years (Expert 4).

Function analysis

An analysis of the function of the product is highly relevant for the product sound. The sound should fit the function of the product and sound itself can be a function of a product. As an example, a dishwasher that does not make any sound could be experienced as defect, while if the dishwasher would make audible sounds the user is informed that the product is working (Expert 2 & Expert 3).

Experience of sound is individualistic

It is impossible to design a sound that fits everyone's taste. On top of that, the culture for which it is designed is important. Some cultures are used to a noisier environment. An example was given between Istanbul and Japan. Istanbul was said to be a noisy city and as a result people living there are less likely to mind noisy products compared to a person in Japan where the environment is less noisy due to more social control inherit to the culture (Expert 2 & Expert 3)

Product experience is multi modal

Next to visual stimuli all senses should be pleased in good product design like pleasant to touch and nice to smell. Sound is therefore likely to add to a good experience of the product but should not be considered alone. Adding to that, acoustics and haptics could be considered together as vibrations in a product might not only be audible but also feel-able (Expert 4).

Reverse engineering

Reverse engineering is a step taken to understand which components in a product produce sounds. This is done with previous models from their own brand and higher and lower price range products from competitors.

Doing this gives a better understanding of which engineering decision leads to which sound. Acoustic cameras are also useful in cases where it is not desired to disassemble a product (Expert 2, Expert 3 & Expert 4)

Record and measure sound

Recording and measuring the sound of existing products is the first step in the product sound design process. For the measurement of loudness, mostly the dB A scale is used. Second to that a sound spectrum (graph of frequency and its amplitude) or spectrograph (spectrum over time) is used to show the frequency range of the sound and might give a hint which range should be adjusted. For example, if peaks at specific frequencies are clearly visible (Expert 2).

For capturing the sounds multiple types of microphones are used. Artificial heads can be helpful as it gives a good representation of how the product really sounds to humans (Expert 3).

Target sounds
To communicate the desired sound for the product multiple tools could be used.
Vocal imitation is often done to quickly gather ideas or communicate to others which sound the designer is talking about.
Audio filtering is also an option. By applying filters to a recording of the product sound, one quickly gets a good idea of how the product could sound is for example if the product has a higher mass or structural stiffness.
On top of that, psycho-acoustic measurements can be taken to test whether this filtered sound is perceived as more pleasant than the current sound (Expert 2 & Expert 3).

Commonly applied design changes
If a motor is present, changing the rotations per minute (RPM) is done first to test whether that improves the sound quality. Next to that, changing the order of events can also have a large impact on the sound quality while no changes to the embodiment have to be done. A change in material and geometry can also be implemented if issues on resonance are to be solved. Material is mostly only changed for smaller components. For larger components more often the geometry is changed i.e. adding ribs or dents to change the elasticity/stiffness of the component. Electronic noise is an unexpected but common problem. The electromagnetic field of some components such as an electro motor might start to vibrate ferromagnetic surfaces which results in unwanted noises (Expert 2 & Expert 3).

Sound virtualisation
Sound virtualisation of complete products is currently limited. This is due to the more complex nature of the transmission and radiation of sound through materials in comparison with deformations due to stress. Currently, sound virtualisation is only possible in the design of single components or sub assemblies such as engines. It is expected that another decade of development is required before useful results can be produced (Expert 1).

However, if sound virtualisation is possible for complete products, it would be useful to quickly test multiple variations of product configurations (Expert 2 & Expert 3).

Jury test

It is hard to evaluate how sound will be experienced in an objective way. Only a few physical measurements can be done that are relevant to the perception of sound (Expert 1). Therefore, also jury tests with around 40 participants are done in which the subjective sound quality of a product is tested. Such tests should give a good overview on how the end user will perceive the sound (Expert 2 & Expert 3). The study of the perception of sound is already done for over a century but we are only in the first stages of really understanding how the human hearing works. By making a computer model of the human hearing, eventually sound quality evaluation could be done in a way that it is true to the physical experience of a sound by a human (Expert 4).

Inform consumers about sound

When searching for a new product, consumers can be made aware about product sounds in multiple ways. One way is the EU energy label. This label is mandatory for specific products groups which are sold within the EU. Next to the energy efficiency it also shows the noise level of the product in dB. Informing noise level only might not be relevant for the consumer's attitude towards a product sound. Therefore, some companies find it more useful to use a sound quality label. This label is given by SLG, an independent certification company. This label is given after jury tests in which the perception of the sound of a product is rated. This certification is not mandatory but is more helpful to inform the consumer on the pleasantness of the sound of the product (Expert 2 & Expert 3).

3.3 Conclusion on expert interviews

Experts mention difficulties with communication between fields within product sound design. Communication between the different experts is happening in an academic manner, but not in-depth. Therefore, a focus can be made how students can be introduced to an interdisciplinary field. This would enable them to understand multiple aspects relevant for product sound design.

To introduce students to acoustics, it is useful to start with the basics and give concrete and audible examples of phenomenons that they experience in real life. If this introduction sparks enough interest, the students' own motivation will help to guide them in the rest of the learning process.

Next to theoretical knowledge some practical knowledge is convenient as well. This could mean including taking recordings, doing acoustic measurements or sound design activities.

Based on input from an analysis phase, design goals for the rest of the design process can be defined. When gathering this design goals it is important to take into account the function of the product. Second to that, sound is experienced together with other senses like vision and touch. However, this is experienced differently between different end users and is also dependent on the culture of the user.

Based on these goals reference sounds of the newly designed product can be made. Ideally a simulation would be useful to test the product sound before creating expensive hard prototypes. Currently, due to the complex physics of sound, simulation of sound using is limited to single components only and not whole product assemblies. However, by editing recordings taken from a reference product after disassembling the product, a good example can be given of how the sound could sound while also providing insight how this sound could be achieved.

After the final design is ready, the sound can be evaluated with jury tests. Such evaluation can be used in sound labels which inform the customer about the sound of the product when buying new products. To make this evaluation as objective as possible large set of participants are needed. In the future such jury tests can be replaced with algorithmic testing.

4.Product sound design framework

In this chapter a framework is proposed that can be used to introduce students to the design of product sounds. This framework is build on the findings from the literature study and expert interviews. It is explaining goals that can be achieved with this framework. After that an overview of the initial framework is given. Based on this initial framework, a user study was performed to test the completeness. This chapter concludes with the definitive proposal of the framework.

4.1 The need of a product sound design framework

In this section, the fundamentals of a design method with which product designers can gather design objectives specifically on the product's sound is proposed. The goal of this is to enable the product designer to take a central role in a product sound design process.

In product design often reference material is gathered in the analysis phase and used to derive design objectives from. The Delft Design Guide describes multiple design methods on how to gather or create reference material and derive design objectives from them (van Boeijen et al., 2014).

In respect to product sounds, Keiper (1997) proposed a concept to create reference material for product sounds in the form of target sounds. According to Keiper, these target sounds are required to ensure that the eventual sound fits the product in relation to the intended market segment and customer. Keiper proposed that such a target sound can be defined after analysis of the sound of "existing older, comparable products including competitors, and possibly simulations."

Keiper gave an example of Singer, the sewing machine company. Singer used a reference sound of a sewing machine which was chosen by the board of management, by hearing only. After selection, this reference machine was stored in a closet.

Solely using sound reference however might results in little knowledge behind the embodiment of the product that creates this sound. And as other sensory references are ignored, such as the product's visual appearance, the appropriateness of the sound to the rest of the product is difficult to define.

Nykänen (2008) also proposed to use sound as reference in the analysis phase as thumbnail sketches, and provides a recommendation for a recording setup that ensures a realistic as possible recording of the product sound. This enables the creation of a high quality reference sound of a current product, with the intention of these recordings to do acoustic analysis. However the implications such analysis can have in further design phases are not discussed.

During the expert interviews, (chapter 3), the analysis of reference products was also mentioned as the foremost step in an early design stage. They claimed that often a previous model or similar product from a competitor is used to analyse their current sound. By disassembling these products it can become clear what influence the mechanics and embodiment have on the sound. However, as a non-expert, one would have a hard time finding solutions suitable to solve or express design objectives that you could base on this analysis.

The requirement of expert knowledge is also needed to be able to use the currently available software which provide sound analysis or the creation of audible reference materials digitally.

Therefore, it could be useful to create a framework aimed to design students which should enable them to consider product sounds holistically in early design phases.

4.2 From analysis to objectives

One method to analyse current products is the Nine Moments of Product Experience (9MoPE) framework by Özcan (2016) .This framework considers aesthetics, meaning, and emotion on three levels of Human-Product interactions. With these levels being: micro, macro and meta, making a total of nine moments in which product experience can be experienced.

The micro level entails properties of product details such as: shape, colour, texture, etc. The macro level considers the product and its function. It includes the use, activities, actions etc. In the meta level the product is considered in its context, including the situation in which the product is used, the relation to other people, brand identity etc. The 9MoPE framework can be used to both, analyse the current product and based on that envision the experiences of the desired product (Özcan, 2016). Figure 4.1 shows such a product experience vision of a Bang & Olufsen speaker.

Due to including both analysis and envisioning it might be useful to solve the current gap between the analysis and conceptualsation phase currently present in product sound design process.

It enables the clarification of how the technical product features influences the user's interaction and experience with the product. In relation to product sound design it is expected that it can be used to explain the relation of the sound of the product to the function of the product and how that influences

Figure 4.1: Example of 9MoPE vision matrix for B&O speaker (Özcan, n.d.)

the product experience.
The 9MoPE framework was designed to consider a broad variety of product properties like shape, colour, geometry, etc. with sound being one of such properties as well. Kasti and Özcan (2017) defined the functioning of the 9MoPE matrix if it was only considered for sound, shown in Figure 4.2.

Nine Moments of Sound Experience	**MICRO**	**MACRO**	**META**
AESTHETICS	**MOMENT 1**	**MOMENT 2**	**MOMENT 3**
	fundamental frequency temporal proximity shape of their spectra intensity apparent spacial origin roughness sharpness tonality loudness	what the listeners are trying to hear? frequency separation speed prediction effect novelty familiarity	emotionally arousing events internal state of the listener social context cultural diversity
MEANING	**MOMENT 4**	**MOMENT 5**	**MOMENT 6**
	familiarity duration of the rhythm location of the source patterns tempo structural properties of the sound cognitive capacity of the listener age of the target group	semantic distance ecological or metaphorical relations direct or strong, indirect associations misinterpretation	the number of sounds visual context cultural differences listener's level of experience
EMOTIONS	**MOMENT 7**	**MOMENT 8**	**MOMENT 9**
	level of urgency (annoyance) pleasantness (sound as an object) modulation frequency modulation depth	balance between the cost of complying with a warning and the cost of noncompliance pleasantness (individual's reaction as an object)	interaction with other senses beliefs and attitudes of the listeners the user's current condition (mood)

Figure 4.2: Nine moments of sound experience (Kast & Özcan, 2017)

4.3 The role of the product designer in the framework

From the literature review and expert interview it came clear that some of the disciplines in product sound design share some common knowledge or skills. It was tested whether creating a terrain with coincident boundary could lead to an area that can be used to introduce students to product sound design.

This resulted in the diagram as shown in Figure 4.3. This figure gives an overview of different stakeholders in a product sound design process and a proposal to what knowledge they contribute to a design process. It is however difficult to define one area that overlaps all areas of expertise.

An explanation to this observation was found by comparing this figure to the thematic map from "Semantic models of sound-driven design: Designing with listening in mind" (Delle Monache et al., 2022).

This thematic map shows the relations between stakeholders in a sound-driven design process. Two axes are given on what attitude different stakeholders have towards sound. As the thematic map showed some similarities with Figure 4.3, these axes were superimposed as the dotted lines.

Adding these axes can explain that it is difficult to find one area with overlap between all stakeholders. For example, an acoustic engineer thinks about how to reduce sound, while a sound designer thinks how to add sound. Leading to differences in required knowledge and tools.

This implies that it might be more relevant to let the student approach a design from the perspective of the different fields and base their design decisions from a central viewpoint. This is similar to design tasks in general, where often requirements from different viewpoints are weighted and the best compromise has to be found.

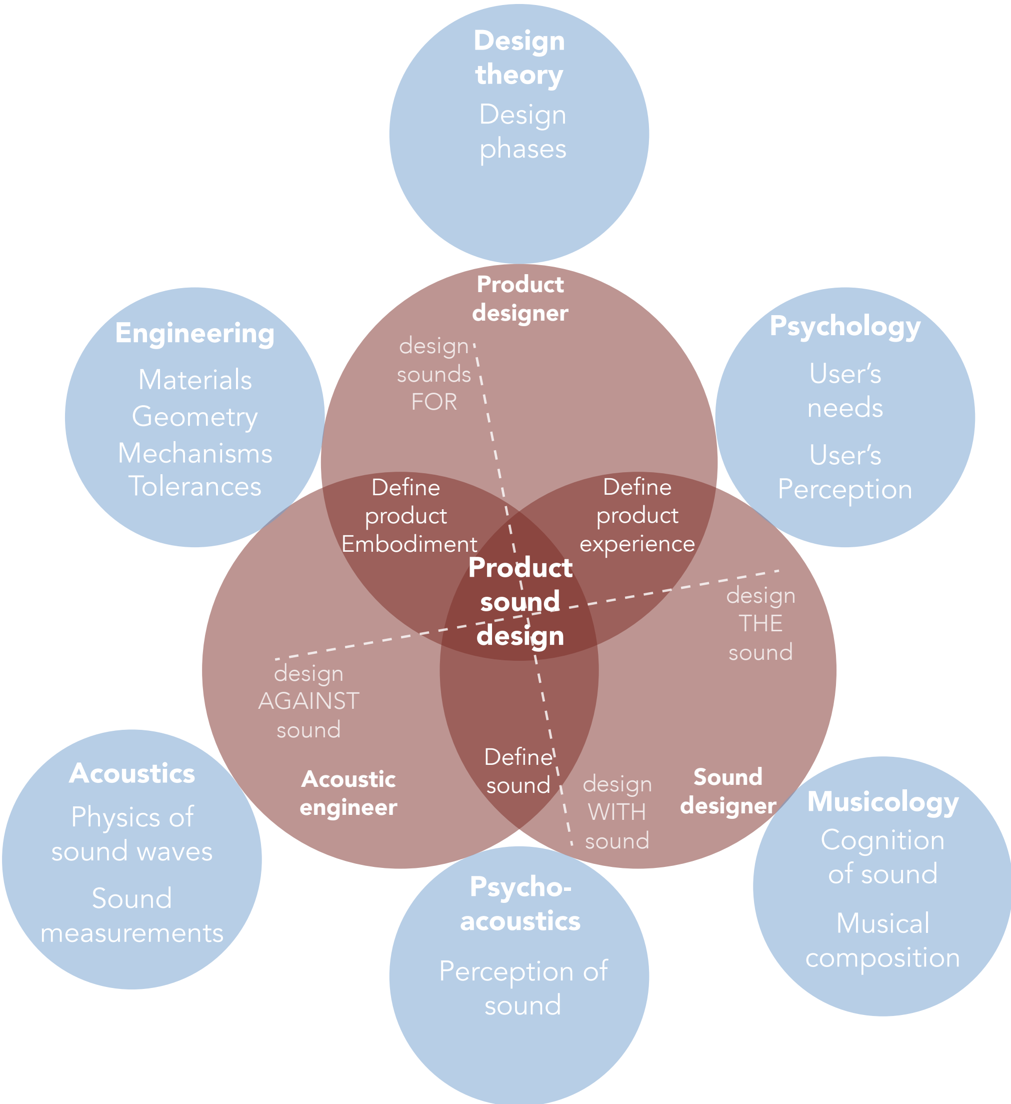


Figure 4.3: Proposed disciplines to enable good product sound design.

4.4 Initial design of a product sound framework

A framework to enable the gathering of the objective for different fields is given in this section. A brief overview of how these elements work together is given in Figure 4.4.

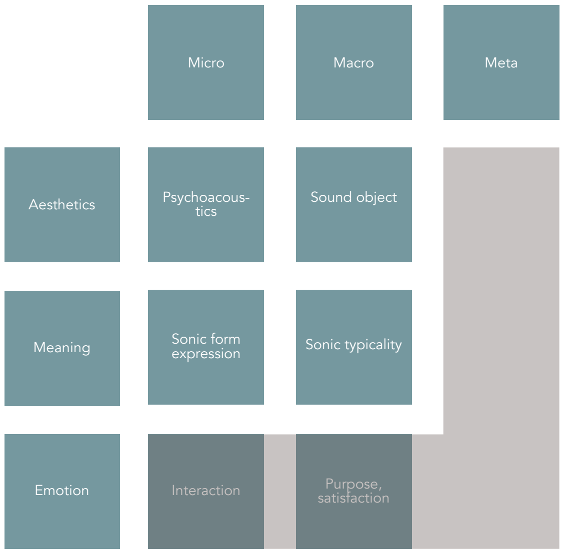


Figure 4.4: Moment from 9MoPE initially considered in product sound design framework.

Moment 1 aesthetics on micro level: Psychoacoustics

According to Özcan (2016), the experience of aesthetics on micro level is the aesthetics pleasure of a product attribute. In the case of sound, this is the aesthetic pleasure of the sound of a single component. Psychoacoustics is a field of science that can be used to answer the question which parameters are useful to rate the aesthetic properties of a sound.

The selection of parameters to include were gathered from The Psychoacoustics of Sound-Quality Evaluation (Fastl, 1997). The included parameters are loudness, brightness, tonality, roughness, and fluctuation strength. These parameters are also used in subjective measurements by jury tests when products are rated for a sound quality label (SLG, n.d.).

Since an industrial design student has probably little understanding of the definitions of those psycho-acoustic parameters, a solution must be found which could introduce them to these definitions. For this the online lexicon Words4sound (Carron et al., 2017) was found to be useful, Figure 4.5.

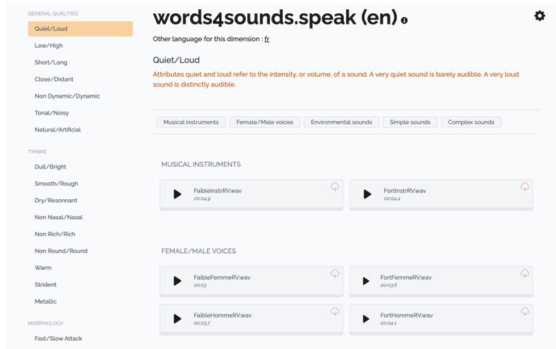


Figure 4.5: Definition of loudness as given in the words4sounds lexicon (Carron et al., 2017)

Two main requirements that were used in the setup of this lexicon are 1) to present definitions in an easy-to-understand way, and 2) the provided concepts in sounds should enable the user to talk in such a way about sounds that it is useful in communication with both experts and non-experts. In this lexicon this is achieved by giving a verbal description of the property, together with sounding examples from music instruments, speech and sounds in the environment.

Moment 2 meaning on micro level: Sonic form expression
In the 9MoPE matrix by Özcan (2016), the experience of meaning on micro level of a product attribute is stated to be the cognition that follows from the sensory perception of the aesthetics of the attribute.

Özcan proposed to express the meaning verbally by answering the question: “If you would describe the attribute as a person what character trait would that person have?”. An example that was given is: the leather handle can feel friendly to touch because it feels warm and soft.

In the case of product sound design, the perception of sound is essentially a variant of the perception of a sense.

Therefore, the meaning on micro level is the cognition of the aesthetic perception of the sound, or the Sonic Form Expression. Analogue to visual attributes, the sonic from expression can be verbally given by answering the question: “If you would describe the sound as a person, what character trait would that person have?”.

Moment 3 aesthetics on macro level: Auditory Scene analysis

Most often sound that we hear is a mixture of multiple sound waves that reach our ear. Due to the functioning of our hearing system this combination is summed up into one wave. We can clearly distinguish which sound comes from which source, our brain has the capacity to separate the multiple sources and organise them again.

Auditory scene analysis (ASA) describes the principles in which this perceptual organisation of sound can occur (Bregman, 1990). The principles described in ASA are in essence gestalt principles in sound.

Using principles for auditory scene analysis could be helpful for musical composition. Composers for example consider the difference in rhythm between two melodies, wide or narrow difference in the register (separation in pitch) in which multiple melodies are played and the timbre (which instrument) in which a part of the composition is played.

Auditory scene analysis thus might help designers in the musicological aspects in the product sound design process, by regarding product sounds as a composition of the multiple components that produce sound.

ASA should give a clear direction of how the combination of all sounds are perceived if the sounding events happen in a different order, or in a different frequency band, or if the timbre of events is changed, or if multiple events have a tonal character, the relation between these tones.

Moment 4 meaning on macro level: Sonic typicality

Kasti & Özcan (2017) defined semantic distance, and direct or strong indirect associations as some properties of sound in the meaning on macro level. The main question in this moment is thus: Does the compound sound of the product fit the product?

According to Özcan and van Egmond (2008) the responsibilities and the role of a sound the perception and cognition of a product sound, is strongly related by the sound group in which one categorises the sound and the product category in which the product is categorised. From their studies they categorised sounds in the following categories: Air, Alarm, Cyclic, Impact, Liquid, and Mechanical.

To test whether such a sound category fits the product, the question can be asked whether the sound category is either typical or novel for the product category. The use of typicality and novelty however does not give a direct conclusion whether that property is desired for the current product (Hekkert, 2006).

A product that is typical for its product category is likely to give familiarity to the user, but too much typicality can also be experienced as boring.

Novelty on the other hand can make a single product stand out from other products in its category, but a too large distance between a product and its product category can result in confusion. It is therefore interesting to relate typicality and novelty with the Most Advanced Yet Acceptable (MAYA) principle.

Reflection
In this part the designer is asked to reflect about what is most unfitting to the current sound in relation to the rest of the product and why. In the form this reflection is done by writing a short summary. This should clarify the relation on aesthetics and meaning moments within micro and macro level. From this, the designer can decide on what aspect to work further on.

Envisioning
This part consists of the same four moments of aesthetics and meaning on both micro and macro level. This time the user is however not analysing the current product but how a new product should sound like. The outcomes of the envisioned moments are put into a design statement. In a design statement a written sentence is used as a reference for further design stages. A written statement was included since it can be used to describe sounds without the need to learn to work with a new tool. However, since a written description is missing the real output it represents, it might lead to different interpretations among designers. Therefore, also an audio envisioning tool was created. This tool is further introduced in section 4.5.

Result
All the moments were collected in a form, shown in Figure 4.6. In this form, all moments previously described are represented together with some questions that were deemed to be helpful to be answered.


Macro/Object/ Product level
Micro/Feature/C omponent level
Design phase
Problem analysis
1. What is the overall experience
aesthetics
meaning
I describe the overall aesthetics of the product as...
If I would describe product as a person, this person is...
meaning
novel
typical
unity
variety
Select common component
Acoustics
Engineering
Material
Geometry
Mechanism
Order of events
Loud
Bright
Rough
High
Tonal
Quiet
Dull
Smooth
Low
Noisy
Loudness
Brightness
Fluctuation
Roughness
Pitch
Tonality
this description was given because of the following psychoacoustic features
Air
Alarm
Cyclic
Impact
Liquid
Mechanical
Breast pump
Novel
Typical
Meaning
Which steps are most interesting to look further?
The [sound category] is [typical/novel] for a [breast pump]
6. Reflect on analysis

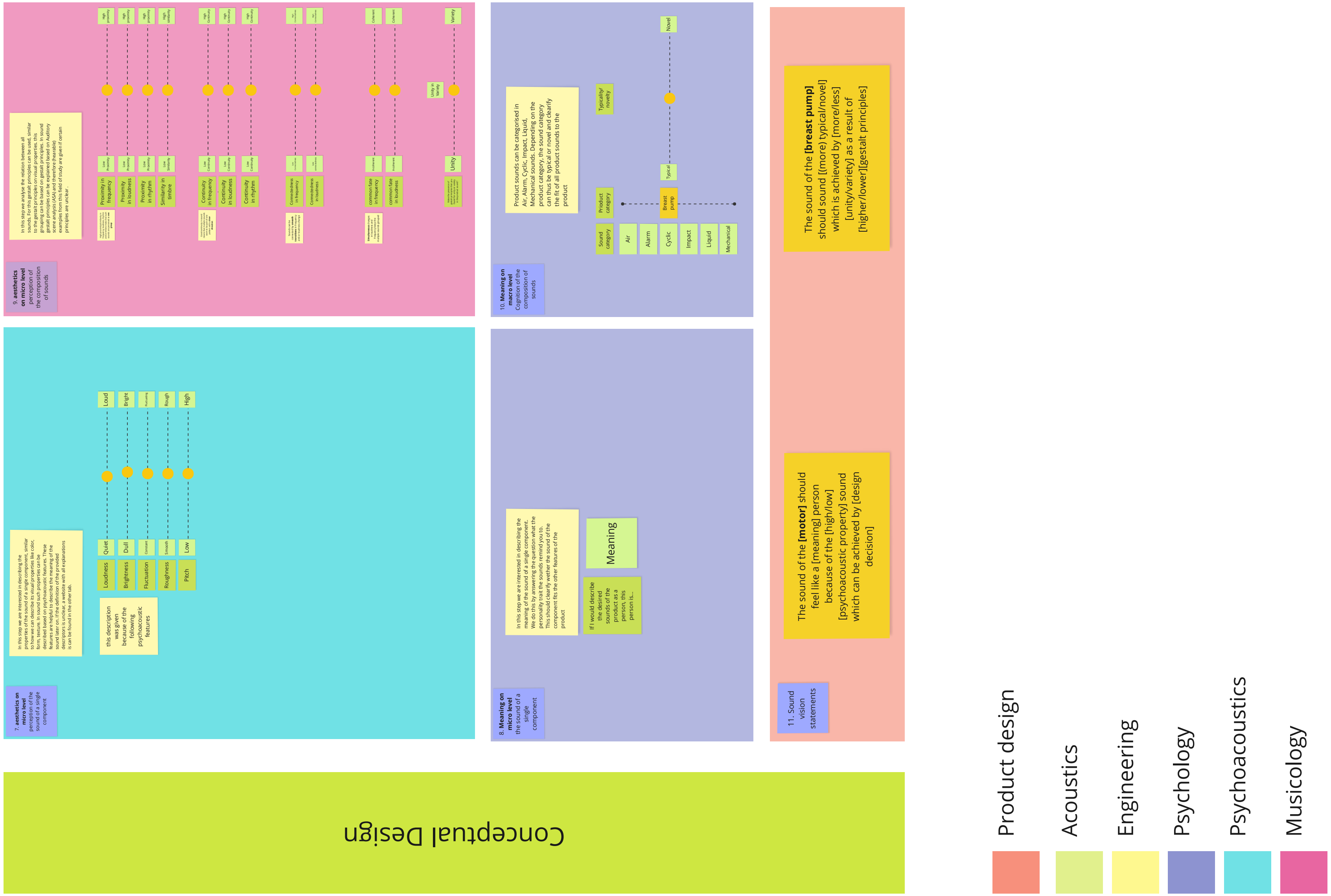


Figure 4.6: Initial framework for product sound design

4.5 Sound envisioning tool

Based on the finding from the literature research in chapter 2 that it might be helpful to have an audible reference when designing product sounds, a prototype for a product sound design tool (Figure 4.7) was made to accompany the framework.

This tool was designed in Reaktor (Native Instruments, n.d.). Reaktor enables the creation of digital audio processing software, by means of a visual programming language.

In the tool two samples of a product can be loaded. Samples of a Philips Breast pump were chosen since samples of this product were gathered while doing the Embodied Audio Design Elective. The audio of these samples can be processed in such a way that the relation between parameters that are included in the analysis and envisioning can be made audible with the sound of the product that is redesigned.

In the left part of the program the samples are provided as heard in the current product. A sample can be played by activating it. By enabling loop, the sample would be looped. Otherwise the sample will be played only once. The addition of this loop function was found convenient since the sound producing components inside the breast pump are repeating sounds and thus can be simulated while recording a short sample only.

The next section provides a short description of the parameters that can be changed with this tool.

Loudness
Loudness is controlled by a simple attenuator and in essence decreases the amplitude of the played sample.

Roughness
To influence the roughness, control over the attack and release of the sample is given. These are similar concepts as a fade-in and fade-out but over very short periods.

Pitch
To change the pitch a pitch shift, a slider is included that plays the sample slightly quicker of slower respectively increasing and decreasing the pitch.

Fluctuation
The fluctuation slider adds slight amplitude variation by means of a low frequency oscillator. The rate and depth slider influences the frequency and amplitude of this variation respectively.

Drawing panel
A drawing panel provides control over the brightness and the composition of sound events by means of drawing boxes.

By sliding the box horizontally on the drawing panel the left edge of the box defines the starting time of the sample and the right edge the total time of the sample.

A bandpass filter which cut-off frequencies are depended on the height of the box. The low-pass frequency is defined by the top of the box and the high-pass frequency on the bottom of the box.

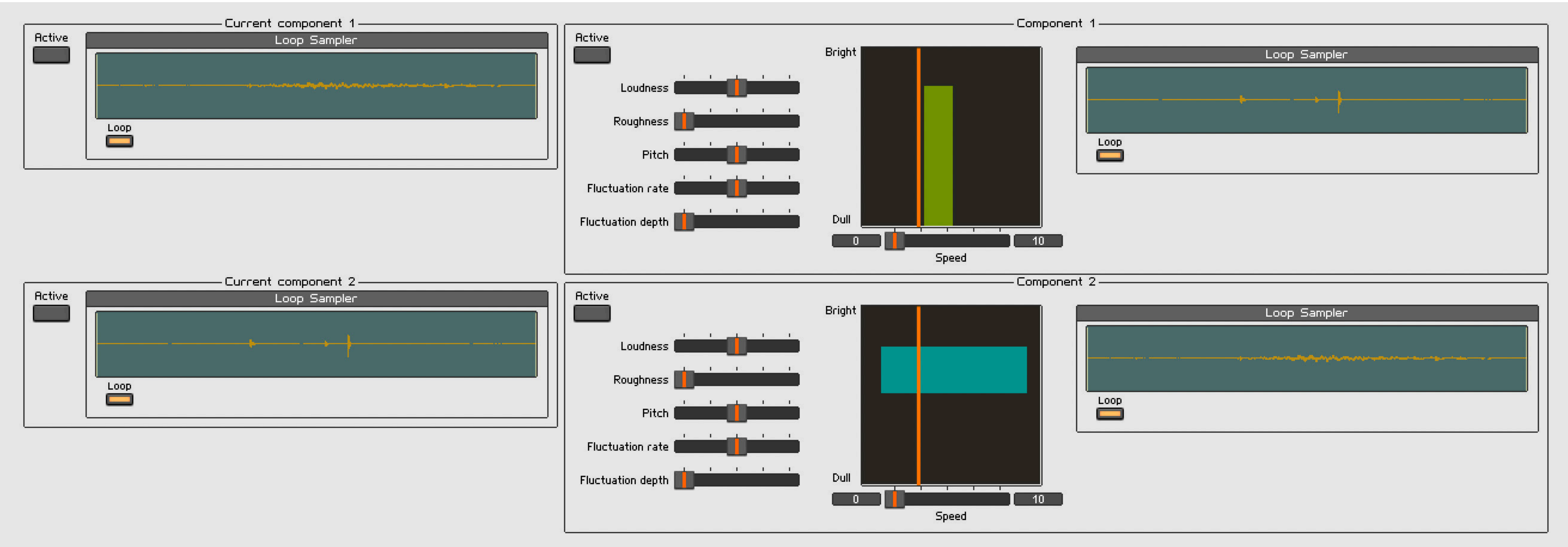


Figure 4.7: Prototype of product sound design tool

4.6 User test on framework

By means of a user research the usability of the framework was tested. This was done in the form of a semi-structured interview. The objectives of this test were to gain knowledge whether all sub-disciplines were ought to be relevant to the participants, whether the explanatory materials were sufficient and clear, and whether an audible sound vision is preferred above only a written one.

The outcomes of this research should lead to actions and directions which can be taken in the further development of the framework.

Method

A small number of interview questions were asked before and after use. These questions were included to gather the participant's current knowledge on product sounds.

In the second part of this research, participants were asked to use the framework in the analysis and envisioning of a Philips breast pump. During this task participants were asked to loudly comment the decisions which were taken in the use of the form and their initial reactions on the framework.

In the third and last part of the interview, participants were asked to reflect on the use, clarity, and coherence of the process that was followed and the tools that were used.

Participants

Five participants were selected between students from different programmes within Industrial Design Engineering at TU Delft and one master student Musicology, see Table 4.1.

Table 4.1: Overview of participants in user interviews

Participant	Study track	Experience with product sound design?
Participant 1	Industrial Design Engineering (Bachelor)	No
Participant 2	Musicology (Master)	No
Participant 3	Integrated product design (Master)	No
Participant 4	Integrated product design (Master)	Somewhat
Participant 5	Strategic product design (Master)	Somewhat

One participant (P2) mentioned to have an affinity with music and plays music instruments since a young age, but did not consider themselve to be an expert on sound or having any experience with sound design. One participant (P4) used sound as a use cue once in a design, but never followed a course on sounds in products. P5 mentioned to have followed a course in interactive audio design and podcasting.

Between participants the research was performed in three different ways. P1, P2, and P3 were presented the framework together with explanatory stimuli and with all concepts and properties fully explained by the researcher;

P4 and P5 were presented the framework together with the explanatory stimuli but would only get a short explanation on the general goal of each step and were asked to find out whether their questions could be explained by the explanatory stimuli only.

At last P3 and P4 were also presented an initial version of an audio editing tool, which was presented after they finished the same procedure as the other participants followed.

Stimuli & apparatus

All participants were given a recorded version of the product sounds of a Philips breast pump. To ensure all participants were listening to the same sound, all sounds were provided by means of digital recordings of the breast pump.

These recordings were done in stereo with a Thomann T-Bone SC140 condenser microphone. The samples of these recordings were provided in an audio tool created in Native Instruments' Reaktor DSP program (Native Instruments, n.d.). The output level of the audio tool was kept on its default level. The sound from this tool was played back on a Beyerdynamic DT 990 Pro (250 Ohm) headphone with a fresh pair of hygiene covers for each participant. The headphone was directly attached to the headphone output of an Apple MacBook Pro M3 with its system volume on 5 "blocks".

During the test, the users could interact with multiple explanatory stimuli, the main one being the form itself. The users also had access to the words4sound (Carron et al., 2017) website to get to know the definition of psycho-acoustic parameters.

Second to that ASA, examples were given in a summarising overview. If these ASA principles were still unclear, participants could listen to Bergman & Ahad's example. An overview of the setup is included in Figure 4.8

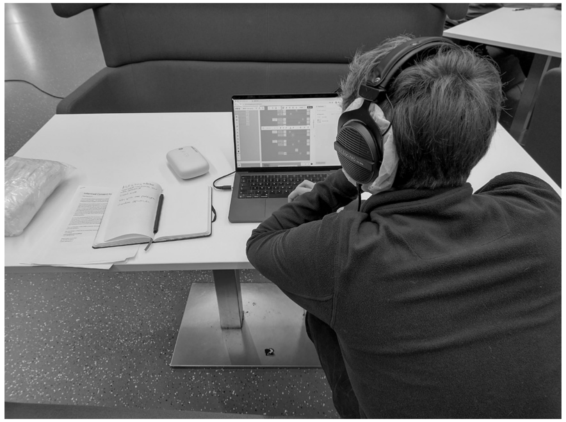


Figure 4.8: Research setup during user test

Participants were allowed to omit any question in the interviews and were able to stop their participation at any moment. Consent of participation was given by means of an Informed Consent Form.

Results

Moment 1: Psychoacoustics

In general, the psychoacoustic parameters in the sonic form expression were found easy to understand.

"Every psychoacoustic attribute is straightforward. If I found some attributes unclear, the examples on the site came out to be easy to use and understand." - P2

"The rating of the attributes on a continous scale was a bit ambiguous. I guess rating on a Likert-scale would feel more logic and less unambiguous." - P4

Moment 2: Sonic form expression

The question to describe a sound as a person gave little difficulties among all participants.

"Thinking about a character description on the sound makes the sound very tangible." - P3

"In general I like the character description for myself. But I do not know how useful this description is if you cooperate with a mechanical engineer, as it might be a too vague description for them." - P4

"The meaning is relevant and relatively easy to think about in this specific design as it is quite clear but it might be more difficult to answer for other products and sounds." - P5

At last, all participants at some point gave a character description in their native language. This presumes it is likely easier for the user to do the description of meaning in their native language.

Moment 3: Auditory Scene Analysis
All participants found it difficult to perform the ASA. Mostly, as the meaning of the different principles were found difficult to understand.

"Is frequency in this case the same as pitch or the rate in which multiple events happen?" - P1

"Do the principles described that happen in the sounds have to be compared between one sound or also within multiple sounds?" - P1

"The illustrations explaining ASA are nice, but there are many factors that have to be considered making it very difficult" - P3

Moment 4: Sonic typicality
From how categories currently are presented and decided it was not clear whether a sound can be multiple categories at the same time or not.

"It might be useful to first ask what type of product category the sound compared to its sound category is perceived, and based on that decide whether the cognition of the perceived product type with the actual product type is logical." - P1

Reflection
The reflection moment was found to be useful to decide whether the current sound fits the product and felt like a small break, keeping the process manageable.

"The summary was a good description of what the sound made me feel before the use of the form, and that it was helpful to decide whether the current sound fits product." -P5

"I would like to have a visual like a coordinate system to show the relation between the sound and the product." - P3

Vision statement
All participants mentioned the vision statement in a sentence to be a useful tool. However, both participants that did not use the audio tool (P1, P2, & P5) and who used the audio tool (P3 & P4) mentioned that an audible vision would even be more useful than a written statement only.

"I expect that the statement is not very useful in communication with people not directly involved in the creation of it, as it is too vague and might contain terminology that others will not understand." - P1

Participants also mentioned that introducing an audible vision should be introduced with care into a design project.

"An audible vision might induce the principle of fixing too much on a solution that you like early in a design stage, but which eventually might not be the perfect solution if the project is finished. If an audible vision is presented, I would like it to be quite flexible so that it can evolve and be adjusted in multiple iterations in a design project." - P4

"A too concrete vision could result in the same way as using 3D modelling in early design stages, creating a feeling of a client or jury that the design is fixed and done and cannot be changed." - P5

Discussion

During the length of the test, participants used multiple descriptions for sounds. Sometimes, the descriptors used seemed similar to psychoacoustics descriptors as asked in the framework in the micro aesthetics level. However mostly not exactly the same descriptor was used, creating ambiguity in what descriptor the participant said and what quality was meant.

From this, it can be concluded that using a strict vocabulary is essential. The descriptors and explanations by Carron et al. (2017) proved clear. However, the user should be made aware to solely use this vocabulary. In this repetitive use of such a vocabulary might be essential but was not tested in this study.

Together with the psycho-acoustic descriptor, providing a character description to describe the product sound introduced little difficulties, and was considered to make the description more tangible. However participants sometimes based this description from the entire sound of the product instead of a single component.

That audible examples in ASA were rarely used, might be the result as they were available in a different full screen window than the window in which the form was presented.

But in general, the main comments on Auditory scene analysis was that included many factors to take into account. Some attention should be paid how ASA relates to the other aspects in the framework, and it is likely more usable if it is provided by even more generalised principles.

All participants were students and had no experience with a breast pump. This made it difficult for participants to decide whether the product was novel or typical. Second to that participants found it difficult to decide whether the typicality had to be considered from a single component or the product as a whole.

With this fact that typicality could be considered on micro level as well, together with that a character description of a sound could also be done on a macro assumes that the separation of micro and macro level is probably too ambiguous, in the currently presented context.

All participants, both participants that were not presented the audiolisation tool (P1,P2, & P5) and participants that used the audiolisation tool (P3 & P4) did mentioned that having an audiolised version of their defined design requirements would be helpful in a sound design process. Therefore, a takeaway is that the framework should lead to enable the creation of audible references of product sounds.

The audio tool in this research showed some potential but Reaktor was found limited in the design of the User Interface. Therefore, it could be interesting to switch to MAX MSP (Cycling '74, 2022). Similar to Reaktor, this software enables the creation of sound processing systems. Compared to reaktor, MAX is directed more towards the creation of general digital interactions and thus should provide better customisation of the user interface.

The relation of the product sound to the rest of the design process should become clearer. Suggestion were done to either provide design/prototyping suggestions that likely result in the envisioned sound or provide the audible vision as an evolutionary tool which can become more concrete in later design stages.

Combined with the decision to focus more on other aspects of a design as well, other than mostly focussing on the experience of the product sound, the goal of such a tool should be to be helpful in the audiolisation of the effect of design changes from multiple perspectives.

In order to make the framework cover more implications of the product sound from multiple perspectives, other than mostly the experience of the sound, the framework should be adjusted. Even better would be if the framework could show how one discipline translates to the other disciplines.

4.7 Product sound design framework

In this section the framework (Figure 4.12) is elaborated that was designed after the user test as described in the previous section.

The final framework addresses the relation between disciplines and what implications they have on the functionalities that have to be included in a tool that allows the audiolisation of product design visions.

The final framework differentiates three levels of detail: feature, object, and scene (Figure 4.9).

Figure 4.9: Feature, objects,scene levels for a shaver

This differentiation was chosen to incorporate separation in levels of detail between multiple fields.

In engineering a product consists of components as part of a sub-assembly and multiple sub-assemblies form an assembly, the final product. Separate levels also play a part in the product sound model: source, radiation and transmission inside product, and radiation to the user (Langeveld et al., 2013). And Özcan (2016) proposed that product experience can happen on a micro, macro, and meta level.

Feature level
In the feature level, all effects that are relevant to a single sound source are included. In engineering, this could be a single component or sub-assembly. But this level also entails the acoustic and psychoacoustic qualities that result from it. Which on their own influence the experience of meaning on micro level.

Object level
In the object level, the composition of the sounds together. But also features that influence psychoacoustics qualities of all other features, such as the effect of how the engineering of the housing influences the acoustics of a product as a whole.

Scene level
Finally, in the scene level external implications on the product sounds are considered. This could be the user-product interaction but also the effects of the location in which the product is used (Özcan, 2014).

Psychology

From psychology, three questions that should be answered with the framework are:

FIrst, what is the meaning of the feature? To address the appropriateness of the perceived sound quality of a feature to the object.

The second question is whether the sound category fits the product. To address the relation between the sound of the object and its other qualities like its visual appearance.

And the last: does the sound fits the context? To consider multiple situations and locations which might change the user needs (Suzini, 2019).

Acoustics engineering

Component selection is one of the factors considered from engineering. This initial selection has an implication on the source type, which on its own has a large influence on the acoustics of the sound (Langeveld et al., 2013) but also in sound categorisation (Özcan & van Egmond, 2008).

Material selection is another factor from engineering that has an influence on the sound of products. The acoustic properties of materials can be used to calculate how changing material properties of connector parts will influence the transmission, and reflection of the sound of the source (feature) to the rest of the product (object).

Materials can also influence the absorption- and radiation capabilities of a housing (Flipsen, 2022). Thus a combination of formulas describing the proportional change of acoustic qualities due to material changes can be used in predicting the influences of engineering decisions on the sound quality in different levels.

Psychoacoustics and musicology

Auditory Scene Analysis is used to incorporate sequential grouping and simultaneous grouping effects. Instead of multiple only the two basis principles are considered, being the spectral- and temporal relation between two sound features in a sound object (Bregman, 1990).

Working further on the work of Pierre Schaeffer (Smalley, 1997) and Thorensen (Thoresen, 2004) how sound events can be notated similar to music notation with spectromorphology.

However, instead of describing musical qualities, spectromorphologic notation separates features in a composition based on descriptions similar to psychoacoustics qualities like brightness and fluctuation. This means that the psychoacoustics qualities could be useful in compositional sense.

In order to take into account the spectral relation between multiple features in the object level.

Within the composition of temporal relations, Thoresen (2004) differentiates three types in which the energy of events can occur, being: impulse (a short thrust of energy), iterated (discontinuous thursts of energy), and sustained (continuous energy). It can generalise the types of excitations of a sound source as proposed by Langeveld et al. (2013).

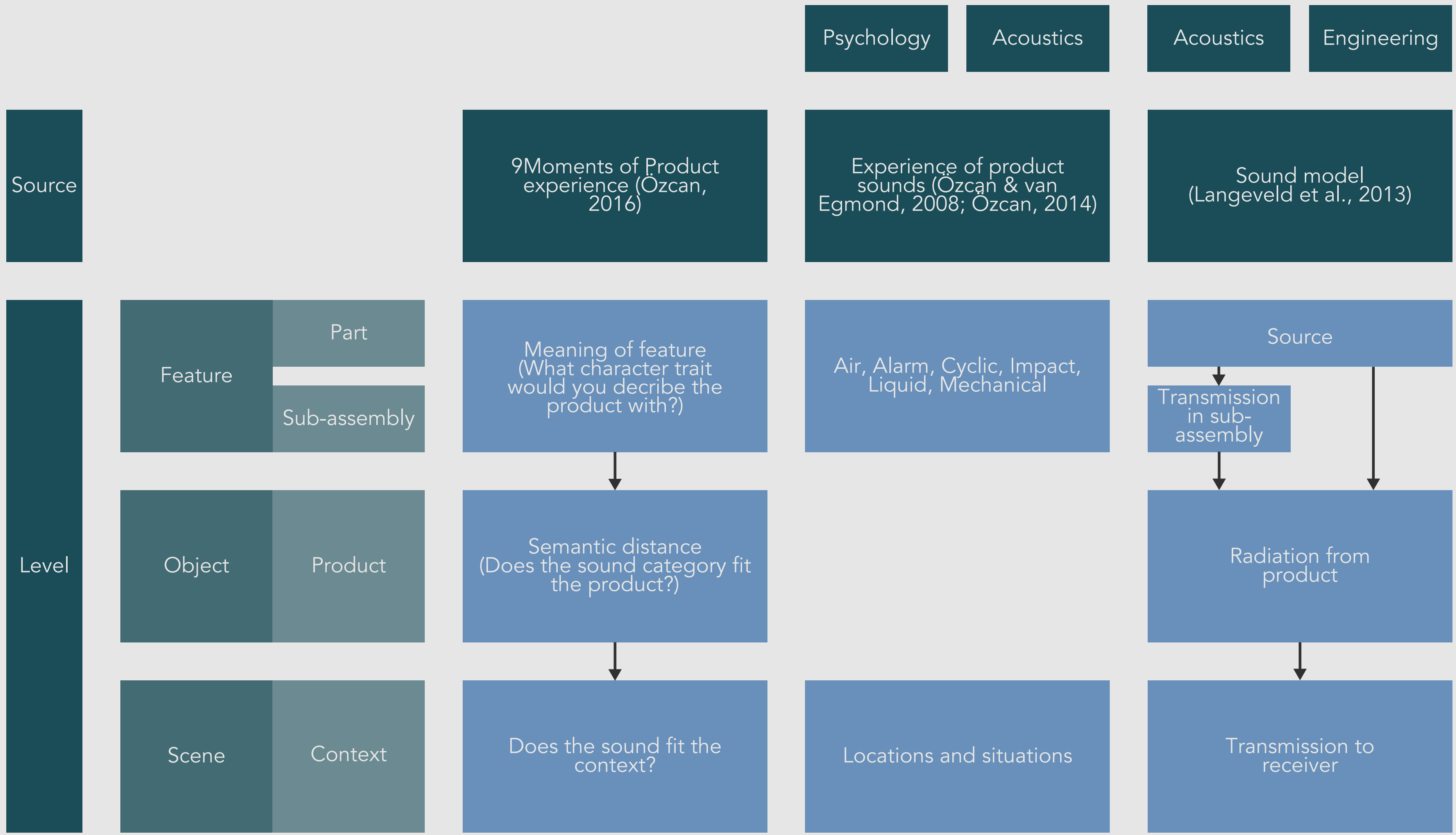
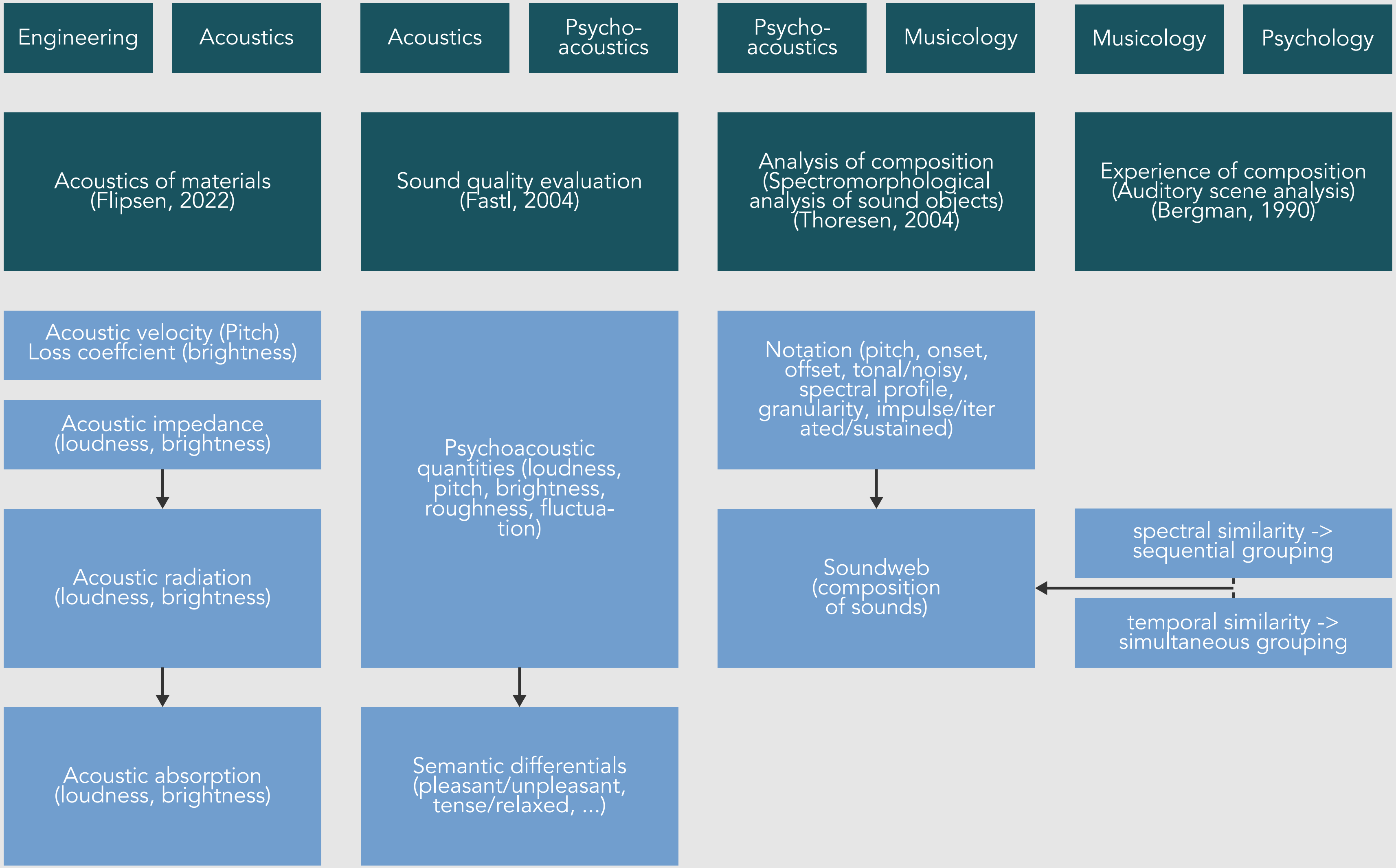


Figure 4.12: Final framework


Engineering
Acoustics
Acoustics
Psycho-acoustics
Psycho-acoustics
Musicology
Musicology
Psychology
Acoustics of materials (Flipsen, 2022)
Sound quality evaluation (Fastl, 2004)
Analysis of composition (Spectromorphological analysis of sound objects) (Thoresen, 2004)
Experience of composition (Auditory scene analysis) (Bergman, 1990)
Acoustic velocity (Pitch) Loss coeffcient (brightness)
Acoustic impedance (loudness, brightness)
Acoustic radiation (loudness, brightness)
Acoustic absorption (loudness, brightness)
Psychoacoustic quantities (loudness, pitch, brightness, roughness, fluctua-tion)
Semantic differentials (pleasant/unpleasant, tense/relaxed, ...)
Notation (pitch, onset, offset, tonal/noisy, spectral profile, granularity, impulse/iter ated/sustained)
Soundweb (composition of sounds)
spectral similarity -> sequential grouping
temporal similarity -> simultaneous grouping

4.8 Conclusions on product sound design framework

To include sound in a design process, it has to be included as early as possible. This made the analysis phase interesting to introduce students into the field of product sound design.
By looking at the current design processes it was found that in the analysis phase it is useful to enable the gathering of design goals. However, current methods only consider a single aspect or area of expertise in the design of product sounds.

Using such methods is thus impractical in a product design process, since requirements from one field do not directly translate to requirements on other fields. Second to that requirements between fields could even oppose each other.

A framework was proposed where all viewpoint are considered together and consensus has to be found within them. This is expected to occur when a single framework is used by a designer or within a design team.

The framework not only enables to consider the product sound from multiple disciplines but also from three separate levels: feature, object, and scene. This separation was introduced to include the dependence of design implications of one element to other elements.

For engineering and acoustics this means the sound of a single feature, a component or sub-assembly, can be differentiated from the implications of the housing, the object, has on the sound. At last this using knowledge from this field can help in understanding how room acoustics, the scene, influence the behaviour of the sound as well.

For psychoacoustics and musicology this differentiates the qualities of single sounds of features and how multiple sounds together form a composition. And for psychology it differentiates the experience of the isolated sound but also in comparison to the entire product and whether that experience is still suitable in certain locations and situations.

From the user research it became clear that a better understanding of the implications of these requirements is necessary. This is likely found when the implications of possible changes to the product sounds are made audible, together with an providing direction for further design phases. As such, the framework serves as a foundation for a tool with which audible product conceptualisation can be done. This is further elaborated in chapter 5.

5.Les_Sons

Based on the notion from chapter 4 that interacting with sound will help in understanding how to design a product sound, a digital audio editing tool was made. In the first part of this section it will be elaborated how the framework was used as input for the tool. In the second part the tool is explained in more detail. In the next chapter the evaluation and discussion of the tool is given.

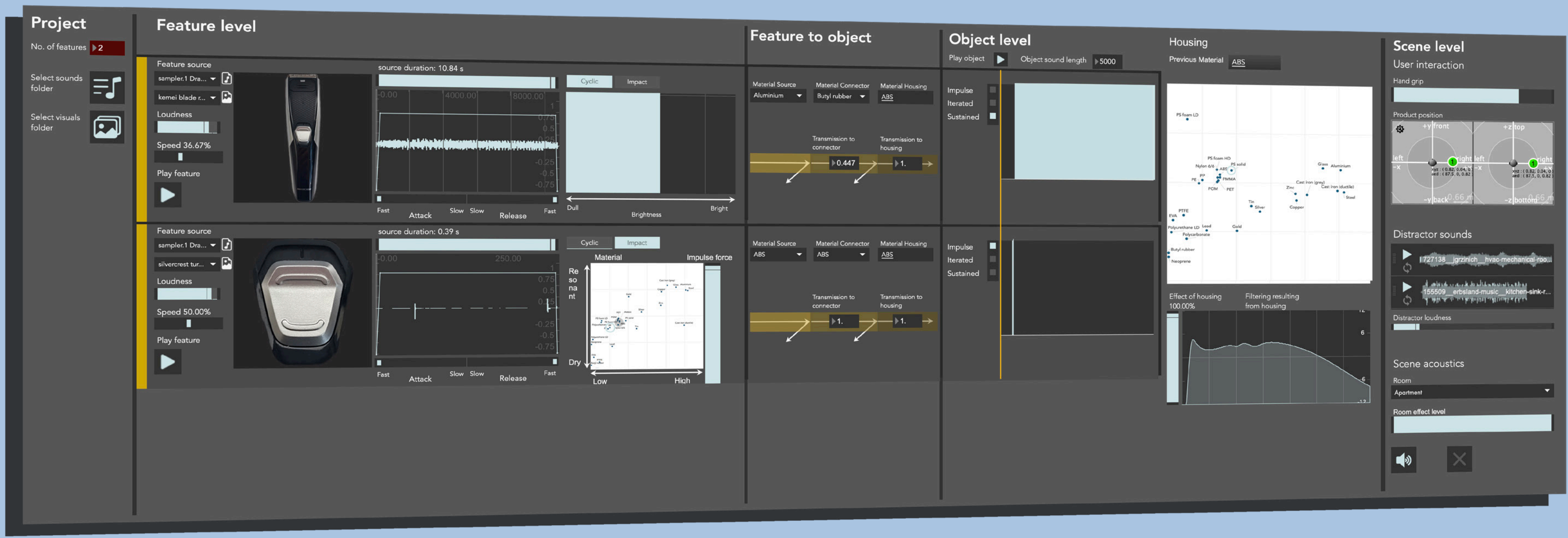


Figure 5.1: The Les_Sons product sound sketching tool.

5.1 Functional overview

The main objective in the design of Les_Sons was to put the framework from chapter 3 in a concrete context. This should ensure that the tool covers some knowledge of all the disciplines that were ought to be relevant in the design of product sounds.

In general, this implies that the order in which the design of product sounds with the tool is approached in a similar order as how sound travels as described in the product sound model from Langeveld et al. (2013).

On feature level, the selected psychoacoustic qualities can be influenced by means of "design decisions" resulted from engineering.

In the object level, the features are considered as an event in the entire product, allowing the designer to compose a sound web. This also allows features to be played simultaneously or sequentially with which principles from Auditory Scene Analysis can be taken into account.

It is also in this level that the influence of the housing is added, as the housing generally influences all features in a product.

To let the user test whether the resulted object sound still fits the product during use, user interactions can be modelled as well. This is done both for the filtering effect of users grasping a product and the effect spatialisation of the object sound relative to the user.

The last two effects that can be modelled are on the environment in which the product is used. Any other sound that can be heard in the use environment can be added. And these distractor sounds together with the designed object sounds can be virtually placed in a room.

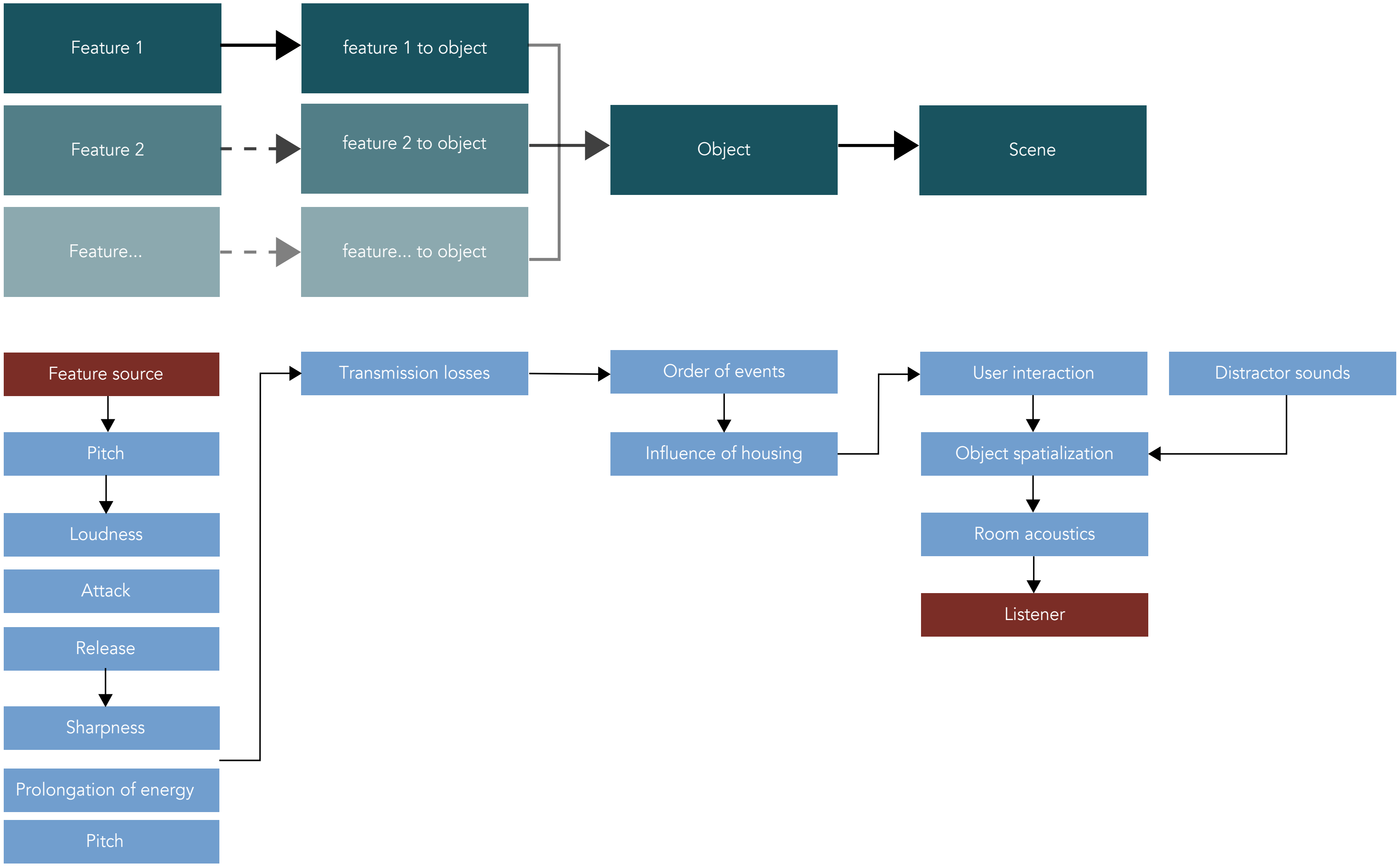


Figure 5.2: Schematic overview of the product sound design tool, showing the order in which the audio will flow.

5.2 Educational Requirements

Since the focus of the framework was directed towards the analysis and conceptualisation phase of a design process, a goal of the tool is to be abstract enough to be creatively usable. But concrete enough to gather some requirements or directions that can be used in further phases in a design process. This results in a requirement on the design of the tool to keep the tool-set relatively limited.

This limited tool-set probably makes it easier to be implemented in design project courses in a sense that little as possible attention has to be given in learning a new tool, but rather learning a new skill. Secondly, a limited tool-set is expected to distract the designer less from the original project. Reducing the risk of the sound designer to endlessly tweak parameters compared to other sound design software that provides a broader range of functions (Delle Monache et al., 2018).

In order to make the tool accessible to a large audience, the decision was made to freely distribute it as open source software. This will also enable contribution from others to the tool. In this way, a library is likely to grow, increasing the capabilities of the tool.

The decision to make the tool to be free and open source adds the requirement that the dependencies of the tool must also be free and open source as well. Care must be taken in the selection of sources. It is important to know. And whether the license allows for open redistribution. And whether open distribution should credit the original author, it can be an adaptation of its original source. And also whether adaptations should be shared under the same license, such as the relevant choices between Creative Commons licenses (Creative Commons, 2019) alone.

To enable access to the tool and open source collaboration, all sources will be provided on GitHub (GitHub, 2024).This applies for all dependencies meaning the software of the tool itself but also external such as samples and impulse responses. To access the GitHub repository either the link or QR code below can be used.

https://github.com/Timdeltrap/Les_Sons

5.3 Deep dive

In this chapter, the Les_Sons will be elaborated in more depth. This is done by looking at smaller portions of the tool.

5.3.1 Feature level

Sound sources
In the tool the sources for sounds are samples. These samples are recordings of separate product features. To capture the sound of the features the products were disassembled (Figure 5.3).

This enables to record sound sources without influence of other features, and also gave insights which components are present and could uncover unexpected sound sources. These recordings were made after calibration of the microphone, after which the microphone was kept stationary. This enables to keep the relative difference in loudness between components in different recordings. Appendix VI describes this calibration process and source gathering more in-depth.

An initial library with a collection of feature sounds of five different shavers sound was created and can be loaded in the tool.

Figure 5.3: Disassembly of a shaver

Speed slider

A speed slider was added to make the pitch go down if the sound is played slower, or go up if the sound is played faster. This is analog to how for example the pitch of a motor is dependent of their rotation speed (RPM) or the pitch from air flowing faster or slower in a tube. On top of that, by increasing or decreasing the playback speed the roughness is influenced as well, since temporal qualities of the source are changed as well.

Amplitude envelope

An amplitude envelope (Figure 5.4 & Figure 5.5) is used to define the maximum loudness of the source, its attack and release. With this, the amount of energy put in a system can be modelled.

The attack is the time needed before a sound reaches its maximum sound intensity. This is mostly in the order of microseconds. In mechanical sense, it is dependent on how quickly energy is put into the system.

Release is similar but for a loss in energy. A short release time will be a system that quickly releases energy and a system that releases energy more gradually would have a longer release time.

The main intention of adding attack and release is to influence the roughness of a sound. However, if a relatively long sample is used with a long attack and release time, the effect might be experienced more as fluctuation as well.

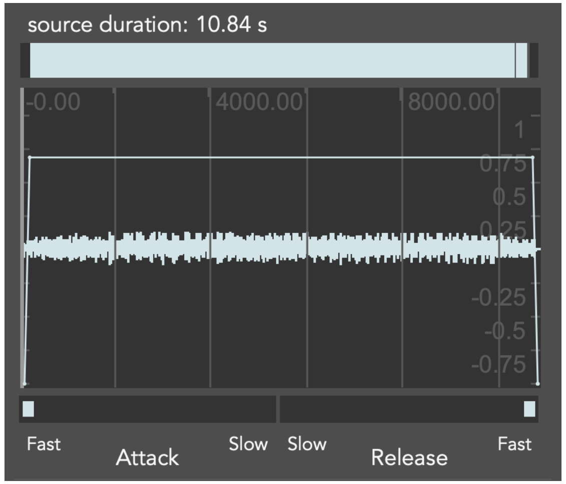


Figure 5.4: Fast attack and release envelope.

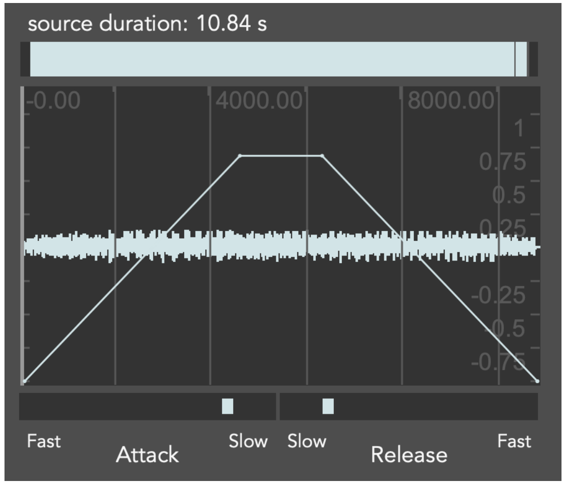


Figure 5.5: Slow attack and release envelope.

Cyclic sources
For sustained sounds, spectral qualities can be influenced with a bandpass filter (Figure 5.6). In this bandpass filter both the low- and high pass frequency is independently selectable. This is implemented by cascading two svf~ filters, one in high-pass mode and the other in low-pass. This bandpass was added to let the user test whether a more bright or dull sound might be more pleasing.

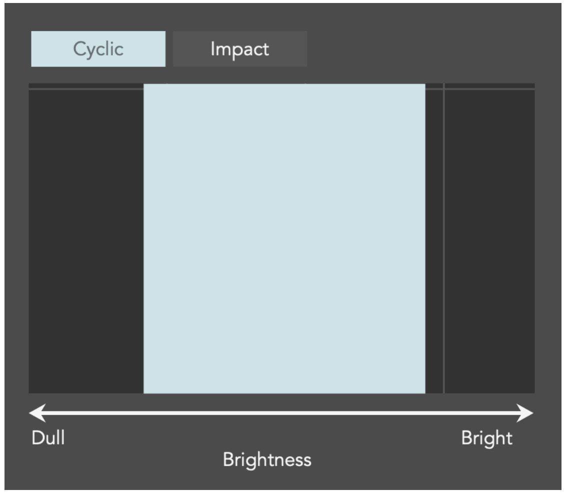


Figure 5.6: Adjust brightness for cyclic sources.

Impact sources
The brightness of impulse sounds is modelled with a Biquad~ filter in peak notch mode. This filter was chosen as this filter only affects a region close to the selected frequency, similar to the influence of the acoustic velocity of a material.

Second to that, the Q factor of a peak filter defines a damping behaviour analog to the loss coefficient of a material has on an excited impulse sound (Laughlin et al., 2008).

The loss coefficient is a material property that indicates the rate in which the material dampens a sound (Fletcher & Rossing, 1991), making glass sound ringing while rubbers sound muffled (Ashby, 1999. The exact Q factor can be derived from taking the reciprocal of the loss coefficient (Ashby, 1999).

Table 5.1: Properties of a selection of materials and their acoustic velocity (Ansys, 2023) and Q factor

Material	Density [kg/m³]	Young's modulus [GPa]	Acoustic velocity [m/s]	Loss coefficient [-]	Q [-]
ABS	1.045e3	2.42	1520	0.0167	60
Aluminium	2.7e3	69.0	5055	0.0011	952
Glass	2.24e3	46.0	4531	0.0008	1227
Neoprene	1.265e3	0.001875	38	0.1150	9
Polyurethane LD	1.2e3	0.1625	116	0.0750	13
Steel	7.9e3	210.0	5156	0.0011	909

Moving the slider vertically over the material graph (Figure 5.7) adjusts the corresponding Q factor of the filter. To define the frequency of the peak notch filter, first the ratio between the acoustic velocity of the material of the original sample and the acoustic velocity, defined by the horizontal position of the slider, is calculated. Then the fundamental frequency of the original sample is specified by the analyzer~ object (CNMAT, 2022). The product of the fundamental and the difference ratio in acoustic velocity eventually defines the frequency of the peak notch filter, and thus what pitch the impact sound will have.

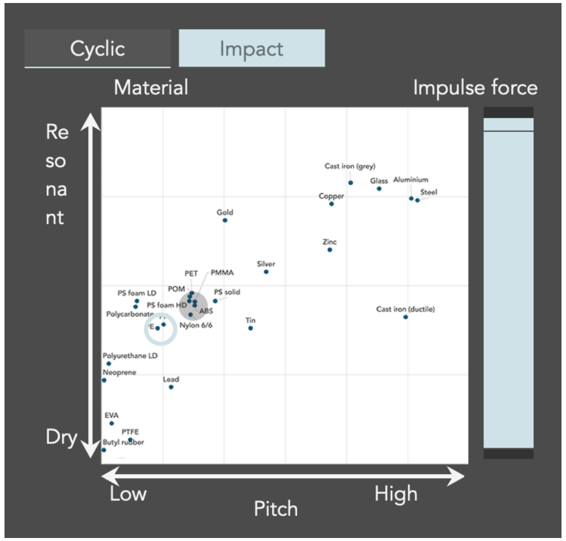


Figure 5.7: Adjust pitch and brightness for impact sources.

5.3.2 Feature to object

Also, in the transmission from the source of a feature to the rest of the object some sound changes can happen. This is mainly due to difference in materials in the connection between the sound making feature and the rest of the product i.e. the housing.

This difference in materials affects what part of the sound is transmitted from the first to the second material and what part is reflected, and thus has an influence in the resulting sound intensity. The amount of energy that is transmitted from the source to the object can be calculated with the transmission coefficient.

$$T = 1 - R$$

Where R is the reflection coefficient which can be derived from the following formula

$$R = \left(\frac{z_2 - z_2}{z_2 + z_1}\right)$$

The z_1 and z_2 in the formula above are the acoustic impedances of the materials. Which in respect is the material of the source and the material of the component to which the sound is transmitted to. The acoustic impedance is the resistance a sound wave experiences when travelling through this material and defined by the square root of the density of the material times its Young's modulus.

$$z = \sqrt{\rho E}$$

In "Material, Engineering, Science, processing and Design"(Ashby, 2014) an overview is given of the acoustic impedances of a small number of materials. In Les_Sons the impedance mismatch effect is generalised. This is provided by a material selector which calculates the resulting attenuation from a difference in impedance in a selection of materials between the source, a connector component and the housing might have (Figure 5.8).

Table 5.2: Properties of a selection of materials and their acoustic impedance (Onda Corporations, 2020) and radiation factor (Ansys, 2023).

Material	Density [kg/m³]	Young's modulus [GPa]	Acoustic impedance [MRayl]	Radiation factor [-]
ABS	1.045e3	2.42	2.33	1.45
Aluminium	2.7e3	69.0	13.6	1.87
Glass	2.24e3	46.0	10.1	2.0
Neoprene	1.265e3	0.001875	2.1	0.030
Polyurethane LD	1.2e3	0.1625	1.38	0.097
Steel	7.9e3	210.0	40.7	0.65

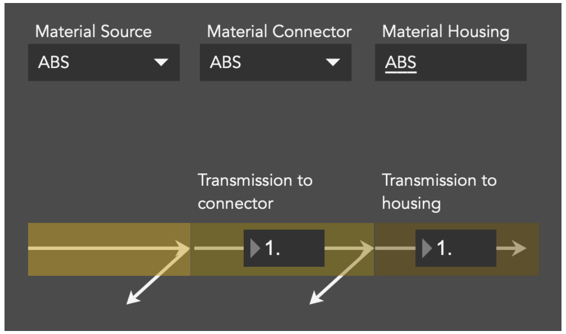


Figure 5.8: Modelling of attenuation due to acoustic impedance mismatch in the tool

5.3.3 Object level

Composition of sounding events

To start composing, first the total use time has to be defined. After that, the composing of events is slightly dependent on the type of excitation of the source. The type of excitation for each feature can be selected between: Impulse, Iterated and Sustained.

An impulse sound is a short impulse of energy that can take place at any time during the composition. An example of an impulse sound could be a button that is pressed.

Iterated sound consist of discontinuous bursts of energy and are relatively similar to impulse sounds. However, the sound is occurring in an interval.

A sustained sound is a continuous burst of energy. During composing the time at which this sound is present can be selected by sliding a slider to define the begin and end time. An example of a sustained sound is an electro motor.

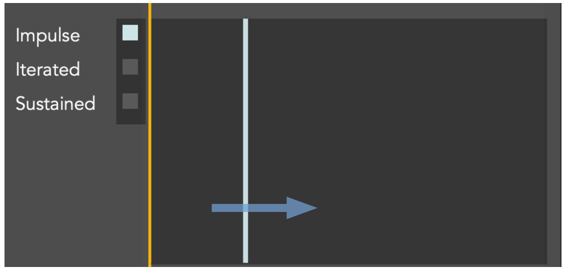


Figure 5.9: Composition with impulse sounds

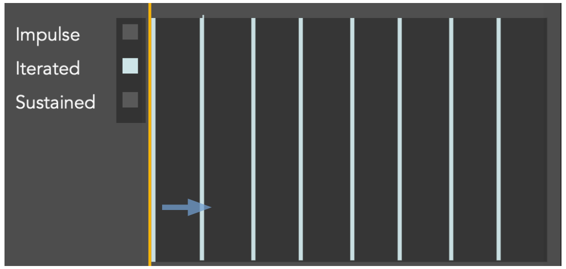


Figure 5.10: Composition with iterated sounds

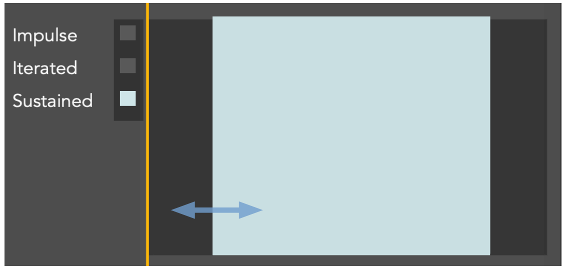


Figure 5.11: Composition with sustained sounds

Influence of housing

The mass and stiffness of a product's housing influences the brightness and loudness of all features inside the housing. Therefore, it was decided to introduce the housing in the object level rather than a feature. The effect of placing a housing over sound sources is modelled with a Cascade filter. With a cascade filter the effect of multiple filters is combined into one filter.

The parameters of the individual filters is based on the difference in spectrum between a recording of one of the shavers complete sound and a recording of the motor only. Thus, a rough estimation of the filtering characteristics of the housing can be applied to feature sounds. A more detailed description how this was done is included in Appendix VII.

For surfaces, like the soundboard in a guitar, the radiation factor specifies the intensity of sound radiation. In the case of products, the housing acts like a soundboard. The radiation factor is the square root of the Young's modulus of the material over the density cubed (Ashby, 1999). By taking the ratio between the radiation intensities of two materials the resulting level change in dB can be calculated (Sengpiel, n.d.).

The radiation intensity is implemented in the tool by a similar material graph (Figure 5.12), as used in the brightness change for impulse feature sounds. However, in this case the vertical position specifies an overall boost or cut in the cascaded filters for the housing.

By sliding horizontally, the difference in acoustic velocity is taken into account and moves the frequencies of the cascaded filters accordingly, and thus models a change in brightness.

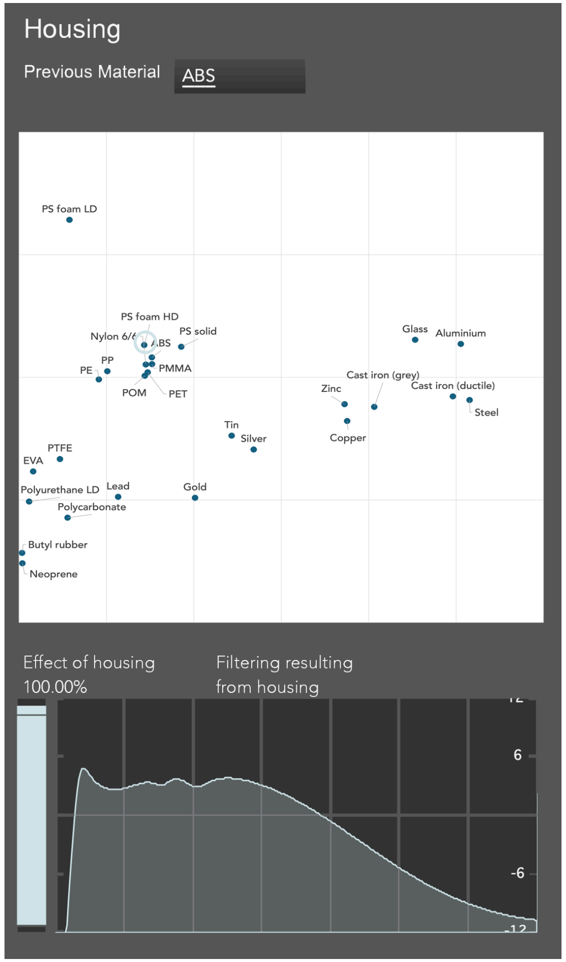


Figure 5.12: Simulating influence of housing with material graph.

5.3.4 Scene level

In the scene the product is considered within its context of use. This can be the influence of the user on the product but also the environment in which the product is used. For sound this means how the user interaction changes the sound, other sounds that are present in the scene and the acoustics of the environment are relevant.

Sound influencing product interactions

Some interactions between the user and the product can influence the sound of the product as well. An example is the hand of the user grasping a product firmer or less firm. This could also be the product and other products or objects such as resonance created by a table.

In the case of a user grasping a product, the hand adds mass and stiffness introducing influences on the object's brightness and roughness. As a result, the interaction of grasping is modelled in a similar way as the object's housing. This time the difference in spectrum between a shaver in free air and firmly held in a hand was used.
It was found that the influence of the hand is similar to adding both a high shelf cut filter and a low shelf boost filter. Again, a cascade filter was used to combine the effect of both filters as shown in Figure 5.13.

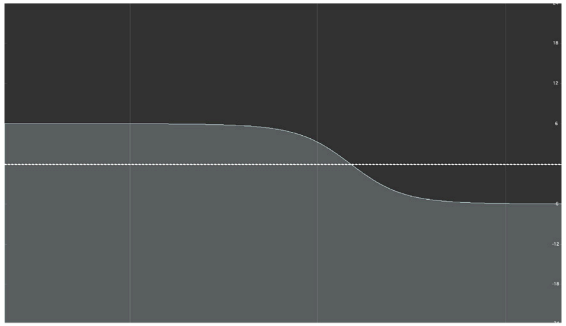


Figure 5.13: Filtering effect of hand gripping on object.

Positioning of object in scene
Modelling the perception of the location of the object's sound relative to the user was another feature that was found to be useful to model the user interaction with the product.

A helpful tool to provide this was found to be the spat.pan~ module, Figure 5.14, from the Spat5 library for Max(IRCAM, n.d.).

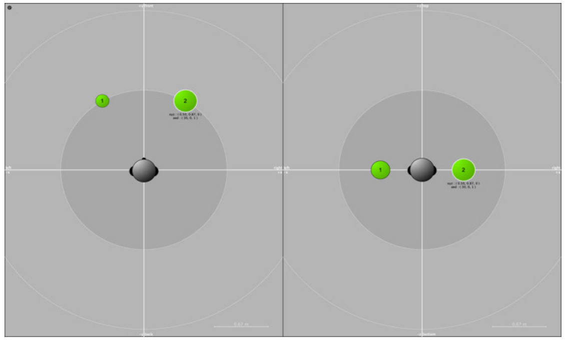


Figure 5.14: Virtual source and listener in Spat5 (IRCAM, 2013)

This module can take any sound source and spatialise it in 3D around a human head. To achieve this, a virtual sound source, in our case the object, can be placed left/right, in the front/back and above/below a virtual listener. The spat.pan~ then processes the sound as if it were recorded with a binaural head microphone. This results in the sound seemingly placed somewhere around the user. To hear this effect best, it is recommended to listen back using stereo headphones.

Distracting sounds
Adding other sounds that are normally present in the scene can add to a more realistic experience. Second to that, the presence of multiple sounds could lead to masking, as mentioned in ASA, meaning that the product sound might blend in easily in the scene as it is masked by other sounds that are louder and covering the same spectrum. But it could also mean that use cues are missed because the environment is too loud or vice versa.

Since designers have little influence on such external noises, the customisability when such sounds are used in the tool can be low. It was decided that such sounds can be provided as samples with few parameters that can be adjusted (Figure 5.15).

Figure 5.15: Sample of distractor sounds loaded that could be heard in a bathroom

To reduce preparation time, distractor sounds are proposed to be gathered from sound databases like freesound.org (Freesound, n.d.). Freesound provides a collection of free and open licensed samples.

It contains multiple recordings of soundscapes such as people having a conversation in the background, or street sounds as heard from inside a house, but also product sounds such as a tap running in a bathroom.

Room acoustics

A last aspect that is considered in the scene is room acoustics. This entails the reflection and absorption of sound by walls in a room influence the reverberation (complex echo) and influence the perceived loudness and brightness of the object. Making the room acoustic an important influence in the transmission of sound from the object to the user in the model of Langeveld et al. (2013).

The reverberation of rooms are modelled using a convolution reverb from the HISSTools max library (Harker & Tremblay, 2012). In a convolution reverb, the signal you want to apply reverb on is convoluted with the impulse responses (IR) of a system (in this case the impulse response of a room). More easily said, after the convolution processes, the sound is perceived as being played in that room. The ASH listening set (ShanonPearce, n.d.) provides a collection of impulse responses of different rooms. These range from apartment-like rooms to office conference rooms and lecture halls. The interesting point of this set is that it was created to train AI models on realistic room acoustics, for purposes of 3D spatialisation in virtually reality.

This is in contrast to some other free and public libraries of IRs, such as Open AIR (Murphy & Stevens, n.d.), which are mainly intended for music production. These provide IRs that are musically interesting, but uncommon spaces with long reverberation times such as in caves and tunnels.

To make all the sounds in the scene sound as one being present in one space, both the object and distractor sounds are run through this convolution reverb.

5.4 Conclusions on Les_ Sons

Les_Sons, a sound editing tool was designed to enable the conceptualisation of product sounds. The main goal of this tool is to be accessible to IDE students. As a result, it was decided to provide a library of pre-recorded calibrated product sound samples. This allows for an immediate start, lowering the threshold to work with sounds.

By means of digital sound processing, these samples can be adjusted. This processing is immediately audible and should provide a clear connection between the adjusted parameters and its result.

Second to that, each sound processing object should exemplify an aspect or part of an aspect that was found to be relevant in the framework from chapter 4. As a result, this processing is done in three levels allowing to adjust the sound of individual components, the total sound of the product and add the product in a location and apply external factors.

Where appropriate, the processing of objects is modelled on formulas from the field of acoustics and engineering, giving insight in possible directions for later stages of embodiment.

Les_Sons also provides some objects that influence the experiential qualities of the sound to explain aspects from psychoacoustics, psychology, and musicology. It enables the creation of a reference sound for subjective evaluation while providing the vocabulary to explain why the sound is experienced as it is.

6.Evaluation

This chapter evaluates the Les_Sons audio tool. This was done by two types of user research. The first research tested whether the tool provides enough freedom for creative exploration while being limited enough to quickly design a sound after an objective. In the second user research a new group of participants was asked to team up and the tool was used in a team consisting of an Industrial Design Engineering student and a Mechanical Engineering student, in order to test whether the tool provides the creation of a reference sound close to an objective goal while staying true to technical limitations.

6.1 Evaluation of creative freedom

The objective during this evaluation is to test whether the tool provides enough creative freedom while being concrete enough to design a sound based on an objective. This was done by means of a qualitative research in which participants were asked to use the tool and design a sound based objective and speak out loud their motivations and experiences on in how to achieve the goal. An additional element of this research was to derive recommendations how the usability of the tool could be improved.

The tool provides multiple parameters that have implications on the acoustics of a product. Since some changes between multiple parameters might result in a similar change of psychoacoustic qualities, it is expected that different settings could result in a similar result of psychoacoustic quality of the whole sound object. Therefore, high similarity is expected when the resulting sounds within one design objective are compared.

Second to that, when giving a new assignment with a different objective, the tool should provide enough creative freedom to produce distinguishable results. As a result, high variety in psycho-acoustic qualities is expected when resulting sounds are compared between two different design objectives.

Method

All participants were briefly introduced to the goal of the research. To make participants aware of all features of the tool, participants were guided how every sub-part of the user-interface works. After this introduction, participants were asked to perform a sound design assignment with the tool. In this assignment participants were divided in two groups. P1 was asked to design two shaver sounds. With the first sound being: *"An aggressive shaver used in a small bathroom"*, And the second sound: *"A sensitive shaver used in a large bathroom"*. All other participants were asked to recreate these two sounds as best as they can.

The participants that were asked to recreate sounds were able to listen back to the reference sounds as often as preferred. During the sound design assignments, all participants were asked to speak their motivations out loud. When a parameter was changed participants were asked to motivate whether this change brings the sound closer or further from the objective (either to the character description or the target sound).

All participants were asked to perform the task linearly from feature, object to scene. But were attended to be free to make adjustments from previous levels. If this happened participants were asked to elaborate their intention of switching back to adjust a parameter from a previous level.

The maximum time each participant could spend on each assignment was 10 minutes. After each assignment, a semi structured interview took place in which participants were asked about their experience on the use of the tool.

In the interview after the sound design task, participants were asked about what strategy was used during the creation of the sounds and which parameters stood out the most in getting closer or diverting from their objective. Comments on usability/ergonomics of the tool were also gathered.
The comments served as basis for the final design iteration, which focused was on making the tool as self explanatory as possible.

Stimuli
During the test, participants were asked to use the Les_Sons (V2), Appendix IX, tool made in Max msp. Sound was displayed through a Beyerdynamic DT 990 Pro 250 Ohm headphones with a fresh pair of hygiene covers. These headphones were directly connected to the headphone output of an Apple MacBook Pro (M3 pro) laptop. Verbal motivations of participants during the sound design assignment and interviews were recorded using a voice recorder and written notes. A MATLAB script, included in appendix XI, was used to compare the created sounds on psychoacoustic qualities.

Participants

Participants were students from multiple disciplines within design and engineering i.e. Industrial design engineering, Architecture and mechanical engineering. All participants self reported to have normal hearing. All participants gave consent by means of a informed consent form and were compensated for their participation.

Table 6.1: Table of participants

Participant	Study track	Experience with product sound design
Participant 1	Architecture, Urbanism and Building Sciences (Bachelor)	No
Participant 2	Integrated Product Design (IDE Master)	No
Participant 3	Industrial Design Engineering (Bachelor)	No
Participant 4	Strategic Product Design (IDE Master)	Somewhat

Results

Results were obtained by comparing the relative differences in settings between the target setup and the settings of the setup that the other participants came up with. A ["] in the settings for P2, P3, and P4, indicates a similar setting as P1 was used.

Secondly, the motivations of participants during the adjustment of parameters are compared. This can be used to explain the differences or similarities between participants in the resulted settings for the same parameters. Similarly, these motivations can be used to explain how two different parameters might lead to a similar experience towards or away from the objective.

Table 6.2: Overview of settings for sound1, an aggressive shaver

Setting	p1 [reference]	p2	p3	p4
Source sample	kemei blade	"	"	"
Loudness	100%	"	"	-30%
Speed	100%	-2.22%	-1.11%	+1.11%
Source duration	100%	"	-22.3%	+
Attack	0%	"	"	+5%
Release	0%	"	"	+5%
Sustained filter	Low-cut 8.7% High-cut 56.3%	Low-cut -8.7% High-cut +23.8%	Low-cut " High-cut +40%	Low-cut-8.7% High-cut +43.7%
Transmission to connector	100%	"	"	-6.6%
Transmission to casing	97.6%	+2.4%	+1.8%	+2.4%
Total transmission	0.976	1.0	0.994	0.934
Composition type	Sustained	Impulse	"	"
Composition length [s]	10	"	+4	"
Delay before start [s]	0	+2	"	+1
Casing material	Slightly above PS foam HD	Aluminium (much brighter, same intensity)	PS foam HD (slightly darker, same intensity)	PS solid (brighter, same intensity)
Hand grip	100%	-80%	-50%	-70%
Position	Slightly left and below	A bit more to the front and lower	Center of head around same height of head	left front somewhat lower
Distractor sample	HVAC	"	"	"
Distractor loudness	42%	"	"	+11.33%
Room	room2 c1	room1 c1	room1 c1	"

Table 6.3:Overview of settings for assignment two, a sensitive shaver

Setting	**p1 [reference]**	**p2**	**p3**	**p4**
Source sample	kemei blade	dragon blade	"	dragon blade
Loudness	100%	-65%	-67.40%	-48%
Speed	100%	"	+10.00%	+16.67%
Source duration	64.40%	+26%	+3.40%	+26%
Attack	0%	"	"	"
Release	0%	"	"	"
Sustained filter	Low-cut 50% High cut 92.6%	Low-cut +2% High-cut +7.4%	Low-cut -31.8§% High cut -50.4%	Low-cut -50% High-cut +7.4%
Transmission to con-nector	0.83	+0.17	+0.17	-0.48
Transmission to casing	0.609	+0.391	-0.11	+0.39
Total transmission	0.502	1.0	0.5	0.408
Composition type	sustained	impulse	"	"
Composition length [s]	10	"	"	"
Delay before start [s]	0	3.3	1.1	"
Casing material	slightly above zinc	quite above ABS (much darker, higher intensity)	ps foam (much darker higher intensity)	PS solid (much darker, slightly higher inten-sity)
Hand grip	6.50%	0%	0%	0%
Position	centered slightly below	inside head	"	slightly right slightly higher
Distractor sample	hvac	"	"	"
Distractor loudness	10%	-4%	"	"
Room	room5 c2	"	room1 c1	room1 c1

Similarity of sounds

In order to measure whether different setting could result in a sound with a similar experience, the euclidean distance of the psychoacoustic qualities Loudness, Brightness, Roughness and Fluctuation is given. Results of this are given in the matrix plots in Figure 6.1 - Figure 6.4.

These matrices can be read graphically where lighter blue indicated more similarity between two sounds. Due to the nature of euclidean distance the number in each cell does not provide an absolute value.

These plots were divided in four quadrants of 4x4 cells by the red crosses, this distinguishing comparisons within assignment 1 (top-left quadrants) and assignment 2 (bottom-right quadrants), and between both assignments (top-right and bottom-left quadrants).

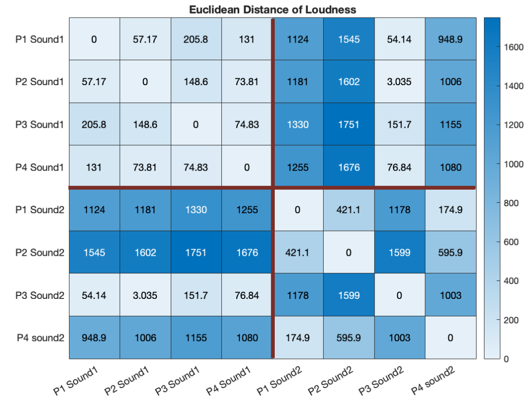


Figure 6.1: Euclidean Distance of Loudness.

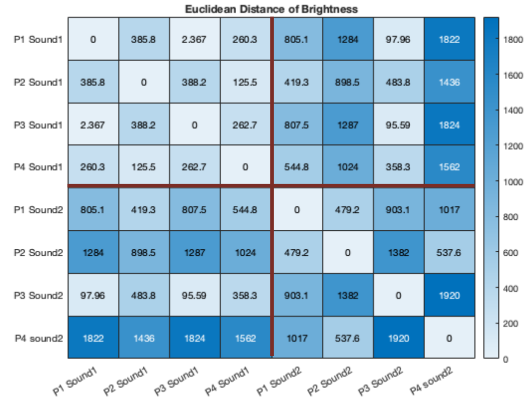


Figure 6.2: Euclidean Distance of Brightness.

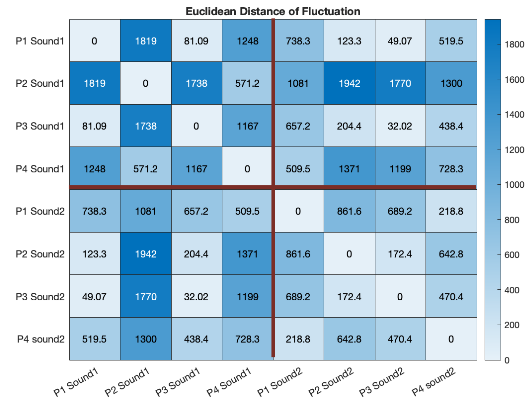


Figure 6.3: Euclidean Distance of Fluctuation.

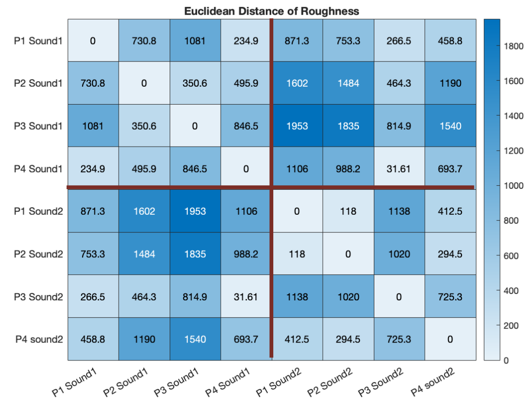


Figure 6.4: Euclidean Distance of Roughness.

Comments from participants
In both assignments, the initial selected sample has a large influence in defining the character of the sound.

This was pointed out by P1 who made the reference sound, but also participants that had to recreate the reference sound mentioned it was easy to distinguish the chosen sample from other samples.

Interestingly, the participant creating the reference sound chose the same sample for both assignments.

Level resulting in passing more high frequency energy content.

The participant creating the reference had the hand grip on full influence since "this imitates how i would aggressively hold a shaver". All recreating participants had the hand grip at a low level of influence. This could be explained by the fact that all recreating participants added more darkness, which would result in higher hand grip, and thus already compensated for the influence of the hand before adding in the actual parameter.

All recreating participants (P1, P2, P3) used the same sample as a distractor sound, this indicates again that the sample is easily distinguished similar to the source sample.

Comments on usability
Some comments on the usability of the tool hindering the creative facilitation, were on the impulse filter. All participants deemed this filter to be too sensitive either adding too much or too little brightness or resonance.

Second to that, the drop-down list when selecting materials of connecting parts provided too many combinations. P3 mentioned they could match the reference better if more time was given, but it would take a long time to match from all possibilities.

P4 mentioned that in this case a combination of materials that produced a desired result was chosen instead of a selection that made sense from the perspective of engineering. P2 also mentioned that if more true to a probable embodiment is designed it would be more sensible to make an initial material selection to chose from, for example plastics or metals only.

Discussion

Euclidean distance assignment 1
By looking at the matrices, it can be concluded that in assignment 1 the loudness and brightness of the produced sounds are fairly similar among all participants. Larger differences are present in roughness and fluctuation.

This absence of low frequency content also explains why the pitch was increased by around 10% by the recreating participants. Similar to the effect of decreased pitch found in the first assignment, the increased brightness of the reference sound was experienced in an increased pitch instead of increased brightness only.

It is interesting to see that the transmission was also changed. All chose different materials but the total attenuation was always around 0.5.

In fluctuation P2 and P4 have a clear difference compared to P1 and P3. This can be explained by the fact that speed and low frequency content is very similar. Even though P4 has the same deviation in speed as P3, the fluctuation is different identifying the influence of other parameters as attack and release and the lower frequency content.

Roughness is the most dissimilar quality in assignment 1. This is probably due to all participant changing the speed compared to the setting P1 used. Even though these changes were very small, in the range of 1-2%, the fact that the initial motor speed is relatively high means that even a small relative change can result in a large absolute change.

Euclidean distance assignment 2
In general, all the sounds that the recreating participants made show more distance from the sound P1 made for this assignment.

It is interesting to see that P2, P3, and P4 participants significantly lowered the loudness compared to P1. This is probably due to the fact that the reference sound had a large portion of the lower sound spectrum removed, which can be experienced as a decrease in loudness. P2, P3, and P4 all increased the intensity in the housing. This was likely done to compensate for the initial decrease in loudness. And resulted in the relatively equal loudness between all participants.

The brightness of the sounds created in assignment 2 shows some more variety. The variety in settings of the filter in this assignment is quite similar to the variety of setting of the filters in assignment. Thus the larger variety of brightness is likely due to the selection of different samples of P2 and P4 or the larger difference in speed for P3 and P4, compared to P1.

Interestingly, P3 is clearly more dissimilar to other participants in loudness, brightness and fluctuation. For the brightness, it is clearly explainable since adjustments in both cyclic filter and selection of housing material should lead to more darkness compared to the reference and other participants.

Euclidean distance between assignment 1 and 2

The darker blue top-right and bottom-left quadrants in loudness, brightness and roughness indicate that overall the psycho-acoustic qualities are not similar between the two assignments.

This was expected as sensitive and aggressive were assumed to express two opposing character traits and thus require a different set of psycho-acoustic qualities. This indicates that the tool allows for the creation sounds of distinct product experiences.

In line with the dark cross of P3 in the bottom-right quadrants in loudness, brightness, and roughness, P3 is present as lighter blue stripes in both top-right and bottom-left quadrants of these psycho-acoustic qualities. This indicates that the loudness, brightness and fluctuation of the sound P3 created for assignment 2 is more similar to the psycho-acoustic qualities of the sounds made in assignment 1 than to the sounds of P1, P2, and P4 for assignment 2.

An explanation could be that P3 used the same sample as all participants in assignment 1. However, P3 used the same sample as P1 in assignment 2. On top of that, P2 and P4 used both a different sample while the final result ended up fairly similar to P1. This means that this dissimilarity of P3 in assignment 2 is more likely due to differences in settings than in the sample selection.

It also shows that although the initial sample selection might feel like having the defining factor in the sound character, the changes done in the sound processing provide to end up with different sound character but also the creation of similar sound characters by different means.

Usability
Participants found it useful to hear the sound change while working on the sound.

None of the participants particularly took into account to make sure their settings would make sense for a realistic embodiment of a shaver. Although some noted that the resulted settings are not realistic. It is thus interesting to research whether Les_Sons is usable, i.e. still leading to a desired sound in a subjective sense, if an approach is followed where a limitation is introduced for participants to consider settings as realistic as possible.

Participants mentioned it could be useful to add explanations to certain functions present in the tool. This could be achieved by using the hints option available in MAX. Such explanation is normally hidden but can be made visible by the user by hovering over an item. This ensures explanatory information is available when needed, but is not unnecessarily cluttering the interface.

The addition of icons could also be used to increase the clarity of the intended functions of the interface. This would remove the need to use text next to some buttons, while providing information in one eyesight.

Suggestions were done to make the lists in the drop down menus smaller. Providing a smaller selection in materials was suggested since multiple combinations provided a similar results.
It is true that some materials have a similar specific impedance and thus influence the sound in an equal way. But these materials can be from separate material groups, ignoring this neglects possible limitation based on engineering. The other way around is also true some materials from the same material group have large differences in impedance simplifying this would neglect the implications on the sound.

As a result it is difficult to provide a limited list. However it be interesting to make an initial material group selection and a specific material from that group. Thus providing the materials in two shorter lists.

It was also recommended to change the titles of the room names. This was a bug that entered when participant 1 just started. This suddenly changed the description in the menu referring to the name of the files rather than a text describing the type of room. To keep all assignment similar titles were not changed back.

Conclusion

This research evaluated whether the Les_Sons tool provides for creative exploration while being limited enough to design for an objective in a limited time. This was done by letting participant recreate a sound another participant created in this tool in two assignments. Results were gathered by comparing differences in approach and the difference in psychoacoustic qualities: loudness, brightness, fluctuation and roughness of the resulted sounds.

Looking to the difference in settings used within one assignment, it can be concluded that participants could approach a similar objective by different means.

When looking to the euclidean differences for the tested psychoacoustic qualities, sounds created within one assignment showed similarity. This indicating that the tool can be used to design for an objective.

A clear separation can be seen between sounds between the two assignments. This indicates that the tool is able to create sounds with different psychoacoustic qualities. And thus the similarity within one assignment is not necessarily due to a limitation of the available tools.

Also suggestions to improve the user interface were done. Some of these suggestion were implemented in a final design iteration of Les_Sons.

6.2 Evaluation of usability in a team setting

The aim of this user research is to test whether the tool can still be used if stricter targets on engineering are introduced.

This was done by facilitating product sound design sessions between an Industrial Design Engineering (IDE) student and a Mechanical Engineering (ME) student. In this study, the Les_Sons (V3), in Appendix X, tool was used to design these sounds. A second research goal was to find out whether improvements in the user interface of the tool made it more self explanatory.

Method

Participants were brought together in a group of two, consisting of a student industrial Design Engineering and a student Mechanical Engineering. They were both asked to perform a sound design task. The objective of the industrial design student was: "Design the sound of an aggressive shaver in a large bathroom, focus solely on achieving the best fitting sound." For the mechanical engineering student the objective was: "Design the sound of an aggressive shaver in a large bathroom, try to use a logical combination of engineering solutions ".

The industrial design engineering student started and got 10 minutes to create a sound. After 10 minutes the other participant could review the created sound and apply changes, with their aim being to make these setting more sensible from the perspective of engineering. Both participants could hear the results in the sound, watch how the other approached the task, and hear the motivations of the other.

After both participants had completed their individual assignment, both participants were asked to take 10 minutes to achieve consensus and apply changes to the tool so that the best sound experience for a logic embodiment start to exist.

A second objective of this study was to test whether the tool is self explanatory. This was tested by providing no explanations on the functioning of the tool in advance. However, participants were able to ask questions to the researcher if they really struggled. During the task, participants were asked to speak their motivations out loud.

Stimuli

During the test, participants were asked to use the Les_Sons (V3) tool. In this version changes after user evaluation 1 were implemented. Sound was displayed through a Beyerdynamic DT 990 Pro 250 Ohm headphones with a fresh pair of hygiene covers. These headphones were connected via a headphone splitter to the headphone output of an Apple MacBook Pro (M3 pro) laptop. Verbal motivations of participants during the sound design assignment and interviews were recorded using a voice recorder and written notes were made.

Figure 6.5: Setup used in this research.

Participants

In this study, a group of four participants was gathered who had no prior experience with the Les_Sons tool.

Table 6.4: Table of participants

Participant	Study track	Experience with product sound design?
Participant 1	Integrated Product Design (IDE Master)	Somewhat
Participant 2	Robotics (ME Master)	No
Participant 3	Integrated Product Design (IDE Master)	No
Participant 4	Biomechanical Design (ME Master)	No

Results

Group1 - Creative exploration

“The play button function is logic and at a sensible place.” - P1

“Aha, I filter out the high and low sounds. This is like a kind of pass filter. For aggressive I keep a wide range.” – P1

“The kemei shaver sample is quite aggressive.” - P1

“It sounds like a chainsaw.” – P2

“Okay, sample 5 sounds good for a knob, let me try another sample. No sample 5 was the best.”

“Wait, do I have to make an aggressive sound or an aggressive shaver because now I have a bass which is quite aggressive but it does not really sound like a shaver.” – P1

Note: the composition types were hard to understand

"Oh, the foam material in the housing makes it sound rather aggressive." – P1

"Yeah, a firm hand grip make it sound more aggressive." – P1

"A large bathroom is not necessarily a large room but quite echoey, let me try a small classroom." - P1

Group1 - Review by ME student

"The knob sound is a bit weird, on the picture it looks like a slide button, let me try whether I can find another sample that sounds more like a slide button." – P2

"Also the sound of the shaver should start after the button not before. It would be strange if the shaving starts before pressing a button." – P2

"The motor is probably steel, and I guess the motor can be directly placed to the aluminium housing." – P2

"Okay, now for material selection of the housing; It is used in a bathroom so it should not rust. Steel is maybe a bit overpowered. Gold haha, no that is too expensive. I guess an aluminium housing is most sensible." – P2

"The position of the shaver depends of course, it would be nice if this position could change over time." – P2

Group1 - Finding consensus

"I have a bone to pick with you. I guess you made the knob a bit more realistic but lets try to get it a bit darker." - P1

"I wanted to change the speed of the knob indeed. But it did not change anything." -P2

"The housing should not be too dull, I think aluminium is exactly right." -P2

"On the material selection I have nothing to say." – P1

"Okay, I think we can agree with this sound and setting and have a good example of an aggressive shaver." – P1

Group2 - Creative exploration

“Before starting the first thing I think about is something deep with a lot of bass. I will just try and see whether I can find something like that.” – P3

“Shaving without a blade is not aggressive. The Kemei it is.” – P3

“I am looking for more heavy tones also I have the feeling that the vibrations in the shaver should be stretched.” – P3

“It seems like by adding only resonance the pitch sounds higher.” – P3

“Well now the pitch is low it sounds more like the battery of the shaver is empty. But with the higher pitches it sounded more like we are dialing in on a modem.” – P4

“Since I am looking for a heavy sound maybe I should look for heavy materials like steel and aluminium.” – P3

“Did you just not make your motor from polypropylene?” – P4

“I do not hear any difference after changing the connector material.” – P3

“Aha in the object level you can place the click sound in front of the shaving sound.” – P3

“I do not really expect any other sounds. I could imagine adding the water sounds but it is not necessarily needed for shaving so I do not add any sounds.” – P3

“Between rooms there are a lot of options. I think the selection is too big. I like the descriptions of some rooms and can imagine from the how they would sound like but I have no idea about control room1 or control room 2.” – P3

Group2 - Engineering review

“Let’s not make a motor from polypropylene. I would change the material to steel.” - P4

“Should the motor not actually use the cyclic filter? Hm, doing that made it softer. But if I look to the materials all transmission is relatively high. I do not think we need an extra layer between the housing and the motor.” - P4

“With cyclic the loudness of the motor sound softer. I guess I will change the loudness of the button accordingly.” - P4

“I will add a little bit of attack to the motor to model the starting of the motor.” - P4

“Also, we will not make the knob from ABS.” - P4

“It sounds hollow now.” – P3

“I agree, it sounds like a dog clicker maybe a little less resonance. No now it sounds like applesauce.” - P4

“I would like to be able to choose a bathroom.” - P4

“I put the hand grip to more firm the hand gripping firm is also an aggressive way to hold it.” - P4

“It does not sound too aggressive but as an engineer I do not really mind.” - P4

Group2 - Finding consensus

“It does sound rather similar to my version, but I would like to add in something grumpier. Some slightly lower tones.” – P3

“I agree now it does sound more like a normal shaver not as an aggressive one.” P4

“If we look to the curves of the housing filter, we need to add in a bit lower. Let’s look how ABS will work. Also, by having a second look to it the housing should be 100% we can either have a housing or not.” – P4

General comments

“The learning curve is not too high, especially compared to some software I use to create music such as FL studio. Although I like the time editors in those programs better.” – P1

“I agree that the learning curve is not too high. I did not really used the hints that might have made it even more easy.” – P2

“In general, I see the added value of the tool, it is relatively easy to use and gives a rather good overview of how sound can change the product experience.” – P1

“I think the tool might be useful if you kind of know what kind of sound you want. But I find it very difficult to imagine what kind of sound I want and thus find it difficult to have an opinion on it.” – P3

“I would present the levels in different tabs. Now the whole scrolling makes it feel overwhelming. Although I can also imagine you lose some overview then.” – P2

"I like the separation in levels, I was able to first focus on the main sound and then adding in smaller details further in the task." – P3

"It would be quite useful if manufacturers could provide samples of their motors for example and make it accessible in this tool. Then you could really listen what type of component is likely best for your application." – P1

Quality of explanations

"I would like to be able to hear a general example explaining some concepts because I did not understand some concepts because their influence was unnoticeable." – P3

"I think being able to hear the influence of a parameter on the sound of the product itself is clear enough and even more useful then when a general example is given." – P4

"It would be nice to have more visual references. I would say the more the better, but I would have no clue what that entails for this tool." – P3

"I would show the composition types as symbols, that would make it easier to remember how these types work." -P2

"The material graph is quite clear except of the axes. But I also just tried sliding over it and tried to find a sweet spot." – P1

"I liked the material graphs it gives a good overview of a probable material group. I also like the visual feedback of the graph in the housing filter." – P4

Discussion

From the reactions of the participants it is concluded that all participants were content after their individual design task.

In both groups both the Mechanical Engineers had comments on some of the decisions made by the Industrial Design Engineer. Meaning that purely focusing on subjective qualities might lead to unrealistic technical implications, in accordance to the results from user research 1.

After the reviews by the ME students, the IDE students were less content with the sound the Mechanical Engineer made compared to their initial sound. Meaning that technical requirements can lead to divert from an goal on the subjective experience of the product sound.

However, when both participants were asked to collaborate, consensus could be found. In both cases only one adjustment was done. In the first group the material of the impact filter for the knob was changed to Nylon 6/6. A material deemed usable by the ME student (P2) in the embodiment of a shaver knob. While also leading in having a deeper sound, as requested by the IDE student (P1).

In the second group this was done by changing the material of the housing which was changed to ABS. According to the ME student (P4) this made the sound deeper than their original selection, as requested by the IDE student (P3).

That consensus could be found implies that the tool is usable from both a creative and technical viewpoint. Technical requirements can add some limitations and may lead in a diversion from the objective on the subjective experience. However the tool considers the product sound from multiple aspects which enable to find consensus between subjective and technical requirements, in order to get closer to the experiential objective again, while staying true to technical limitation.

Without clear request the levels were approached linear from feature, object to scene. In this linear process changes were experienced from most influential to less influential respectively. This leads to a process where little has to be switched back and forth.

Without introducing the tool, participants experienced less difficulties in the use of the tool compared to the . It was interesting to see that none of the users used the hints. Participants were not made aware about them. Although hints sometimes showed up by accident when a participant hovered over a text with hints included, all participants ignored them. Adding a small icon next to the texts with a hint added might make the users more aware that such hints exist.

However some comments were made mostly on the manner in which sounds are composed. Partially this problems might be solved if the hints were provided better since the composition types were understood poorly. Suggestions were also made to include icons for every composition type. This could make it easier to remember what every type entails.

Conclusion

This research tested whether Les_Sons is usable when approached from both a product experience and engineering perspective. This was done through a user study in which a team consisting of an Industrial Design Engineering student and a Mechanical Engineering student used the tool to complete a sound design task.

The ME students commented that the IDE students used unrealistic settings. However, when the ME students were asked to adjust the settings to make them more realistic from an engineering point of view, the IDE students were less satisfied with the experience of this sound compared to the reference sound they had initially created.

By collaboration between two students consensus could be found. This was achieved by slight adjustments to the settings as provided by the ME student, which resulted that in a more desirable sound experience as requested by the IDE student, while still considered realistic by the ME student.

The usability of the tool was also tested. Without an initial introduction to the tool, the participants were quite able to use the tool in the intended way, however, some comments were made on how to improve the user interface, Due to the time constraints of this project, these comments served as a basis for future recommendations and were not implemented in the design.

6.3 Conclusion on evaluation

Through user research, a group of participants were asked to create two separate example sounds in the Les_Sons tool from a reference sound for two different objectives. It was concluded that the tool provided enough functionality to allow for creative exploration and the creation of diverse example sounds. But limited enough to achieve an objective in a limited amount of time.

This was because the sounds within one target contained a high degree of similarity when produced with different sets of settings. Comparing the sounds between the two objectives revealed differences in subjective qualities. This means that the similarity within an objective is not due to a limited influence of the processing capabilities provided.
The main comments on the usability of the tool in the first user evaluation were to provide better explanations and to include visuals to better communicate the functions of the tool.

A design iteration was carried out based on these comments. After this iteration, textual hints were added to explain the function of the editing objects together with the expected subjective influence of the parameter. In addition, visual improvements were made by adding icons and colour differences.

In the second user evaluation, fewer problems occurred during the use of the tool, even though the participants did not receive an explanation of how to use the tool beforehand. This means that the changes made in the iteration improved the efficiency of the tool. However, the participants still had some recommendations. These are discussed in more detail in the general project recommendations in section 7.2.

However, the main objective of this second user research was to test whether Les_Sons was usable from both a subjective and technical perspective. Working with an industrial design engineer and a mechanical engineer, it was found that the tool could reach a consensus on a reference sound that was close to a subjective goal, while remaining true to the limitations of the technical requirements.

7.Overall conclusion on the project

This final chapter provides an overall conclusion on the project will be given. This consists of a discussion of the limitations of the project together with recommendations on how to proceed. Finally, a personal reflection o the whole project is given.

7.1 Discussion

The main purpose of the tool is to enable the consideration of sound in an early stage of product. This is because there is little focus in current design education on the contribution of sounds to the product experience.

The limited feature set together with pre-made sound library gives the user a quick start. Lowering the threshold for incorporating sound into a design process. It is likely that by simply raising awarereness of what can be done in the product sound design, students are more likely to include sound as an aspect of the products they design. For this exploration Les_Sons has proved to be a good starting point.

If the initial start sparks enough interest, the student or designer may being to dive deeper into the field of product sound design. In order to make the transition to a more expert level smoother, the vocabulary, tasks, and outcomes provided in Les_Sons have been gathered through literature research and consultation with experts in the field.

This should help the student or professional product designer to take a central role in the design of the product sound. Les_Sons enables the designer to communicate with other experts by providing examples of how the product should sound and what steps could be taken to achieve this sound.

The main intention in designing the tool was to make it usable in the late analysis to early conceptualisation design phase. This led to the decision to provide pre-recorded samples of product sounds, thus eliminating the time needed to record them. However, the designer can also add self-recorded samples. This means that the tool can be used in further stages in the design cycle as well. If in a physical audible hard prototype exists at a later stage, it can be recorded and loaded in to the tool. The tool can then be used to change some parameters.

The division into the feature, object, and scene levels proved to give focus on which parts of a product contribute most to sound character of the product, while also highlighting the relationship between the different parts. This division can also be made more flexible. A combination of features could be rendered together as an object. In a new project, this object could be loaded as a feature. This allows the creation of sub-levels, enabling the creation of more complex systems.
As the tool is freely available, it is ac-

cessible to a wide audience. Even if students are interested in incorporating sound into their design projects, current software and tools for analysiing and conceptualising sound are aimed at experts. This makes such software less available and more difficult to learn. Meanwhile, the more accessible software is more focused on music creation, resulting in little understanding between the software and the desired results.

7.2 Recommendations

The aim of the tool was not to provide a true simulation of a product sound, but rather to provide a tool to quickly test ideas. Therefore, implications of acoustics have been simplified.

The filtering characteristics of the housing are very specific for individual products. It would be useful to have more examples of housings available so that a similar library will start to exist as currently present in the selection of samples for features and impulse responses in for room acoustics.

The manual creation of the filter interaction from recordings is very time consuming. It would be useful to automate the creation of housing filters. Automating this, would also help in adding more interactions. As this was implemented in a similar way. Another recommendation for user interactions would be to make them evolve over time. This could be done in a similar way to how modular synthesizers work or, as automation tracks like those found in some DAWs or video editing programs.

Enlarging the sample library.
To make the tool more useful in the design of different products other than shavers, the sample libraries need to be extended. This would include feature sounds, distractor sounds and room impulse responses. Making them available in an open online repository allows users to upload and share self recorded sounds.

However, this may result in a wide range of quality in the recordings. A basic library should therefore be provided. As recording of multiple product sound samples is time consuming, it could be explored how this recording can be simplified with dedicated recording setups.

It can also explored better how algorithmic source separation can play a role in enlarging the library. Currently used ML methods for source separation are based on a library containing examples of the sounds to be separated. In the absence of a specific library for product sounds, the initial recorded library could be used as such a reference library, opening up the possibility of expanding the library of samples with ML-separated sounds in the future.

Adding intentional sounds.
The main focus of this thesis was to provide a platform for the design consequential sounds. As some products contain intentional sounds as well,

the lack of their inclusion can be seen as a limitation. If a desired intentional sound already exists, either as a found- or recorded sample, this sound could be added as an additional source. In this way, it can be evaluated whether this sound will be audible or masked compared to the rest of the composition of the product sounds. However, the current tool does not provide a good way of creating such sounds.

Additional features

Les_Sons does not currently provide any metrics or tools for analysing or evaluating product sounds. The ultimate goal of the project was to enable early conceptualisation of sounds, so adding such functionality was not a focus of this project. However, it may be useful to include such functionality in the tool. Incorporating on-the-go evaluation would allow the designer to conduct jury tests with Les_Sons and enable to quickly test changes during a test, while recording measures to explain why a certain outcome.

Another feature could be to provide the editing functions at different levels of detail. This could work in a similar way to how Granta Eduopack (ANSYS, 2024) provides different information about materials in libraries with different levels of detail. It might be useful to provide both “explore” and “detail” settings. In an example of material graphs and selectors, this could mean that in the “exploration” setting, only material groups such as metal or plastic are shown. While differences within different types of metal could be provided if the “detailing” setting was selected.

Limitations in research

All user research was conducted with students. This was done based on the assumption that if the tool is understandable to students, it will be useful in a professional setting as well. In order to verify this assumption, the user research conducted in this thesis could be repeated with a group of participants consisting of professional industrial design engineers.

All adjustments that can be made in the tool are modelled on how the sound should change in real life. However, without proper research it is difficult to say how well the objectives derived from using the tool translate to the actual embodiment of a product.

This could be tested in a research where participants are given a design task where the tool is used to conceptualise a sound and then asked to embody this sound in a physical model. This model should be based on recommendations derived from the tool. Satisfaction with the sound of this physical model could be used to assess whether Les_Sons was useful in this more integrated design process.

7.3 Personal reflection

Due to my studies, electives and personal interest, I already had some competences within the five fields of expertise that proved to be useful to consider in a product sound design project. This enabled me to do some more extensive research and was helpful in the communication with experts.

A broad perspective
When doing literature research on product sounds, it seemed that only a few scholars are researching this field. In conversation with experts consulted for the interviews, it became clear that only in the last few years sound had started to be considered, except of the automotive industry, making an exciting field to explore.

However, this was also a pitfall, multiple facets could be addressed. Especially in the early exploratory stages it felt that the project had little coherence. But in the end this is inherent to a fuzzy front end. The recommendation of my supervisors during weekly meeting helped to start adding a focus in the project.

Gaining knowledge in the field of product sound design
Already having some practical knowledge in the creating (digital) music instruments proved to be handy in the conceptualization of the tool. However, the specific application of the tool made me learn more about sound in a system rather than sound as a product or in a musical composition. The project made me more aware of how product sounds are considered in professional settings and what tasks performed and what tools are used.

Consulting experts
Interviewing experts seemed to be a good practice to gather information from a professional point of view.
I was afraid of wasting the participant’ s time. However the enthusiasm of all experts brought in extra energy to the project.

Functional prototyping
Creating a concept was one of the goals before starting this project.
Since no proper and accessible sound design tool existed, at least not in the direction of consequential product sounds, I expected this concept would rely on more “Wizard of Oz” type of prototyping. However, Max came out to be a helpful design tool for creating functional digital prototypes.

One aspect I did not cover in this thesis is the possible integration of Max with another interest of mine, mechatronics. In this sense learning Max is likely a good design tool to serve as an interface for prototyping digital and physical interactions in products.

Learning more on product interactions

The use of functional prototypes in combination with user studies also provided extra insights. Some details I considered only to be a minor issue before a study, like the large list of materials in the object to feature level, played a large influence in the experience of the interaction the users had with the tool. This proves the importance of user testing in design.

References

Ansys. (2024). *Ansys Granta EduPack* (2024R1) [Computer software]. https://www.ansys.com/products/materials/granta-edupack

Ansys. (n.d.). *Ansys Sound.* https://www.ansys.com/products/acoustics-analysis/ansys-sound

Ashby, M. F. (1999). *Materials selection in mechanical design* (2nd ed). Butterworth-Heinemann.

Audacity Team. (2023). *Audacity* (3.4.2) [Software]. https://www.audacityteam.org

Baldan, S., Delle Monache, S., & Rocchesso, D. (2017). The Sound Design Toolkit. SoftwareX, 6, 255–260. https://doi.org/10.1016/j.softx.2017.06.003

Boersma, P., & Weenink, D. (2023). *Praat* (6.4.01) [Computer software]. https://www.fon.hum.uva.nl/praat

Bregman, A. (1990). Auditory Scene Analysis: The Perceptual Organization of Sound. In Journal of The Acoustical Society of America—J ACOUST SOC AMER (Vol. 95). https://doi.org/10.1121/1.408434

Bregman, A. S., & Ahad, P. A. (1990). *Demonstrations to accompany Bregman's Auditory Scene Analysis The perceptual organization of sound MIT Press, 1990.*

Brüel & Kjær. (2021). *The Fundamentals Of Sound Intensity Measurement.* https://www.bksv.com/-/media/literature/Primers/Hidden/sound-intensity-booklet-A4-2021.ashx?la=ko&hash=6921344037F67DF7A4550422022F9826EEC7623F

Carron, M., Rotureau, T., Dubois, F., Misdariis, N., & Susini, P. (2017). Speaking about sounds: A tool for communication on sound features. *Journal of Design Research*, *15*(2), 85–109. https://doi.org/10.1504/JDR.2017.086749

Consumer Reports (2016). *CR082K10-TECH-TESTING-HEADPHONES* [Photograph]. Wikimedia Commons https://commons.wikimedia.org/wiki/File:Consumer_Reports_-_product_testing_-_headphones_in_anechoic_chamber.tif. CC-BY-SA-4.0

Creative Commons. (2019). About CC Licenses. Creative Commons. https://creativecommons.org/share-your-work/cclicenses/

Cycling ’74. (2022). *Max 8* (8.5.6) [Computer software].

Dejonckere, P. H. (2001). *Occupational Voice:* Care and Cure. Kugler Publications.

Delle Monache, S., Misdariis, N., & Özcan, E. (2022). Semantic models of sound-driven design: Designing with listening in mind. *Design Studies*, 83, 101134. https://doi.org/10.1016/j.destud.2022.101134

Delle Monache, S., & Rocchesso, D. (2019). *Sketching Sonic Interactions* (pp. 79–101). https://doi.org/10.4324/9781315106359-4

Donahue, C., McAuley, J., & Puckette, M. (2019). *Adversarial Audio Synthesis* (arXiv:1802.04208). arXiv. https://doi.org/10.48550/arXiv.1802.04208

Fastl, H. (1997). *The Psychoacoustics of Sound-Quality Evaluation. 83.*

Fastl, H. (2002). FROM Psychoacoustics TO SOUND QUALITY ENGINEERING. Proceedings of the Institute of Acoustics, 24(4). https://mediatum.ub.tum.de/doc/1138340/146050.pdf

Fastl, H., & Zwicker, E. (2007). Psychoacoustics. Springer. https://doi.org/10.1007/978-3-540-68888-4

Févotte, C., Vincent, E., & Ozerov, A. (2018). Single-Channel Audio Source Separation with NMF: Divergences, Constraints and Algorithms. In S. Makino (Ed.), *Audio Source Separation* (pp. 1–24). Springer International Publishing. https://doi.org/10.1007/978-3-319-73031-8_1

Fierro, L., & Välimäki, V. (2021, September 6). *SiTraNo: A Matlab App For Sines-Transients-Noise Decomposition of Audio Signals*. https://doi.org/10.23919/DAFx51585.2021.9768212

Fletcher, N. H., & Rossing, T. D. (1991). *The Physics of Musical Instruments*. Springer New York. https://doi.org/10.1007/978-1-4612-2980-3

Flipsen, B. (2022). Materials & Acoustics: Where sound comes from and how to deal with it.

Freesound. (n.d.). Freesound. Retrieved 21 November 2023, from https://freesound.org/browse/tags/?f=tag:%22compmusic%22

Friesike, S. (2022). *Grenzobjekte: Kooperation ohne Konsens | Ding an sich | Wissenschaft erklärt - YouTube*. https://www.youtube.com/

GitHub. (2024). *GitHub*. GitHub. https://github.com/

Granta. (2023). Granta EduPack (23.2.1) [Computer software]. https://www.ansys.com/products/materials/granta-edupack

Haumann, N. (2015). An Introduction to Cognitive Musicology: Historical-Scientific Presuppositions in the Psychology of Music. *Danish Musicology Online*

Harker, A., & Tremblay, P. A. (2012). The HISSTools Impulse Response Toolbox: Convolution for the Masses. In ICMC 2012: Non-cochlear Sound. The International Computer Music Association (pp. 148–155). https://eprints.hud.ac.uk/id/eprint/14897/

HEAD Acoustics (n.d.). *HSU III: Artificial head with condenser microphones*. [Photograph]. https://www.head-acoustics.com/products/artificial-head-binaural-recording/hsu-iii

Hekkert, P. (2006). Design aesthetics: Principles of pleasure in design. *Psychology Science*, *48*(2), 157–172.

Hermann, T., & Hunt, A. (2011). *The Sonification Handbook*. Logos Verlag Berlin.

IRCAM. (n.d.). *Spat*. Retrieved 4 April 2024, from https://forum.ircam.fr/projects/detail/spat/

Jansen, R. J., Özcan, E., & Egmond, R. V. (2010). *PSST! PRODUCT SOUND SKETCHING TOOL.*

Kasti, E., & Özcan, E. (2017). *How to Design Sounds: The Nine Moments of Sound Experience*. TU Delft.

Katz, B. (n.d.). *An Integrated Approach to Metering, Monitoring and Levelling*. https://www.aes.org/technical/documentDownloads.cfm?docID=65

Keiper, W. (1997). Sound Quality Evaluation in the Product Cycle. *Acta Acustica*, *83*.

Langeveld, L., van Egmond, R., Jansen, R., & Ozc, E. (2013). Product Sound Design: Intentional and Consequential Sounds. In D. Coelho (Ed.), *Advances in Industrial Design Engineering*. InTech. https://doi.org/10.5772/55274

Laughlin, Z., Naumann, F., & Miodownik, M. A. (2008). *Investigating the Acoustic Properties of Materials with Tuning Forks.*

Lemaitre, G., & Susini, P. (2019). Timbre, Sound Quality, and Sound Design. In S. K, S. C, M. S, & F. R. Popper A. (Eds.), Timbre: Acoustics, Perception, and Cognition. Springer Handbook of Auditory Research (Vol. 69, pp. 245–272). Springer. https://hal.science/hal-02270931

Mark, G., Lyytinen, K., & Bergman, M. (2007). Boundary Objects in Design: An Ecological View of Design Artifacts. *Journal of the Association for Information Systems*, *8*(11), 546–568. https://doi.org/10.17705/1jais.00144

Milan, R. (2022). *What is A-Weighting?* https://www.ansys.com/blog/what-is-a-weighting

Mitchell, A., Aletta, F., & Kang, J. (2022). How to analyse and represent quantitative soundscape data. *JASA Express Letters*, *2*(3), 037201. https://doi.org/10.1121/10.0009794

Native Instruments. (n.d.). *Reaktor 6* (6.5.0) [Computer software]. https://www.native-instruments.com/en/products/komplete/synths/reaktor-6/

Nykänen, A. (2008). *Methods for Product Sound Design*. Luleå University of Technology.

ONDA Corporation. (2020). Acoustic Tables. https://www.ondacorp.com/resources/

Özcan, E. (2016). *Nine Moments of Product Experiences: The effect of micro, macro, and meta level human-product interactions on the experiences of aesthetics, meaning and emotions*.

Özcan, E., & van Egmond, R. (2006, September 27). *Product Sound Design and Application: An Overview*. Proceedings from the 5th Conference on Design and Emotion 2006.

Özcan, E., & van Egmond, R. (2008). *Product Sound Design: An Inter-Disciplinary Approach?*

Özcan, E., & van Egmond, R. (2012). *Basic Semantics of Product Sounds*.

Özcan, E., van Egmond, R., & Jacobs, J. J. (2014). Product sounds: Basic concepts and categories. *International Journal of Design*, 8 (3), 2014.

Pahl, G., & Beitz, W. (1986). *Konstruktionlehrne; Handbuch für Studium und Praxis* (2nd ed.). Springer.

Presonus Audio Electronics. (2024). *Studio One 6* (6.6.1.99821) [Computer software]. https://www.presonus.com/en-US/studio-one.html

Roozenburg, N. F. M., & Eekels, J. (2016). *Productontwerpen, structuur en methoden* (2nd ed.). Boom uitgevers.

Sanz Segura, R., & Manchado Pérez, E. (2018). Product Sound Design as a Valuable Tool in the Product Development Process. *Ergonomics in Design*, 26(4), 20–24. https://doi.org/10.1177/1064804618772997

Sengpiel, E. (n.d.). *Levelchange calculator.* https://sengpielaudio.com/calculator-levelchange.htm

ShanonPearce. (n.d.). *ASH-Listening-Set*. Retrieved 14 March 2024, from https://github.com/ShanonPearce/ASH-Listening-Set/blob/main/BRIRs/Rooms.csv

Siemens Digital Industries Software. (n.d.). *Acoustic simulation.* https://plm.sw.siemens.com/en-US/simcenter/simulation-test/acoustic-simulation/

Smalley, D. (1997). Spectromorphology: Explaining sound-shapes. *Organised Sound*, 2(2), 107–126.

Smith, J. O. (2023). Introduction to Physical Signal Models. https://ccrma.stanford.edu/~jos/pasp/Introduction_Physical_Signal_Models.html

Smith, J. O. (2024). *Spectrograms.* https://ccrma.stanford.edu/~jos/mdft/Spectrograms.html

Star, S. L. (1989). The Structure of Ill-Structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving. In *Distributed Artificial Intelligence* (pp. 37–54). Elsevier. https://doi.org/10.1016/B978-1-55860-092-8.50006-X

Star, S. L., & Griesemer, J. R. (1989). Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420.

Tholander, J., & Jonsson, M. (2023). Design Ideation with AI - Sketching, Thinking and Talking with Generative Machine Learning Models. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 1930–1940. https://doi.org/10.1145/3563657.3596014

Thoresen, L. (2004). *Spectromorphological Analysis of Sound Objects An adaptation of Pierre Schaeffer's Typomorphology.* [The Norwegian Academy of Music]. http://www.ems-network.org/IMG/EMS06-LThoresen.pdf

Timmerman, L., Deltrap, T. & De Vries, J. (2022). *Improving the sound experience of the Philips Avent breast pump.* [Student report].

van Boeijen, A., Daalhiuzen, J., Zijlstra, J., Van der Schoor, R., & Technische Universiteit Delft (Eds.). (2014). *Delft design guide: Design methods* (Revised 2nd edition). BIS Publishers.

van Egmond, R. (2022). *EAD 2022—2—Recording techniques* [Lecture].

Weenink, D. J. M. (2014). BarkSpectrogram. https://www.fon.hum.uva.nl/praat/manual/BarkSpectrogram.html#:~:text=The%20bark%20to%20hertz%20transformation,hertz%2F650)2).

Appendix

I Selection audio design software

Reaktor	-	-	+	++
Platform accessibility		■		
Programming			■	
Pre-build libraries			■	■
Customisation of GUI			■	
Price		■		

Max	-	-	+	++
Platform accessibility		■		
Programming			■	
Pre-build libraries			■	■
Customisation of GUI			■	■
Price		■		

Faust	-	-	+	++
Platform accessibility			■	■
Programming		■		
Pre-build libraries			■	
Customisation of GUI		■		
Price			■	■

II Interview questions Product director

Background

1a. Prior to your current position and/or affiliation, what was the extent of your knowledge in (product) sound design or sound/acoustics? For example, what education did you follow before your professional career?

1b. If your knowledge was limited, what strategies did you use to acquire the necessary expertise?

2. What sparked your interest and served as the driving motivation behind your involvement in this project?

Initial considerations:

3. Who is the intended user of Ansys Sound?

4. In broad sense, how does Ansys Sound simulate sound?

5. What does the user have to define before they can use Ansys Sound?

6. What knowledge do designers or engineers deliver/ made clear before Ansys Sound can be used?

7. How does Ansys Sound explain concepts that the intended user might not know yet?

8. How would one used Ansys Sound if a clear overview of components is lacking?

Ansys Sound in user testing

9. To evaluate psychoacoustics, what types of metrics are used?

10. How does the testing environment influence the results; for example, the room/laboratory, quality of the provided test material and or quality of the test equipment?

11. If testing is done with non-experts such as the intended consumer, does the software help in enhancing the communication if they have little knowledge in sound design?

Designing sound design tools

12. What tools or methodologies are used in the design process that is followed within your company? Are there any specific techniques that are particularly effective?

13. Is a user-centric approach used in the design process? if so, how are the user needs and preferences integrated in the design process?

14. What key factors are considered in the beginning of a new product (sound) design project?

15. How does conceptualization work, generating new ideas or more collecting existing concepts/software that combine are a new product?

Figure I.I: test

Figure II.II: test

Testing and Iteration:

16. How do you test and iterate designs to ensure they meet the desired objectives? So, what global process is followed and how do they relate to each other?

17. What are some common challenges you faced in the design process, and how do you typically address them?

18. What improvements or advancements do you believe are necessary to enhance the product in the future?

Collaboration and Multidisciplinary Teams:

19. What different teams/experts are involved in projects that you work in, such as design, engineering, programming and marketing etc.?

20. How is good collaboration and communication assured between these different teams/experts?

21. Is to your opinion everyone in the design team required to have some knowledge within the just mentioned fields?

The user's experience of product sound:

22. Can you elaborate how sound design influences the overall user experience and perception of a product?

23. Could you elaborate on key requirements if a unique sound identity for a product or brand is created?

24. How are the aesthetic qualities of sound balanced with the functional aspects of a product's sound design?

Concluding advices

25. In hindsight, what are some key learnings or improvements you've identified from past projects?

26. What do you foresee as upcoming trends or innovations in the field of product sound design?

27. For those aspiring to enter the field product sound design, what advice or resources would you recommend for learning and development in this field?

III Interview questions lead engineers

Background of interviewee

1. What sparked your interest and served as the driving motivation behind your involvement in this project?

2a. Prior to your current position and/or affiliation, what was the extent of your knowledge in (product) sound design or sound/acoustics?

2b. What education did you follow before your professional career?

2c. If your knowledge was limited, what strategies did you use to acquire the necessary expertise?

Initial Considerations:

3. What are the key factors you consider when beginning a new product (sound) design project?

Tools and techniques:

4. What tools or methodologies are used in the design process that is followed within your company? Are there any specific techniques that are particularly effective?

5. How is sound addressed in this process?

6. How well does it integrate in the rest of the process?

7a. Are sound visions/examples used in this process?

7b. If so, how realistic are they and what implications do they have on design requirements?

8. How is a balance found in quick prototyping/sketching of the sound and a meaningful result?

User Experience Impact:

9. Can you discuss how sound design influences the overall user experience and perception of a product?

10. Could you elaborate on how you create a unique sound identity for a product or brand?

11a. Is a user-centric approach used in the design process?

11b. if so, how are the user needs and preferences integrated in the design process?

12. How are the aesthetic qualities of sound balanced with the functional aspects of a product's sound design?

Collaboration and Multidisciplinary Teams:

13. What different teams/experts are involved in projects that you work on, such as design, engineering, programming and marketing etc.?

14. How is collaboration and communication assured between these different teams/experts?

15. Is to your opinion everyone in the design team required to have some knowledge within the just mentioned fields?

Testing and Iteration:

16. How do you test and iterate designs to ensure they meet the desired objectives? So, what global process is followed and how do they relate to each other?

17. How do you measure the success or effectiveness of a product's sound design, i.e. what metrics are used?

18. If testing is done with non-experts such as the intended consumer, how do you enhance the communication if they have little knowledge in sound design?

19. What are some common challenges you face in the design process, and how do you typically address them?

20. What improvements or advancements do you believe are necessary to enhance the overall design process in the future?

Reflection and Improvement:

21. In hindsight, what are some key learnings or improvements you've identified from past projects?

22. What do you foresee as upcoming trends or innovations in the field of product sound design?

23. For those aspiring to enter product sound design, what advice or resources would you recommend for learning and development in this field?

IV Interview questions Professor Acoustics and Haptics

Background

1. What sparked your interest in acoustics and sounds?
2. What is your background both on educational and professional level?
3. What is the subject of the courses that you lecture?

Background of students

4. Which study did students follow whom you educated about acoustics and sounds?
5. How do you approach teaching acoustics to students with varying levels of prior knowledge in physics and engineering?
6. How do you foster collaboration and interdisciplinary learning among students from different academic backgrounds when teaching acoustics and vibrations?
7. Have you collaborated with industry professionals to create a bridge between academia and practical applications in acoustics and vibrations? How does this collaboration benefit your students?

Tools and equipment used in teaching

8. What (kind of) tools and or equipment is used during the process of educating students about sound and acoustics?
9. How is the use of these tools included in education?
10. Considering the rapid advancements in technology, how do you integrate modern tools or software into your teaching methods to enhance students' understanding of acoustics and vibrations?
11. What difficulties do you experience during course programmes that involve acoustics and sound design?
12. How can practical and theoretical knowledge be combined in the field of acoustics and product design?

Balance between theoretical and practical knowledge

13. In your experience, what are some common misconceptions or challenges that students initially have when learning about acoustics, and how do you address them?
14. Are there any specific real-world applications or projects you incorporate into your courses to help students connect theoretical concepts to practical scenarios in acoustics?

15. Can you share any memorable projects or experiments that have effectively engaged students and deepened their understanding of acoustics?

16. How do you balance the need for hands-on experience with theoretical knowledge in your teaching approach, especially when it comes to complex topics like acoustics?

Recommendations and future prospects of acoustic and vibration

17. What advice do you have for students who are interested in pursuing a career in acoustics or sound design, and what skills do you believe are essential for success in this field?

18. Are there any specific research areas or emerging trends in acoustics that you think students should be aware of as they embark on their studies?

19. Can you share examples of successful projects or research endeavours that your students have undertaken in the field of acoustics, showcasing the practical application of their knowledge?

V Selecting ASA principles to include

In Demonstrations to accompany Bregman's Auditory Scene Analysis The perceptual organization of sound (Bregman & Ahad, 1990), some of these principles were given with an accompanying CD where each example can be heard on. In this paper 41 examples were given that were found to be understandable without the need of training. To evaluate a product sound on 41 principles is not likely to make a better understanding of the composition. It is assumed that giving a selection of principles with high relevance to products sounds is more manageable. Some principles are based on vocal speech making it less relevant for product sounds.
Second to that some principles work on stereophony (two different sound waves entering each ear). Since we listen to product sounds with two ears one might argue that stereophonic principles are relevant. However, Bergman and Ahad (1990) highly recommend listening to these examples with headphones and if one is to listen with speakers these should be widely separated as possible. This assumes that these stereophonic principles work on two sounds which are widely spaced from each other, which Bregman & Ahad (1990) also explain in example 40. Stating that sounds entering both ears only sound as two sounds if there is little correlation between the two sounds.

As most products are smaller than the distance between two ears the correlation between the sound entering both ears is assumed high, and therefore it is expected that product sounds are perceived similar monophonic source. If the size of a product is larger than the space of human ears, take a laundry machine one might argue that such a sound can be perceived in stereophony. But as we mostly do not stay close when such a product is in use the distance between the product and the user make that we hear it as a monophonic sound source.

Grouping in gestalt principles

It is hard to keep an overview of possible 30 principles it is probably a better idea to group them. As most ASA examples are a form of a gestalt principles, it is a logic idea to group them based on gestalt principles. Since IDE students also learn about these gestalt principles it is also likely that these groups are easy to understand (Hekkert, 2017).

Different scholars use different groups of gestalt principles such as: Similarity, Proximity, common fate, closure, continuity, connectedness, figure & ground. In ASA similarity results in the same cognition as very high proximity and can therefore be one group. Also, closure will be perceived as connectedness and could therefore be one group as well. Resulting in the groups: Proximity, Continuity, Connectedness, and Common fate. Depending on the principle each can happen based on the Frequency, Loudness, Rhythm or Timbre of a sound.

Proximity general

1. Stream segregation in a cycle of six tones.

The faster rhythms, the more likely tones are grouped by proximity in pitch

2. Pattern recognition, within and across perceptual streams.

it is more difficult to recognise patterns across perceptual streams then within

14. Stream segregation of high and low bands of noise.

This also works with noise if it is present in different bands

Proximity in frequency

3. Loss of rhythmic information as a result of stream segregation.

The smaller the proximity in pitch between tones the more likely a pattern will be perceived as part of one rhythm/group

5. Segregation of a melody from interfering tones.

The lower proximity in pitch range of a distracting melody to a target melody, the easier it is to distinguish a main melody

Proximity in rhythm

13. (mistakenly 12 in paper) The effects of stream segregation on the judgment of timing

Easier to judge timing within a stream of sounds rather than between two streams

Proximity in timbre

9. Effects of a timbre difference between the two parts in African xylophone music.

Segregation can also happen by timbre. Enables to hear two melodies played in the same register

10. Stream segregation based on spectral peak position

The same effect occurs when the tone is replaced by rich tones with the same fundamental frequency but with the middle tone with a peak at different frequency.

Continuity in pitch
16. The release of a two-tone target by the capturing of interfering tones

It is harder to judge the direction of a pattern if the target is surrounded by other tones

17. Failure of crossing trajectories to cross perceptually.

Crossing pattern are almost always perceived as a bouncing pattern instead of a crossing pattern. Can be overcome be segregation in timbre

22. Rhythmic masking release

An on-target mask make it more difficult to detect a target adding more narrowband masks called flankers make it easier to recognise the target

28. Apparent continuity

An interrupted tone seams to be continuous if interruption is masked with noise

29. Perceptual continuation of a gliding tone through a noise burst.

Tone seems to keep gliding if separated by noise

Continuity in loudness
32. Homophonic continuity and rise time.

a steady noise will be heard as a continuous even if increased in loudness for a short while, will be perceived as joined briefly by a second burst

Continuity in rhythm
4. Cumulative effects of repetition on streaming.

Longer repetitive listening results in easier pattern/stream recognition.

30. Absence of pitch extrapolation in the restoration of the peaks in a rising and falling tone glide.

Apparent continuity stops if the noise gap is wide enough

Connectedness in frequency
12. Effects of connectedness on segregation.

Continuous changes in pitch create a sense of connectedness

18. Isolation of a frequency compo-

nent based on mistuning.

Harmonic sounds will sound like one tone

13. (mistakenly 12 in paper) The effects of stream segregation on the judgment of timing

Easier to judge timing within sounds from the same perceived stream compared to judging the timing between two groups

15. Competition of frequency separations in the control of grouping

It is harder to recognise a target pattern if it is followed by another pattern with high proximity in pitch

25. Capturing a tonal component out of a mixture: Part 1

A tonal component B, that is fused (simultaneously played) with C, can be segregated from tone C if the pitch of tone A, presented before B + C, becomes more proximate to B

26. Capturing a tonal component out of a mixture: Part 2

Asynchronous onsets and offsets of B and C make their fusion weaker.

27. Competition of sequential and simultaneous grouping

If a tone D, with a high proximity in pitch compared to C, is presented after B + C weakens the fusion between B + C even though B and C are played simultaneously resulting to the grouping of A and B

36. Capturing a component glide in a mixture of glides.

Connectedness in loudness

21. Effects of rate of onset on segregation.

"The auditory system seems to be particularly interested in sounds with abrupt onsets. Such sounds stand out better from a background of other sounds than do slow-rising sounds." (Bregman, 1990, p. 47) Meaning that faster onset rate (attack) makes it easier to segregate tones

Common fate

19. Fusion by common frequency change: Illustration 1.

Adding same amount of frequency modulating to some partials segregates into two streams

20. Fusion by common frequency change: Illustration 2.

"Common fate" still works if sound are frequency modulated at a different amount and rate

Figure-ground

33. Creation of a high-pitched residual by capturing some harmonics from a complex tone.

A sound B will be perceived as B = A + C (residual) if A, containing overlap in harmonics, is presented before B

34. Capturing a band of noise from a wider band.

from a short burst of noise partially overlapping with another noise burst only the residual will be perceived as new

35. Perceptual organisation of sequences of narrow-band noises.

if three narrow band noises with partial overlap are presented in a sequence they will be perceived as three separate streams

ASA principles that were not included

6. Segregation of high notes from low ones in a sonata by Telemann.

Example of a musical piece not relevant in product sounds

7. Streaming in African xylophone music.

Example of a musical piece less relevant in product sounds also example of multiple principles at the same time so less useful in explaining separate principles

8. Effects of a difference between pitch range of the two parts in African xylophone music.

Example of a musical piece not relevant in product sounds. Also explained in example 5

11. Stream segregation of vowels and diphthongs.

Example in vowel not relevant in product sounds

23. Sine-wave speech.

24. Role of frequency micro-modulation in voice perception.

About (computational)speech perception less relevant for product sound design

31. The picket-fence effect with speech

About perception of speech less relevant for product sound design

37. Changing a vowel's quality by capturing a harmonic.

About vowels not relevant for product sounds

38. Streaming by spatial location
39. Spatial stream segregation and loss of across-stream temporal information
40. Fusion of left- and right-channel noise bursts, depending on their independence
41. Effects of a location difference of the parts in African xylophone music.

About dichotic sounds not relevant for product sounds

VI Recording procedure

In this appendix, the recording procedure to create the initial library of shaver sounds is discussed. The same procedure can be used if more samples of products sounds are to be added to the library.

Calibration of speaker

Pink noise was generated with the tone generator in Studio One 6.6 (Presonus Audio Electronics, 2024) at a level of 0dB (K-20). The output level of a speaker playing this noise was adjusted until an SPL meter, placed at the same location of the microphone, measured 85dB C SPL (Katz, n.d). For this measurement a SPL level meter app was used on a Nokia X20 smartphone (Keuwlsoft, 2024) as seen in the setup in Figure III.III.

Figure III.III: Setup for Microphone calibration setup.

Calibration of microphone

To calibrate the t.bone SC-140 condenser microphone, the speaker kept playing white noise. A Focusrite Scarlett 2i2 was used as an ADC to connected the microphone to the computer. The input level knob of the ADC was adjusted until the input level of the microphone in the DAW showed 0 dB (K-20), Figure IV.IV.

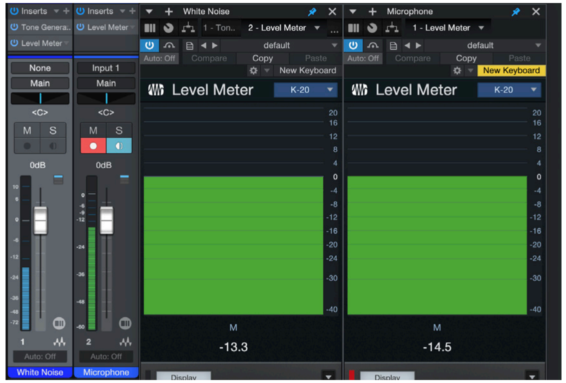


Figure IV.IV: Comparing desired sound level with measured sound level.

To keep relative information of the intensity of multiple components, the recordings were done by keeping the microphone and placement of the recorded product/feature stationary after this calibration.

Since the room acoustics can influence the perception of a recorded feature, some measurements were taken to remove unwanted reverberations from the room. Curtains were closed and some other sound absorbing products such as pillows were added. To eliminated the effect of the product on the table all products were placed on a pillow while being recorded.

VII Modelling the product housing and user interactions

Deriving filtering characteristics
User interactions are modelled by applying a filter which provides the filtering effect such an interaction might have. To retrieve the characteristics of this filter, two recordings were made. One of the object in free space and one recording with the interaction, for example grabbing by hand, applied to the object.

Figure 7.1: Taking separate recordings for the neutral use and with hand force applied.

To retrieve the spectrum of each recording, both recordings were loaded in Praat (Boersma & Weenink, 2023). This spectrum gives an overview of the average intensity at each frequency of the whole recording. To get numerical data from this spectra, first an excitation graph was made from it. The excitation graph gives the loudness (in phon) of each sample over frequency (in bark scale). In the default setting, each bark band is 0.1 barks wide, by measuring for a total of 256 bands. The loudness is given for a range of 10-11550 Hz (Weenink, 2014).

The data of this excitation was exported to a text file after which this data was processed in excel. In excel the ratio in loudness at each sub bark bank was calculated by dividing the loudness of the interaction sample with the loudness of the neutral sample. The correct amount in gain, which Max filters use, was taken by using the loudness ratio to level change calculator (Sengpiel, n.d.).

Graphing this difference for each bark bank should give an overview on how much the intensity of the original sample has to be amplified or attenuated to achieve the same change in sound as grabbing the product should have. This line could be modeled directly with a parametric EQ filter or a generalization could be made.

Modelling hand interactions
For the hand interaction, this generalization is done by retrieving a trend line from the graph. In the case of the shavers a linear trend line resulted in a downward slope, crossing the X-axes at y = 1 at 13.345 bark. This means that frequencies lower than 13.345 Bark (2138.63 Hz) are amplified with lower much more and frequencies

higher than 13.345 Bark are attenuated with the higher the frequency the higher the attenuation.

In the Max tool two shelf filters were used to model this trend line, one low shelf filter with adjustable increasing gain and one high shelf filter with adjustable decreasing gain. Adjusting the gain of each filter simulates grabbing the object firmer or less firm.

Modelling the filtering of the housing

To model the filtering characteristics of the housing. The gain graph was made similar to how the hand interaction was made. This graph, Figure 7.5, was as accurately reshaped as possible using six cascaded filtergraph~ filters. With four in peaknotch setting to add in the subtle peaks and notches in the mid spectrum, a highpass filter to add in the steep roll off at the lower frequencies and a highshelf to add the shelving effect in the higher frequencies.
The gain of each separate filter can be set gradually from 0 (no effect) to the respected retrieved gain (full effect). This enables to mix in the effect of the housing instead of a binary on and off only.

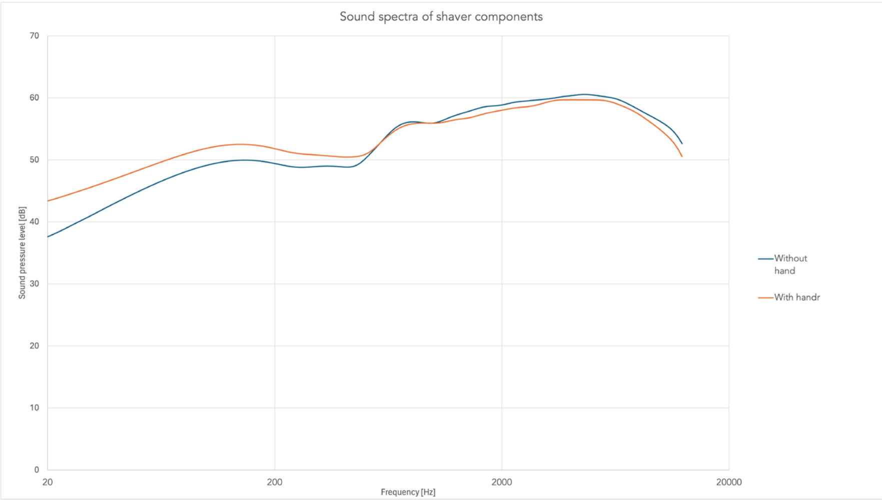


Figure 7.2: Spectrum of a shaver in free air and a shaver held in a hand

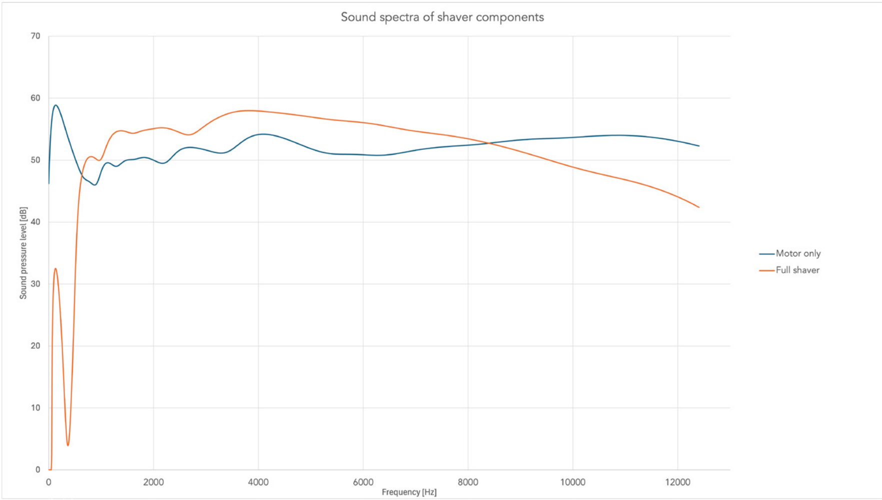


Figure 7.4: Spectrum of the motor of a shaver and the motor inside the housing

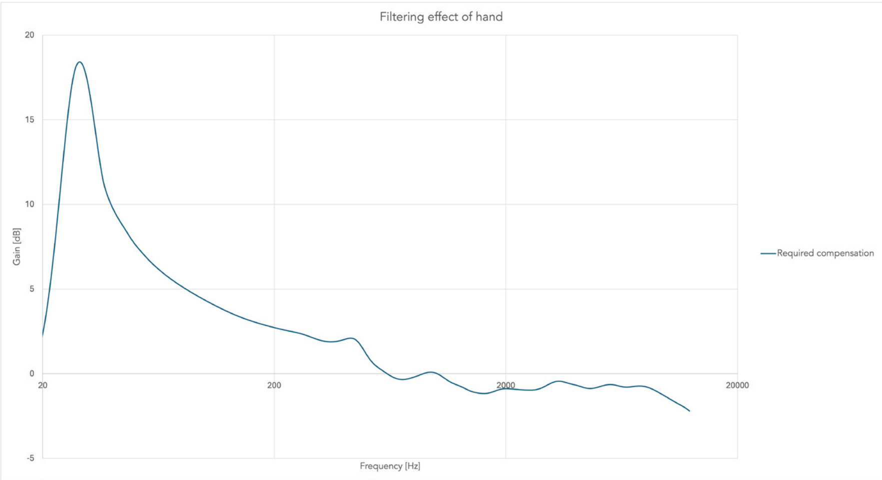


Figure 7.3: Derived filtering characteristics of hand

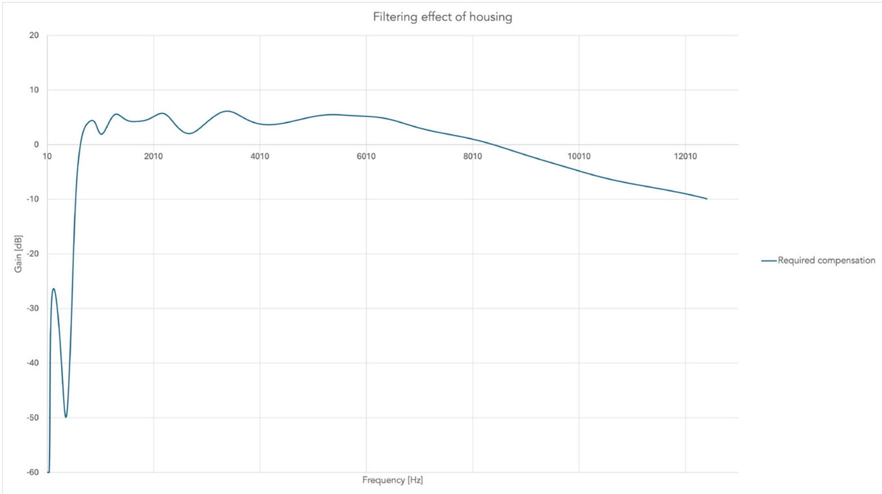


Figure 7.5: Derived filtering characteristics of housing.

VIII User research interview questions after assignment

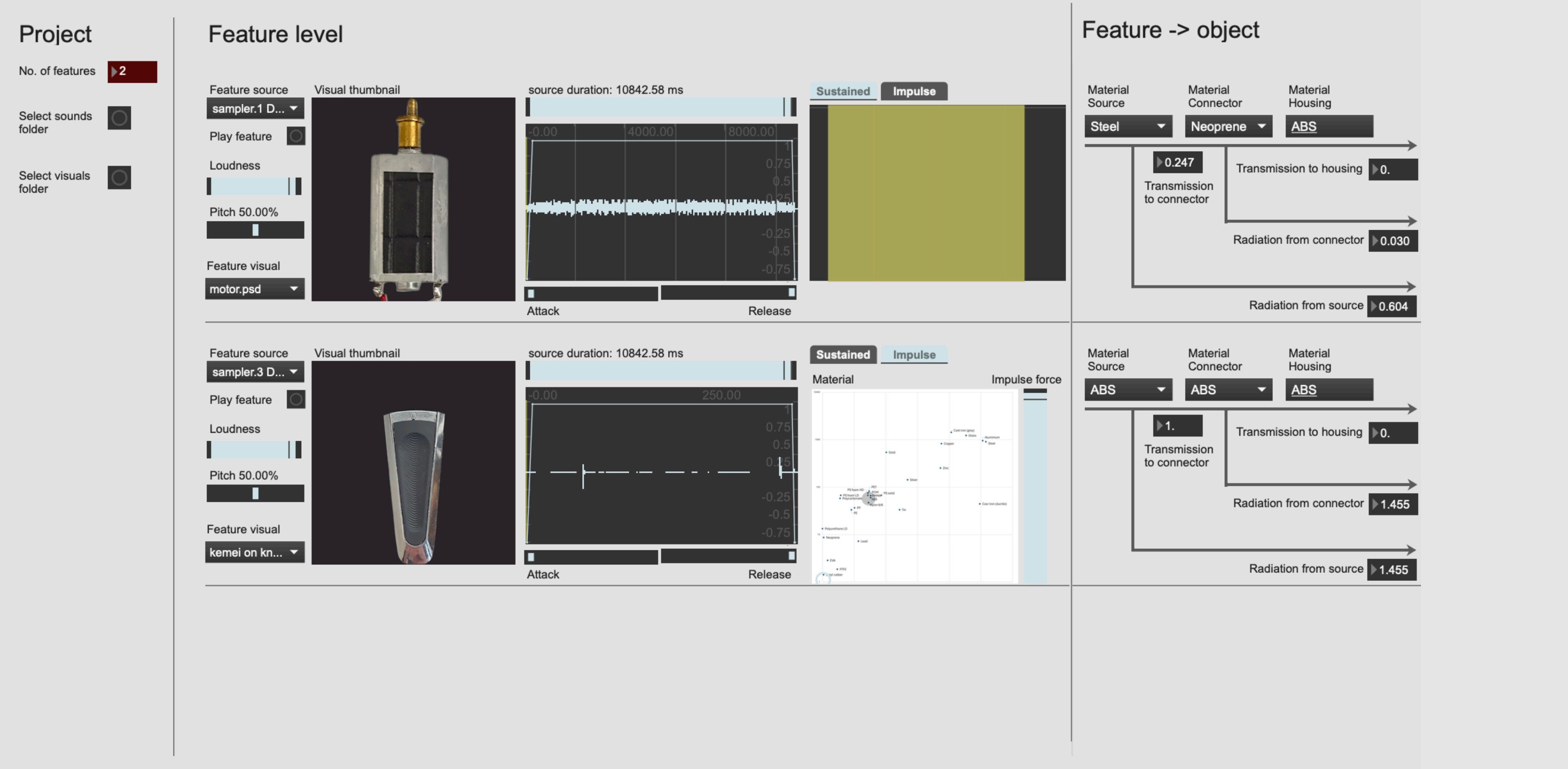
For participants that had to recreate target sounds:

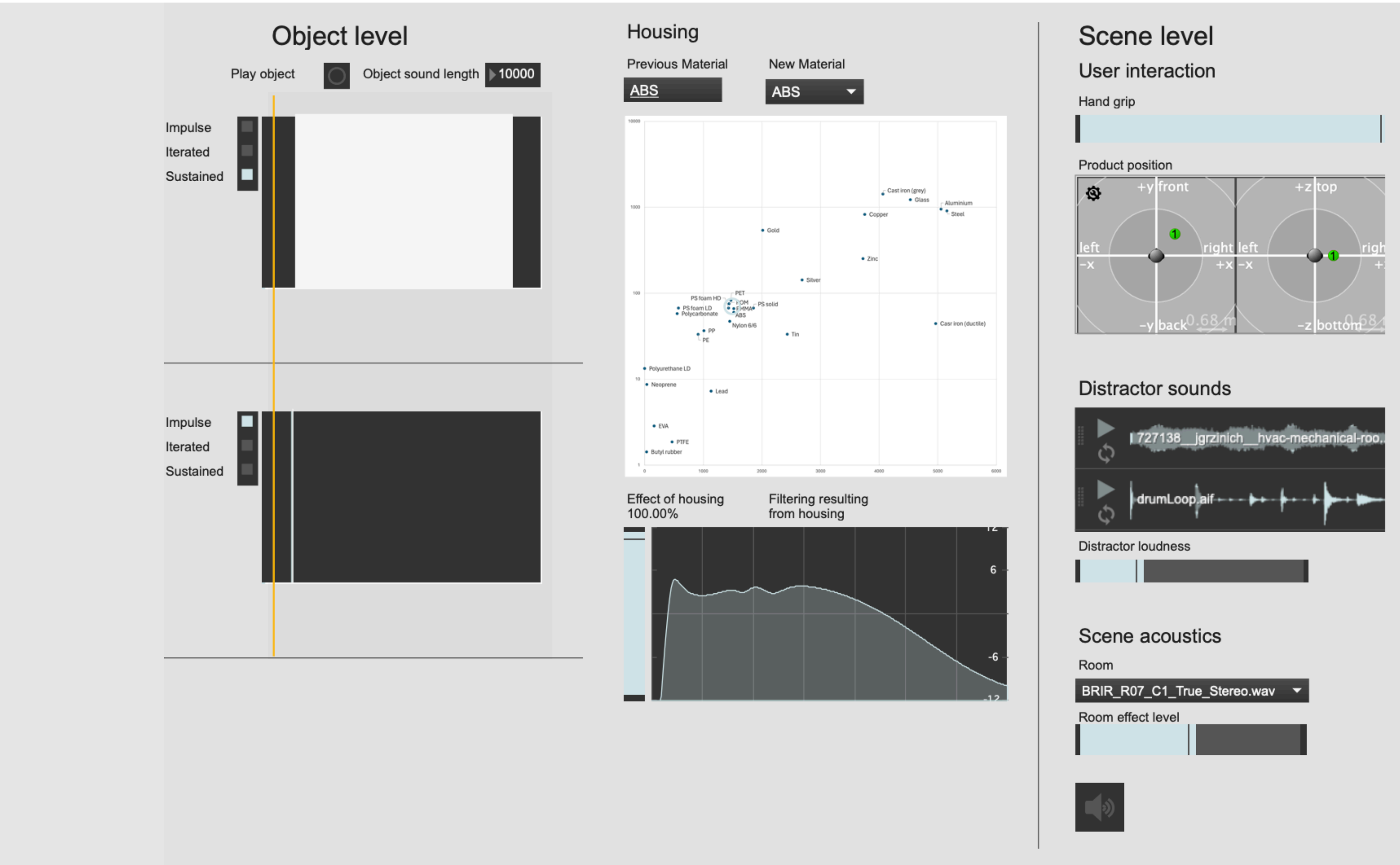
1. With which character description would you describe the sound you had to recreate?

For all participants:

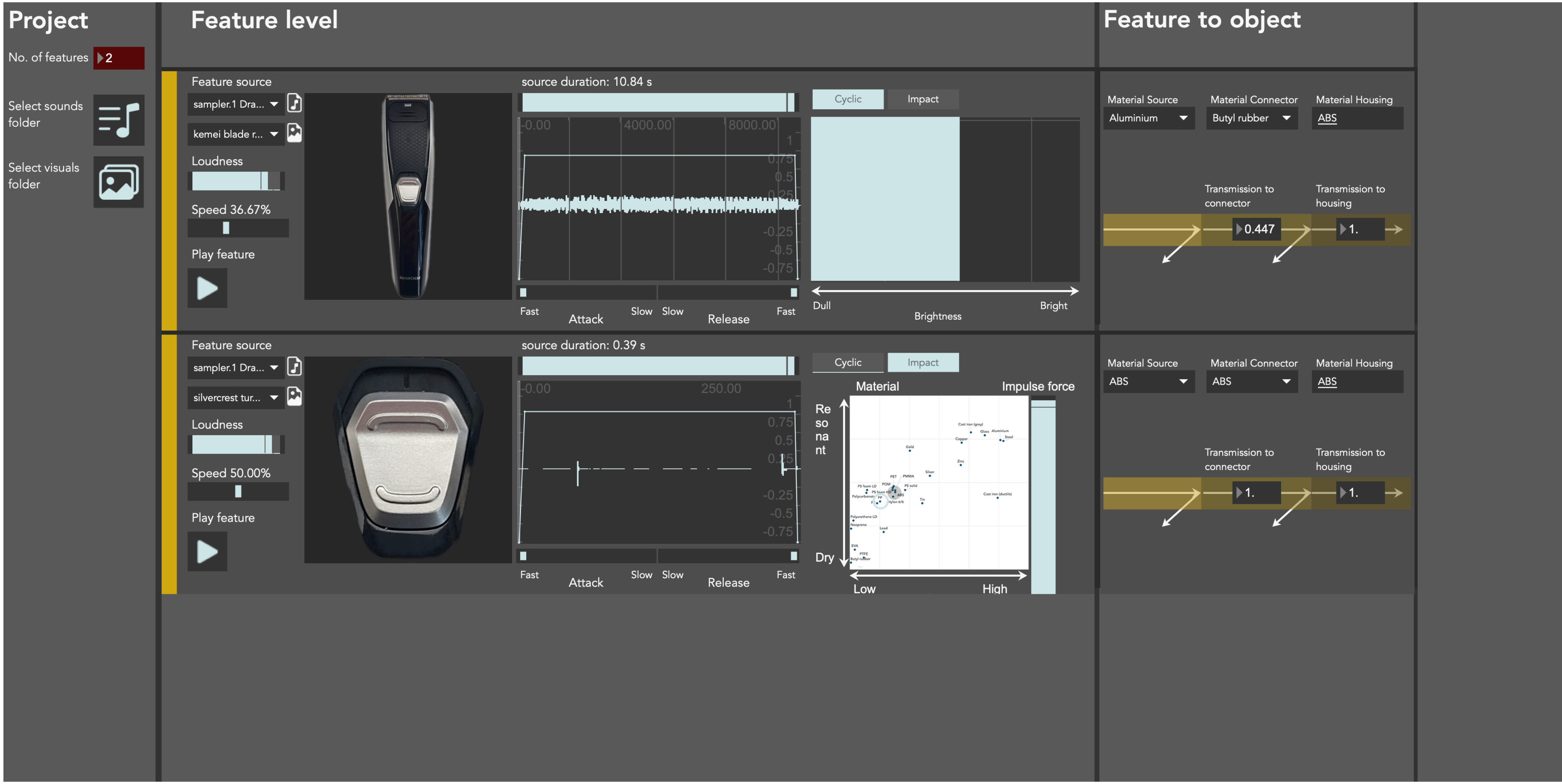
2. What strategy did you take to design the sounds?
3. Did you feel a sense of hierarchy, and how did this influence your approach to the task?
4. Could you elaborate your satisfaction of your result compared to your objective?
5. What parameter(s) of the tool contributed the most to come closer to the objective you were given?
6. What parameter(s) of the tool had the most influence that made you divert from the objective you were given?
7. What comments do you have on the difficulty of the tasks?
8. What general design requirements for use in further design stages can you derive from the use of the tool?

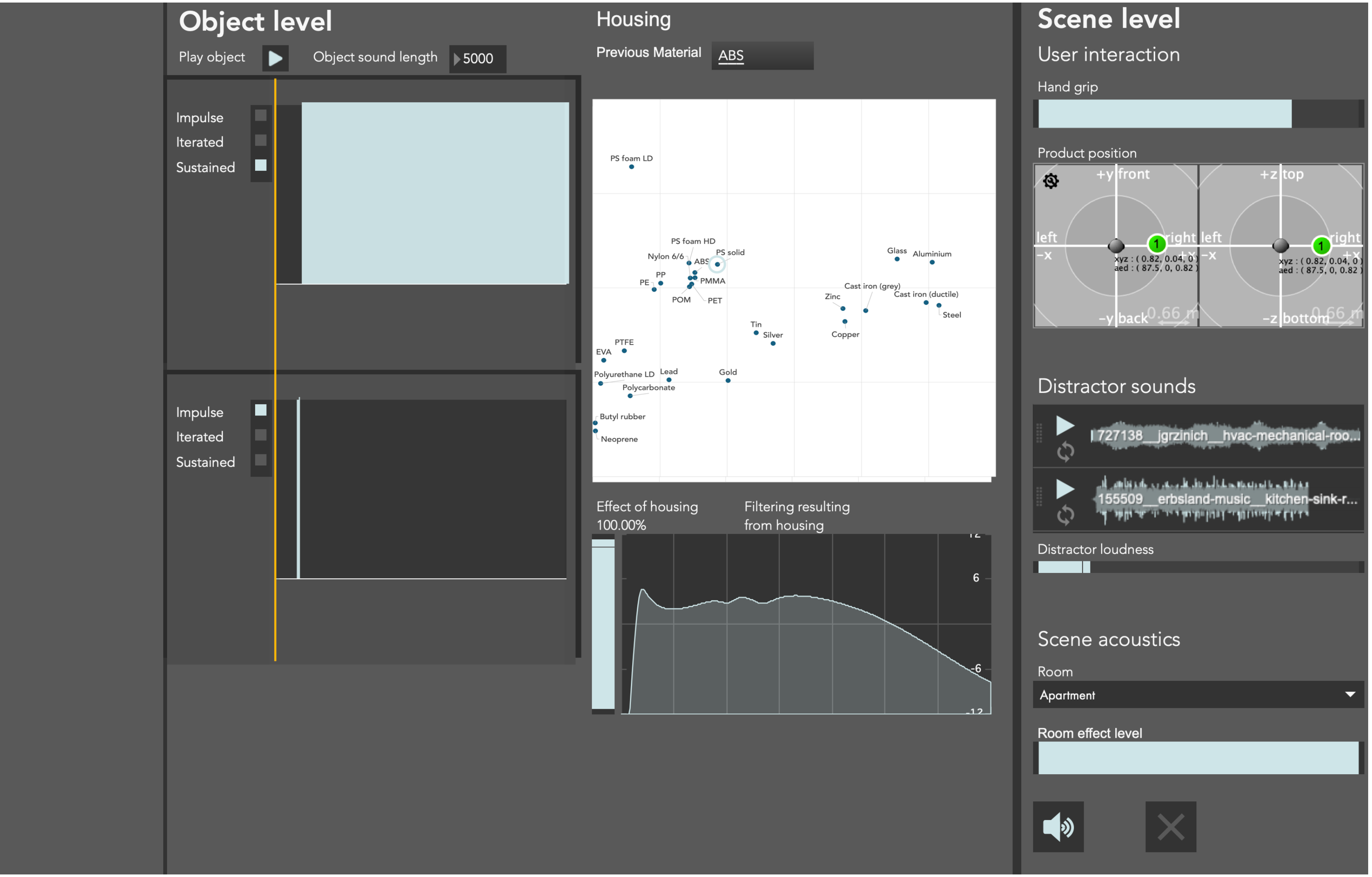
IX Les_Sons (V2)




Object level
Play object
Object sound length
10000
Impulse
Iterated
Sustained
Impulse
Iterated
Sustained
Housing
Previous Material
ABS
New Material
ABS
Effect of housing
100.00%
Filtering resulting
from housing
Scene level
User interaction
Hand grip
Product position
+y front
left
right
-x
+x
-y back
+z top
-z bottom
Distractor sounds
727138__jgrzinich__hvac-mechanical-roo...
drumLoop.aif
Distractor loudness
Scene acoustics
Room
BRIR_R07_C1_True_Stereo.wav
Room effect level

X Les_Sons (V3)


Project
No. of features
2
Select sounds folder
Select visuals folder
Feature level
Feature source
sampler.1 Dra...
kemei blade r...
Loudness
Speed 36.67%
Play feature
source duration: 10.84 s
0.00
4000.00
8000.00
Fast
Attack
Slow
Slow
Release
Fast
Cyclic
Impact
Dull
Brightness
Bright
Feature source
sampler.1 Dra...
silvercrest tur...
Loudness
Speed 50.00%
Play feature
source duration: 0.39 s
0.00
250.00
Fast
Attack
Slow
Slow
Release
Fast
Cyclic
Impact
Material
Impulse force
Re so na nt
Dry
Low
High
Feature to object
Material Source
Aluminium
Material Connector
Butyl rubber
Material Housing
ABS
Transmission to connector
0.447
Transmission to housing
1.
Material Source
ABS
Material Connector
ABS
Material Housing
ABS
Transmission to connector
1.
Transmission to housing
1.


Object level
Play object
Object sound length
5000
Impulse
Iterated
Sustained
Impulse
Iterated
Sustained
Housing
Previous Material
ABS
PS foam LD
PS foam HD
Nylon 6/6
PS solid
ABS
PP
PE
PMMA
POM
PET
Glass
Aluminium
Cast iron (grey)
Cast iron (ductile)
Zinc
Steel
Copper
Tin
Silver
PTFE
EVA
Polyurethane LD
Lead
Polycarbonate
Gold
Butyl rubber
Neoprene
Effect of housing
100.00%
Filtering resulting from housing
6
-6
Scene level
User interaction
Hand grip
Product position
+y front
+z top
left
right
-x
-y back
-z bottom
Distractor sounds
727138__jgrzinich__hvac-mechanical-roo...
155509__erbsland-music__kitchen-sink-r...
Distractor loudness
Scene acoustics
Room
Apartment
Room effect level

XI MATLAB script for psychoacoustics evaluation

```
% With this file audio can be compared on psychoacoustic qualities
% This script was based on a script by Brian Hemmat (2019) on the MATLAB Answers forum available on https://de.mathworks.com/matlabcentral/answers/141137-how-can-i-compare-two-audio-files

% To be able to use this script the MatLab Audio Toolbox has to be installed.

%specify the folder containing the samples and define the exact file that are to be analysed.
folder = fullfile(matlabroot,'toolbox','audio','samples','test/');

files = {'/P1 Sound1-.wav', '/P2 Sound1-.wav', '/P3 Sound1-.wav', '/P4 Sound1-.wav', '/P1 Sound2-.wav', '/P2 Sound2-.wav', '/P3 Sound2-.wav', '/P4 Sound2-.wav'};

ads = audioDatastore(strcat(folder,files));
numFiles = numel(ads.Files);
% Create a preprocessing pipeline so that all of the audio is mono, 16
% kHz, and normalized such that the max absolute value is 1.
desiredFs = 48e3;
adsMono = transform(ads,@(x)mean(x,2));
adsMono16 = transform(ads,@(x,info)resample(x,desiredFs,info.SampleRate),'IncludeInfo',true);
adsMono16Normalized = transform(adsMono16,@(x)x/max(abs(x)));
% Create an audioFeatureExtractor object to extract the spectral centroid,
% rolloff, and flux for 30 ms windows and 10 ms hops.

afe = audioFeatureExtractor('SampleRate',desiredFs, 'Window',blackmanharris(round(desiredFs*0.03),'periodic'), 'OverlapLength',round(desiredFs*0.02), 'linearSpectrum', true);
% In a loop, read a file from the datastore, extract features, and then average the features across the analyzed file.
featuresPerFile = zeros(numFiles, 480000);
for ii = 1:numFiles
    audioIn = read(adsMono16Normalized);

    loudness = acousticLoudness(audioIn, 48000);
    sharpness = acousticSharpness(audioIn, 48000);
    roughness = acousticRoughness(audioIn, 48000);
    fluctuation = acousticFluctuation(audioIn, 480000);

    %uncomment the feature the is to be analyses
    features = loudness();
    %features = sharpness();
    %features = roughness();
    %features = fluctuation();

    featuresPerFile(ii,:) = mean(movmedian(roughness,10),1,'omitnan');
end
% Normalize each feature across the dataset so no one feature dominates the distance measurement.
featuresPerFile = (featuresPerFile - mean(featuresPerFile,1))./std(featuresPerFile);
% Calculate the Euclidean distance between each pair.
distanceMatrix = zeros(size(featuresPerFile,1));
for ii = 1:size(featuresPerFile,1)
    distanceMatrix(:,ii) = sqrt(sum((featuresPerFile(ii,:) - featuresPerFile).^2,2));
end
% Create a heatmap to inspect simalarity.
filenames = extractBetween(ads.Files,'test/','-');
heatmap(filenames,filenames,distanceMatrix)

title('Euclidean Distance of Loudness')
```

TUDelft

DESIGN FOR our future

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	Deltrap	IDE master(s)	IPD ✔ / DfI ☐ / SPD ☐
Initials	T	2nd non-IDE master	
Given name	Tim	Individual programme *(date of approval)*	
Student number	4661567	Medisign	☐
		HPM	☐

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Dr. Elif Ozcan	dept./section	Ctitical Alarms Lab
mentor	Dr. Dave Murray-Rust	dept./section	Human-Centered Design
2nd mentor	Stefano delle Monache		
client:			
city:		country:	
optional comments			

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Name Dr. Elif Ozcan Date 13.11.2023 Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total ______ EC

Of which, taking conditional requirements into account, can be part of the exam programme ______ EC

☐	**YES**	all 1st year master courses passed
☐	**NO**	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Name ______ Date ______ Signature ______

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	☐	Supervisory Team approved
NO	☐	Supervisory Team not approved

Comments:

Based on study progress, students is …

☐	**ALLOWED** to start the graduation project
☐	**NOT** allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Name ______ Date ______ Signature ______

![DESIGN FOR our future]

Personal Project Brief – IDE Master Graduation Project

Name student Tim Deltrap **Student number** 4661567

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Product Sound Sketching for Design Education

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

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Sound is an important aspect in product design. Nonetheless, it is left to last stages in the design process. As a result of this, little can be done to adjust the sound or a whole redesign of the product is needed. If visual and auditory product properties are used early in the design phase, requirements and wishes could be setup and refined throughout the whole design process accordingly (Keiper, 1997).

Özcan and Van Egmond (2008) found that to include product sound design, an inter-disciplinary approach is required. They stated that the designer should have knowledge on engineering, musicology, acoustics, psychoacoustics, and psychology. Based on that, Langeveld et al. (2013) proposed a product sound process which can be integrated in the product design process. This is an iterative process consisting of four stages: 1. Sound analysis, 2. conceptualization, 3. Embodiment, and 4. Detailing which is similar the product design processes defined by Roozenburg and Eekels (2003). Accordingly, design vision for product sounds in general can be defined in the conceptualization stage via sound-specific design activity. One example of this is sonic sketching (Delle Monache & Rochesso, 2019). With sonic sketching designers are encouraged to explore sounds in a very free way, for example using a foley box or vocalization. However, when sound is explored in isolation from the product properties the relation between the envisioned sounds and the eventual product becomes broken. This makes it unclear how the qualities derived from these sketches can be achieved in the product in the later design stages. Tools that can be used to edit or synthesize these sound- sketches/visions in a more realistic way are on the other hand complex and require extensive knowledge on acoustics and or music production.

Some research on how to explain sound to non experts, like product designers, already exists. From multiple papers that discuss the evaluation of the experience of product sound, Carron (2017) bundled verbal descriptors of sound into a lexicon for sound designers. As this vocabulary is easy to understand, it enables designers to talk and think about sound within their design team. Furthermore, it also facilitates communication and discussions with experts on sound or during user tests with non-experts.

→ *space available for images / figures on next page*

introduction (continued): space for images

click to add picture

image / figure 1 Verbal descriptions of sound (Carron et, 2017); Sound design process (Langeveld et al. 2013).

image / figure 2 Some tools to design sounds (Baldan et al. 2017; Muse group, 2023; Jansen, 2010; Vardanyan, 2023).

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Designing sounds is often a self-taught design skill or limited attention is given to sound design in design education. Consequently, current product designers have little knowledge on how to design for sound, especially with taking consequential product sounds into account. These are sounds that are emitted by the product as a result of their functioning (Özcan and Van Egmond, 2008). This is due to a lack of usable tools and methods to design for product sounds. A major problem is that the currently used sound design tool are difficult to understand for product designer. This as these tools are directed to sound designers, such as the Sound Design Tool (Baldan et al., 2016) and or music producers, like a digital audio workstation. Resulting that the use of current tools require an advanced understanding of acoustics or musicology. If these tasks were delegated to an external expert on sound design the process might be hindered from speed and and proper application, due to the recursive nature of the design process. Two problems with the current easier to use or understand tools is on low customisability limiting creative exploration and- or two the connection between the created sound and embodiment is unclear making it hard to translate the envisioned sound to requirements on the embodiment. Another factor is the interaction with this tool. Some of these tools like PSST! (Jansen, 2009) and Timbreworld (Vardanyan, 2023) use a tangible interface. The tangibility of their interfaces was found to promote collaboration within teams. It is interesting to research if a tangible interface is required and if so how a portable setup can be achieved, as both PSST! and Timbreworld came out to be awkward to setup. My project focuses on the design of an educational tool for sound sketches.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a platform of a sound sketching tool that enables design students to create design concepts for product sounds.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Discover: Research by means of interviews and small practical sound design assignements with existing tools will be done with product design students. This is done to get to an understanding of the base level of the understanding of product sound within this group. Second to that by means of expert interviews and literature research the current state of technical possibilities to create product sounds and current interactions/processes/methods in product sound design can be explored.
Define: From the discover phase multiple criteria on the interaction and embodiment of the tool are generated. These can be used in the further stages to come up with new ideas and concepts and test them.
Develop: Based on the criteria multiple ideas for an advanced sound sketching tool are generated. These will be tested with users by means of LoFi prototypes. After the evaluation of these LoFi prototypes the design requirements will be revisioned. After that, multiple concepts of new product systems will be generated and HiFi prototypes will be made to test these concepts with users more thoroughly. After the evaluation of these concepts one concept will be developed further, tested and validated in a last iteration.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	31 Oct 2023
Mid-term evaluation	16 Jan 2024
Green light meeting	26 Mar 2024
Graduation ceremony	7 May 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✔
For how many project weeks	25
Number of project days per week	4

Comments:
I have a 16 hour job so I will work 4 days on the graduation project and 2 days work leaving obe day in the week free. A two week break is included during christmas.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

In my free time I like to make music and also design and build (electronic) music Instruments. I have Interest in sound in general and want to broaden my expertise in sound creation and the experience of sound and its relation in product design. Sound in products design was discussed in multiple courses during my studies at Industrial Design Engineering. But in most courses product sound was only touched on the surface. Only in the two master elective courses Interactive- and Embodied Audio Design methods and tools were given to design product sounds. In these courses it came clear the the current ways to design product sound is cumbersome and difficult to do, especially if one has no prior knowledge in music production.

Competences to prove:
- Look broad into problems
- Creating functional prototypes
- Following an innovation process

Competences to improve:
- Knowledge on interaction design
- Gain knowledge or verify assumptions by contacting experts and users.
- Understanding of acoustical properties in product design and sound design in general