SEMI-PERSONALISED EARPHONES :

SCAN FOR COMFORT

Figure 1: Concept close up

Semi-Personalised earphones : scan for comfort

Master thesis

Ruben Hugo Ruth van Es

Integrated Product Design

Faculty of Industrial Design Engineering
Delft University of Technology

In collaboration with

Dopple

Supervisory team

Dr. Toon Huysmans
Dr. Stefano Delle Monache
Dr. Jaap Haartsen

Preface

In primary school I started playing drums for the first time. I discovered the fun of playing along with the songs I love to listen to. It meant that I started to listen to more music in my spare time, while practicing new rhythms and beats. This also meant that I was more frequently exposed to loud music: hearing protection became more important. As a protection, I have used general earplugs of Alpine. These reusable plugs consist out of silicone exterior with a hard plastic tube at the end. Although the plugs seal off the walls of the hearing channel, the plastic tube has a small hole to allow some sound to get through. This way, the quality of the sound is better, but the level of noise is reduced. However, it often happened that my earplugs were not correctly inserted and became loose while playing. The round generalised shape of the plugs did not fit well enough within my ears.

The same thing happens when listening to music via earbuds. When listening to music, I like to fully immerse myself in the music. However, after a while, my earbuds (with generic tips) would loosen, allowing surrounding sounds to become more audible. For me, this is a huge loss in the listening experience. In that sense, I often prefer my headphone. However, headphones have other disadvantages. They are big and therefore harder to store. They seal the ears completely, which, over time, causes discomfort due to heat. Furthermore, due to their weight, they are not practical for running or other sports either. Therefore, I personally still prefer earbuds over headphones, due to their convenience in use.

During my minor in Hong Kong, I first came into contact with using 3D-scan data of body parts within design. Through this course, I became more interested in how products can be made to fit perfectly to the human body. I especially became interested in using Additive Manufacturing for personalised products. This project will give me the opportunity to work on a parametric design, which will incorporate personalised 3D data. For this, I will need to learn new CAD software (Rhinoceros and Grasshopper) and test different solutions and materials, such as AM technologies and shape morphing materials.

Acknowledgements

I would like to express my deepest gratitude to everyone who has supported me throughout this exciting and challenging project.

I want to especially thank my supervisory team, who helped me to lift my design to a higher level. Together with my chair, Toon Huysmans, I have had multiple discussions on how to improve and evaluate the database, which led to new discoveries and conclusions on how to build the shape of the final concept. I would like to thank my mentor, Stefano Delle Monache, for supporting me on how to approach my project, keeping me on track and giving me insights on how to collect meaningful data from the participants.

To my mentors from Dopple, Jaap Haartsen, Rachid ElOuad, Johan Schreuder and Tim de Jong, I would like to say how much I appreciate all the time and effort you have taken to collaborate with me on my project. The fact that the four of you were always present during our meetings and that you always had time available to answer my questions made sure that I really enjoyed working on this project.

I would also like to extend my gratitude to Jose Martinez Castro, the Grasshopper expert, who helped me through the difficult start of the project in the CAD software. And to Joris van Dam, who made it possible to print many of my prototypes on time with the Multi-Jet printer at IDE.

To my friends (and other participants), who, in some cases, did not only provide a listening ear, but their physical ears as well. Thank you for participating in my research.

And especially to my girlfriend, Jennifer, and my parents who helped to check this report on clarity and spelling. I know these are not my strongest skills.

List of abbreviations

- *AI : artificial intelligence*
- *SSM : Statistical Shape Model*
- *AM : Additive Manufacturing*
- *E-module : electronic module*
- *UE drops : Ultimate Ear Drops*
- *UPPS : Ultra Personalised Products and Services*
- *SLA : Stereolithography*
- *CAD : Computer Aided Design*
- *TRL : Technology readiness level*
- *MJ : Multi-Jet*
- *IR : Industrial Revolution*
- *CAM : Computer Aided Manufacturing*
- *CR – 50 : Category Ration 50*
- *SLS : Selective Lase Sintering*
- *FDM : Fused Deposition moulding*
- *RoI : Region of Interest*
- *OSHA : Occupational Safety and Health Administration*
- *PEL : Permissible Exposure Limit*
- *NRR : Noise Reduction Rating*
- *dB : Decibel*
- *IEM : In-Ear Monitor*
- *VCSEL : Vertical-cavity Surface-emitting Laser*
- *UV : Ultra Violet*
- *VPP : Vat Photopolymerization*
- *MPVPP : mask Projection Vat Photopolymerization*
- *MSMP : Magnetic Shape Memory Polymers*
- *MSM : Magnetic soft material*

Glossary

- *Personalised: using Customer data to make a tailored service or product.*
- *Customised: using input from the user to change the design/function of a product.*
- *Personalisation of identity: focuses on the perception of the product*
- *Personalisation of capabilities: the personalisation of functionality*
- *Personalisation of fit: fitting to the body*
- *Audio canal: part of the personalised earphone which sticks in the ear.*
- *Auditory canal: part of the ear which goes inside your head.*
- *Audio tube: tunnel inside the audio canal*
- *Retention: the force which keeps the earphones in the ear.*
- *Sealing: how well the earphone closes off the auditory canal (in terms of noise).*
- *Comfort: associated with feelings of relaxation and well-being*
- *Discomfort: associated with physiological and biomechanical factors.*
- *Model: refers to physical models before the concept phase.*
- *Prototype: physical model of the concept.*
- *Landmarks: extreme points in the shapes.*
- *Outliers: measurements outside of the statistical range*
- *Hygiene product: products that are necessary for the personal health and cleanliness of an individual, which can therefore not be returned by (dutch) law.*
- *Shore hardness It describes the resistance a material has to indentation (Bentley, n.d.)*
- *In-ear monitor : Type of personalised earphone used by professional musicians during a performance. These earphones are often equipped with technology which is optimised to receive music without lag.*

Summary

Current earphone designs follow a universal approach, which might fit average body shapes comfortably but lead to discomfort for others. Leveraging technologies like AI, simulations, and digital models enables efficient creation of personalized products at scale (Sony, 2018). With the development of new AM techniques, printing options are becoming faster and the materials more versatile. Techniques for printing flexible materials, such as silicones and printing multiple materials within the same print (Rossing et al., 2020), allow a larger scale of design properties, increasing the possibilities for which products will be fit for mass customisation.

When people customise or personalise a product, they intensify their emotional connections to the product (Mugge et al., 2009). Involving customers in the creation of their earphones leads them to be more emotionally invested in the product.

To create a personalised product, it is essential to obtain data of the individual body part as everyone is unique. For this project, the customer should be able to scan their ears by themselves at home. To evaluate which scanning methods best represent the shape of the ear while being easy to use, the 3D scanning methods and the physical representations of those scans are validated. Through tests it is determined that the Truedepth scanner provides the best results for the envisioned use case of scanning at home.
Customers perform multiple activities per day with which they would prefer to use their earphone. By designing for extreme use cases (dancing with lots of head movements and long consecutive use of the earphones), the design is expected to perform well in other use cases as well.

Since earphone tips provide the main point of retention in the ear, they typically are the cause of irritation among users. To increase the level of comfort, the pressure should be equally distributed to parts of the concha.

The concept Seal is based on the Truedepth scan data of the concha. Seal distributes the retention force across the concha, rather than providing retention in the auditory canal. The part that fits in the cymba concha is made of flexible material, providing a softer touch and therefore more comfort. The seal creates a sealing effect at the entrance of the auditor canal using a flexible collar. Therefore, it does not need to enter the auditory canal which means that its audio canal can remain short. The advantage of this is that the seal fabricates as little extra geometry as possible.

The prototypes show that it is possible to design earphones based on scanned data that are gathered by a smartphone or tablet. This provides the customer with new listening experiences. However, the success of the concept partly depends on the availability and the quality of scanners in smartphones in the future.

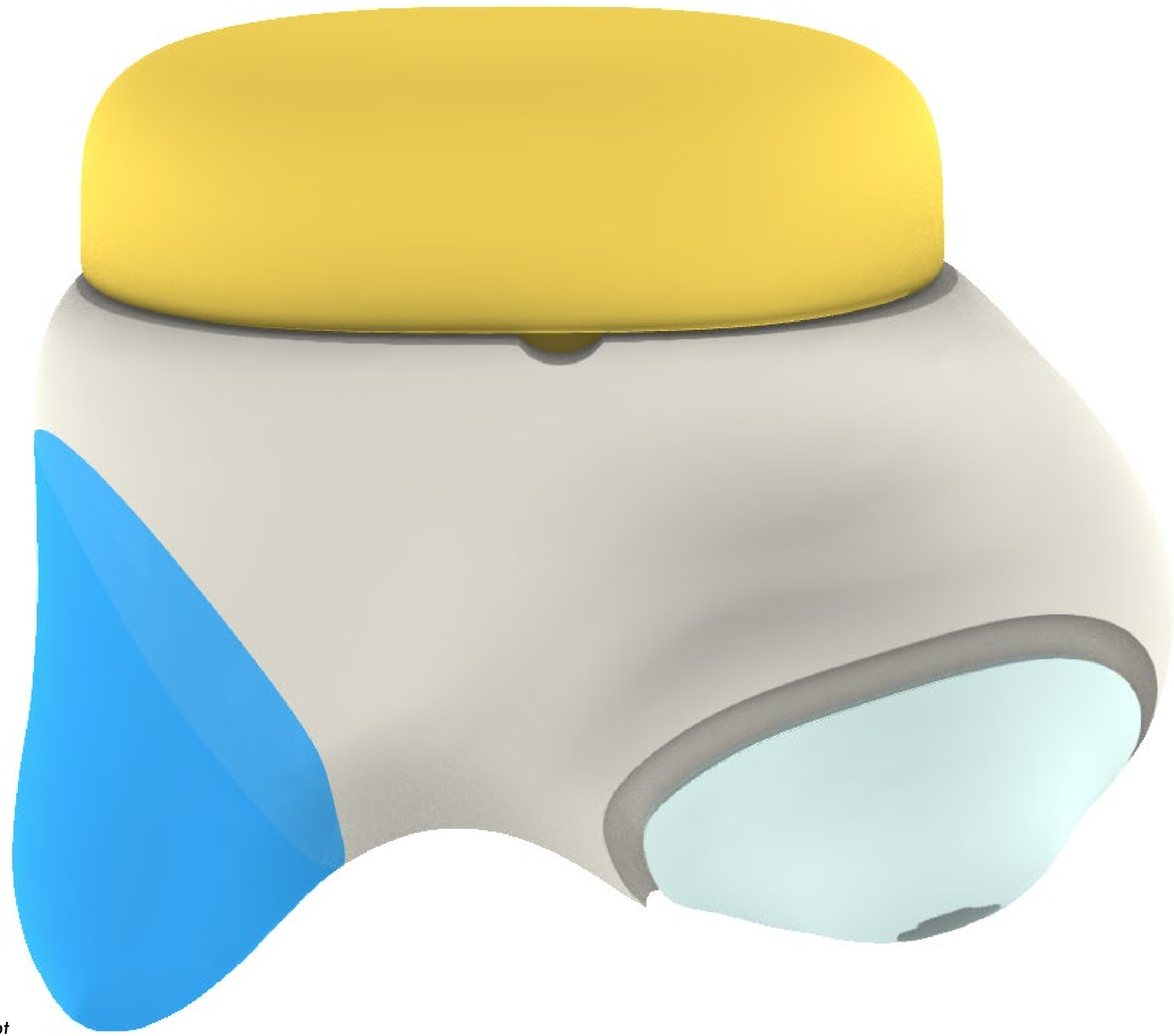


Figure 2: Render of concept

Table of content

1. Introduction

1.1. Project motivation

Current products are designed based on averages of human data. This one-size-fits-all approach means that the product will be comfortable close to the average body shape while this could be very uncomfortable for other people.

More technologies are adopted into the everyday workflow of companies, including Artificial Intelligence (AI), computer simulations and digital models. Therefore, it is becoming easier to produce personalised products for a large audience (Sony, 2018). Thanks to more automation in design processes and improvements in Additive Manufacturing (AM) techniques, it is possible to produce complex products in small to unique batch sizes. Furthermore, there is no delay to switch between the production of various products or by making adaptations to the product (Gibson et al., 2021). This is not feasible with injection moulding which requires high investment costs to produce specific tools. A different approach is required for the supply chain of Additive manufactured products: Agile manufacturing. This approach is order driven (Minnoye et al., 2022; Sony, 2018), instead of producing large batches of a product and estimating the demand, products are manufactured after an order is placed by a customer. Selling products in low quantity batches or products that allow for customisation by the customer reduces wasting resources and risks.

However, since products that are made by AM are not fit to be manufactured in bulk, lead time and manufacturing location will play a larger role in how quickly the customer will be able to receive their product (Gibson et al., 2021). With the development of new AM techniques, printing options are becoming faster, and the materials more versatile. Techniques for printing flexible materials, such as silicones and printing multiple materials within the same print (Rossing et al., 2020), allow a larger scale of design properties, increasing the possibilities for which products will be fit for mass customisation.

Another challenge will be to convince the customers to provide personal data. The customer needs to be able to trust that the privacy will be guaranteed by the service (Gefen et al., 2003). Trying out personalised products before buying is not common as the products first needs to be made to be experienced.

When the product can evoke an emotional response from the user, it could be the decisive trigger for buying the product (Jordan, 2000). When people customise or personalise a product, they effectively are not just the consumer of the product but also partly its creator. Creating the product requires input and effort from the side of the user. The more energy customers put into personalising their products, the deeper their emotional connection is with the product (Mugge

Figure 3: Left earphone of the UE Drop

et al., 2009). By involving the users to make their own scans and personalise their earphones, customers will become more emotionally invested in the product which could convince them to buy the earphones.
Personalization for products can be split up into three types: (1) Identity, which focuses on perception; (2) Capabilities, which focuses on functionality; (3) Fit, which focuses on physical interactions (Minnoye et al., 2022). In this project, the focus will be on personalisation in fit, since it focuses on the shape and ergonomics of the product. As the earphone will follow the contours and shapes of the body of the user, the product will not force its own form on the user and will thus feel more natural and comfortable to wear.

To create a personalised product, it is essential to obtain data of the individual body part as everyone is unique. This data can either come directly from the customer by scanning or it could be generated using a digital model (Minnoye et al., 2022). The model can either be based on anthropometric measurements, 3D scanning, or a statistical shape model (SSM), the latter captures the variation in shape, compiles the models to an average shape and finds shape variations. A SSM can also function as a wrapping tool that is placed over scan data, it provides a more homologous representation of the ear of the participant as it contains statistical information about the anatomic parts. Therefore, the gaps of the scan data are closed more naturally. Another advantage is that each of the scans are therefore of the same quality and the number of vertices and points of the mesh are always the same. This means that a point of a specific index will always be roughly in the same area. Therefore, the index of the vertices can be used to estimate the location of a specific point in the scan. Therefore, specific geometries that appear in each ear can be selected. These landmarks are key to develop a parametric design which can be used to create products for everyone.

A new way to generate personalised 3D data consists of AI trained with a database of 3D scans and a database with photos of ears (2D). By providing the programme with 2D pictures of an ear, it can approximate a 3D model based on the knowledge of the database of ears, or on the learned relationship between the 2D photo and the 3D ear shape (Huang et al., 2023). The second step is to generate a design based on the parametric human data, which is done with CAD programmes to help designers to visualise and define their designs in 3D, in this case earphones.

1.2. Project brief

Using AI or 3D scanning methods to generate 3D models of an ear will never give a perfect representation of the ear of the user. Pictures can give a good representation of the auricle, but they cannot provide information on the auditory channel. The generated model of the auricle also has limitations. Although the AI algorithm can be trained and improved to become more accurate over time, the model will remain an interpretation. Currently, Dopple uses scans of physical moulds to design fully personalised earbuds. This is time and energy intensive while automated digital representations of the ears could offer a solution for a quicker design process for (semi-) personalized earbuds.

The new concept needs to integrate the 3D-scan data of an individual (which is generated based on the pictures made by the end user), the electronics module with audio and sensors from Dopple and an audio canal, which directs the sound towards the auditory canal of the user. The auditory canal needs to be determined based on the available scan data and the data available in the database. This is the basis for a parametrical model in Rhinoceros and Grasshopper. The script should generate a model fit comfortably to the ear for each individual.

The difference in representation of the generated and the actual ears can be compared with the 3D database of Dopple which are scans based on the silicone ear moulds. These moulds are made by pouring two viscous silicone components into the ear of the customer. The reaction of the two components hardens the silicone into a foam resulting in relatively accurate representation of the ear. It is not a perfect representation due to the slight force which is exerted by the expansion of the foam(see figure 4). However, since the force is very low, the moulds provide an accurate representation of the ears, and are therefore taken as benchmark for comparing the different scan techniques.

When comparing the outcomes, a rough margin of error can be determined. As a solution to mitigate the margin, soft materials, shape morphing, or multiple materials can be implemented to provide the customer with comfort. The ear of the customer needs to provide sufficient sealing, while sitting comfortably in the ear of the user for long periods of time. Since the concept will integrate personalised data, the parametrical model should be set up in such a way that the scans can be easily interchangeable with one another. By making the design parametric, the design can interchange 3D models of different customers. Therefore, the design process can be automated, reducing the workload of the engineers.
In the ultimate scenario, the model will be generated without human intervention. However, due to the uncertainties within the AI-generated model, solutions might make use of soft or multi-material, but methods of producing these materials with AM are still being researched and developed. As a final step the electronic-module (E-module) needs to fit within the shape. In the future Dopple aims to adapt this module depending on the preferred functionality for the user. This will influence the shape of the module and will give different boundary constraints as to how it should be integrated into the overall shape of the earbud.

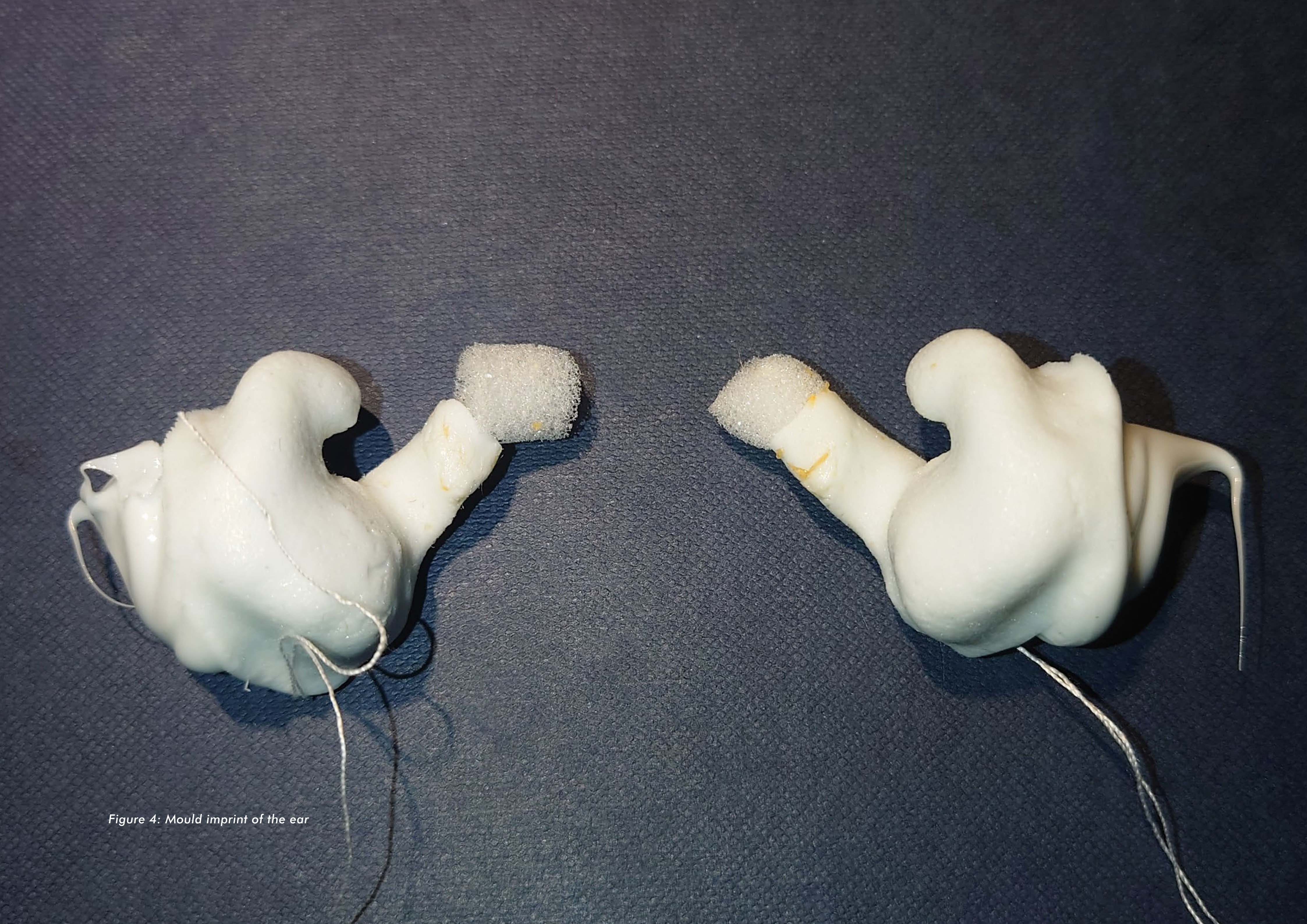


Figure 4: Mould imprint of the ear

1.3. Collaboration with Dopple

Dopple specialises in the design of wireless earphones. With many years of expertise in designing and developing earphones for other brands (e.g. Sennheiser, Jaybird and Logitech), the company has a lot of inhouse expertise on wireless communication. Jaap Haartsen (chief technology officer) helped in the development of Bluetooth at Ericsson Bluetooth. One of the products that Dopple has developed with Logitech is the Ultimate Ear (UE) Drop wireless earphones (see Figure 5). These wireless earphones are fully personalised. This is done by creating a silicone mould of the outer ear (Yan et al., 2022). Dopple wants to make personalised earphones more accessible for a wider range of people. Therefore, the new concept aims to develop a new type of earphone that will be semi-personalised. The aim is to replace the physical mould with pictures of the customers' ears. Either with Scans or images(s), in combination with AI, data will be translated into a 3D model of the ear of the customer. By generating the model with an AI, the customer can directly see a preview of how the earphones will fit in their ear, before

making the decision to purchase. Another advantage is that the scan data will already consist of virtual data points and can therefore be easier implemented into a parametrical computer aided design (CAD) model for the earphones.

Dopple is part of a government-funded collaboration initiative between several companies and the Delft University of Technology for the Design of Ultra Personalised Products and Services (UPPS). The goal is to support companies with setting up a (re)design process for personalised products. As a previous project, Dopple has taken the mould imprints of 537 ears at the TU Delft to collect a database of ears, which can assist the development of earphones in assessing dimensions and standard shape deviations in the outer ear.

Figure 5: UE Drops with cradle


CHARGER CASE
MADE IN MALAYSIA

1.4.Product architecture of Ultimate Ear Drops

The shells of the UE drops are made with the AM technique of stereolithography (SLA). SLA printers are generally known for their high precision (Gibson et al., 2021), which is needed to give the surface a smooth finish without the need for intensive post production processes. The model can be printed without the need for support structures which is why the “audio tube” (see figure 6) can be printed in the shell. The printer uses a clear resin which gives the design a see-through look. At the tips of the audio canal, a wax guard is placed to prevent earwax entering further down the audio tube.

The E-module, with the speakers, battery and wireless module is put inside the housing with a single screw connection. To charge the earbuds, the UE Drops are placed inside the cradle. The cradle has a specific docking geometry, holds the Earphones using magnetism.

The production of the shells, electronics and cradle are all done in-house by Dopple.

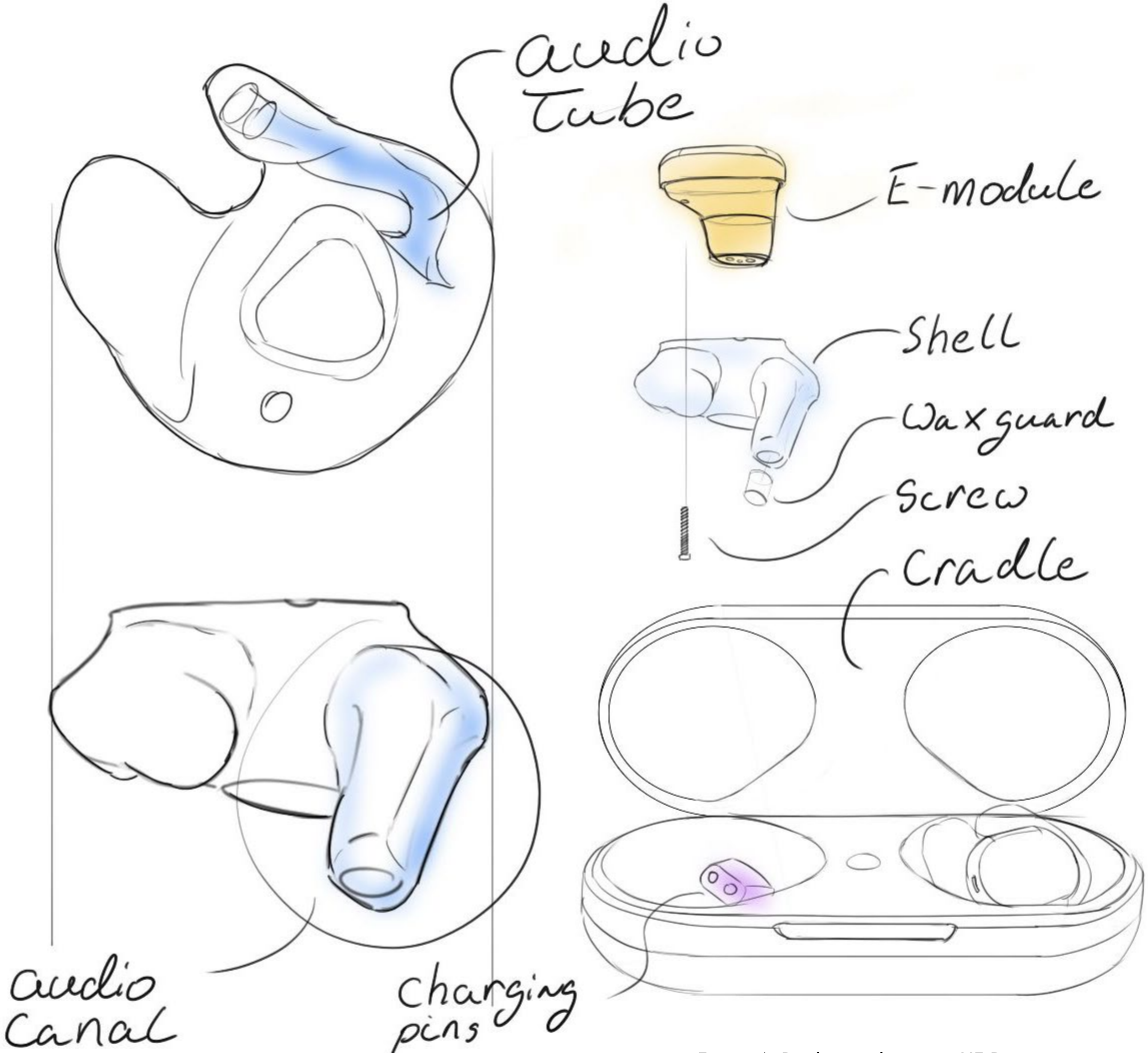


Figure 6: Product architecture UE Drops

1.5.Project assignment

The goal of this thesis will be to (1) develop a concept for semi-personalised earphones based on the in-ear database, (2) evaluate which scan methods are suited to collect individual 3D "scan" data and (3) integrate the current electronical module from Dopple into the concept. The model should be easy to adapt for every individual and feel comfortable within the ear of the user, while keeping a sufficient amount of retention and providing enough sealing (with relation to sound).

Overall, I will approach the project iteratively, meaning that I will make use of short design loops which includes prototyping in the early stages of the project. Prototypes will be a key factor to evaluate and incorporate findings for the result. In early stages, prototypes will be tested on my own ears to provide quick feedback loops. When the concepts mature, I will test the ergonomic comfort and retention of the prototype with five participants. I will compare the generated ear data with actual scans of the same ear to determine how reliable the generated data is and how to mitigate these unreliability's with the design. Some interesting area's I would like to explore for are shape morphing materials and multi-Jet (MJ) 3D – printing.

The deliverables will include a Demonstration prototype (Technology Readiness Level 6) (Technology Readiness Levels (TRL), 2022) of the final concept, a report with the findings of my research and test results on the ergonomic comfort, and a parametrical model in Rhinoceros and Grasshopper (see figure 7).

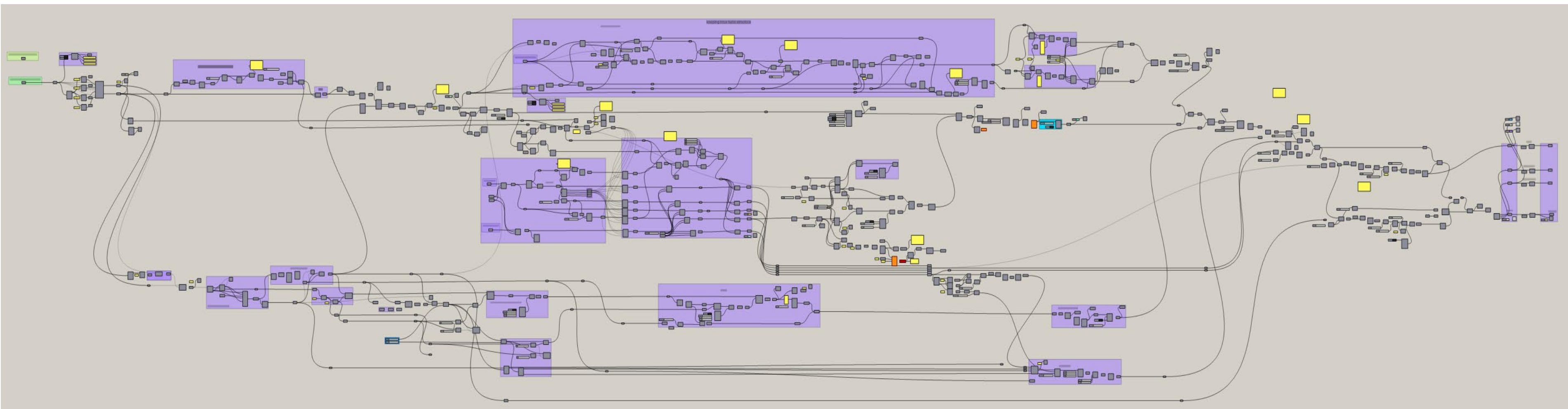


Figure 7: Grasshopper script of the final prototype

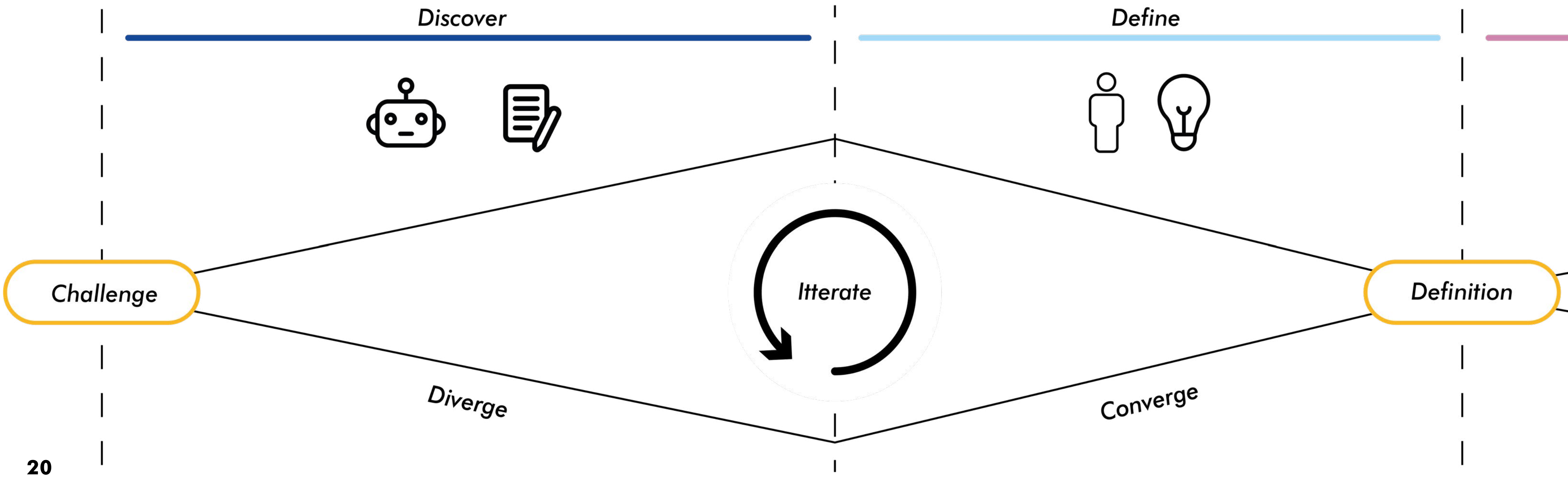
1.6.Project approach

1.6.1. Double Diamond

My design process can be best described by the Double Diamond approach. It symbolises the design process by research and design in several diverging and converging phases (van Boeijen & Zijlstra, 2020). Through research, the right problem definition can be formulated for which a suitable solution can be designed.
The phases can be described by five stages in this thesis (See figure 8):

- *Introduction describes the context, setup and overall objective of this project;*
- *Discover describes the context of semi-personalised earphones, ears and how users experience it;*
- *Define is the link between the research and design phase. The insights of the research phase led to the design direction.*
- *Design describes the model explorations, concepts, development of the parametric design which led to the final prototype which is evaluated.*
- *Conclusion describes the recommendations and reflects on feasibility, viability, desirability and my own learning process.*

In the discovery phase, the designer looks at different aspects of the problem and aspects related to the problem. With this knowledge, conclusions are drawn that are useful to come to a better understanding and definition of the design problem. With the defined definition, which in my case focusses



around the definition the selection and evaluation of a scan technology, the creation of a use case and the development of persona's, specific solutions can be created. These ideas will need to be validated in user tests to verify the viability of the solution for the use case. (van Boeijen & Zijlstra, 2020)

1.6.2. Design by doing

To design earbuds that are comfortable to wear, it is essential to validate the prototypes with the target group. Comfort is difficult to quantify and is perceived differently per person. Therefore, the validation cannot just rely on CAD data. The intricate geometry of the ear and the uncertainty of the precisions of the scan data and the generated model based on AI, can shift the position of the earphones within the ear of the participants, which distributes the pressure differently than envisioned in CAD. Therefore, it is crucial to evaluate the perceived comfort within the ear in early stages of the design process with physical models. (van Boeijen & Zijlstra, 2020)

1.6.3. Questionnaire

Questionnaires are used to collect quantitative data on varying topics. (van Boeijen & Zijlstra, 2020). In the analysis phase the questionnaires are used to reach a broad target audience of (wireless) earphone users to create a better understanding of how, where, and why current products are used. In the modelling phase, questionnaires are used to obtain information on the descriptors of comfort and discomfort of separate models and prototypes.

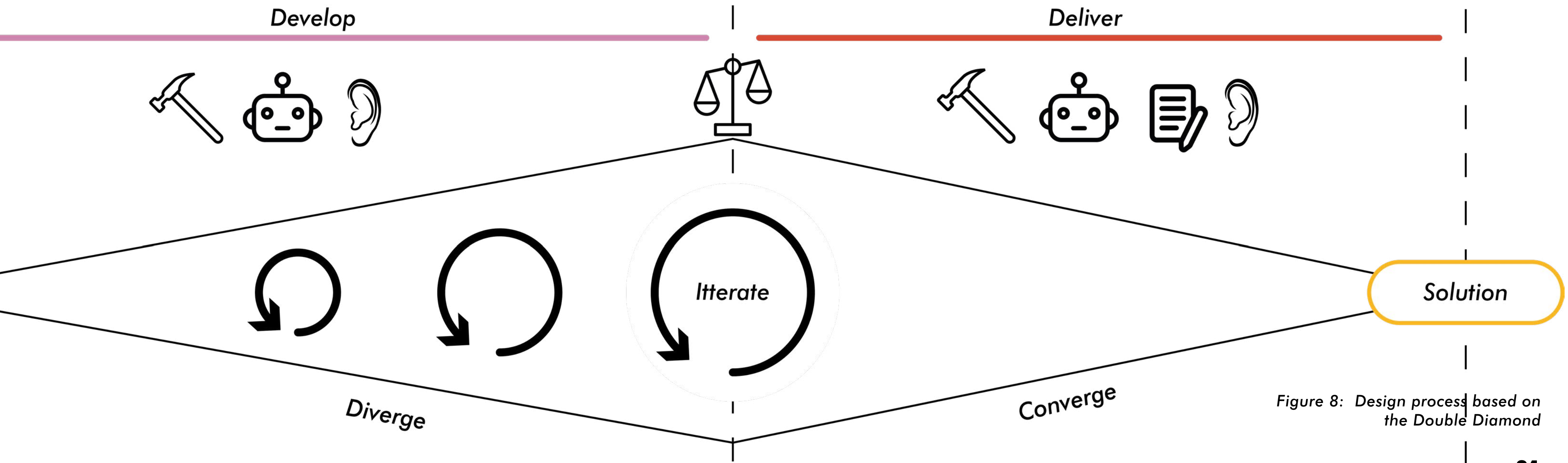


Figure 8: Design process based on the Double Diamond

1.6.4. Personas

Personas are created before the ideation phase. A persona is a way to describe and visualise key characteristics of the behaviour and needs of the target group (van Boeijen & Zijlstra, 2020). These characteristics can be translated to requirements and wishes. Since the project is about mass personalisation, the earbuds function for many different types of users. For this reason, personas are developed for some extreme use cases which will challenge the limits of the design (see figure 9).

1.6.5. Brainstorming: How to's.

Brainstorming is used in the ideation phase. How to's breakdown the overarching topic into several action topics. Each topic is formulated in a how-to-question(van Boeijen & Zijlstra, 2020). A designer can use this question to brainstorm either alone or in a group, about different ways in which the problem could be solved.

Figure 9: Personas

1.6.6. Concept selection: Harris profile

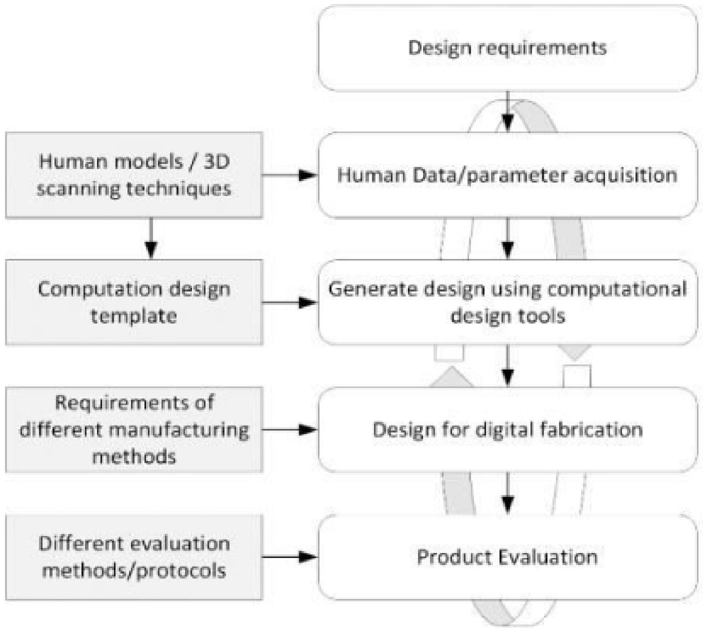
The Harris profile is a way to visually rate concepts on a list of wishes. The order of the wishes determines how much weight is attributed to each wish (van Boeijen & Zijlstra, 2020). Just like the moment forces working on a tower, the further away from the ground the stronger the effect of the attributed weight is. For the method, the concepts are rated on a scale of four options. If a concept fulfils a wish, it is either rated with a 1 + or if it fulfils it extremely well it is awarded 2 +. When the wish is not met at all, it is awarded 2 -, however, when the which does get fulfilled a little but not satisfactory, it will only receive 1 -. When all the concepts are rated, the one with the highest overall rating is the best concept for this scenario.

1.6.7. Parametric Design workflow

The prototypes will be developed according to the computational design approach proposed by Minnoye et al. (2022) (see figure 10). The process follows four iterative steps, to realise a personalised product: "1) Human data/parameters acquisition; 2) Generate design using computational design tools; 3) Design for digital fabrication; 4) Product evaluation." (Minnoye et al., 2022).

1.6.8. Heat map: perceived pressure

As a tool to evaluate the different models and prototype, participants are asked to mark pressure points on topographical of the ear (Fernández-de-las-Peñas et al., 2010). The perceived pressure maps will indicate at which points the design will need to be improved. When there is too little pressure detected the design can be updated to provide more retention. if too much pressure is detected in certain area the design should be improved to relief some pressure from this area (see figure 11).



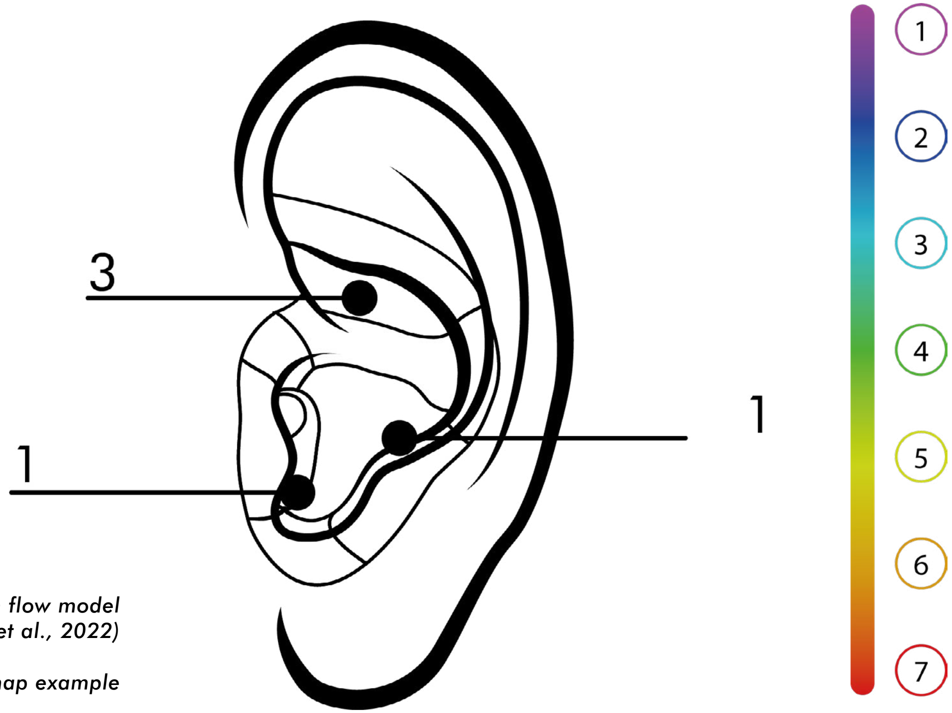


Figure 10 (top): Parametric design flow model (Minnoye et al., 2022)

Figure 11 (bottom): Heatmap example

2. Context of the problem

This chapter will discuss several aspects of the context around semi-personalised earphones.

- *The following research questions gave guidance in this phase.*
- *What makes it possible to provide customers with semi-personalised earphones?*
- *What challenges do we face when designing semi-personalised earphones?*
- *What factors should be accounted for in the design of semi-personalised earphones?*

The first part of this chapter introduces how the improvements of AM and CAD programmes have made it possible to think differently about how we produce and design products. The second part introduces how other technologies of the last century have influenced the way we experience music. The third and fourth part introduce wireless earphones, how they fit in ears and how this influences the perception of comfort. The fifth part discusses the concept of comfort and how comfort in relation to earphones could be validated with customers.

2.1. Industrial change

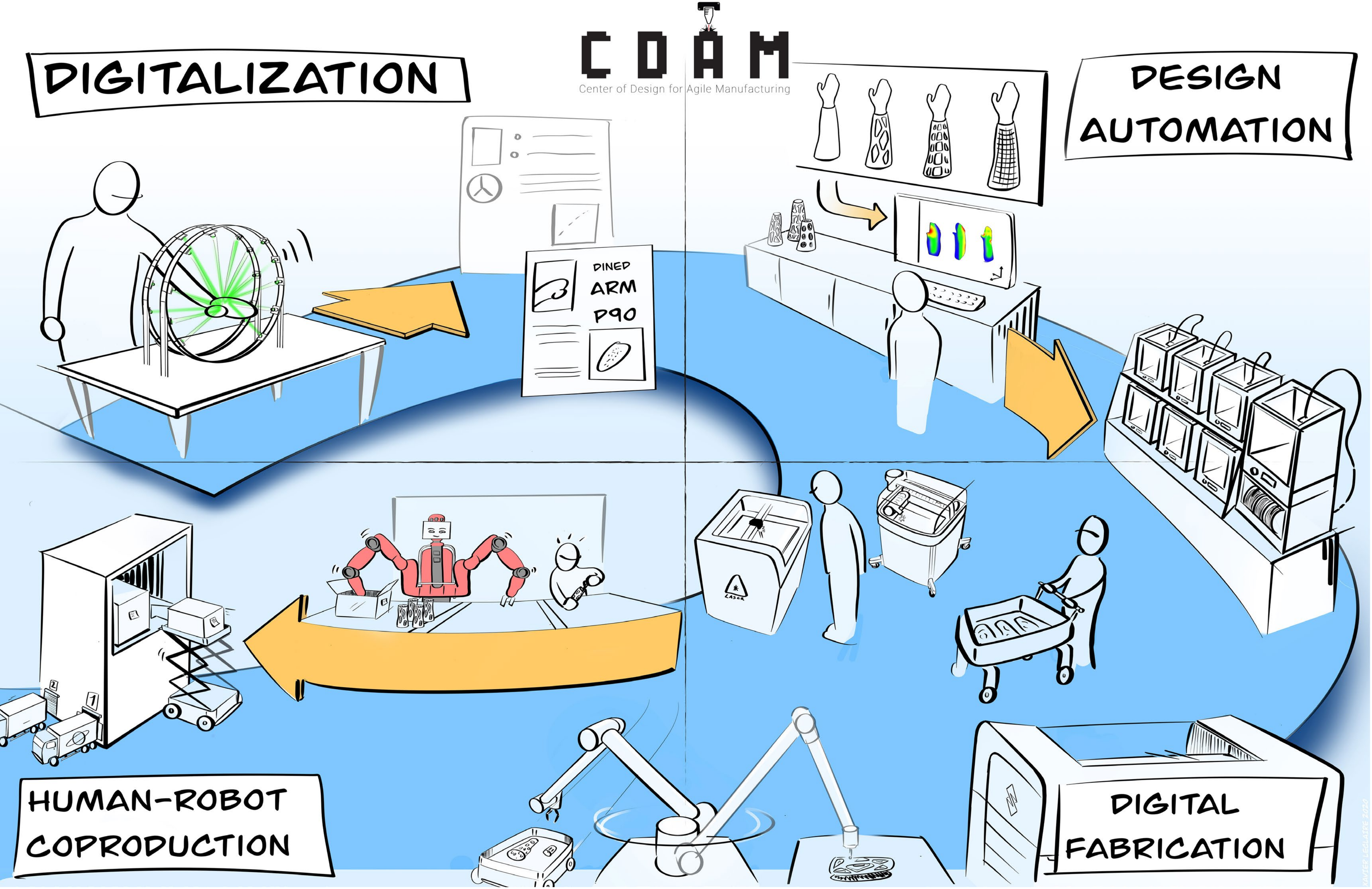
The first industrial revolution (IR) was started by the invention of the steam engine, which suddenly made it possible to mass produce products by machines. Production became more efficient and started to replace artisanal craft industries. The second IR came with the invention of electricity and the introduction of assembly lines, increasing production efficiency even further which made mass production of products easier. The third IR started with the integration of electronics and the automation of processes (Maddikunta et al., 2022).

Currently, we are in the fourth IR, which uses automation technologies like cyber-physical systems (Sony, 2018) and the Internet of Things. There is a focus on the integration and digitalisation of end-to-end engineering (Tan et al., 2010), for example, CAD software and Computer aided Manufacturing (CAM). Additionally, the principle of lean manufacturing, in which companies try to maximise resources by reducing waste, has been further expanded (Sundar et al., 2014) (see figure 12). One way of doing this is by manufacturing on demand, like Dopple does, and where the product is only manufactured after the order has been placed. The combination of additive manufacturing, parametric design and online data sharing makes it possible for companies to produce customised products quickly and (nearly) automated (see figure ...FIXME). By using these processes well together, the need for large investment in terms of manpower, time or storage space can be largely reduced, this process is also called agile manufacturing.

Conclusion

The new advancements in technologies which brought about the latest IR, make it feasible to design for mass personalisation. Previously designs were optimised to fit a large group of the population to drive down investment costs whereas personalised products were manually crafted and, as a consequence, more expensive. Now, companies can offer personalized products at a lower cost while providing their customers with more comfort and freedom to tailor the design to their specific needs. The semi-personalised earphones will also allow the customers of Dopple to choose and adapt the design for their personal needs.

Figure 12: Automated design process by Center of Design for Advanced Manufacturing (TU Delft)


CDAM
Center of Design for Agile Manufacturing
DIGITALIZATION
DESIGN AUTOMATION
DINED
ARM
P90
HUMAN-ROBOT COPRODUCTION
DIGITAL FABRICATION

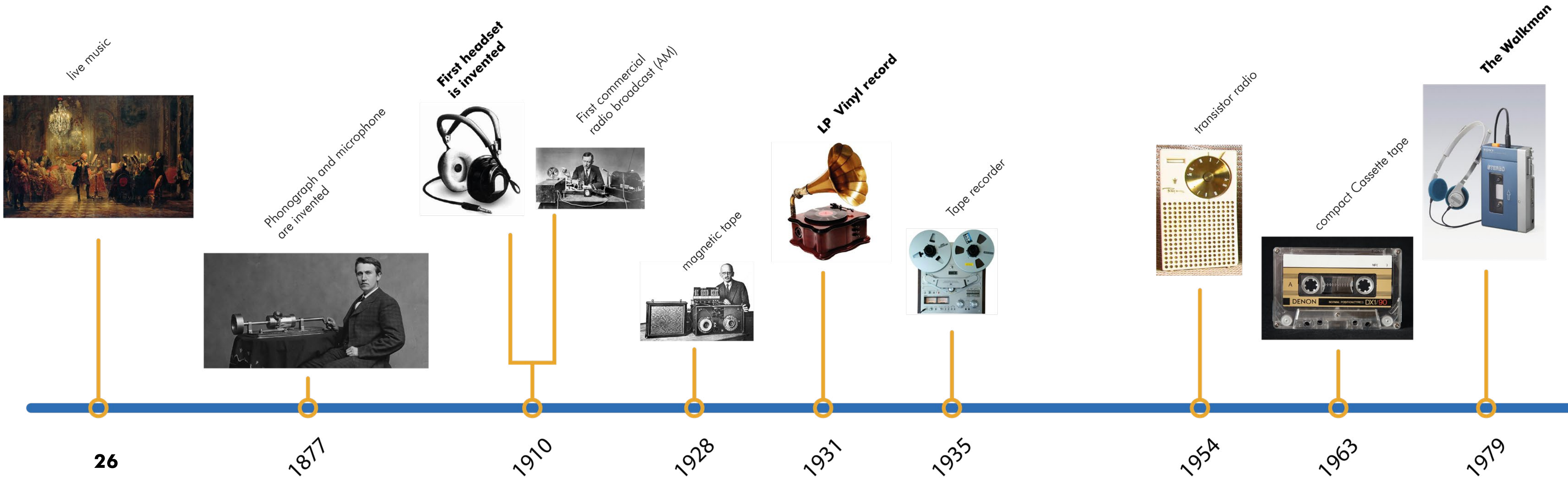
2.2. Listening experience

Music has a long part in human history, it is a tool for expressing and conveying emotions, story-telling and cultural identification. Over the past century, through globalisation and the internet we are exposed to a world of new sounds cultures. With new technological advancements, our listening experience to music has become more personal. The music we listen to has become part of our identity.

This chapter will look at the evolution of our listening experience up to the modern status, as well as providing a future vision to which it micht evolve.

2.2.1. History of Music

The way we listen to music has changed rather drastically and quickly over the course of the last century. With every invention (see figure 13), music has taken a step closer to our personal space. First from live music at a tavern to recorded music in our homes (invention of the phonograph). After that, we could listen to music when- and wherever we want with personal portable radios (transistor radios). The next step is to not only carry our favourite music with us but to listen to it privately wherever we are through headphones (a combination of the invention of the headphones, cassette tape and Walkman™). With the rise of the internet, we can stream almost every song ever recorded within a few clicks. Now it is possible to move around without restrictions and perform any action with the pleasure of listening to any song we want, on our Bluetooth earphones.



2.2.2. Future vision

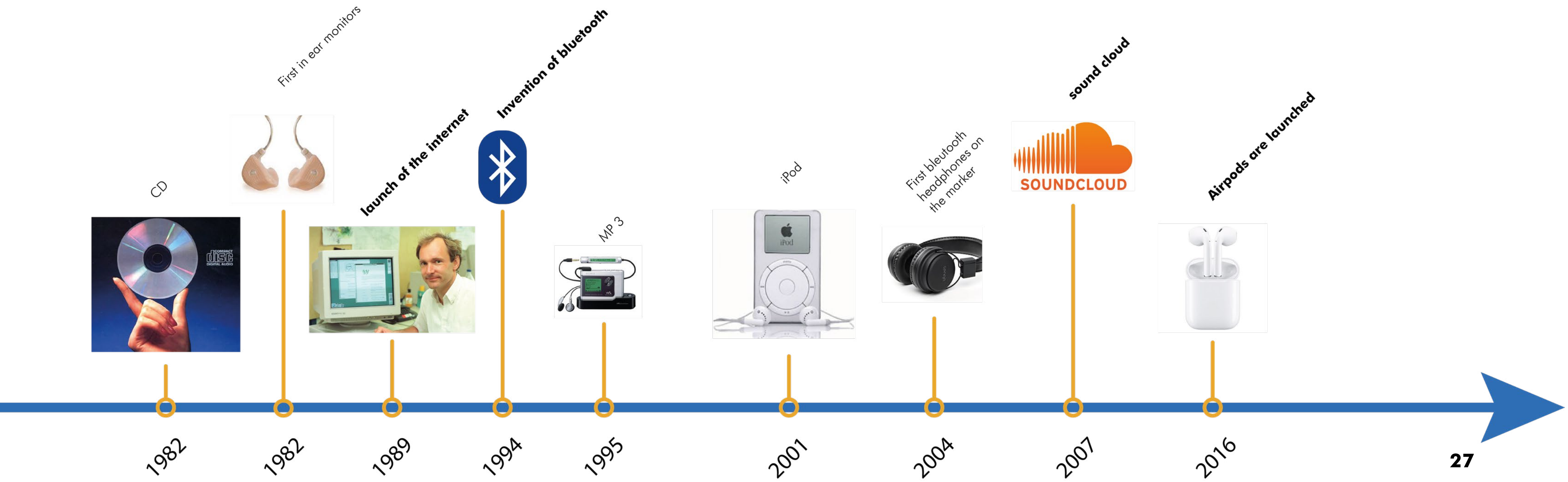
With the improvements in AI technology, CAD software and additive manufacturing it is possible to produce personalised products. By collecting more specific data from users, either utilizing camera footage or through the integration of scanning technology into smartphones (such as the iPhone 12 pro range) (Mikalai et al., 2022), products have the potential to become fully personalised to the needs of the individual. By using technology which can be integrated in a smartphone, the product can be sold and ordered by the customer in the comfort of their own home, without the need for a physical appointment with a hearing-aid professional or retail store. This lowers the initial effort for purchasing a (semi-) personal earphone.

Since personalised products follow the contours of the body of the individual, forces can be better distributed, which feels more comfortable to the skin of the user. The logical next step for our listening experience will thus be custom-fitted earphones for the general public, which would be as easy to acquire as mass-produced earphones.

2.2.3. Conclusion

The personalised earphones should not only provide more comfort and less discomfort to the users, but they should also not cost the customer more effort to acquire such earphones. Therefore, the technology for acquiring the data should be easily accessible to the customer.

Figure 13: Evolution of technology for music



2.3 Wireless earphones

Earphones have become a standard product in our everyday lives. We use them for entertainment as well as during work to reduce noise and enhance hearing or communication (Yan et al., 2022). With the launch of Apple's Airpods in 2016, the market has seen a rapid increase in products and interest. Last year the global wireless market grew 6.2% and is now estimated at a 5.19-billion-dollar industry (Wireless Earphones Market Size, Trends and Global Forecast To 2032, n.d.).

Reasons for buying wireless earphones are the freedom of movement of not having a cord which is connected to your phone or tangled in your pocket (see figure 14). Moreover, they are small and convenient to take on a trip, especially when compared to headphones.

However, there are also limitations and reasons why people still choose wired earphones over wireless. For people who emphasise audio quality, the main argument given on forums and in interviews with experts (Hi-end audio users and sellers), is that wireless earphones are limited to the bandwidth of Bluetooth, while wired earphones are only limited by sending and receiving nodes and the quality of the recording (Scheiber, 2020). Wired earphones can therefore send more precise signals which results in better sound quality. However, in the case of an average user who, for instance, listens to Spotify, the quality of the audio file is lower in quality for storage reasons and will therefore not have an impact on the listening experience.

Another limitation of Bluetooth is connectivity. Since Bluetooth only works within a limited bandwidth, the signal of your device is sometimes interrupted by the signals of other Bluetooth devices in the same room, which causes disruptions in the music.

2.3.1. Conclusion

Due to the limitations of the sampling rate of Bluetooth, it is not suited for High-end audio users. However, the average users that do not use audio platforms that provide a music source supporting high-end audio, will not have an issue with the quality. Hence, the final product should not target high-end audio listeners.
For many users, wireless earphones provide a high enough audio sampling rate for their day-to-day listening experience and preferred wireless earphones over the traditional wired earphones due to the freedom and convenience it provides.

Figure 14: Tangled ear phones

2.4 Earphone fit

Each earphone has an orifice at the end of a tip directed at (or in) the auditory canal. Through this orifice, the sound is delivered to your eardrum. The design of the tip and its placement in the ear of the individual has a big influence on the amount of sealing, retention and comfort the product can provide.

There are 3 main categories of earphone tips :

- *Personalised (see figure 15)*
- *Open (see figure 16)*
- *(Flexible) tube-shaped (see figure 17)*

Figure 15: Personalised

Figure 16: open

Figure 17: Tube shaped

The open and tube-shaped tips are the most common ones on the market since they can be mass-produced using conventional moulding techniques such as injection moulding. Especially the Tube-shaped tips from silicone and foam are standardised and can therefore be sold cheaply as a separate component. These tube-shaped tips are pushed into the hearing canal up to (and in some cases a bit beyond) the first bend (see figure FIXME (add to figure)). This provides a seal for outside noise, as well as the necessary retention the product needs to stay fixed within the ear. In doing so, it applies a constant pressure to the walls of the auditory canal which causes discomfort over time. However, for some users the tip sizes could be too small for the shape of their auditory canal (see figure 18), resulting in little retention and therefore earphones that easily fall out of the ears.

The open types are not pushing against the walls of the hearing canal. Instead, they rest between the tragus and anti-tragus (see figure 18). Since they exert little pressure other than their weight, they score high in comfort (Song et al., 2020). However, this characteristic means that the perception of the retention of the product is worse, and they do not provide a large amount of sealing.

Personalised earphones can be manufactured in multiple ways. One method requires to firstly create a positive mould of the ear in silicone. As a next step, the shape is dipped in molten wax to provide a smooth surface finish to the model. From this, a negative mould is produced. To create the shells, a UV curable resin is poured in the mould and is shortly exposed to UV light. The hardened resin forms a shell of a few millimetres thickness in the

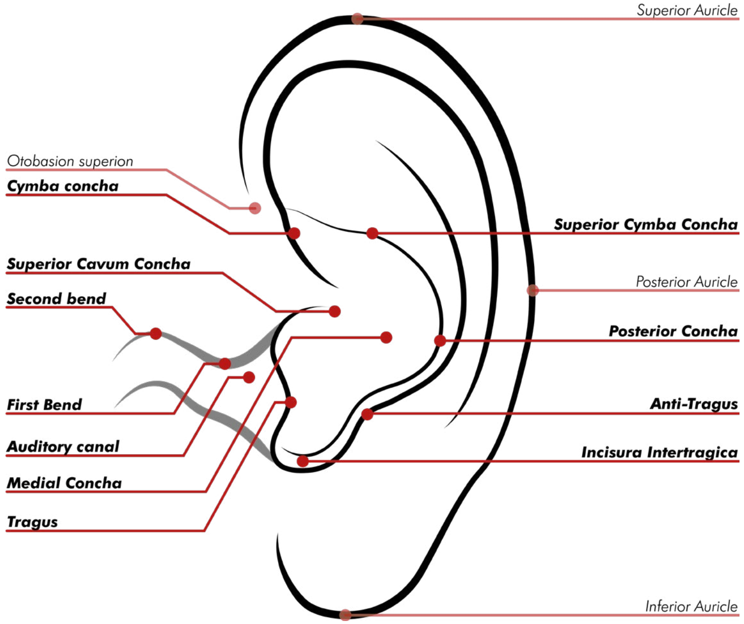


Figure 18: Landmark names

mould. The excess liquid resin is removed from the shell. The electronics and hole for the audio are added in manually. (Watching an Eartech Monitor Being Made | Audiofool Reviews, 2018). Modern techniques use precise 3D scanners to translate the mould to a digital CAD model which can be printed (Technology 3D FIT, n.d.).

Conclusion
The tips fulfil two main functions in the earphones: they provide passive sealing, and they are the main source of fixation. Because they provide pressure to the auditory canal to fix the earphones in the ear, they are often the main cause of irritation. Due to the complexity of the shape of the ear, it is very difficult to place a one size fits all solution in this region, especially when you want to guarantee a proper sealing. Personalised earphones could offer a solution to the user.

2.5. Comfort

Since customers cannot try out earphones before buying, customers end up with a pair that does not fit perfectly within their ears. This can either result in earphones that are either too small or too big, typically in either the body of the earphone or the tip.
A good fit can provide a customer with a comfortable experience. A bad fit often translates to a discomfortable experience. Both comfort and discomfort are subjective terms which are difficult to quantify. In the following text is discussed how comfort and discomfort can be described, what influences our feeling of them, and how both terms can be quantified.

2.5.1. Comfort models

In case the earphones are too small, they can shift during the movements of the user, losing their retention and sealing, reducing the listening comfort of the user which was indicated as the main reason for dissatisfaction among users of earphones in general (see Chapter 4.2).
In case the earphones are too big, the body pushes against the anti-helix which is one of the most sensitive areas of the concha (Yan et al., 2022), which can also lead to discomfort. Or in an even worse scenario, the earphones do not fit in the concha at all, in which case the user is left with a pair of expensive earphones which can neither be used nor returned. Comfort and discomfort are often seen as two ends of a linear scale. However, upon further evaluation, it was argued (Zhang et al., 1996) that discomfort and comfort act on different aspects of our feelings. While comfort is associated with feelings of relaxation and well-being, discomfort is associated with physiological and biomechanical factors. While both cannot be described as linear, there is a strong relation between the two as shown in figure 19. The model describes that a product cannot bring comfort and discomfort at the same time. The relation between the two can be seen as a reciprocal function between 2 perpendicular axes. Feelings of discomfort are mainly associated with pain, tiredness, soreness and numbness (De Looze et al., 2003; Zhang et al., 1996). The absence or reduction of contributors to discomfort, does therefore not necessarily lead to a comfortable feeling. However, comfort can only be experienced when the discomfort factors are low.

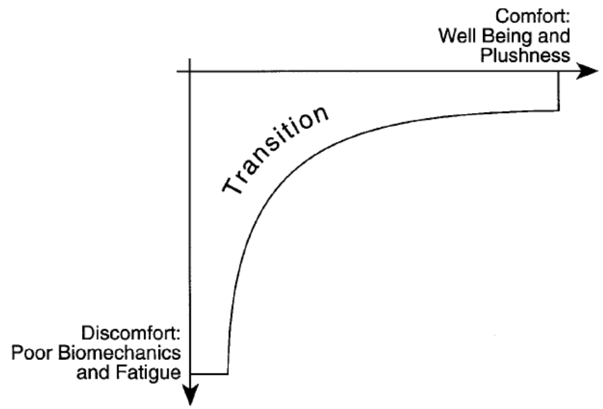


Figure 19: comfort – discomfort relation (Helander & Zhang, 1997)

Another misconception is that discomfort always leads to pain when its source is increased. Although pain and discomfort can originate from a large list of the same occurrences, including pressure, shear forces, skin irritation, heat, moisture or osteophytes (extra bone structure), it does not mean that discomfort always leads to pain (Neumann, 2001).

Evaluating comfort and discomfort can be difficult due to their subjective nature (De Looze et al., 2003). They are not only influenced by physical or physiological factors of their environment which are easier to measure but also the impact on psychological factors that have an influence.

The model of Vink & Hallbeck, (2012) describes these factors in a single model (see figure 20). Comfort and discomfort are influenced by the contact between the user, the task and the product which causes an internal effect in the body (e.g. activation of the muscles) (H). The effects that the user perceives (P) are influenced by not only the internal body effect but also by the expectations (E) of the user which could either lead to discomfort, comfort, or nothing. In case the outcome results in insufficient comfort or too much discomfort, there is often a feedback loop in which the user takes an action and changes the way the product is used.

Since our perception of comfort and discomfort are influenced by multiple factors, it is useful to split both terms into several clear classifications (Zhang et al., 1996). Classifications for discomfort are: fatigue, restlessness, pain/biomechanics and strain. The classifications for comfort are : impression, relief/energy, well-being and relaxation. In the study by Zhang (1996), the descriptors are used in relation to a chair and relate to joints and posture (see figure 21). Therefore, not all descriptors are equally useful in relation to earphones as they are in a fixed position. However, the overarching classifications are still valid. The descriptors in the paper will be used during the evaluation of the prototypes to rate the comfort and discomfort levels per design.
The main relevant descriptors for discomfort in ears: fatigue, ill at ease, fidgety, restless, (dull) ache, hurting, pain, strained, tingling, numb.
The main relevant descriptors for comfort for ears are: softness, luxurious, agreeable, refreshing, content, pleasant, relaxed, and calm.

To illustrate comfort and discomfort in relation to earphones, the following example is given. In case the tube-shaped tips of generic earphones are too large for the auditory canal, the customer will perceive a combination of restlessness, numbness and ache in the auditory canal which increases the level of discomfort. On the other hand, when the tube-shaped tip is too small for the auditory canal of the user, the earphone will keep falling out of the ear which the user will not perceive as pleasant or relaxed. This would diminish the comfort of the listening experience.

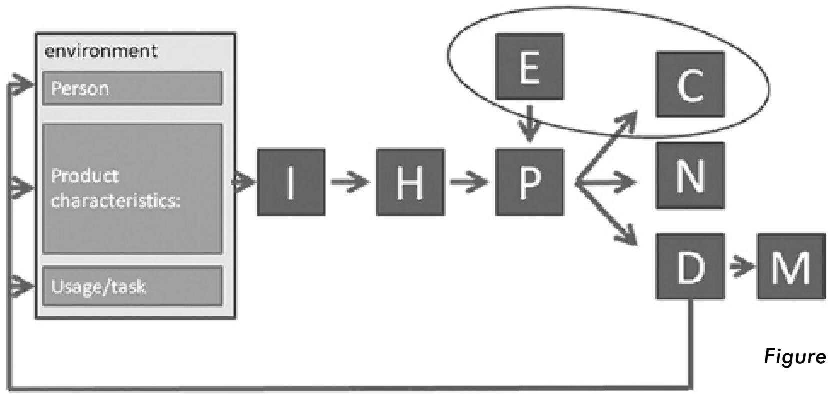


Figure 20: comfort model (Vink & Hallbeck, 2012)

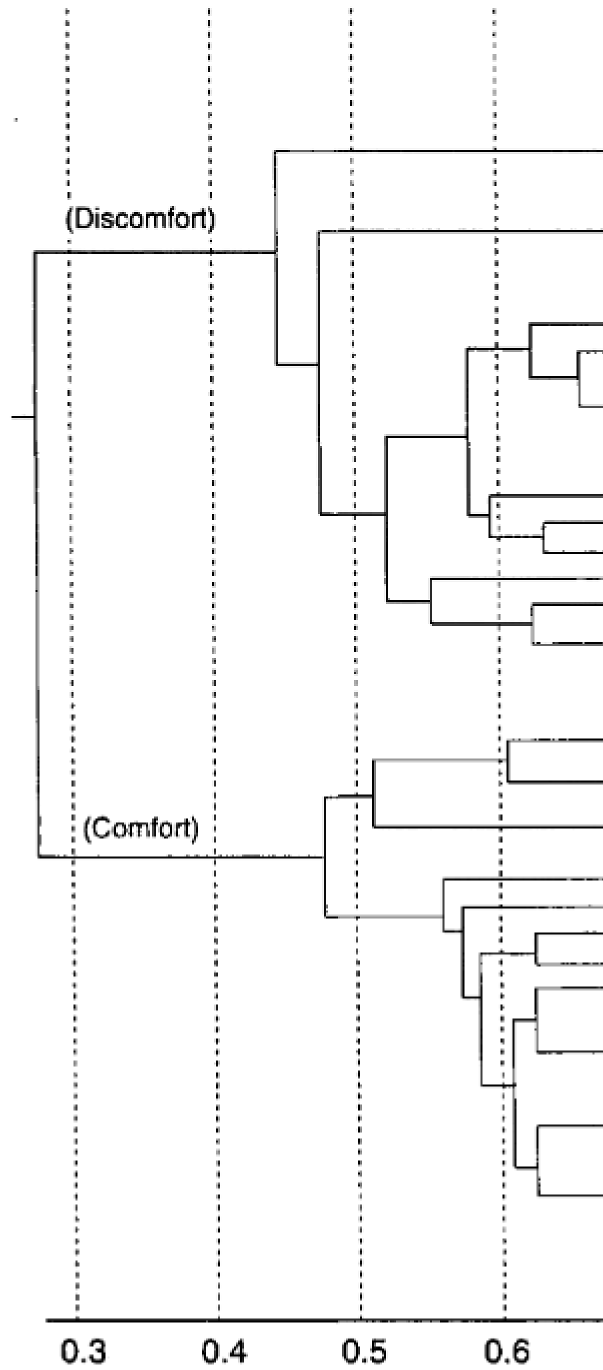
2.5.2. Evaluation test

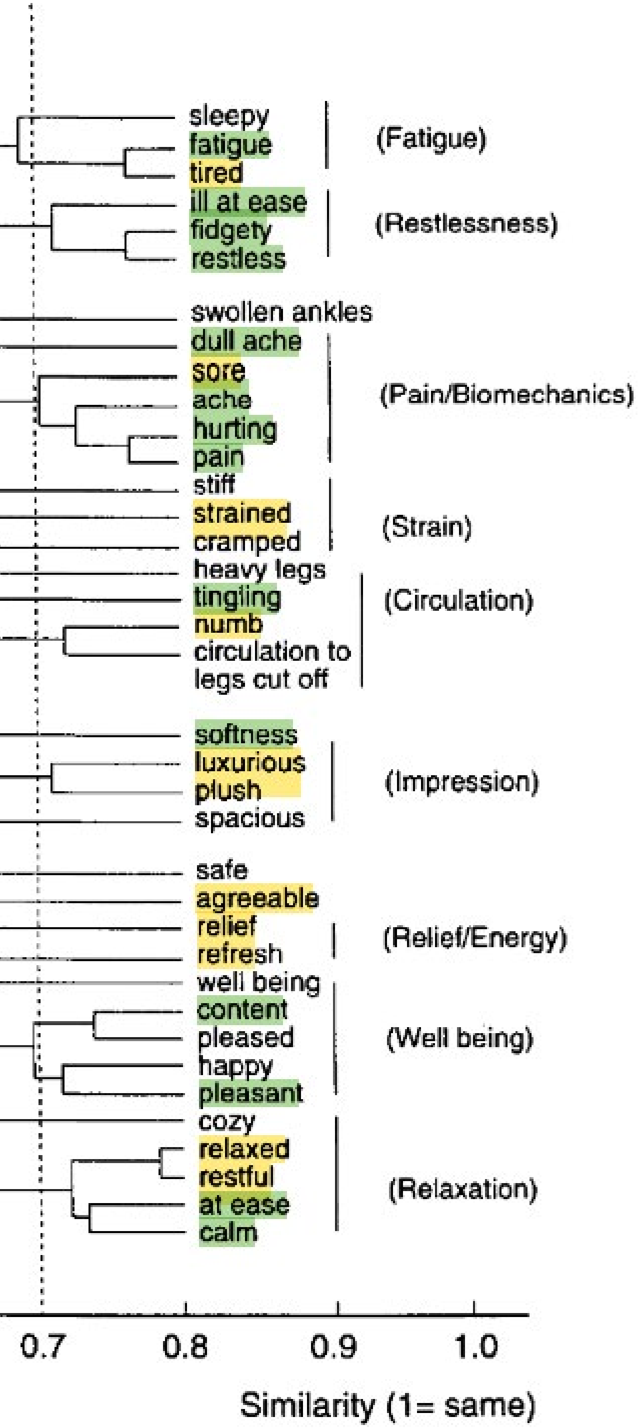
Based on a literature review, 15 questionnaires were selected that are often used to rate comfort and discomfort. They were compared to find out which questions were most practical to use in which situation. As a result, it was concluded that for studying prototypes and comparing two products the best scale to use is the Category Ration 50 (CR-50) scale (Anjani et al., 2021) (see appendix G.4 for an example). The CR-50 scale is the most accurate and reliable way to validate pressure intensity and discomfort (Shen & Parsons, 1997). The scale ranking is set up from 0 to 50+, which is subdivided into 7 sections, like the 7-point Likert scale. For example, the division for discomfort is as follows: no discomfort, very slight discomfort, slight discomfort, medium discomfort, severe discomfort, very severe discomfort and above. Unlike the Likert scale, participants can better specify the exact feeling they are experiencing. It should be noted however that the scale could skew toward the lower sensation end of the scale (Anjani et al., 2021).

The CR-50 scale is an extensive scale which is good to provide detailed insights in how the models will relate to each other, but this makes it more difficult to fill in for participants. Therefore, in the early prototyping stages, the 7-point Likert is used to ease filling in the questionnaire for the participants, even though it provides less nuance.
An earlier study to compare the comfort of different types of earphones (four in total), concerning ear size, was conducted by Song et al., (2020). During the study, participants were asked to wear one of the types for 10 minutes, and then evaluate the earphone on comfort, pain, pressure and fixation, as well as some product-specific attributes such as size, texture and weight. The same topics will also be addressed in this study when evaluating the different concepts of the shells. Additionally, the most relevant descriptors of comfort and discomfort will be evaluated, as mentioned above. The questions should be answered separately for the left and the right ear if the participant feels a distinction. Therefore, we will be able to evaluate if there is a difference in comfort and discomfort between the ears.

To create a more holistic overview on the perception of comfort and discomfort in the users' ears, the questions of both Helander & Zhang (1997) and Song et al., (2020) are combined in a questionnaire to determine how the participants perceive the prototypes.

Figure 21: Descriptors of comfort and discomfort (Zhang et al., 1996)





Comfort

1. *Do the earphones feel soft on the skin?*
2. *Do you feel the earphones are luxurious?*
3. *Do you feel relaxed (while wearing the earphones)?*
4. *Do the earphones feel refreshing?*
5. *Are you content with the earphones?*
6. *Do the earphones feel pleasant?*
7. *Do you feel at ease?*
8. *Is the concha area comfortable when wearing the earphones?*
9. *Is the ear canal area comfortable when wearing earphones?*

Discomfort

1. *Do you feel restless?*
2. *Do you feel fatigued?*
3. *Do you feel strain?*
4. *Do you feel any ache?*
5. *Do your ears feel numb?*
6. *Do the earphones feel heavy?*
7. *Is the pressure unevenly distributed over the ear?*
8. *Do you feel pressure in the concha area when wearing the product?*
9. *Do you feel pressure in the ear canal when wearing the product?*

Pain

1. Do you feel any pain in the concha while wearing the product?
2. Do you feel any pain in the hearing canal while wearing the product?
3. Do you feel any pain in the concha after wearing the product?
4. Do you feel any pain in the hearing canal after wearing the product?
5. Fixation (/retention)
6. Does the product come out of the concha easily when wearing?
7. Does the product come out of the ear canal easily when wearing?

Texture

1. *Is the contact between the material and your skin appropriate?*

Size

1. *Is the size of the earphone appropriate?*
2. *Is the size of the tip appropriate?*

2.5.3. Conclusion

Although comfort and discomfort are linked to each other, they do not have a linear correlation. Each are influenced by different physiological and psychological factors. Where comfort is related to positive factors of relaxation and well-being, discomfort is associated with negative emotions of physiological factors. The perception of a product changes per individual due to previous experiences, the expectation of the individual and the result of the product.
The feelings of comfort and discomfort of the models and prototypes will be quantified using a series of agree – disagree statements in the format of an CR – 50 scale. Through this method, the final prototypes will be judged on whether they are suited to fulfil the determined use cases (see chapter 4.3).

2.6. Main take aways

Text below is meant to give an overview about the main conclusions of the topics in the previous chapter.

- *If the aim is to make mass personalisation available, it for a wide audience product should be easy to obtain. The user should therefore not have to leave the comfort of their home to acquire the product.*
- *The product should not be targeted to the hi-fi market. But rather tailor to other use case which would benefit of Personalisation for fit.*
- *Since earphone tips provide the main point of retention, they typically are the cause of irritation among users.*
- *Comfort and discomfort are connected, but the connection is not linear.*
- *Comfort is related to positive factors of relaxation and well-being; discomfort is associated with negative emotions of physiological factors.*
- *The perception of a product changes per individual based on previous experiences, expectation and the results of the product.*

Figure 22: image of a user using the UE drops (UE drops)

3. Ears

The previous chapter discusses the context around semi-personalised earphones, but an important aspect was still missing: the ears in which the earphones will fit.

The first part of this chapter introduces the anatomy of the ear and how their shape is unique for everyone. The second part discusses how the most important landmarks can be determined. The third and fourth part discuss the evaluation of the landmarks of the concha and auditory canal. Based on this, conclusions and main take-aways are drawn.

3.1. Variance of the ear

The outer ear can be divided into three main areas: the external auditory canal, the concha and the pinna (Lee et al., 2018). The most relevant areas to look at for the design of earphones are the Concha and the auditory canal since the earphones will use these areas for retention and sealing. The concha is in turn subdivided into eight areas (see figure 23) (Lee et al., 2018; Yan et al., 2022). The shape of the ears is formed from cartilage and covered with skin. Some areas are close to the skull such as the cavum concha and deeper parts of the auditory canal. These areas are rigid and have fewer sensory receptors than the cartilage areas. Since the cartilage areas can stretch out a little, they can be used to add retention to the earphones to hold them in place. However, since these areas are also more sensitive, too much force over an extended period can easily lead to discomfort (Yan et al., 2022). The most sensitive areas in the study from Yan et al. (2022) are therefore the anti-helix and the Incisure Intertragica. The study did not test the discomfort levels over an extended period of time but focused instead on gradually increasing the pressure in one point of each of the ear regions. However, since the study showed which areas of the ear are more sensitive than others it should be avoided to exert too much force on these areas when designing the earphones.

Our ears are one of the most sensitive parts of the body. The weight and shifting of mass of the earphones are therefore perceived quite well (Chiu et al., 2014). As a consequence, lighter earphones are preferred over heavy earphones (Song et al., 2020). For this reason, the earphones should be as light as possible and distribute their weight evenly across the concha

Our ears are unique and different for each individual: there are large variations between ethnic groups (Ahmed & Omer, 2015; Bozali et al., 2023; Japatti et al., 2018; Niemitz et al., 2007), gender (Verma, 2016) and age (Niemitz et al., 2007). However, ears can even vary on the same individual, attesting to the uniqueness of our ears. The variations do not just relate to different physical aspects such as the size and shape of our ears, but also in sensitivity. On average, women have smaller ears than men (Fan et al., 2019; Japatti et al., 2018; Niemitz et al., 2007) and have lower pressure thresholds (Yan et al., 2022).

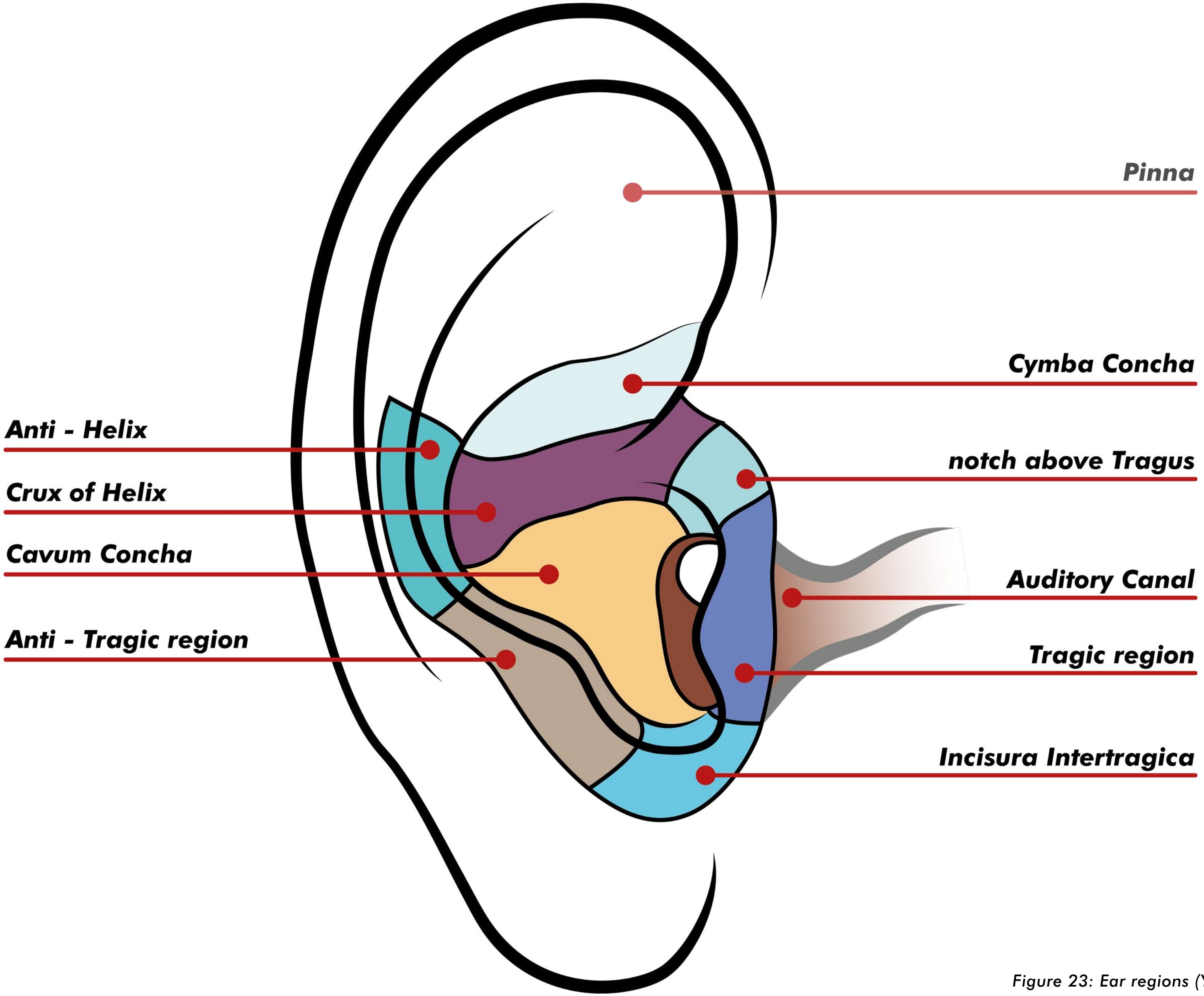


Figure 23: Ear regions (Yan et al., 2022)

3.2. Landmark selection

The evaluation of the 3D ear scan data is done in the CAD software Rhinoceros in combination with Grasshopper, which allows for parametric designing by visual programming.

The landmarks are recognisable features. They are defined on extreme geometries of the ear, meaning that they are located at the top of a bend or where the derivative of the shape is equal to zero. This location can be found to match the average vector of in a region to the closest normal vector of a point in the region (see figure 24). The location of the landmarks will differ slightly in each ear. To evaluate the database efficiently, a script is generated in Grasshopper that calculates in a few iterative steps which point is the most extreme in a region of interest (ROI) close to the landmark.

To determine the extreme point in the ROI, first a reasonable starting point needs to be determined. Through iteration loops, the code will find its optimum of each landmark within each individual ear shape. By using the SSM model, an estimation of the placement of an independent floating point is generated in Grasshopper. In this example we will look at the Tragus (see figure 24step 1). The floating point is checked against 16 other randomly selected ear shapes to adjust its position. This point is projected onto the closest point on the surface of the concha scan (see figure 24 : step 2). A ROI is defined by a sphere. For each point within the sphere, we look at the given unit vector (see figure 24: step 3). By calculating the average normal vector direction in the region around the first projected point, the extreme point in this region can be determined (see figure 24: step 4). This point is iterated 4-6 times while decreasing (80%) ROI's to account for the variations in ear shapes (see figure 24: step 5).

Considering the inherent diversity in ear shapes, it is essential to establish a new coordinate system. This allows each scan to be judged in a similar manner along the established x', y', and z' axes. The x'-axis in each scan is aligned with the length of the concha (measured between the Intertragic Incisure and the superior cymba concha). Perpendicular to the x'-axis is the z'-axis. This axis is determined by assessing the perpendicular component on the x'-axis of the vector between the tragus and the anti-tragus landmarks. The reasons for choosing these landmarks as a base for the z'-axis are that firstly, the landmarks are often clearly visible at the edge of the concha making them easy to detect in the scans, and secondly, the landmarks are already somewhat perpendicular to the x'-axis. As a result, the constructed x'z'-plane closely parallels the exterior curvature of the concha when positioned over the tragus.

The final axis (y'-axis) is calculated perpendicular to the x'z'-plane and indicates the depth of the ear in relation to the plane, completing the three-dimensional coordinate system necessary for the comprehensive evaluation of ear shapes.

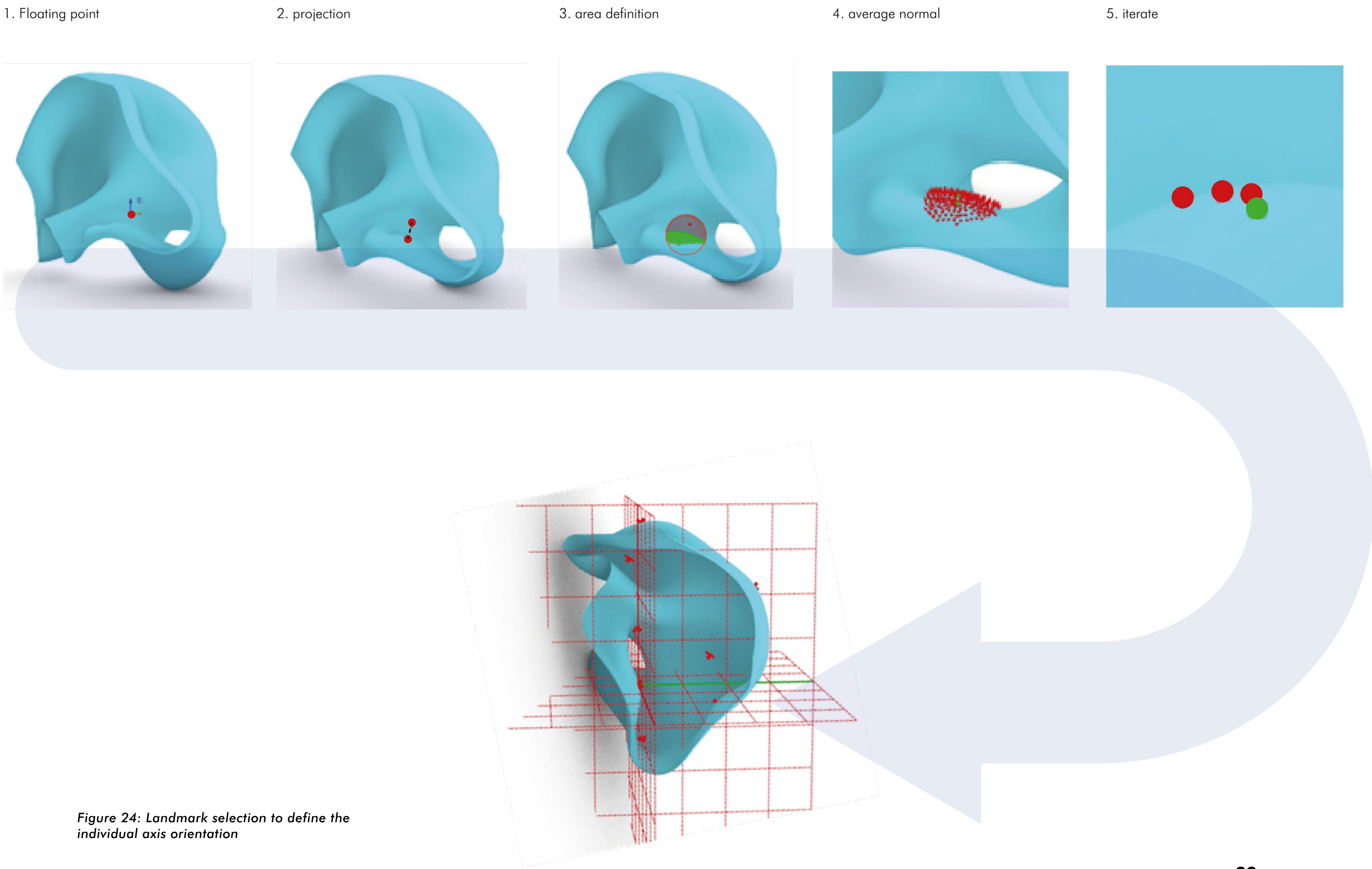


Figure 24: Landmark selection to define the individual axis orientation

3.3. Concha evaluation

In a previous collaboration between Dopple and the TU Delft, the ear imprints of 268 participants were taken and 3D scanned by pouring silicone in the ears of the participants (see figure 4). From this data, a statistical shape model (SSM) was generated. This average model can help designers to get an idea of the general shape of the ear. Statistical shape variations in the ear can be used to verify if the design also holds up for a more atypical shape of the ear. To get a better idea of the dimensions of the concha and the variation between the ears, a parametrical set-up was devised to automatically search for the extreme point on the landmark for each of the ears of the participants.

Based on the study of Lee et al. (2016) and Song et al. (2020), the most relevant measurements for the concha are (see figure 26):

- *The length of the concha: Intertragic Incisure – superior cymba concha.*
- *Cavum concha length : intertragic incisure to superior cavum concha)*
- *Posterior concha – intertragic incisure*
- *Tragial length: tragus to anti-tragus*
- *Tragus – Posterior concha*
- *Concha depth: tragus to medial concha*
- *Concha width: superior cavum concha to Posterior concha*
- *Length between the deepest points of the bowls (medial concha - cymba cavum)*

Apart from the lengths of the concha, it is relevant to have an indication of the average angle and the shape deviations of the auditory canal from its entrance towards the first bend and how much the canal rotates after the first bend.

The data from the measurements will be used to get an indication of how the E-module should be positioned and how deep the module can be placed within the ear (and thus how far it is outside of the ear).

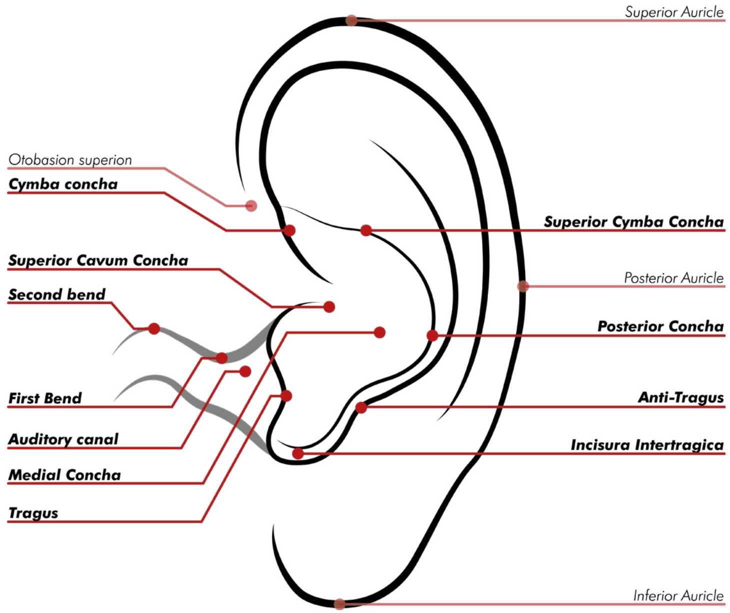
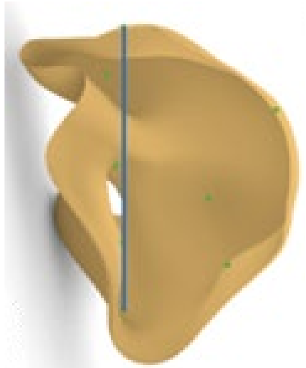
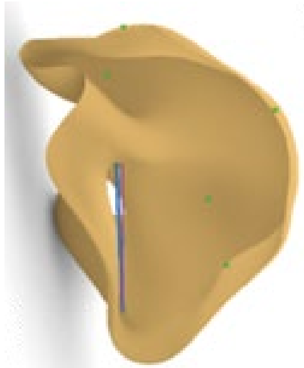


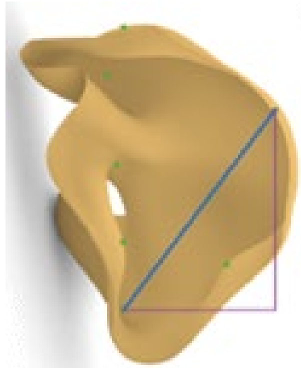
Figure 25: Ear landmarks (Lee et al., 2016)



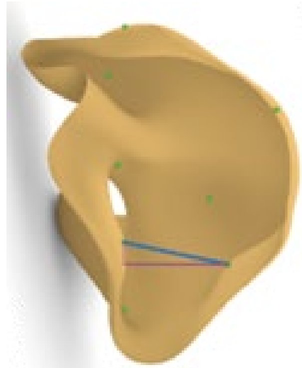
1. Concha length (front view)



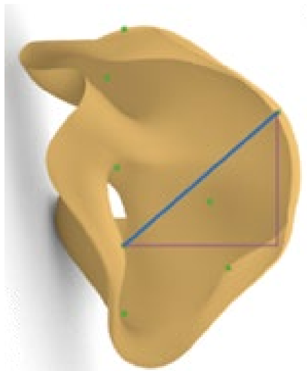
2. Cavum concha Length (front view)



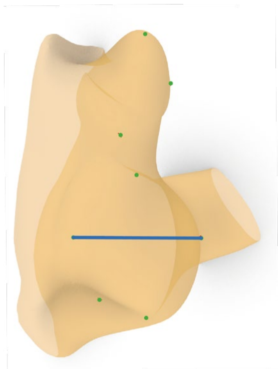
3. Posterior concha – intertragic incisure (front view)



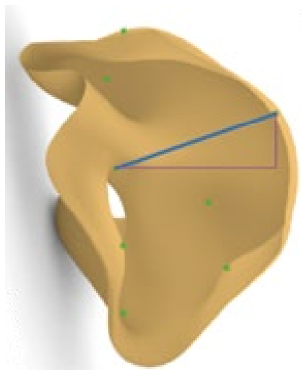
4. Tragial length (front view)



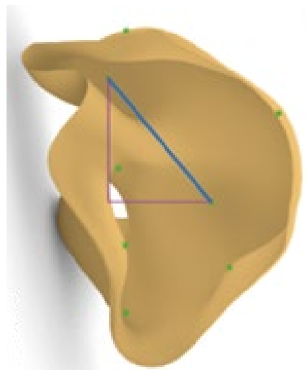
5. Tragus - posterior concha



6. Concha depth (Top view)



7 . concha width (front view)



8 . length between concha's (front view)

Figure 26: Concha distances

3.4. Auditory canal evaluation

The goal is to establish an understanding of the deviations in the shape and direction of the auditory canal. This information will be used to design the audio canal in the final design of the semi-personalised earphones, since the scanners will not be able to collect information on the auditory canal.

The entrance of the auditory canal is not clearly defined in literature. Therefore, the entrance of the auditory canal in this study is defined as the smallest circumference which can be drawn over the axis of the intertragic incisure and the superior cavum concha (see figure 28: step 7 & 8). The entrance is found by revolving planes around the axes. The intersection of the planes with the models are first filtered for closed and open loops. The loops that are formed in the Cymba concha region are discarded (see figure 28: steps 2 to 6). To evaluate the shape of auditory canal, it is sliced by multiple planes from both the entrance and the end of the auditory canal. Through the centre points of the section lines, a spline is drawn (see figure 28: steps 9 to 11).

The spline is in its turn divided into multiple sections with planes perpendicular to the direction vector at that point. By placing the planes perpendicular to the spline, the true circumference of the auditory canal at each section can be calculated. As well as its normal direction, the angle in relation to the axes and its position (see figure 28 : steps 12 & 13). However, not all the circumferences are relevant. The most relevant measurements are the measurements at the entrance, at the average direction vector and at the last circumference before the second bend (see figure 28: steps 14 & 15).

For each of these three circumferences, data on five features is collected :

- *Circumference*
- *Normal vector direction*
- *Angle of the normal vector direction compared to the coordinate system.*
    - *Angle between the vector and X-axis projected on to the XZ-plane.*
    - *Angle between the vector and Z-axis projected on to the YZ-plane.*
    - *Angle between the vector and Y-axis projected on to the XY-plane.*
- *Length between the centre points*
- *Coordinates of the centre points (in relation to the tragus)*

Another definition proposed for the entrance would be the last full circle (see red line in figure 27), which can be drawn in the bowl of the concha and the tragus and the anti-tragus. The reason for not choosing this definition is that that it is harder to find the correct orientation to draw the circumference. The current definition relies on the two landmarks that can be found in every ear which makes it better for parameterization.

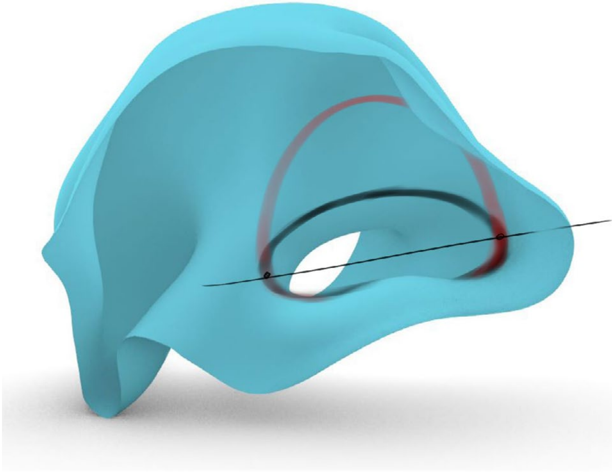


Figure 27: Alternative definition of the entrance of the Auditory canal

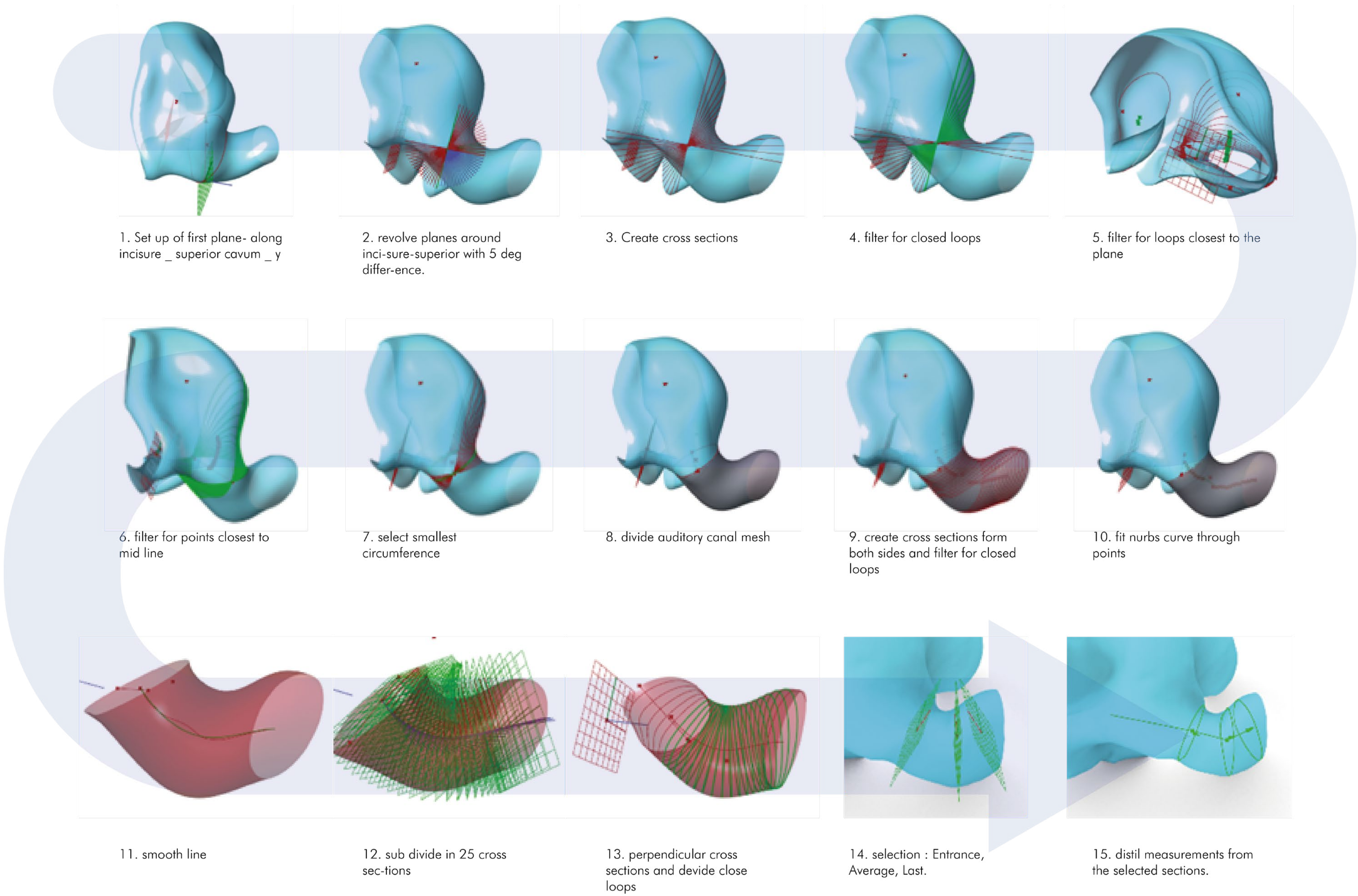


Figure 28: Measurements of the auditory canal

3.5. Results

	Concha Lenth (mm)	Cavum concha Length (mm)	Posterior concha – Intertragic incisure (mm)	Tragial length (mm)	Tragus - posterior concha (mm)	Concha depth (mm)	Concha width (mm)	Length between concha's (mm)	Circumference E (mm)	Circumference A (mm)	Circumference L (mm)
count :	537.00	537.00	537.00	537.00	537.00	537.00	537.00	537.00	537.00	537.00	537.00
mean :	23.08	14.29	23.17	8.43	18.35	14.29	18.23	15.14	32.77	37.75	33.87
std :	0.02	1.38	2.66	1.41	1.93	1.14	1.77	1.09	12.71	24.72	18.63
min :	22.75	10.28	10.50	4.38	11.10	9.98	14.25	11.65	0.00	0.00	0.00
5% :	23.08	12.07	18.33	6.34	15.19	12.57	15.55	13.25	19.63	19.78	21.89
50% :	23.08	14.36	23.53	8.34	18.50	14.23	18.17	15.18	30.32	26.69	27.75
95% :	23.08	16.42	27.05	10.83	21.37	16.19	21.39	16.83	59.12	91.20	87.64
max :	23.08	19.05	29.86	13.01	23.66	18.42	24.13	18.33	100.29	106.21	105.88

Table 1: General statistics of the ear measuremnts

The outliers are checked using the Mahalanobis distance which analyses how far removed a point is from the mean of a distribution, therefore taking into account the correlation in a multivariable data set. An outlier can occur for several reasons. It could be that the shape of the ear is very different and therefore has multiple variables which are un-common in the dataset. The other option could be that it is due to the change in shape, for example a nearby hill or dent in the shape. In this case, the average direction of the vectors could have led (see figure 24) to a different position than intended. The measurements are therefore skewed in these cases.

For each of the measurements the outliers should be determined individually. The outliers could either be based on the shape or due to a faulty position of the landmark. To prevent this, the landmarks should be manually corrected to a more suitable position. Another solution would be to exclude the measurements all together.

For the evaluation of the auditory canal, a skewed landmark in either the superior cavum concha or the intertragic incesura could mean that the evaluation of the entrance circumference malfunctions. This happened in model 274 (see figure 29). In this case, the landmarks ended up closer to the tragus, which in turn was bigger than usual. This meant that the circumference lines went around the tragus instead of through the bowl of the concha.

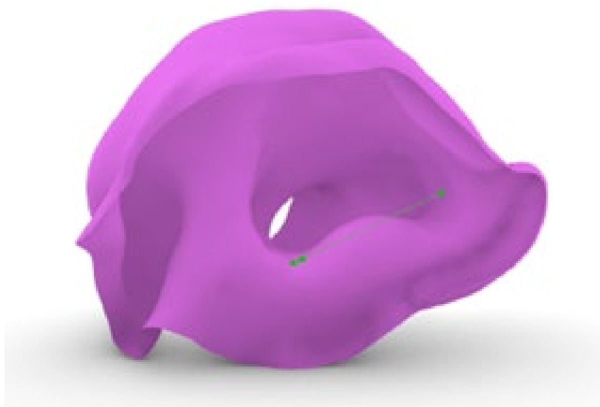


Figure 29: Outlier based on wrong landmark selection

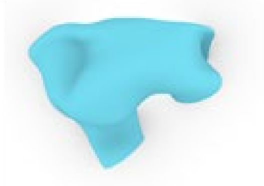
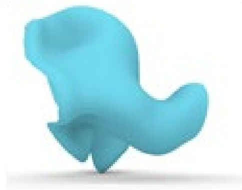
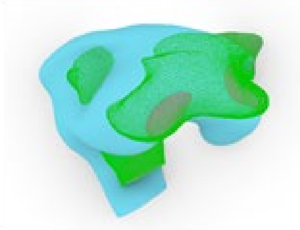
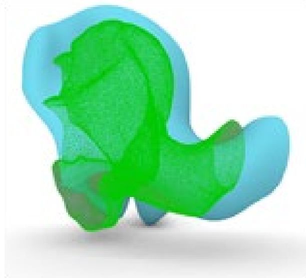
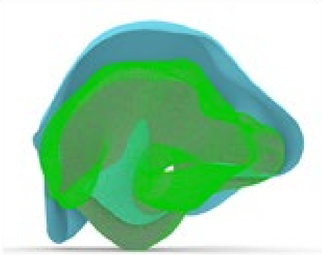
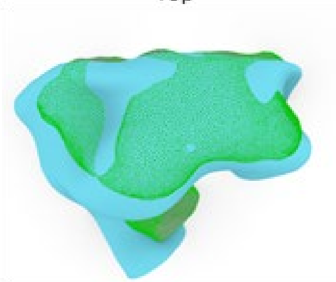
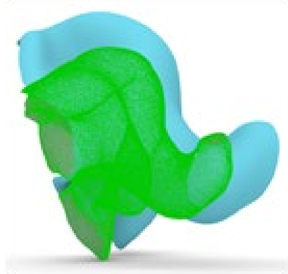
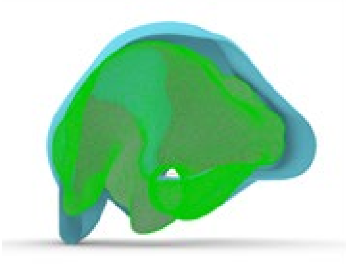
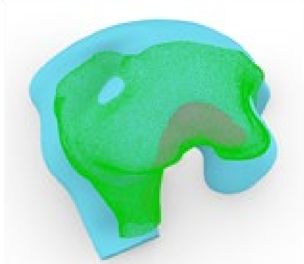
SSM -front	Top	side
		
Outlier (014) - front	Top	side
		
(163) P0.05 Concha - front	Top	side
		
(229) P0.05 auditory - front	Top	side
		

Table 2: Statistical outliers based on their shape

To evaluate if there are some connections between the measurements, multiple Pearson correlations were executed. When the Pearson coefficient is close to 0, there is no association between the values. The closer the coefficient is to 1.0, the stronger the correlation between the data is.

For instance, the data shows that there is a significant correlation (0.729) (see appendix A.3) between the length of the concha and the length of the cavum concha, which is used to estimate the entrance of the auditory canal.
Therefore, if the ear is large, the entrance to the auditory canal will most likely be large as well.

The correlation between the circumference at the entrance of the auditory canal and the circumference at the average vector location is significant but low (0.275). Due to the low correlation value, it is not advisable to use the circumference data to predict how to model the audio canal.

The entrance, the average vector position and the exit all have an orientation which can be expressed with a normal unit vector. The vector can be deconstructed into its x,y,z – components on the global axis system of the ear model. By taking the unit vector, the components can range between 0 and 1. In this case, the y-component is always directed into the negative direction on the axis (see figure 3).
All components of the entrance vector seem to have a significant correlation with the corresponding vector component of the average circumference location.

Pearson correlation values between 0.8 and 0.6 are considered strong, values between 0.6 and 0.4 are moderate and values between 0.4 and 0.2 are considered weak (Zhi et al., 2017).
The correlations between the Nx and Nz components of the entrance and average location are moderately strong, while the correlations of the Ny component can be considered strong.

component	Pearson correlation	Significance Sig. (2-tailed)
Nx	0.47	< 0.001
Ny	0.65	< 0.001
Nz	0.58	< 0.001

Table 3: Correlation

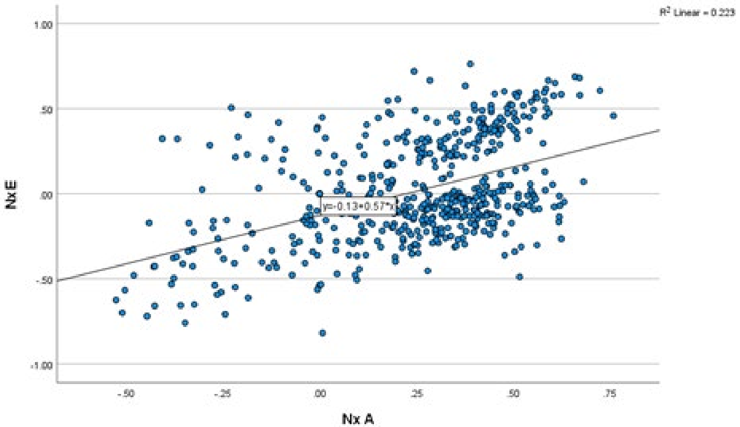


Figure 30: Scatterplot Nx

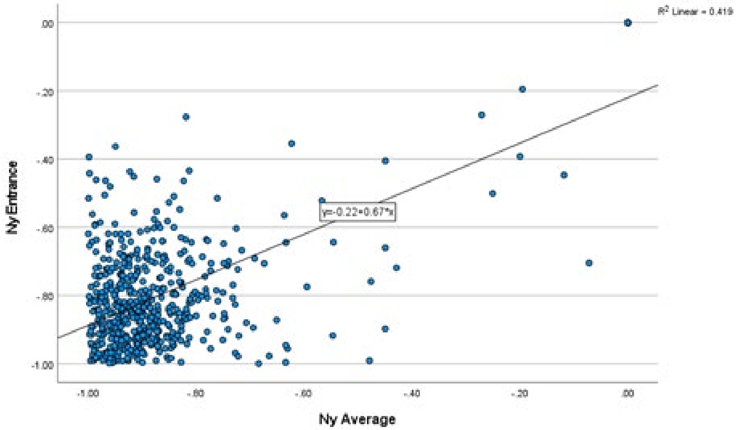


Figure 31: Scatterplot Ny

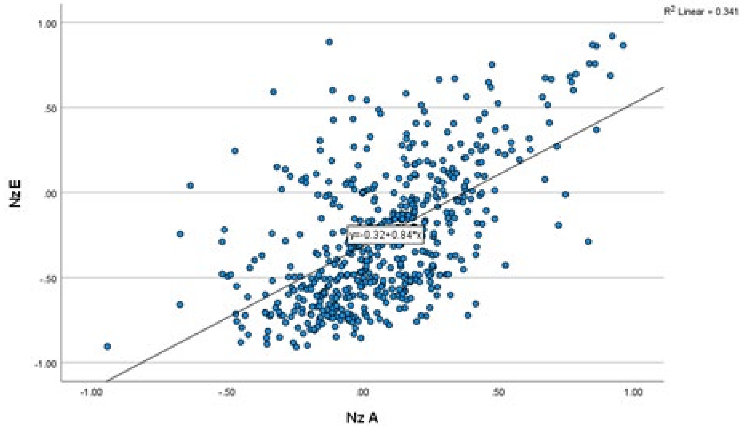


Figure 32: Scatterplot Nz

3.5.1 E – module evaluations

The dimensions (width, height, length) of the E-module are compared to the corresponding measurements of the ears of the database to get a better understanding of the desired placement of the E-module. The dimensions of the E-module are plotted against the measurements of the 3D database. The plots give an indication of how many of the measurements are above or below the size of the E-module (see figure 33).

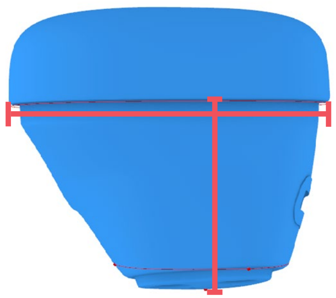


Figure 33: Length and width of the E-module

Measurement set up

The E-module is evaluated using Rhinoceros. The outer shell of the module has a clear split in what goes into the shell and what will stick out (the cap). The flat part underneath the cap will be used in the final prototype to create a loft function, therefor enclosing the E-module into the shells. To accomplish this the outer shape of the cap and the location of the bottom of the cap are calculated by evaluating the vector directions of the meshed E-module. The bottom of the cap should be perpendicular to the YZ-plane of the CAD Software.

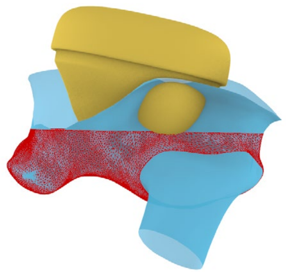


Figure 34: Placement of the E-module in the scan data

At this plane, a section curve is drawn. The length and width of the curve are determined by the maximum and minimum points viewed from both the XY-plane and the YZ plane.
The height of the emersed part of the E-module is, again measured from the section plane to the furthest point of the model.
The results show that all ears are larger in length than the maximum length of the E-module (20 mm) (see figures 35 & 36), the smallest measured ear is 2mm larger than the E-module.
With regard to the width of the module and the width of the ear (measured from the Superior Cavum Concha to the Posterior Concha (see figure 26), the majority of measurements were larger than the dimension of the E-module. However, a small subset of measurements is smaller. As for the depth of the ear, the part which should be integrated into the shell is larger than most of the ears in the database.

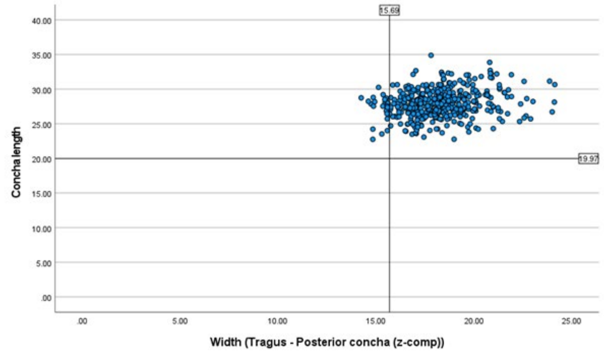


Figure 35: Scatterplot of the concha width and length compared to the width and length of the E module.

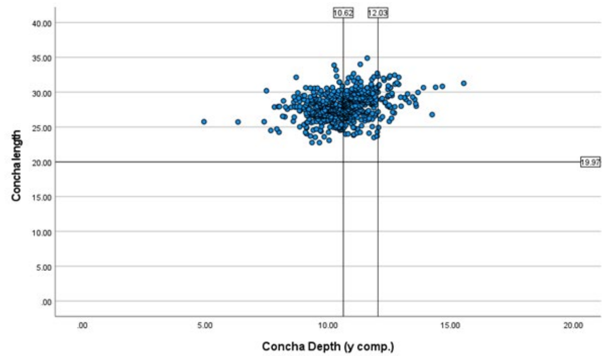


Figure 36: Scatterplot of the concha depth and length compared to the depth and height of the E module.

3.6. Conclusion

The data shows that there is not much overlap between the outliers of the concha measurements and the auditory canal measurements. Therefore, the scan data from the concha cannot predict whether the auditory canal is close to the SSM or whether it is an outlier. This outcome is expected since the scanning methods are unable to map the auditory canal. As it is impossible to make this prediction, it is therefore also not possible to make a long rigid parametric design for the audio cannel.

In the end, it can only be concluded that the size of the ear is correlated to the size of the entrance since the length between the intertragic insesura and the superior cavum concha show a large correlation. Since the Ny components are strongly correlated, the value of the Ny Entrance (E) vector can be used to predict the strength of the unit vector in the y direction at the average vector location, by multiplying the unit vector of y with the component of Ny E.

In theory, the E-module should be able to fit to all ears in length since the concha is larger than the length of the E-module. However, the audio canal still needs to be added. In case of the small length of the concha it might be needed to rotate the E-Module around its height axis to provide more space for the audio canal. However, this would mean that the width will increase. Although the width of the E - module is in most of the cases larger than the width of the concha, defined by the measurements, this might not always be the case. The measurements do not take into account the shape and position of the crux of the helix, which can be more prominent than others and therefore limiting the space for the placement of the E-module further. A solution for the placement might therefore be to move the E-module further out of the ear, since the E-module becomes narrower at the bottom. Moving the E- module further out of the ear should already be done since it does not fit most ears. Therefore, the E-module should be placed with a variable offset from the Medial concha to be able to fit in the ear of the participant as well as some freedom for rotation.

In some outlying shapes where the dimensions of the ear are very small, it might not be possible to find suitable orientations for the E-module without a very large offset. This places the centre of gravity of the earbud further away from the ear, which could increase the effect of head movements and therefore lessen the perceived comfort. For this reason, a maximum height should be established in future research. In discussion with the experts from Dopple, the current maximum height is set to 5 mm above the tragus.

3.7. Main takeaways

- *Ears keep growing until we die which effects the comfort, retention and sealing of the product. Therefore, it should be taken into account for the assessment of the product lifecycle.*

- *Landmarks can be used to evaluate the differences between ears.*

- *There is almost no overlap between the outliers of the concha measurements and the auditory canal measurements. Therefore, the scan data cannot be used to predict the shape of the auditory canal.*

- *There is a significant correlation between the direction of entrance and direction of the first bend.*

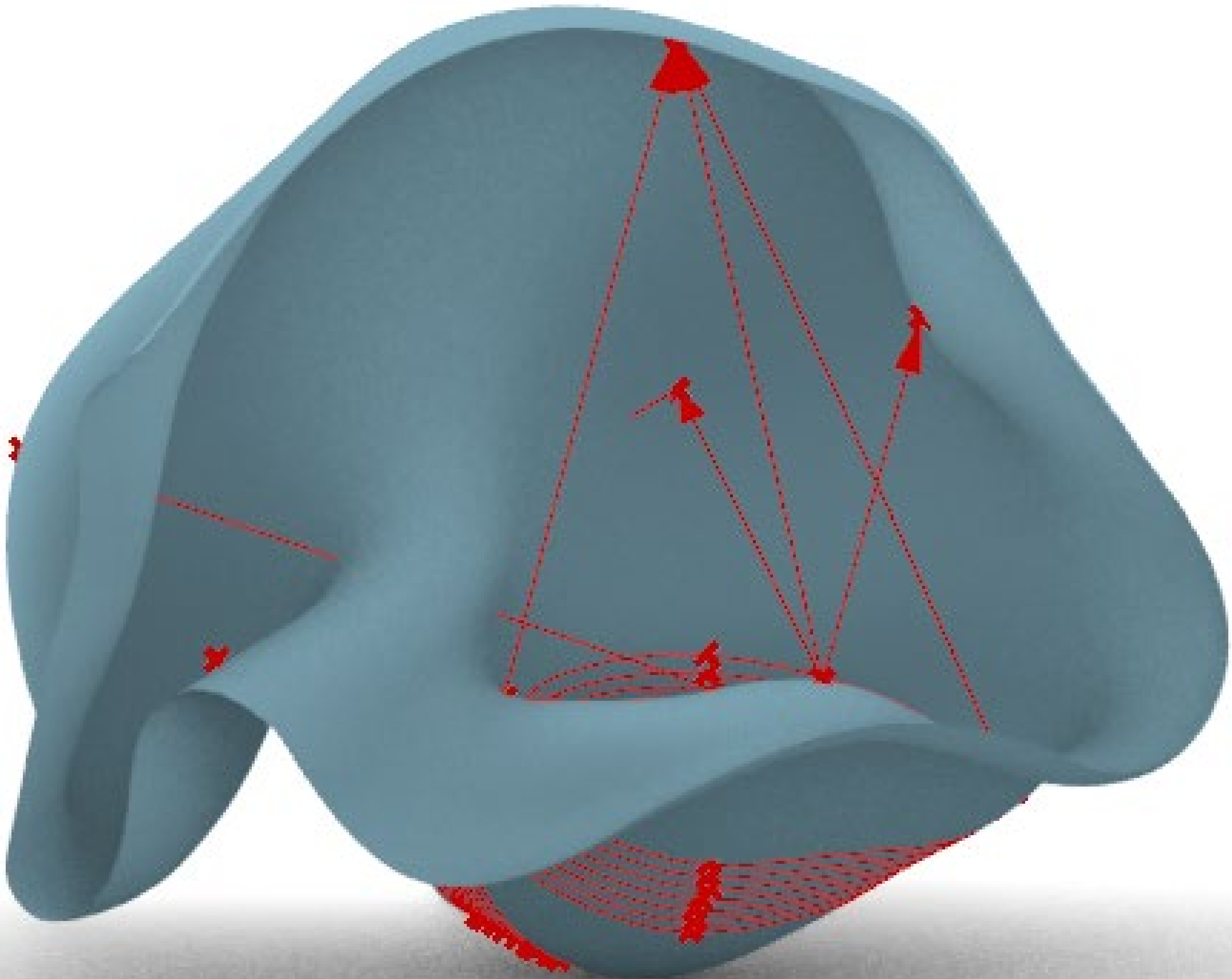


Figure 37:measurments in one concha

4. User research

Earphones (both wireless as well as wired) are labelled as a hygiene product in the Netherlands (Mediamarkt, n.d.; Bol, n.d.; Coolblue, n.d.). Products with the label “Hygiene” cannot be returned unless the seal, which is outside on the packaging, is still intact (Koninkrijksrelaties, burgerlijk wetboek 6). Therefore, customers have no way of experiencing the fit and quality of the earphone when they are buying and how they compare to other products. Because each ear shape is as unique to each individual as their fingerprint (Bhanu, 2011), it is important to have earphones with the correct fit. The consumer is therefore forced to decide on a relatively expensive product, which might not provide a good fit for them. In case that the customer is not completely satisfied, there are only two options left; accepting the earphones for what they are or accepting that the money is lost and continuing the search for new earphones. It is for this reason that providing personalised earphones or even semi-personalised earphones can provide a solution. Since the modelling is done on the ear of the user, a good fit can be guaranteed. Furthermore, personalisation can consider specific user needs. Therefore, the design can be optimised to fit the lifestyle of each user.

As discussed before, the term personalisation goes beyond fit (Minnoye et al., 2022). Currently Dopple is already testing the next steps in personalisation for identity by providing users to personalise the colour of the E-module and the cradle. As a next step, the earphones could also consider personalisation for capabilities, which would let the customer choose which functionality the earphones should have. However, to optimise the design process and help customers to make choices, it would be beneficial to split up customers into overarching personas with which the customers can identify themselves to select the functions they need for their lifestyle. Another reason for setting up personas is to check whether certain requirements fit the use cases of the user and if not, how they should be changed to fit the needs of this particular user group.

To gain a deep understanding of the users’ current experiences around (semi-personalised) earphones, user research is conducted. Based on this, use cases and personas cases are developed. Use cases help to gain insight into the context in which earphones are used and personas deepen those insights to gain a better understanding of their needs in those contexts.

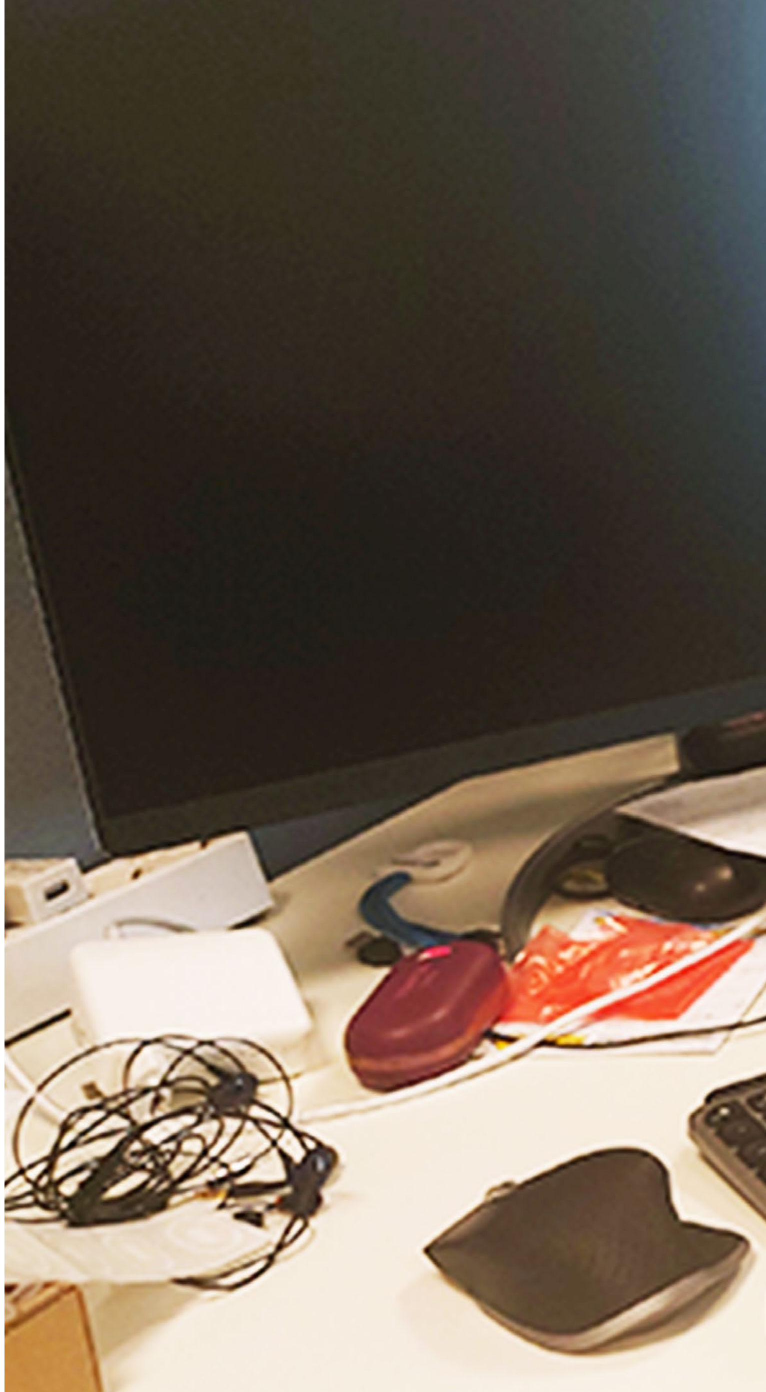


Figure 38: Prototype evaluation with Dopple expert

4.1 User behaviour

To discover how users interact with earphones and for what activities they use their earphones, two online questionnaires and a few informal interviews were conducted.
The first questionnaire was aimed at the public to gather information on general behaviour of earphone users. The questionnaire tries to get an understanding of the activities that people do while wearing earphones, in which situations they use the earphones, if they are satisfied with their current type of earphone and why. In this questionnaire I deliberately did not differentiate between wired earphones and wireless earphones, to see if there was a difference in the way of evaluating the questions.
The following research questions gave guidance in this questionnaire.

- *What are the main goals for using (wired and wireless) earphones?*
- *What goals are regarded as the most important attributes for (wired and wireless) earphones?*
- *What are the main reasons for (dis-)satisfaction with (wired and wireless) earphone?*

The second questionnaire is specifically directed to users of wireless earphones to have a clear view on the interactions with a wireless earphone and whether the use differs from the use of standard earphones. The questionnaire takes into account some demographic factors (such as age and occupation). Apart from being directed to general wireless earphone users, the questionnaire also targeted a group of Hi-fi audio users, audiophiles and some musicians. The Hi-fi audio users were targeted (through online platforms), because they are more familiar with the expected quality within the price range of Dopple and are thus more likely to offer meaningful feedback about what they value in a high-quality earphones. (Professional) musicians were targeted (via a personal network) because they might have experience with personalised in-ear monitors. Again, their perspective on certain criteria would be valuable input.

The following research questions gave guidance in this questionnaire.

- *What are the main goals for using wireless earphones?*
- *What goals are regarded as the most important attributes for wireless earphones?*
- *What are the main reasons for (dis-)satisfaction with wireless earphones?*
- *What areas of the ear are most sensitive for (dis)comfort?*

4.1.1. Results of questionnaire 1

The survey was answered by 33 participants. In the first question, participants were asked to select for what reason they would use their earphones. The participants could choose from pre-selected answers (multiple choice). The most popular reason to listen to music was for relaxation. However, in 78% of answers multiple use cases were indicated. Other common use cases were for instance calling, exercising and for concentration.

According to the survey, the most important factor for product satisfaction is whether the retention of the product is good enough. Retention was both the main reason for dissatisfaction as well as the main reason for satisfaction for an earphone (see figure 39). When participants were dissatisfied with the product, this was most of the time caused by earphones falling out of the ears, while on the other side, the feeling of security in the ear was the main contributor for satisfaction. This result is unexpected as it is not the audio quality of the earphones which is mainly evaluated but rather the feeling of the product within the ear.

In the questionnaire, the participants were asked to place the following attributes on importance:

- *Sound quality*
- *Look / design*
- *Comfort*
- *Retention*
- *Battery life*
- *Active noise cancelling*
- *Sealing quality (passive noise cancelling)*
- *Sensors*
- *Interaction of with the earphone*
- *App integration*

When asked which attribute of the earphones is the most important, participants ranked sound quality the highest. There was no difference in ranking between different price ranges.

One explanation could be that customers are simply satisfied with the price-quality ratio of their product. Another explanation could also be that customers can only relate their current sound experience to previous experiences. However, since earphones cannot be tried out in many cases due to hygiene reasons, it is hard for customers to experience a wide range of audio quality.

Figure 39: Reasons for sattisfaction (Blue) reasons for dissattisfation (Red)

4.1.2. Results of questionnaire 2

The survey was answered by 55 participants.

Participants indicated that the main reasons for purchasing wireless earphones was the convenience, the ease of use and the option to personalise their sound experience. The most popular use cases are relaxation, concentration, and exercise. Running, cycling and gym were given as activities while exercising. In the majority of the responses, the participants use their earphones for multiple use cases. Concluding, the earphones should be able to fulfil the needs of the customer not in just one but multiple use cases.

Participants were also asked in this questionnaire to rate the attributes on importance. Of the attributes, participants ranked (1) comfort, (2) sound quality and (3) retention as the most important attributes. When dividing the answers into clusters per use case, the ranking shifts depending on the use case. For instance, the top 3 of participants with the use case of concentration often included sealing quality or active noise cancelling.

When the participants were asked in which region discomfort most often originates, 52% replied that the hearing canal (6) provided the first symptoms of discomfort. The bowl of the concha (5) followed with 15% of the votes (see figure).

Participants indicated that they were willing to pay more for personalisation in fit compared to non-personalized products with the same audio quality. The average price that participants of this survey are willing to pay for personalised earphones is €226.52, which was on average an increased amount of 37% above the purchasing price of their current earphones.

For personalisation of identity, most participants did not want to pay extra for further personalisation of identity.

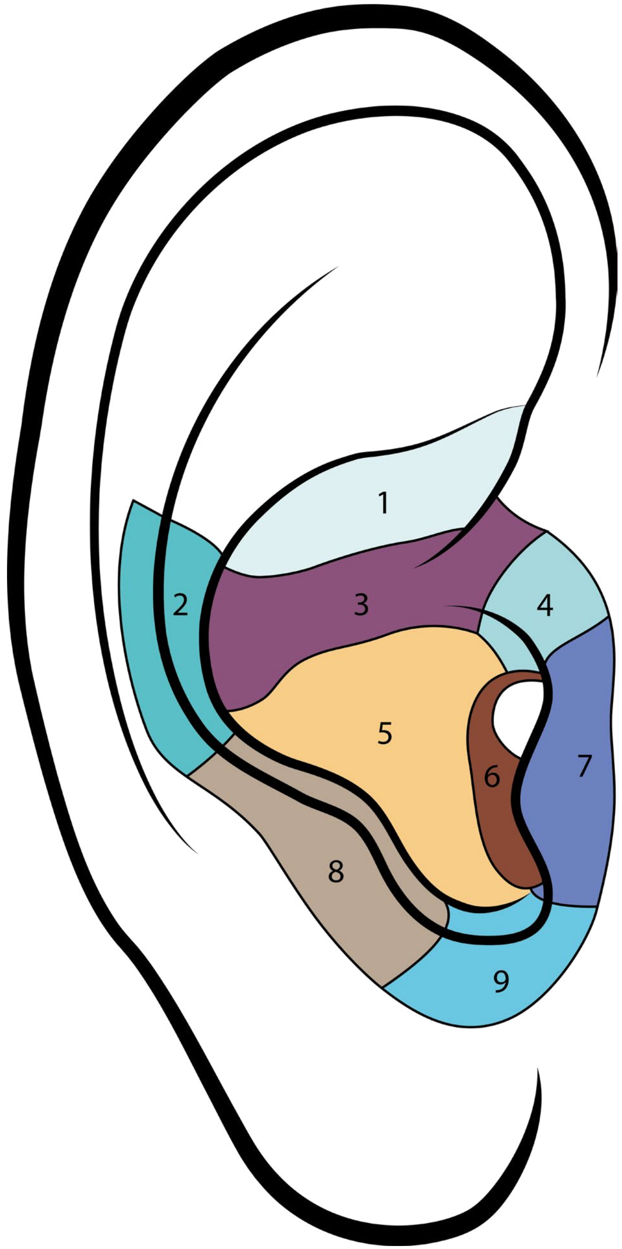


Figure 40: Ear region visual given in the questionaire

4.1.3. Conclusion

In questionnaire 1, the results seemingly indicate a contradiction in the answers of the participants. Despite retention being the main reason for dissatisfaction and satisfaction, the highest-ranking attribute was still audio quality. In the second questionnaire, more participants voted for comfort than audio quality, which was second. However, retention was still only the 3rd ranked attributes.

Although participants mentioned that they perceive audio quality as important, this is often not reflected in the amount that is spent on their earphones. High-end audio consumers are usually prepared to spend more for a product with better audio quality. There seems to be a different understanding of quality between customers. It could either be that participants look at audio quality relative to the price and it is likely that the audio quality is compared to past experiences. The latter is especially likely since customers are unable to test the audio quality of a product before purchasing. This observation was also corroborated in an interview with the owner of high-end audio store (ears unlimited) in Delft as well as discussions with several users of wireless earphones. Based on the questionnaires and the interview, it can be concluded that audio quality is a subjective term.

The area that was indicated as having the most discomfort symptoms for tube-shaped tips (see chapter 2.4) is the auditory canal. This is not surprising since the tips are designed to clamp themselves in the auditory canal. To increase the level of comfort, the pressure should be equally distributed to parts of the concha.

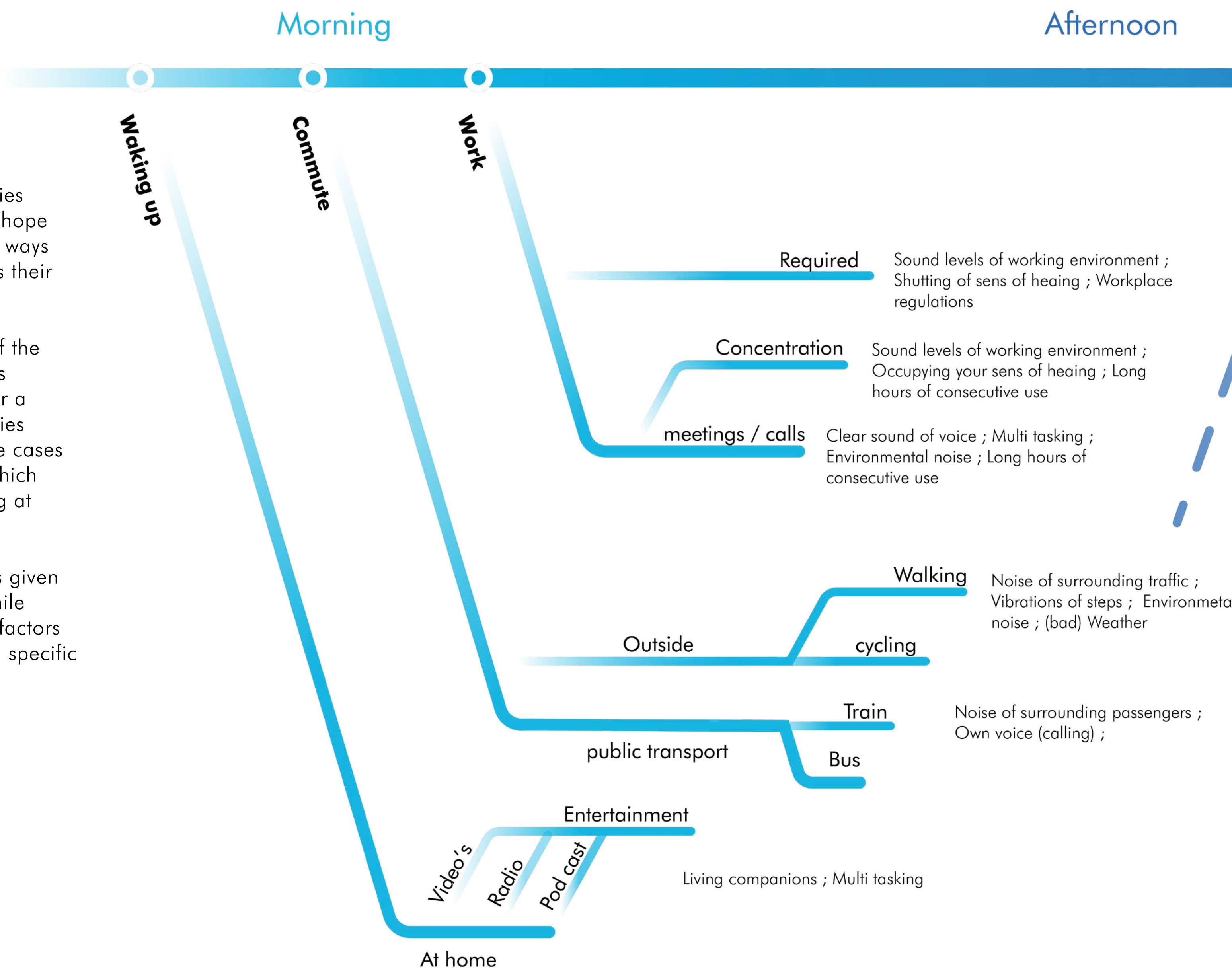
Since both questionnaires indicated that earphones are used in multiple scenarios over the course of the day, the design should be able to fulfil multiple use cases.

4.2 Use cases

By making an explorative map of the activities when people usually use their earphones, I hope to provide a better overview of the different ways earphones are used and how this influences their use of the earphones.

These activities are based on the answers of the questionnaire. However, further validation is needed to verify whether these actions cover a large enough range of activities. The activities should give a representation of different use cases with different needs and requirements for which the design could be optimised when looking at personalisation for capabilities.

Next to each of the actions, an indication is given of what is happening in the environment while executing the activity. These environmental factors could deliver specific requirements for each specific use case.



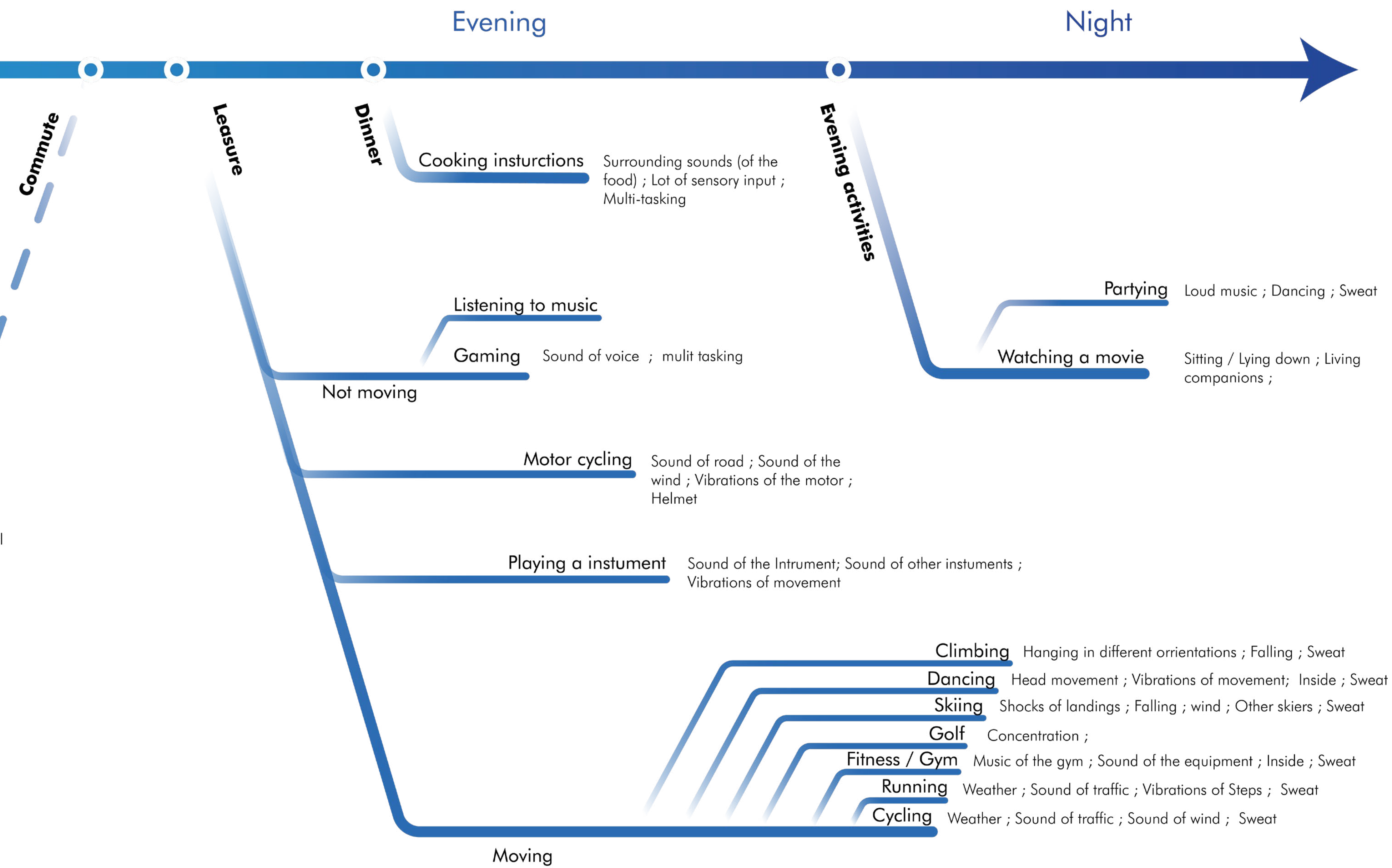
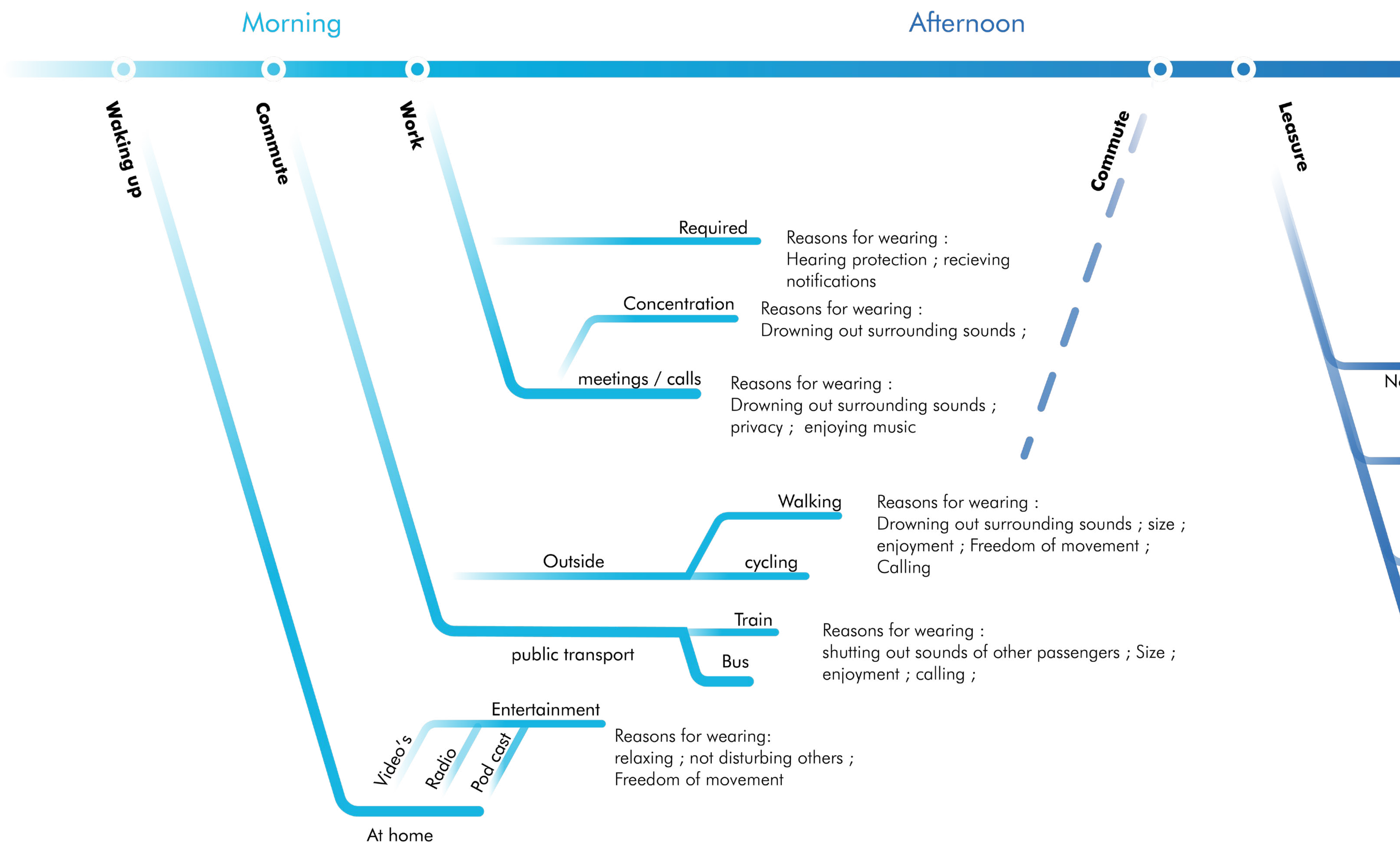
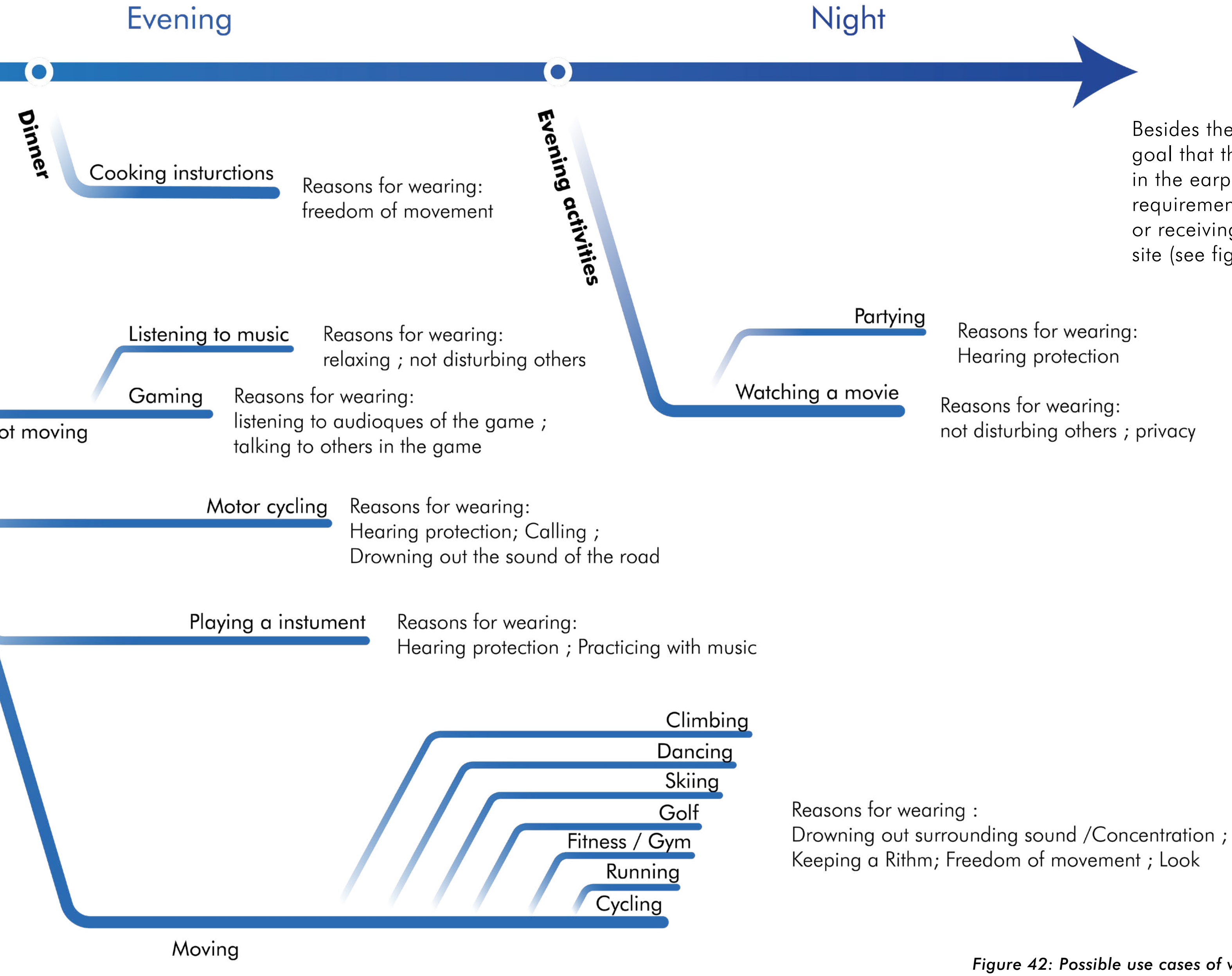


Figure 41: Possible use cases of wireless earphones and their environmental influences



Morning
Afternoon
Waking up
Commute
Work
Commute
Leasure
Required
Reasons for wearing :
Hearing protection ; recieving notifications
Concentration
Reasons for wearing :
Drowning out surrounding sounds ;
meetings / calls
Reasons for wearing :
Drowning out surrounding sounds ;
privacy ; enjoying music
Walking
Outside
cycling
Reasons for wearing :
Drowning out surrounding sounds ; size ;
enjoyment ; Freedom of movement ;
Calling
Train
public transport
Bus
Reasons for wearing :
shutting out sounds of other passengers ; Size ;
enjoyment ; calling ;
Entertainment
Video's
Radio
Pod cast
Reasons for wearing:
relaxing ; not disturbing others ;
Freedom of movement
At home



Besides the environment around the activity, the goal that the user wants to achieve by putting in the earphones could also lead to interesting requirements, such as keeping rhythm for dancing or receiving warning notifications at a construction site (see figure 42).

Figure 42: Possible use cases of wireless earphones and the reasons for wearing.

To evaluate which use cases will benefit from personalised earphones the most, I evaluated several common use cases on the need for comfort, which is expressed in hours of use per day (see figure FIXME). People will experience discomfort after being exposed to pressure over extended periods of time, especially when the pressure is applied to a small, localised area (Yun et al., 1992).

As a measure for retention, the use cases are rated in the form of a questionnaire on the severity of the acceleration of the head movement. The reason for choosing acceleration (/deceleration) a measure for retention is that the weight of the mass of the earphones will stay constant. Therefore, the increase in force can only be induced by a quick/high acceleration or deceleration.
Ranking the use cases on sealing quality is harder. This is because on one hand there are cases in which hearing protection is required by law. On the other hand, there are uses cases which would benefit from noise cancelling but are dependent of their surroundings, an example is studying. The ideal conditions for concentration stated by the Occupational Safety and Health Administration (OSHA) do not exceed 40 decibel (dB). As a guide for exposure limits to sound, the OSHA (Directive 2003/10/EC - noise) states that the permissible exposure limit (PEL) is a 90 dB environment for 8 hours per day (see figure 43). For every added 5 dB, this time is cut in half. Music concerts usually produce between 110 – 120 dB and can last from 2 to over 8 hours, exceeding the recommended PEL level. It is therefore vital for people in the music industry (and visitors) to protect their ears to prevent hearing loss. Hearing protection is rated on a noise reduction (NRR) (NRR Rating, 2017). General hearing protection like party plugs can reduce noise in a range between 9 – 21 dB, while customised earplugs can reach NRR levels of 25 and even up to 30 dB (Alpine,nd.).

Figure 43: Decibel scale (OSHA)

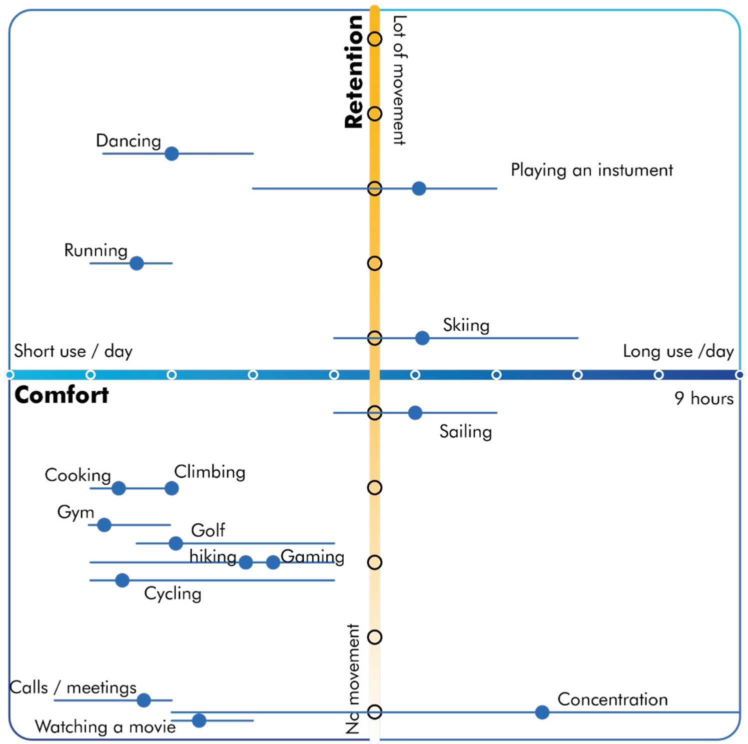


Figure 44: Ranking of use cases

Since the new earphones will be designed based on the pictures and 3D scanners, the expectancy is that the data we can get from behind the tragus will be very limited. Therefore, it is expected that the final design will be a semi-personalised earphone. Since it is not possible to get precise data on the hearing canal, it is expected that a high degree of passive sealing will be difficult to achieve, based on discussions with the experts of Dopple.

In case the sealing is required, for instance for hearing protection, customers would likely benefit more from a fully personalised wireless earphone like the UE drops or even an In-ear monitor. Furthermore, they could benefit from a highly flexible product which can bend and deform to the shape of the ear of the user.

Therefore, the optimal quadrants for the design are on the side of high retention and long hours of use as well as high levels of retention and up to medium levels of sealing (see figure 44).

The activities that do not make optimal use of the benefits of personalisation, according to the survey (10 participants) are:

- *Watching movies*
- *Calls*
- *Hiking*
- *Gym / fitness*
- *Climbing*
- *Cycling*
- *Gaming*
- *Golf*
- *Cooking*

These scenario often only takes a few minutes up to a few hours of every day, while laying, sitting, or standing. The most noise of the environment is either soft or not that important. In some cases, the opposite effect of transparency might even be required, for instance to be aware of surrounding traffic.

At the upper right quadrant of both graphs, the use cases require high retention, sealing and comfort qualities in the design. As these functions can be best provided with personalised fit, the groups in that quadrant make the ideal target group for fully personalised earphones. For example, users could be musicians who perform live onstage and people who have jobs that contain physical labour in loud environments. However, whether the semi-personalised earphones can provide enough sealing protection will first need to be evaluated. Use cases that would benefit from semi-personalisation are several popular solo sports, or are used by the user for a large part of the day:

- *Dancing*
- *Running*
- *Skiing*
- *Sailing*

- *Working/studying*

The above use cases each have their requirements that could be difficult to solve with generic earphones and therefore pose an opportunity for personalisation.

The use case of working/studying in which users use their earphones to focus for a long duration of time was indicated in the questionnaires. In this case, earphones and music are used to keep our hearing senses occupied so the user can focus on other tasks. This group, therefore, requires a design that is optimised for comfort.

4.2.1 A-typical use cases

Personalised earphones are expected to provide more comfort to their users than generic earphones thanks to the better-equalised pressure over the whole concha. Since personalized earphones are shaped to the concha of an individual, the earphone will have more regions of contact. In use cases with a lot of movement, more force is exerted on the earphones. Therefore, the retention can be increased by using the overhangs of the ear as part of the design to provide even more retention. Most generic earphones rely on the auditory canal for retention, which causes discomfort.

Another advantage of a fully personalised earphone over a generic earphone is that it considers a part of the auditory canal which cannot be evaluated easily from the outside. The generic tube-shaped tips often come in standard sizes. The manufacturer of the earphones hope that the limited sizes are good enough to satisfy most of their customers. However, when the shape of the auditory canal is known, the path can be blocked completely providing the user with better hearing protection.

For people with abnormal ear dimensions or small ears (see figure 45), earphones with generic tips do not fit. The improper fit of the earphones can mean that the retention in the ear fails, which can be caused in three ways. The shape of auditory canal is too narrow for the tips to fit, the shape of the auditory canal is too large for the ear tips to fit and/or the concha does not provide enough room for the body of the earphone to fit, pushing it out of place. This could lead to either earphones falling out of the ear of the user (or becoming loser) or that there is too much retention in which case it feels very uncomfortable or even hurts to put in the earphones (if it is even possible to put them in at all). For these customers, personalisation can provide a solution.

In case the earphones also need to function partially as hearing protectors, it is not likely that the semi-personalised earphones provide a solution, since the auditory canal cannot be sufficiently evaluated by the scanning methods (see chapter 6.2). in this case the customer should consider buying fully personalised earphones. Depending on which dimensions of the ear are abnormal, it could be harder for a parametric programme to generate a model. In these cases, it could be necessary for a human to intervene and readjust the model to create the product.

Figure 45: Example of a small ear


L

4.3 Personas

From the questionnaire, it can be concluded that people use their wireless earphones for multiple reasons. In some cases, these use cases are relatively in the same direction, like commuting, concentrating, and watching a movie. However, in many cases, participants indicated using earphones for concentration as well as sports. In this case, the earphones need to provide enough retention for the sport while still providing enough comfort to be worn for over 7 hours per day (Questionnaire.2). The following personas represent a few extreme use cases based on the user scenarios of the questionnaires.

4.3.1. Office worker

Listening habit : *[6 h/day]*
Maximum expected noise levels : *50 – 70 dB (Directive 2003/10/EC - noise)*

Needs for using wireless earphones:

- *Concentration*
- *Commuting by public transport*
- *Calling*
- *Cooking*

… does not move around a lot during the day except to get a cup of coffee from time to time. When is working from the office, they walk from home to the train station. On the train, it is always very busy since it is rush-hour and therefore… is surrounded by the noise of fellow passengers either talking to each other or on the phone. … just wants to be left alone and shut themselves off from this noise. After the Covid pandemic, their office has decided to make all the office's open flex offices which can easily fit 50 workers on a busy day. For work, they spend most of the day either in meetings or doing desk research and setting up reports. During the meetings, the background noise must be nearly eliminated so they can always hear their clients, as well as concentrate on getting their work done. Secondly the earphones need to filter out his voice so they can communicate with their clients. To relax … likes to cook. They often try to learn new things by following recipes on social media.

Figure 46: Representation of an officeworker

4.3.2. Dancer

Listening habit : *[3 h/day]*
Maximum expected noise levels : *30 – 60 dB (Directive 2003/10/EC - noise)*

Needs for using wireless earphones:

- *Freedom of movement: Likes the convenience of wireless.*
- *Concentration : No distractions form other dancers.*
- *Cycling: Needs to hear surrounding traffic.*
- *Active movements: Actively moving around a lot, either cycling or dancing.*

… is a high school student. Their dream is to someday become a professional dancer. Every day after school they go to the dance studio, either for lessons or to practice. During the lessons, they do not wear earphones, since the pace is determined by the rest of her dance group. However, when they practice the choreography by themselves, they do so in a common area of the dance studio. Therefore to not distract others and to focus on their movements on the music they wear earphones.
… uses wireless earphones to give them the maximum freedom of movement they needs for her performance. Therefore they prefer to not hold their phone in their hand or pockets. However, they still need to have control over the music to replay difficult parts of the songs. … practices both ballet as well as modern dance. After practice, they cycle home for 30 minutes through the city.

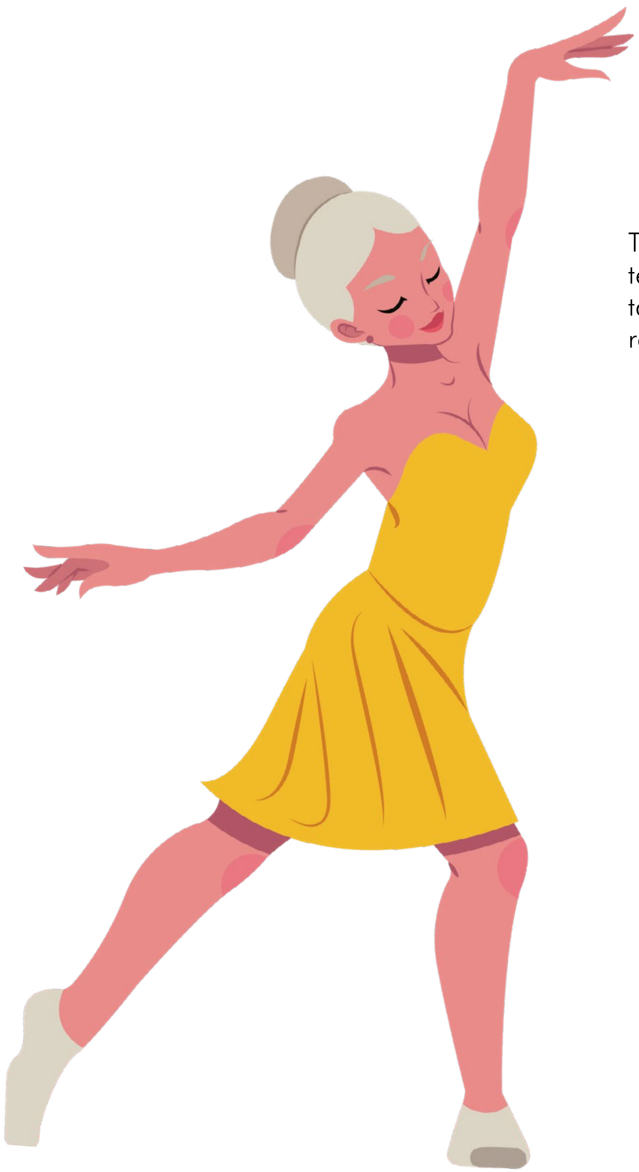


Figure 47: Representation of a dancer

To prevent or check against personal bias, interviews are be conducted with people form the target groups to better understand their needs and requirements.

4.4. Conclusions

The questionnaires indicate that earphones are not used for just one specific purpose. Preferable customers would like to use the same earphone in multiple scenarios. Some of these scenarios have a very specific subset of requirements compared to others.

At the upper-left and lower-right quadrant of the Comfort and Retention graph, the use cases would benefit the most of semi-personalised earphones. In the lower-right quadrant, the long consecutive use cases would benefit from the semi-personalised earphones since the forces will be divided along the concha, redistributing the load which in tube shaped types of earphones is exerted on the auditory walls. Because of this redistribution the earphones will provide more comfort for longer periods of time.

The higher-left quadrant retains use cases which require high levels of tension. Again, these use cases will benefit from a better distribution of forces along the concha. Since the shells have more touch points with the ear they can apply the force over a larger area, which provides the user with more retention. As these functions can be best provided with personalised fit, the groups in that quadrant make the ideal target group for fully personalised earphones. The personas are chosen based on extreme use cases of Dancing and long consecutive concentration. If the concept can fulfil the needs of both at the same time it is expected that they will also be able to fulfil the less extreme use cases in between.

The Comfort-sealing graph is not considered for now, since it is not yet possible to judge whether the scan methods provide a seal for passive noise cancelling and if so, how much noise cancelling can be guaranteed. Creating a design with a seal which reliantly produces passive noise cancelling is out of the scope of the project. Instead, the focus will be on creating a concept which is comfortable and provides retention to the user. Only after this is accomplished, sealing can be integrated.

Based on the characteristics of the Personas, requirements will be formulated that will be used to validate the ideas and concepts.

4.5. Main takeaways

- *However, since earphones cannot be tried out in many cases due to hygiene reasons, it is hard for customers to experience a wide range of audio quality.*
- *earphones are not used for just one specific purpose.*
- *customers would like to use the same earphone in multiple scenarios.*
- *customers would benefit the most from use-cases in which high levels of comfort or retention are required, while sealing is not required.*
- *The persona of the dancer stands for the extreme use case for retention.*
- *The persona of the office worker stands for the extreme use case of concentration during long consecutive wearing.*
- *The quality of the seal cannot be guaranteed, therefor it is not yet integrated as a requirement in this research.*

Figure 48: image of one of the shake tests of the models

5. Programme of Requirements

The insights of the previous chapters led to the programme of requirements and wishes, of which the complete list can be found in appendix D.

1. Performance

1. *The earphones should be able to survive 5 years (which is a requirement of Dopple);*
2. *After 5 years the, the earphones should be able to survive 10 (use cycles per day) x 1820 (days) = 18.200 use cycles;Note: One use cycle describes putting the earphone in and out the ear and 1820 days is based on using the earphones 5 days a week for 5 years.*
3. *The E-module does not separate from the shell after a fall of 1.80 m (which is a requirement of Dopple)*

2. Environmental influences

1. *The product is rinsible (which is a requirement of Dopple);*
2. *The product can be cleaned by the user themselves (which is a requirement of Dopple).*

3. Maintenance

1. *The electric components can be separated from the shell (based on the right to Repair (ERPS, 2022);*
2. *The shell can be replaced (ERPS, 2022).*

4. Ease of acquiring

1. *The product can be obtained by the customer in the comfort of their home (see chapter 2.6).*

5. Size and weight

1. *The earphone must fit in the cradle (which is a requirement of Dopple);*
2. *The earphone must make contact with the charging pins in the cradle (which is a requirement of Dopple);*
3. *A minimum offset of 0.5 mm is added to the scan data (see chapter 6.4 : model evaluation);*
4. *The earphones have a maximal audio canal length of 6.5 mm (see chapter 6.4)*
5.

6. Aesthetics

1. *The earphones do not stick out of the ear more than 5 mm above the tragus point (Dopple, see chapter 3.6).*

7. Materials

1. *The earphones should comply with the Hazardous Substances Directive (RoHS/RoHS2) (2011/65/EU);*
2. *The earphones should comply with the General Product Safety Directive (2001/95/EC);*
3. *The materials should be biocompatible.*

8. Ergonomics

1. *The earphones distribute the pressure evenly over the concha (see chapter 2.5 Comfort);*
2. *It is clear to the user how the earphones should be positioned in the ears;*
3. *Difference between Left and Right is clear (to comply with cognitive ergonomics);*
4. *The orientation from the top and bottom of the product is clear;*
5. *After 5 use cycles, the user is able to place the product in the ear without complications.*

9. User requirements

1. *The earphones should still comply with the use case after 5 years of use (see chapter 3).*

10. Office worker

1. *Earphones cause no noticeable discomfort after 2 hours of consecutive wearing (see chapter 4.3);*
2. *The earbuds do not shift position during 20 minutes of walking. (see chapter 4.3).*

11. Dancer

1. *The earphone allows for a constant pressure within the hearing canal;*
2. *The earphone allows the user to dance for 30 minutes without the earphones losing their retention (falling out of the ear) (see chapter 4.3);*
3. *The earphones are sweat resistant (see chapter 4.3);*
4. *The earphones allow for control on device (see chapter 4.3).*

Programme of wishes

1. *The earphone is as comfortable for as long as possible.*
2. *The earphones look personalised.*
3. *The functionality/performance of the earphones is predictable.*
4. *The earphone stays in the ear of the user regardless of their movements.*
5. *The earphone is easy to clean by the users themselves.*
6. *The earphone can easily be inserted in the ear of the user.*

6. Model exploration: Design by doing

To develop concepts for semi-personalised earphones, there are some knowledge gaps which need to be filled. In this chapter, the questions on scan methods, material use and offset distance will be answered through a series of iterative steps with design by doing. Models will be tested, evaluated and redesigned in short cycles, each cycle improving and building on the learnings from the previous cycle.

As a first step, multiple scanning methods will be used to scan in-ears of participants. These scanning methods are evaluated on ease of use, adaptation to the intended use scenario, and precision (p. FIXME to FIXME). The ease of use will be evaluated during the scanning process as well as preparing the files for import in Rhinoceros. The adaptation to the use case is determined by the general availability of the scanning method. The precision of the scan methods are determined in the virtual environment using Rhinoceros and Grasshopper. The following research question gave guidance in evaluating the scanning methods:

- *What are the margins of error of the scanning methods?*

The virtual representation can only tell so much since the scans will not be a perfect representation of the actual ears and the landmarks can shift. This influences the alignment of the scan which makes it more difficult to evaluate the whole shape. For this reason, 3D prints of each of the methods will be made to evaluate the fit in the ear of the user (p. FIXME to FIXME). To validate the scan data, the data is adapted as little as possible. The following research questions gave guidance in evaluating the physical representations of the scans:

- *How do the models of the different scans fit physically in the ear?*
- *How are the models of the different scans experienced in the ear?*

After the exact scan data is evaluated, the next step will be to determine how to account for the loss in data of the scans. The surface of the scans will therefore be provided with an increasing overall offset of 0.25 mm. The offset will be increased over three steps. Each step for each scan will be evaluated over 30 minutes. The perceived pressure is evaluated at the start and end of each test. At the end of each test the retention is evaluated by wildly shaking the head. At the end of the evaluation, a scanning method will be chosen to continue to the next phases (p. FIXME to FIXME). The following research questions gave guidance in determining how to account for the loss in data of the scans:

- *Which offset feels most comfortable and least discomfortable?*
- *Which offset (in combination with scan method) provides enough retention?*
- *Which scanning method is best suited in the envisioned context?*

Different materials and manufacturing techniques have an influence on the performance and precision of the models. Several models are generated to validate their influence on the comfort and retention in the ear of the user (p. FIXME to FIXME). In these models, the importance of the audio canal cannot be neglected. Therefore, an audio canal is added based on information of the scan data and SSM. The following research questions gave guidance in evaluating the materials on (dis)comfort:

- *What is the effect of different materials on the comfort and discomfort in the ear?*
- *What is the effect of the audio canal on the placement of model in the ear?*

A final series of models will be produced based on the findings in the previous cycles (p. FIXME to FIXME). These models are meant to verify and validate final adjustments in the design. Different lengths of audio canals will be integrated into the models and tested. The overall shape of the concha will be smoothened, and a wrapping tool will be introduced which allow for homologous mesh, which allows the scans to be manipulated in a similar fashion. The following research questions gave guidance in evaluating the models:

- *Do the design changes improve the comfort of the models?*
- *What it the preferred audio length?*
- *What influence does the material have on the evaluation of the audio canal?*

6.1 Evaluation of the 3D scanning methods

For personalised products, it is essential to obtain the data of the user. Since the goal is to obtain information of a user without the presence of an expert, non-contact methods like 3D scanning could provide a valuable source of information on the shape of the human body (Mikalai et al., 2022).
In general, scanners that provide a higher resolution, capture scans with more details. This means that smaller distinctions are shown that are unique to that customer. The level of detail in the scans should be taken into account when designing.
The following sections will discuss different methods and results of the data collection of the users. The first three scan techniques use data that are provided by (specific) smartphones AudioEar (Huang et al., 2023), Lidar and Truedepth. The final scan technique uses a separate handheld scanner. While the Revopoint scanner uses the same technique as industrial scanners (blue structured light), it is still a relatively low-end scanner which is fit for domestic use.
The different scan techniques will be rated on their quality and ease of use. By measuring at how precise four landmarks are recorded in relation to the mould scan of the ear, it is possible to get some idea of the margin of error of the scan. Furthermore, the scan data is placed on top of the mould scan in Rhinoceros to evaluate the overall shape.

To determine whether the scan is sufficient to create models, the crux of the helix, the tragus and the anti-tragus amongst other areas should be well represented in the scan. The ease of use will mainly be evaluated by how easy it is to scan the ear and how easy it is to use the output.

6.1.1. Lidar

Lidar is an acronym for the words Light Detection and Ranging. The scanner calculates the distance to an object using the "time of flight" method, which measuring with amount of time it takes for a particle to travel (Mikalai et al., 2022; Vogt et al., 2021). In this case, the lidar scanner emits pulses and measures how much time it takes for the pulse to be reflected to the sensor. This scan technology is owned and patented by Apple and is integrated in the back facing cameras of the iPhone 12 Pro and newer models, as well as on the iPad pro models since 2020. In this study, the participants were recorded using an iPad pro.

Figure 50: Scan with LIDAR

Results
The results of the Lidar scan cannot be used for the realization of customised earphones. Almost none of the details of the concha were recorded, as can be seen in figure 50. Therefore, the scans were not considered for model making and testing. This outcome was expected due to the study of Vogt et al (2021). In this study, the accuracy of the Lidar scanner was evaluated by scanning a brick of Lego, and it was concluded that, Lidar is not suitable for scanning small objects. Ears have a small and intricate shape and are therefore not suited to be scanned with the Lidar scanner.

6.1.2. AudioEar

Figure 51: Model generated by AudioEar

AudioEar is initially set up to research the effect of individual auricle shapes on the perception of sound, which could be used in the gaming industry to create a personalised immersive special audio experience. AI software generates a digital representation of the ear based on a single front facing image of the ear, by comparing it to a database of 3D and 2D ears (Huang et al., 2023)

Results
Compared to the other scan techniques, only the depth of the concha has a comparable distance (although still off by more than 1 mm). In the other dimensions, the model is much smaller and hardly accounts for the undercut geometry of the ears. Therefore, the results of AudioEar are not yet sufficiently detailed enough. The scans are missing critical landmark geometry for placing landmark points (see figure 51). On of the major losses of data is the absence of information on the crux of helix structure. Therefore, the models that were made using this technique provided very low levels of retention or even fell out of the ears with left to right head shake movements.

6.1.3. Revopoint

Figure 52: Model generated by Revopoint

The Revopoint scanner is a small portable scanning device, which projects a grid of blue lines at the object. This technique is called structured light and is also used in industrial scanners, which are used for inspection and reverse engineering. The angular width of the light, which is fixed, is used to triangulate the distance of reflected points picked up by the sensor (Vogt et al., 2021). The blue colour of the light helps the sensor to distinguishing between the light of the projector and the light of the environment. The sensor takes measurements at roughly 16 frames per second.

Resuls

The scanner was able to detect the ear shape accurately (see figure 52). By angling the scanner in multiple positions, parts of the undercuts under the anti-helix and antitragus could be mapped. As expected, the scan has more difficulties with mapping the cymba concha under the anti-helix and the entrance of the auditory canal, especially under the tragus. Other details such as the crux of the helix were clearly mapped in the scans.

6.1.4. Truedepth

The TrueDepth scanners are integrated in the front facing camera of Apple Pro products made after 2020 and iPhones after iPhone X. The scan is mainly used for facial recognition to unlock the product. It uses Vertical-cavity surface-emitting laser (VCSEL) technology to do so. It projects around 30.000 infrared Dots, which are reflected on the face of the user (or another surface). The reflection pattern is recorded by an infrared camera and analysed using a depth map algorithm.

Results

The results of the TrueDepth scanner is able to capture a lot of the details of the landmarks and therefore delivers well defined results of the different geometries of the ear (see figure 53). The scanner is comparable with the results of the Revopoint scanner which uses the structured light method. The models did have some inaccuracies when compared to the mould scans. The scans had a deviation between the 0.5 mm and 2 mm, representing the ear smaller than the actual ears. This was also what the study of Lego bricks concluded. The scanner had greater inaccuracy on rounded and cylindrical surfaces, which had an average deviation of 1.17 mm with roundness (Vogt et al., 2021). The study revealed that the Truedepth scanner was not able to scan black surfaces. Therefore, extra tests should be conducted to see the effectiveness of the scan on black or darker skinned individuals.

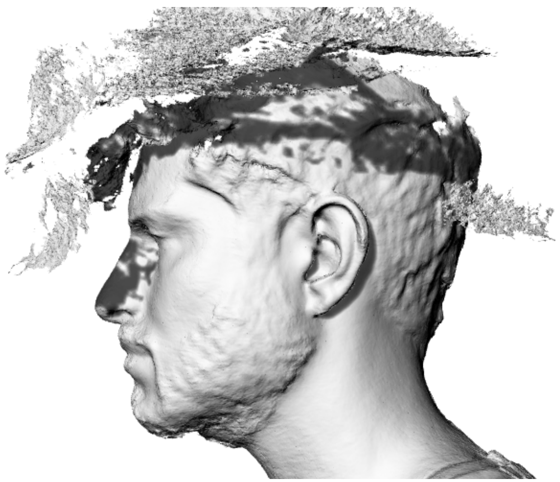


Figure 53: scan with Truedepth

6.1.5. Methods of comparing

Before the scan data could be compared with each other, noise and holes in the scans need to be removed (see figure 53). Since only the concha information is relevant for the project, all the scan information outside the concha was removed, leaving a rough margin on the anti-helix, anti-tragus and the tragus. In the case of the Revopoint scanner, some extra attention is required to remove unwanted noise of the scanner which was generated around the auditory entrance. The suspected cause of this clutter is the width of the light emitters to the sensor in the middle. Especially when trying to scan the auditory canal and the cymba concha, one of the two emitters was not able to reach the intended location, making it hard for the software to keep track. The TrueDepth scan uses a single emitter, making it easier to direct at certain geometries of the ear without the software losing track.

To evaluate the accuracy of the scan technique, each of the scanning techniques are compared to a digital representation of an ear mould. To evaluate each of the scans in the same manner, four landmarks are placed on each of the scans (see figure 54).

1. *Superior cymba cavum*
2. *Intertragic incesure*
3. *Tragus*
4. *Anti*

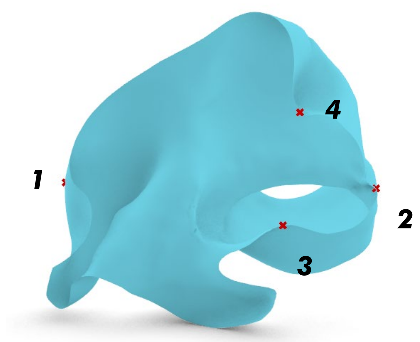


Figure 54:** **Landmarks for evaluation and orientation of the scans

The direction between point 1 and 2 represent the x-axis of the model, while direction vector between point 3 and 4 orients in z-axis (see figure 54). The tragus (3) is taken as the origin in all scans since it is the most prominent landmarks in each of the scans.

By determining the origin and orientation of each of the scans, the distance between each of the landmarks of the scans and the landmarks of the mould can be evaluated.

The measurements of two participants were compared with the scan data of AudioEar, Truedepth and the Revopoint scanner.

Participant	Landmarks name	Localisation error of the concerned landmarks in the scan methods underneath		
		Revopoint	Truedepth	AudioEar
P1 – Left ear	Anti-tragus	6.35 mm	2.10 mm	8.32 mm
	Incesure intertragica	3.14 mm	2.08 mm	5.36 mm
	Superior cymba concha	0.93 mm	0.53 mm	0.70 mm
	Average	3.47 mm	1.57 mm	4.79 mm
P1 – Right ear	Anti-tragus	1.40 mm	3.01 mm	3.65 mm
	Incesure intertragica	2.15 mm	2.00 mm	5.26 mm
	Superior cymba concha	1.40 mm	2.31 mm	3.01 mm
	Average	1.65 mm	2.44 mm	3.97 mm
Average of both ears		2.56 mm	2.00 mm	4.38 mm

Table 4: landmark deviation of the scan data compared to the land marks of an ear mold.

6.1.6. Conclusion

Overall, the ear shapes produced by the scans were smaller than the actual ears. Of the measurements the Truedepth scanner has the lowest average overall deviation error of 2.00 mm (see table 4). The Revopoint scanner comes in second place with a total average of 2.56 mm, however for the right ear of participant 1 the average recorded distance was smaller than the Truedepth scanner. The 3D model generated by AudioEar has the largest scores in both measurement. Since the total average measurements of AudioEar amounts to 4.38 mm, which is almost double the value of the other two scanning methods, there is likely a lot more room between the ear and the printed models.

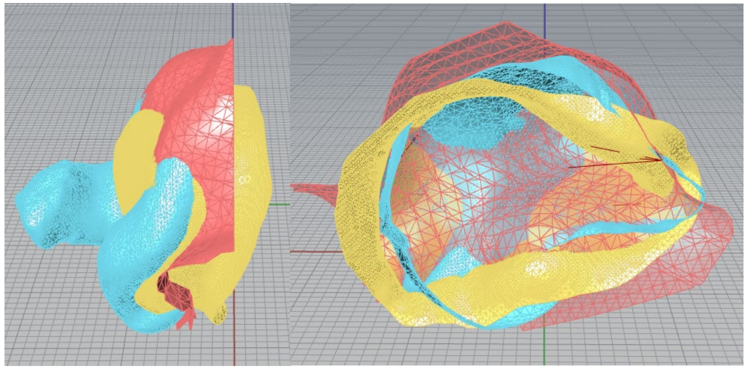


Figure 55: Deviation of the shapes between the different scan techniques and the mould data in blue

6.1.7. Discussion

The measurements offer a global representation of the margin of error of the scans, but cannot be relied upon for exact measurements. Although the scans are aligned in the same manner as the ear mould, the landmarks are generally less clear in the scans. When the landmarks shift position, it influences the entire alignment and orientation of the scan and therefore the measurements in relation to the ear mould.

To determine the average precision of the scanning techniques with a higher accuracy, a large subset of participants is required. These participants should preferably already be in the database of Dopple or have moulds taken of their ears as well as scans using the three previously mentioned scanning methods. Therefore, the distances between the landmarks on the mould representation and scan data can be collected and an average distance can be calculated in coordinates (of x,y,z) rather than exact lengths.

Another scan technique is photogrammetry. This scanning method relies on computing multiple images from different angles to form a 3D model. Therefore, the advantage would be that the method can be used by any smartphone. However, as can be seen in the images in figure 56, the scans are not very accurate and miss crucial details when it comes to the entrance of the auditory canal, crux of the helix and even depth of the concha. Therefore, I decided not to consider this method for further research. However, if this technique can be used in combination with AI such as AudioEar, it could be interesting to re-evaluate this method again for the potential of widespread application.

Figure 56: Example of photogrammetry

6.2 Evaluation of the physical representations of the scans

To evaluate the scans, physical models of each scan method are created based on the 3D scan data of each of the three determined techniques (Revopoint, Truedepth and AudioEar). This evaluation is necessary to see how the models will behave when placed in an actual use environment. In its virtual environment, the models are aligned on the tragus. In reality, the models will fall to the lowest point in the concha due to gravity. The shape of the ear can also push the model into a different orientation, which causes either more discomfort or comfort.

Simultaneously, the models are printed with a surface offset (in all directions), in three steps of 0.25 mm. The offsets that are generated account for the missing and/or smaller scan data, and to find a more optimal fit for the ear.

6.2.1. Method

The models were validated using a perceived pressure map of the ear. The duration of the test was 30 minutes per model. The models were worn from smallest (0.00 mm offset) to largest (0.75 mm offset). The order of the offsets is important to minimize the effect of the previous measurements. The perceived pressure was indicated at the start of the test, as well as at the end. Therefore, it shows the changes in the perceived pressure over time. The scale of the map ranges from slightly noticeable pressure (1: purple) to high levels of discomfort / pain (7 : red).

The models are printed on the same SLA resin printer. The SLA printer uses a mask projection to irradiate the whole layer at once. SLA printing is known for its high level of precision (Gibson et al., 2021).

6.2.2. Results

When comparing the pressure of the same offset over time, the perceived pressure is often larger than indicated at the start of the tests (see appendix E.1). The same can be concluded for increasing the in size of the models of the Revopoint and Truedepth scanners. The models with an offset of 0.75 mm increased the number of perceived touchpoints (mainly in the Cymba concha). In the Revopoint model, this caused slight discomfort near the Superior Cymba Concha. Since all the models generated by AudioEar where much smaller, the models would rest at the bottom of the ear behind the tragus and anti-tragus. The models did not show much difference between the 0.25 and 0.5 offset. At an offset of 0.75 mm the model was large enough to be able to be supported above the anti-tragus as well. However, the main support remained at the bottom of the ear.
When testing the models on their retention through a shake test, all models made by Revopoint and Truedepth remained in the ear. However, with the decrease in offset, it felt more likely that the models would fall out during the test. This feeling increased the sensation of discomfort. The 0.00 and 0.5 mm AudioEar models fell out of the ears during the shake test. Only the 0.75 mm remained but also did not feel secure (see figure 57 & 58).

6.2.3. Conclusion

The models with zero offset did not have enough touch points within the ear and are therefore placing all their weight at the bottom of the concha, which was indicated on the ear maps. (see appendix E.1).

Revopoint and Truedepth were the best methods to scan the ear. Both scanning techniques capture enough detail of the users' shape to be used as data for semi-personalised earphones. Between the two techniques, the Revopoint delivered more accurate results of the overall shape. The reason for this is that in some parts the size and the geometry of undercuts was recorded more precisely. However, when comparing only the four given landmarks, the Truedepth scans comes closer to the scan data of the mould.

The model with an offset of 0.5 mm was preferred over the others. The model with an offset of 0.25 mm did not fall out of the concha, but it was able to move around. The model with an offset of 0.75 mm on the other hand was slightly too big, pushing against the top part of the anti-helix structure. Although this provided extra retention in the ear, the pressure also caused more discomfort as can be seen in the pressure map (see figure : FIXME).
The Truedepth scans provides a cleaner result than Revopoint. Therefore, the scan just needs to be cropped to the size of the concha. As the Truedepth scanner was less time and energy intensive, it was easier to implement the scan into the Grasshopper workflow.

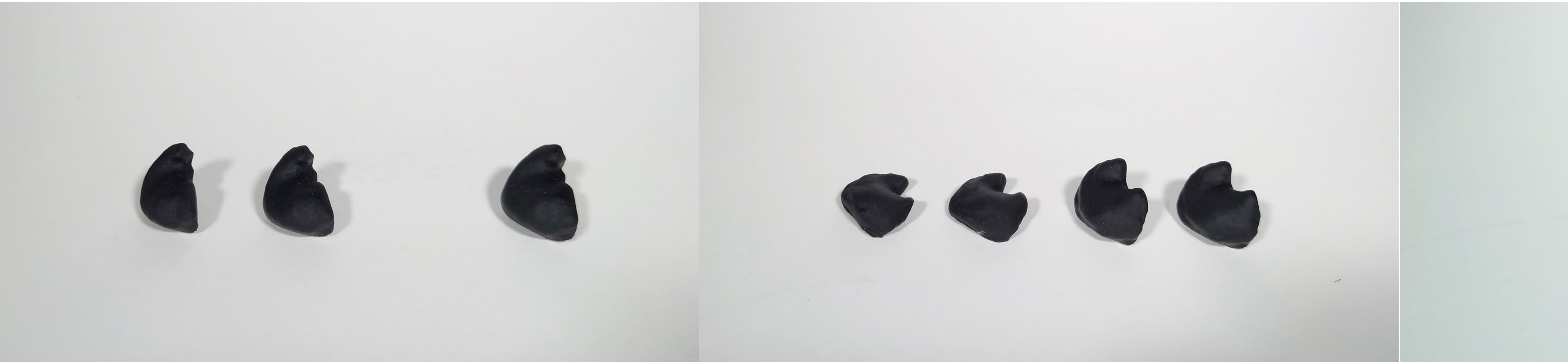
For the intended use case in which the customer can use the scanner by themselves in the comfort of their own home, AudioEar would provide the easiest solution (see table 5). However, when other phone brands, besides apple, will start to adapt 3D scanners into their products. Scanning the ear with a smartphone is also an easy method to obtain the personal data.

In conclusion, the Truedepth scanner will be used for further testing. It provides a sufficient level of details for personalised products and users can scan their ears remotely without the help of an expert (which aligns with the project brief).

	Ease of use	Intended use case (see Chapter 2.2.2)	Precision
Revopoint	The handheld scanner needed to be connected to a laptop, which restricted the movement. Making scanning difficult. The scan output shows a lot of noise and holes in the data. The data therefor needs to undergo cleaning before it can be used.	This method of scanning is the least accessible since users need to have access to a handheld scanner. Although, scanners can be bought commercially it is not expected that a lot of customers have access to one in their homes.	The evaluation of the data in CAD shows that the average Localisation error of the landmarks is 2.56 mm. The model stayed in the ear of the user and was comparable to the results of the Truedepth scanner.
Truedepth	The method requires the users to scan the ears using the selfie camera (of iPhones after model X). The scan output is a clean mesh of the head. The concha has to be cut out of the mesh.	Although the scans can still be taken by the users themselves using a software on the smartphone. The hardware is currently only integrated in iPhone models after iPhone X.	The evaluation of the data in CAD shows that the average localisation error of the landmarks is 2.00 mm. The model was rated the best among the three methods.
AudioEar	Easiest to use, only a frontal picture is required as input. For preparation a mask of the picture needs to be made. Once the mask is done, the software outputs a clean audio file of the ear. The concha still needs to be cut out.	The technology to take a picture is available to everyone who owns a smart phone. Therefore, the technology is easily available for gathering scan data at home by the users themselves.	The evaluation of the data in CAD shows that the average localisation error of the landmarks is 4.38 mm. The model was rated the worst among the three since it was too small, which caused it to fall out of the ear of the participant.

Table 5: Scan method comparison table

Figure 57: Overview of physical models of the scan methods



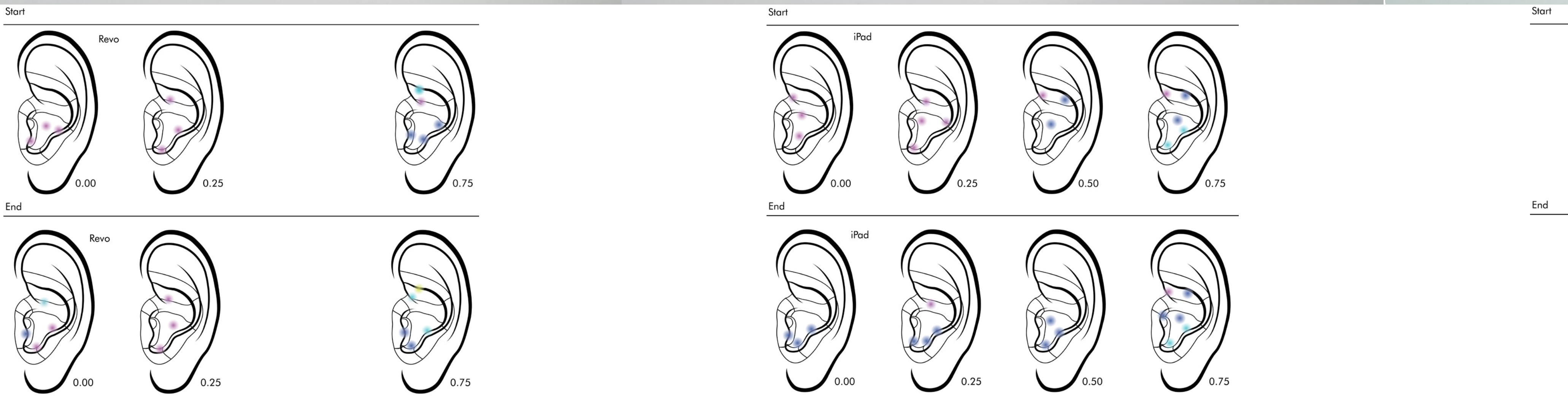
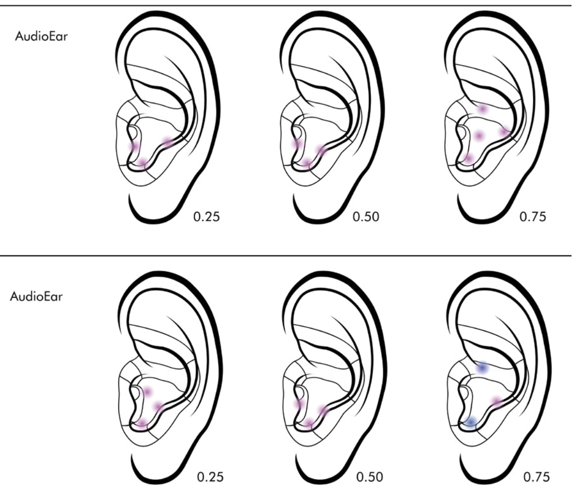


Figure 58: Corresponding heatmaps to the offsets



6.2.4. Discussion

Unfortunately, it was not possible to test the model with an offset of 0.5 mm of the Revopointer and the 0.00 offset of the AudioEar model due to malfunctions in the Grasshopper script. However, the evaluation of the 0.25 model and the 0.75 model indicated that an offset in between would be a better fit. This can be seen in the pictures and on the pressure map as well (see figure 57 - Left).

The 0.75 model has more touchpoints spread across the ear, but the initial pressures are much higher than the pressure points noticed in the 0.25 model (see figure 58 - Right). Over time, the pressure points will become more agitated and the perceived pressure will be much higher (see figure 58).

The drawback of relying on Truedepth is that this technology is currently only available in the latest Apple products. Therefore, the feasibility of using this scan technique depends on whether other brands will adapt similar scanning technology in the future.

Although the results of AudioEar software were still inadequate at this time, the envisioned use and ease of use of the method are better adapted for the envisioned use case, in which customers can easily upload a file online which will generate a product. When improvements are made to the algorithm that provides more precise end results, the method should be reevaluated. Improvements could for consist of relying on multiple images or a video of the ear instead of just one image.

6.3. Materials & Production

In the following section, relevant AM production techniques for wireless earphones are highlighted. Since the earphones are relatively small products and need to fit perfectly to a complex body part (and form a seal), the technique should be able to produce the parts precisely and smoothly enough, since it will dissipate the forces more evenly over the skin. Another requirement for the product is that it should be as light as possible. Therefore, the material should add as little extra weight as possible.

In the tests, multiple materials with different flexibility are tested. The material is rated by their shore hardness which refers to the resistance of a material to indentation.

One of the limitations of testing is the availability of AM techniques. The available techniques are SLA, MJ and FDM printing.

Other promising techniques could be considered as well to further optimise the design of the earbuds in the future. For example, shape changing materials and other types of printing methods.

6.3.1. MPVPP

One of the earliest methods for AM is SLA. SLA is a process that uses radiation in the form of UV light to harden a liquid polymer (resin). This process is called Photopolymerization. Since the liquid polymers are stored in a container in the printer, the process is also called Vat Photopolymerization (VPP). The two main characteristics of VPP technology are the surface finish and its high accuracy.

The printer used for the models at Dopple is a Mask Projection VPP (MPVPP) technique. This means that polymers are exposed to a whole cross section of the print at the same time instead of exposed by a laser. Although this makes the print somewhat less precise, it speeds up the printing time tremendously. This is especially desirable when multiple prints need to be printed at the same time. While the laser requires to trace each model individually, MPVPP cures all the prints on the same layer at the same time. This makes the limiting factor for speed of MPVPP the height of the highest print, rather than the size of the prints.

Results

All the initial models of the different scan techniques are printed using the SLA printer (see figure 59). This provided high resolution models of the ear which were required to evaluate the direct output of the scan data. Therefore, it takes small bumps and defects into account. Compared to FDM prints where the layers are clearly visible (even with fine print settings), the layers of the SLA prints are much smaller providing a smooth surface without necessary post processing.

Figure 59: SLA model in its mould

Figure 60: SLA model in the ear

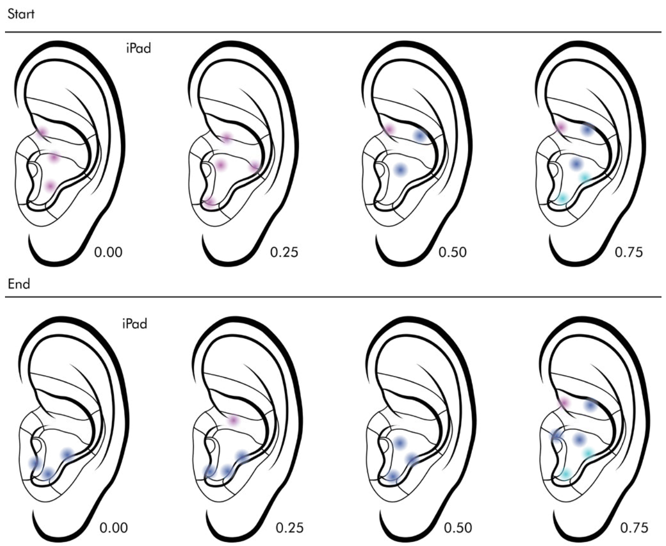


Figure 61: Heatmap of the SLA model

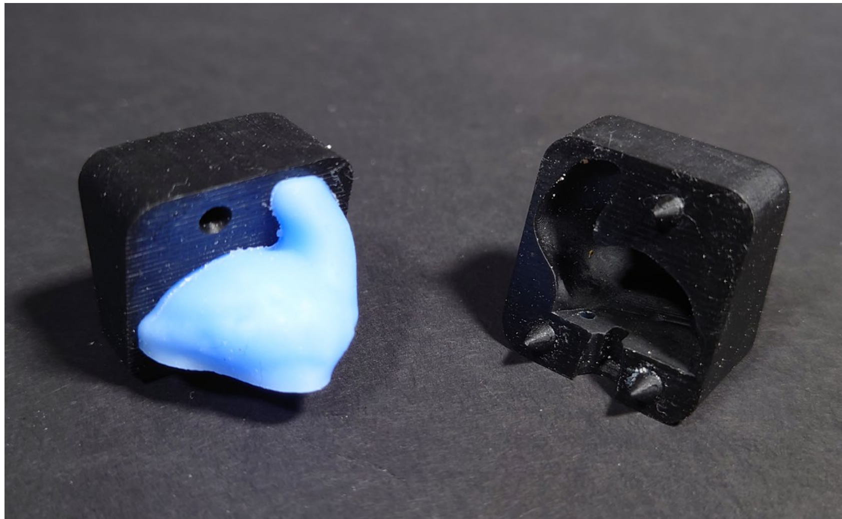
6.3.2. Silicone moulding

The prototype mould is made using an SLA printer. For the first model, the prototype was based on the iPad scan with the integrated SSM of the auditory canal. In the MJ printer, this shape felt increasingly more uncomfortable along with the increase in shore hardness (highest of 80) (see figure 66: blue model). The lowest shore in which the MJ printer is able to print, is shore 30. The shore hardness tested with the silicone pouring method delivered a result of shore 15 which is more flexible than the MJ print.

Result

The softness of the silicone meant that the model is very flexible and is more forgiving on both flaws of the scan technique as well as the estimated placement of the auditory canal on the scan (see figure 63). Therefore, the overall pressure of the model does not increase much once it is placed in the correct position. However, due to the same flexibility of the material, it is very difficult to place the model in the correct position within the ear.

Figure 62: Silicone model in its mould



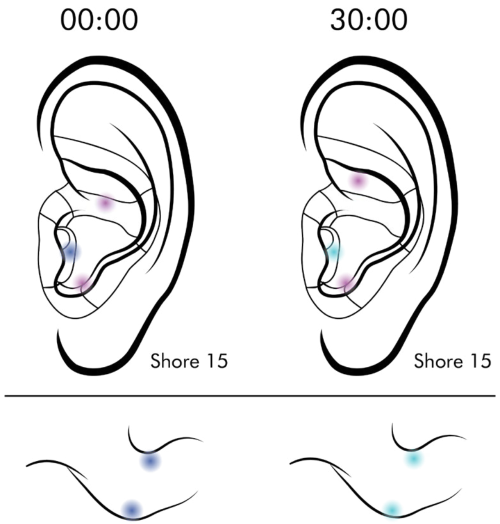


Figure 63: Heatmap of the silicone model

Figure 64: Silicone model in the ear

6.3.3. Material jetting

By using material jetting (MJ), small droplets are dropped in rapid succession, forming a continuous line of material. For polymers, the droplets can consist of molten material like wax which solidify when cooling down or liquid monomers which are hardened using UV light. One of the advantages of MJ is that multiple nozzles can be placed in a sequence. This does not only allow for faster printing but also printing with different materials (Gibson et al., 2021). Therefore, this technique makes it possible to control the material properties of very specific parts of the design which makes it possible to make parts of the design flexible. For the models, a Stratasys machine is used which prints acrylic based photopolymers. Each layer is cured while printing and the supports are built in a gel-like material (SUP705), which can be removed by hand (Kerstenetzky, 2022).

Results

Four different shores were tested in the model. Compared to poured silicone models (of shore 15), the material is quite slow to react and recoil to their original shape. The highest shore chosen is 80, which is almost solid and allows for little indentation. When increasing the stiffness of the audio canal, the shape plays an increasingly important role. It does not only put more pressure on the walls of the auditory canal, but it is also less forgiving on following the shape of the auditory canal and will therefore put pressure on the rest of the ear (see figure 67).

Figure 66: MJ model in its mould

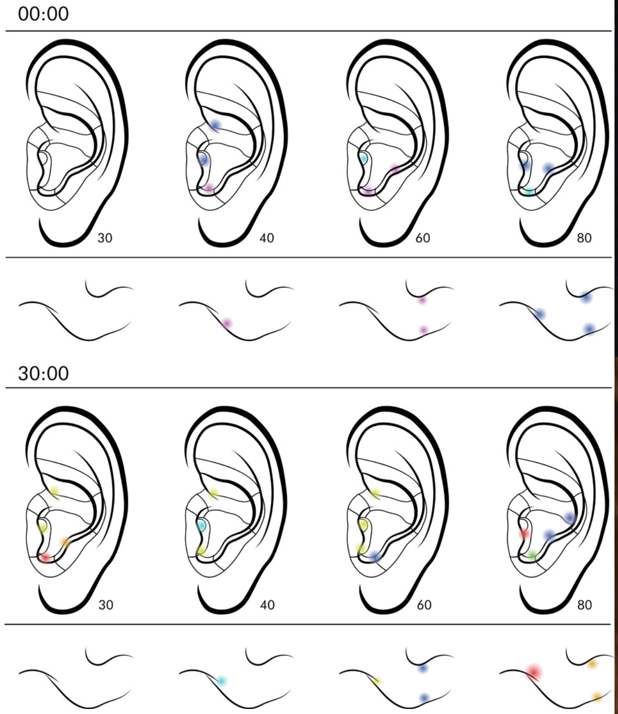


Figure 67: Heatmap of the MJ model

Figure 65: MJ model in the ear.

6.3.4. Fused Deposition Modeling

Fused deposition modelling is a widely used 3D printing technique and it is often used in rapid prototyping. A spool of filament is heated and liquified in a nozzle and pushed to form a small layer of material on a heated ground plate. For each layer, the hot nozzle is moved up slightly and passes over the previous layer again. This melts part of the layer below, making it possible for the new layer to merge with the layer below to form a solid material upon cooling down. The technique is relatively cheap in relation to investment cost for machines and material. Furthermore, the filament does not require any special treatment for storing and offers a wide range of different materials, making it very accessible. The prints often need to build up extra support structures (when an angle is larger than 45 degrees), since the models cannot lean on anything else. The defects that are caused by this can often be seen in the final prints. The downside of FDM is that the technique does not offer a high accuracy, build speed and material density (Gibson et al., 2021). Parts often experience shrinkage due to evaporation in the material, making the dimensions less reliable.

Results

The stacked layers of the prints increase the surface area of the model. This makes the surface finish of the model feel rough to the skin. Another unavoidable characteristic of this additive manufacturing technique is that, at the start and end point of each layer, a little bit of extra material is accumulated, also known as a seam. The seams in the model cause a localised pressure point which is uncomfortable (see figure 68). Seams can be removed in post processing, but this can be a very labour-intensive process in organic shapes.

Figure 69: FDM model with a offset 0.25 mm in the ear

Figure 70: FDM model with a offset 0.5 mm in the ear

Figure 71: FDM model with a offset 0.75 mm in the ear

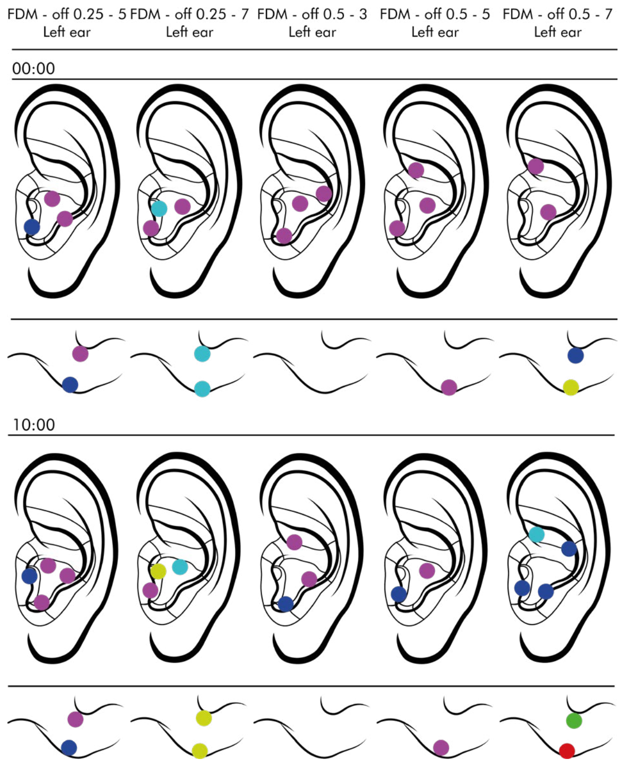


Figure 68: Heatmap of the FDM model

6.3.5. Emerging technologies

The production methods and materials described in the previous chapter have been tested and validated for commercial purposes in other products and are therefore safer to use. It is for instance easier to produce proof that the materials are not harmful to the skin over long-term use. The technologies described in the following text are still new and sometimes experimental. It is therefore still uncertain what the possibilities are. However, when the techniques mature, they could provide new opportunities to further improve the design.

Rapid liquid printing

Rapid Liquid Printing is a technique that uses a robotic arm to build up its shape layer by layer, by exerting a liquid material out of a needle-like nozzle (see figure 72). The technique does not require any support since the liquid is exerted into a tank with a gel suspension (self-assembly lab, n.d.), which provides the design with support from all sides. After curing, the design is airtight and can be used in applications such as soft robotics. With pneumatic controls, the printed structure can be transformed into various shapes and fulfil multiple functions, such as localised support or gripping objects. This technique could therefore make it possible to print airtight inflatable structures. This could make it possible to design a pneumatically controlled earphone, that lets it user set the preferred retention.

Shape morphing materials

There are multiple categories of shape morphing materials. There are materials that change shape because of temperature, magnetism or even radiation. The materials can exist as polymers or alloys.

Magnetically shape changing materials can be divided into two groups: Magnetic Shape Memory Polymers (MSMP) and Magnetic Soft Materials (MSM). The difference between MSM and MSMP is that the changes in MSM's are reversible. Therefore, the shape can be changed back and forth depending on the conditions of its environment. The materials in which the particles are distributed are soft. This allows the reversible shape change. The softness of the material also allows the particles to react quick (< 1 s) to the magnetic field. The particles meet little resistance, when rearranging themselves in the material.

In the case of MSMP, the transition is only in one way. In MSM, magnetic particles are activated, which case the material to change its shape. The particles can move multiple times due to the softness of the material. The resins of MSMP's are

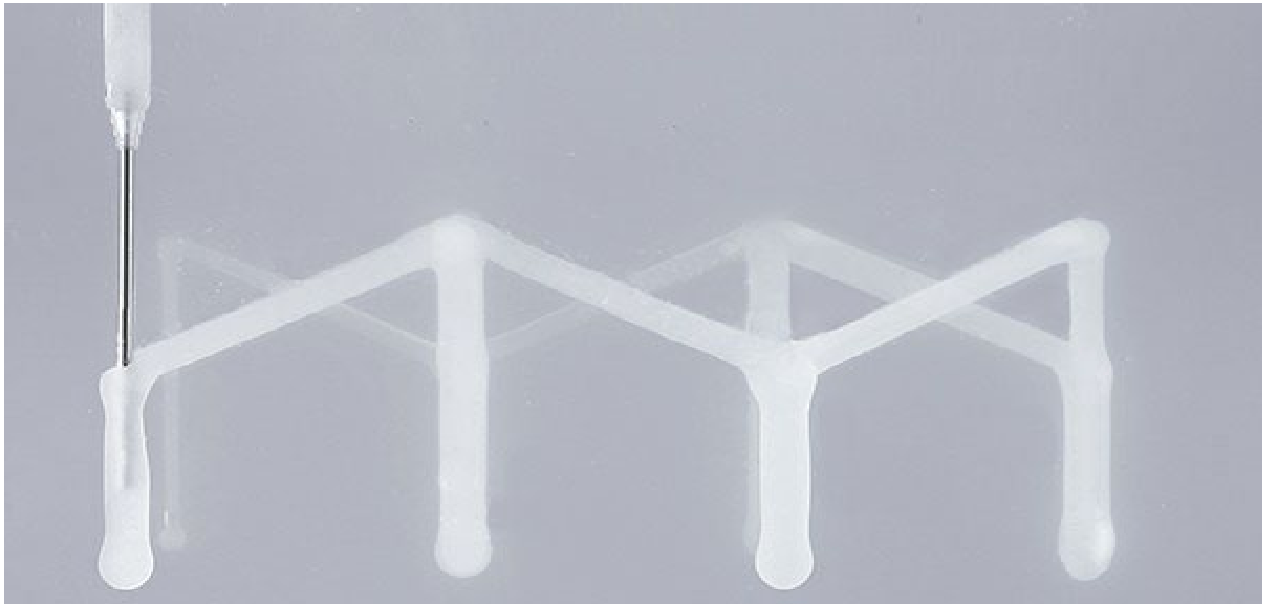


Figure 72: Example of rapid liquid printing (self-assembly lab, n.d.)

stiffer since the changing material is a polymer, which makes it harder to move. The response time is usually around 10 s. However, MSMP's can obtain stiffer properties than MSM (van Vilsteren et al., 2021). The particles can create micro torque within the material when an external magnetic field is applied, forcing the elastomer to change its shape.

Unfortunately, MSM and MSMP materials are still being research. especially for MSM (van Vilsteren et al., 2021). Therefore, it is hard to determine after how many expansions cycles the material will start to deteriorate. Even though there is a lot of potential in the material for medical purposes, long-term effects on skin exposure have yet to be determined. Even though the material shows potential for the field of semi-personalised wearables, the viability of the material is still doubtful due to its newness and complexity of the material.

In recent years, more research has been conducted into the use of different materials, such conductive metals and inks with magnetic particles. By magnetising these particles, it is possible to create flexible material properties which can be steered by magnetic fields (van Vilsteren et al., 2021).

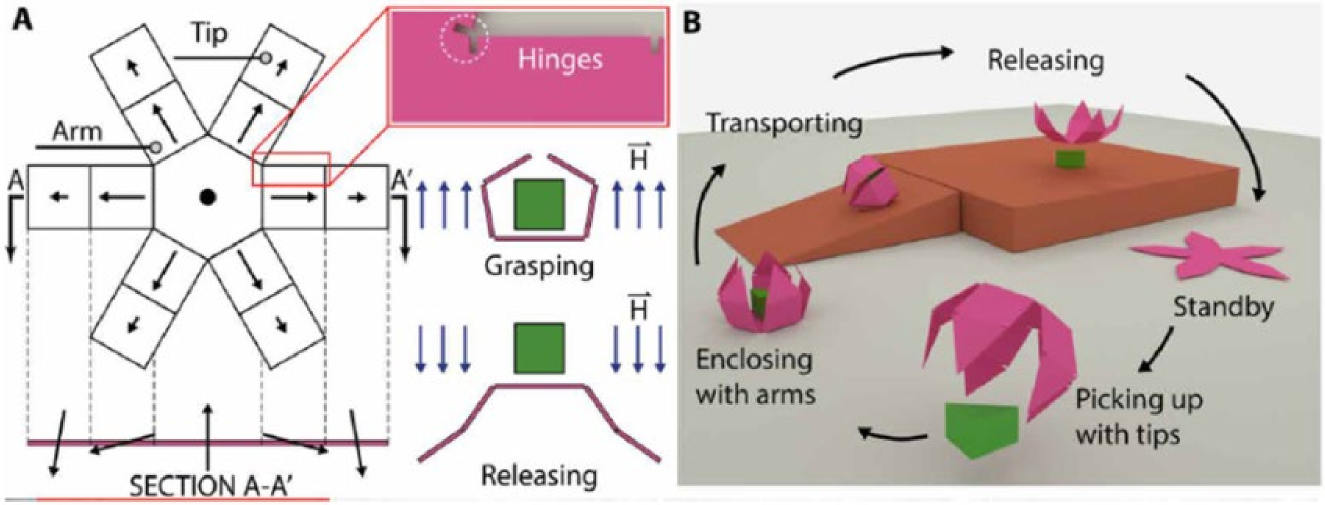


Figure 73: Example of MSM mechanism (van Vilsteren et al., 2021)

Figure 74: Overview of the models

6.3.6. Conclusions

The perceived pressure maps of the MJ printed models, show that a lower shore hardness is preferred compared to a solid auditory canal. The reason for this is the uncertainty of the placement of the audio canal on the model. To relieve as much pressure as possible from the auditory canal, the audio canal should either be very short or be able to bend to the shape of the ear.

On the other hand, when the material is too soft, it becomes more difficult to place the model in the ear as the material will try to take the easiest way, which is not always in line with the intended orientation of in the auditory canal.

Unfortunately shape morphing materials are not yet developed far enough. Therefore, it is not possible what the long-term effects of the materials will be in contact to human skin. The direction is therefore, not in accordance with the stated requirements for this project. However, as time progresses and more research has been done, these materials might offer good alternate solutions.

The print resolution of the manufacturing technique needs to be high to make sure that there are no visible printing layers in the model. This will give the model a smooth feeling and make it more pleasant to wear.

6.4 Model optimisation

Based on the insights of the models through the previous design explorations, the model is optimised by smoothing, freeing the crux of the helix, the audio canal and wrapping.

6.4.1. Smoothing

By evaluating the models, it became clear that the dimensions of the scans were smaller than reality. To provide a more retention, the offset of the models were increased. This also enlarged other imperfections (such as bumps) in the scans which caused localised pressure points on the ear. By increasing the size of the model, the pressure increases as well, and thus increasing the discomfort levels. A smoothing function in the CAD software is implemented to decrease the size and sharpness of the bumps. The disadvantage of smoothing the shape is that the shape of the model shrinks. To counter the shrinkage, the offset is recalibrated and re-evaluated in the new models.

Figure 76: Concept of depressurizing the crux of the helix

6.4.2. Crux of helix intact

During the evaluation of the initial models, it became clear that a slight offset is needed due to the inaccuracy of the scans. When offsetting the mesh, the mesh will expand in every direction, effectively making the crux of the helix structure smaller in the model. This puts more pressure on the top part of this structure (see figure 76), making it less comfortable especially with longer time of wear. To make sure the crux of the helix is not or less compressed, a sweep cut with the width and depth based on the original scan data is made. This cuts out a part of the offset surface, returning the crux of the helix to original measurements of the scan data (see figure 75).

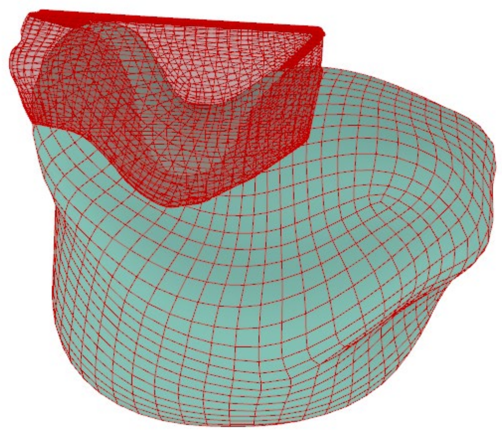


Figure 75: Red subtraction region of the Crux of the helix

6.4.2. Auditory canal

The scan techniques are only able to scan the visible surfaces of the ear. Therefore, there is little to no information available for the auditory canal. Only the entrance of the auditory canal can often be estimated. However, this is not enough information for guessing the rest of the shape and length of the auditory canal itself as can be concluded from the measurements of the database. The reason why the auditory entrance can only be estimated is the lack of information available in the scan data. The problem mainly occurs at the back of the tragus region, where the scanners are unable to reach and detect the surface. The initial model was tested by placing the auditory canal from the SSM on the scan data.

In the previous tests with the MJ models that consisted of flexible material, the softer models were rated as less uncomfortable than the more rigid models. However, the overall experience for the test subject (myself) was not very pleasant due to the difference in size and shape of the auditory canal, which is much narrower than the dimensions of the SSM when comparing the two auditory canals in CAD.

The SSM of the auditory canal reaches up to the second bend. After discussing with experts from Dopple, it was decided to focus on sealing at the entrance of the auditory canal as this is shown in the scan data. Since the rest of the auditory canal is an estimation with lots of variables, the length of the audio canal (part of the model which will be inserted in the auditory canal) will be decreased. An estimation of the length was done using a variable length of 3.5 mm, 6.5 mm and 8.5 mm calculated from the entrance. This test will evaluate the suitable length for the audio canal.

The tests were conducted with both hard material and multi material printing. The hard material (SLA and FDM) was mainly used to see the influence of the placement of the audio canal with relation to the orientation of the whole model within the ear. The length between the intertragic incesure and the superior cavum concha does not only provide information on the location and the direction of the auditory canal. The length between the two landmarks can be used as input for the shape of the audio canal.

6.4.3. Wrapping

Each of the scans were first reduced to the concha area in the 3D modelling software MeshLab. The scan data contains holes at locations where the scanner was unable to scan. In MeshLab it is possible to close holes in the mesh surface. MeshLab closes the holes using a surface reconstruction algorithm. The technique used in the first scan models to reconstruct the surface is the Poisson reconstruction method, which used the point cloud of the mesh as boundary constraints and interpolates these points to fit a new surface over the existing mesh. However, the reconstruction of the surface smoothens the scans, rounding the geometry of the holes (see figure 77).

As a new method to obtain a higher precision in the parts where data is missing, a wrap can be used (see figure 78). The wrap consists of a SSM of the ear that is deformed to fit over the scan data. This fills in the gaps more realistically in relation to the Poisson reconstruction method. Another advantage of using the wrapping method is that the number of vertices/points are the same for each individual scan. This means that every point of the point cloud is roughly in the same area in each scan. Therefore, a fixed index number can be called as a starting point for finding the average direction vector in the area, instead of projecting a floating point onto the mesh (see figure 24).

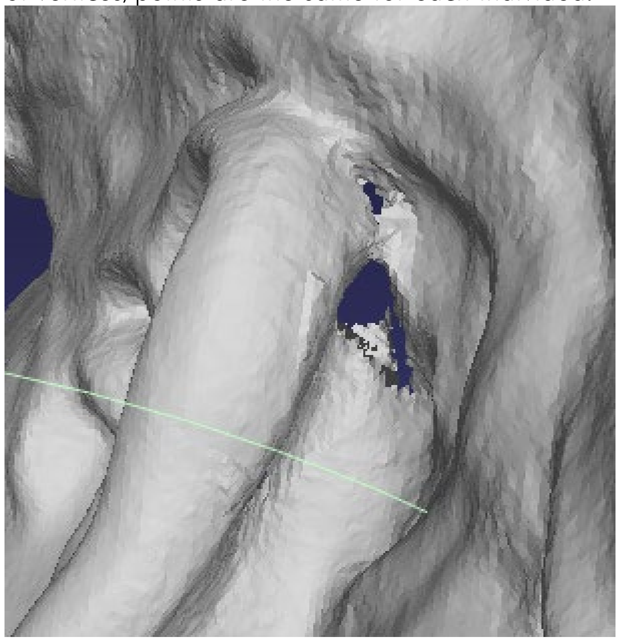


Figure 77: Example of holes in the Truedeth scan data

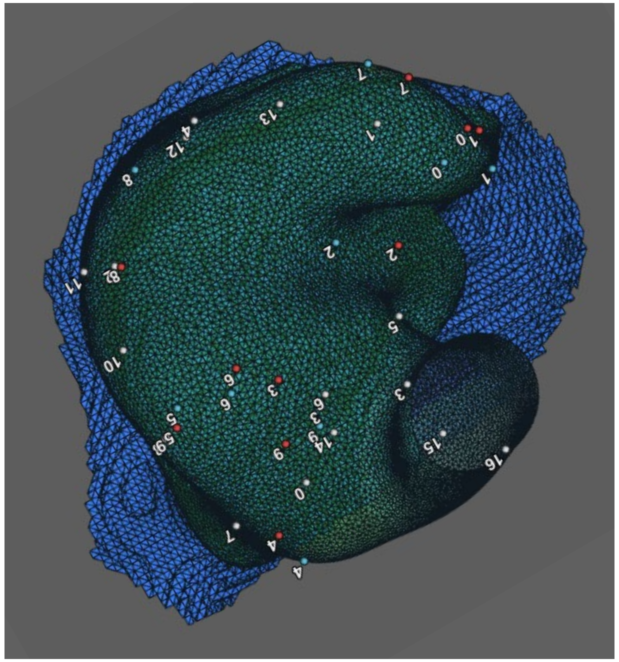


Figure 78: Example of the function of the wrapping tool

6.5. Model evaluation

The optimised models for SLA, MJ and FDM are evaluated with three participants. Based on the evaluation, conclusions can be drawn for the model on comfort, discomfort and retention for material, overall offset and the audio canal.

6.5.1. Method

To evaluate the improved version of the models, multiple printing techniques were used to compare and evaluate what the differences are between the material, the offset, and the length of the audio canal. The tests consisted of FDM prints (see figure 81), SLA prints (see figure 79) and MJ prints (see figure 80. Multiple variations in offsets and audio canals were used in each of the techniques. The audio canal varied between two values : 6.5 mm and 8.5 mm. Since the offset was recalibrated in the last adjustment, the models were printed with multiple offset intervals of 0.25 to validate if the distance is correct.

The three participants were asked to place each model into their ear. Directly after the placement of the model, the participant is asked to fill out the initial perceived pressure on the pressure map. After 8 minutes of waiting, the participants were asked to fill in an online questionnaire, rating several descriptors of comfort, discomfort, and retention on a 7 step Likert scale from disagree to agree. Before taking out the models, the participants are asked to check the retention of the models by shaking their head.

All the models of SLA, MJ and FDM were tested in the same way for each participant.

Figure 79: SLA print with new audio canal

Figure 80: MJ print with new audio canal

Figure 81: FDM print with new audio canal

6.5.2.Material

Through data analysis, the following conclusions for the material in terms of comfort, discomfort and retention can be drawn.

Comfort

The MJ model was perceived as the softest to the skin and felt the most pleasant in the ear of the participants. The FDM prints were the least pleasant and soft due to the material roughness. This shows that a higher resolution print is preferred. Therefore, the comfort scores of the FDM prints are lower than the SLA prints. One explanation is that this is caused by the characteristics of the production method. FDM always requires a certain layer height in relation to the size of the nozzle. This makes the surface feel rougher.

Discomfort

The perceived pressure maps show (see appendix : 5.3 FIXME Model evaluation) that participants experience little increase of pressure while testing the MJ prints. This suggests that material flexibility diminishes the effects of the feeling of discomfort.

Retention

There was no noticeable difference in the retention capacity depending on the material since all the models stayed in the ears of the participants even while shaking their head. However, the participants felt more confident that the MJ models would stay better in the ears.

Conclusion
Overall, the MJ print with the auditory canal of 6.5 mm was preferred by all participants, due to the confidence that the models would stay better in the ears, felt more comfortable, softer, and caused the least amount of discomfort.
The hard material prints are not well suited (especially FDM) for the audio canal, due to the uncertainty of the dimensions of the auditory canal. By decreasing the length of the audio canal the amount of perceived pressure decreased as well (see appendix : FIXME Model evaluation). When a longer audio canal is needed to guarantee a seal, this part of the model should be made with a flexible material.

6.5.4. Audio canal
Through data analysis, the following conclusions for the audio canal in terms of comfort, discomfort and retention can be drawn.

Comfort
The overall comfort of the models with the short audio canal (6.5 mm) felt more pleasant in the ear for the participants than the models with a larger audio canal (8.5 mm). The length of the audio canal does not seem to have an effect on perceived comfort of the concha. However, it does have an influence on the cymba concha. An explanation could be that the audio canal is pushed up out of the auditory canal and therefore pushing the whole model up against the anti-helix.

For the MJ models, there was no noticeable difference in comfort between the variations of the audio canals due to the flexibility of the material.

Discomfort
As expected, the hard material prints with a longer audio canal caused the most discomfort in terms of numbness, ache, strain and hurt. Furthermore, the pressure maps show that the large audio canals caused more and higher-pressure points.

One of the participants rated all the audio canals higher on discomfort than the other participants. This increased the overall score. For the explanation we have to look at the imprint date of the ear of this participant. In the case of this particular participant the auditory canal is quite narrow in hight (see figure 82), while the audio canals of the models are narrower in width.

Retention

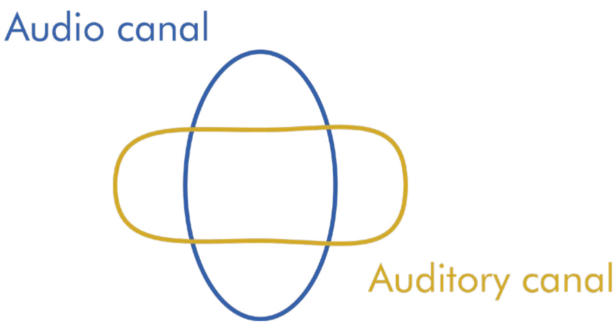


Figure 82: Example of a wrong fiting audio canal, due to the shape of the auditory canal.

It cannot be concluded which of the audio canals was preferred for retention. For the MJ models both audio canals were rated equally. For the FDM models, the shorter audio canal was preferred over the longer, while for the SLA models the longer audio canal was preferred. It could be that the larger offsets of the FDM prints had an influence on this score since the larger offset will put more pressure on the auditory canal.

Conclusion
The fixation of the audio canal has a huge impact on the fit of the rest of the shape within the ear, since it can settle the model in a different orientation then intended. This shifts the pressure distribution within the ear which can lead to discomfort outside of the auditory canal.
Overall, the smaller audio canal was preferred over the longer audio canal as it provided less discomfort to the participants.

6.6. Main takeaways

- *The Truedepth scanner provides the best results for the envisioned use case of scanning at home.*
- *An offset increase of roughly 0.5 mm away from the original shape is required to provide the user with enough retention while providing comfort in the ear.*
- *The preferred length of the audio canal is 6.5 mm. Smaller lengths could offer more comfort, but it makes sealing more difficult. It also diminishes the perception of retention within the ear.*
- *The audio canal should be flexible due to the uncertainty of the shape of the audio canal.*
- *A cymba concha of soft material, provides the user with extra comfort.*
- *The end of the audio canal needs to be rounder and smaller to accommodate for variations in the auditory canal.*
- *When the material is too soft, it becomes more difficult to place the model in the auditory canal.*

Figure 83: Collection of all of the models

7. Ideation

Based on the research in the previous chapters, I generated ideas. First, the focus of generating ideas is on producing multiple diverse ideas (diverge, p. FIXME to FIXME). Then, the ideas are clustered on feasibility and originality (converge, p. FIXME to FIXME). Based on the analysis of the ideas, concepts will be presented in chapter 8 FIXME.

7.1 Diverge: How to ...

A technique for brainstorming ideas is the use of How-To’s. Prior to the brainstorm, the problems are redefined as problem statements which pose the question: “How to solve this particular problem?” (van Boeijen & Zijlstra, 2020). When brainstorming, it is important that the participants do not yet judge the quality of the idea, but rather focus on the quantity. Through association, one crazy idea might lead to an out-of-the-box solution for the problem. Therefore, the problem statements are stated relatively broad to include as many ideas as possible.

Since most of the general shape of the concha is already defined by the scanning method. The focus of the brainstorm is to find solutions for providing the earphones with more retention.

Therefore, the statement used for the brainstorm is “How to provide retention in the ear?” (see figure 84)

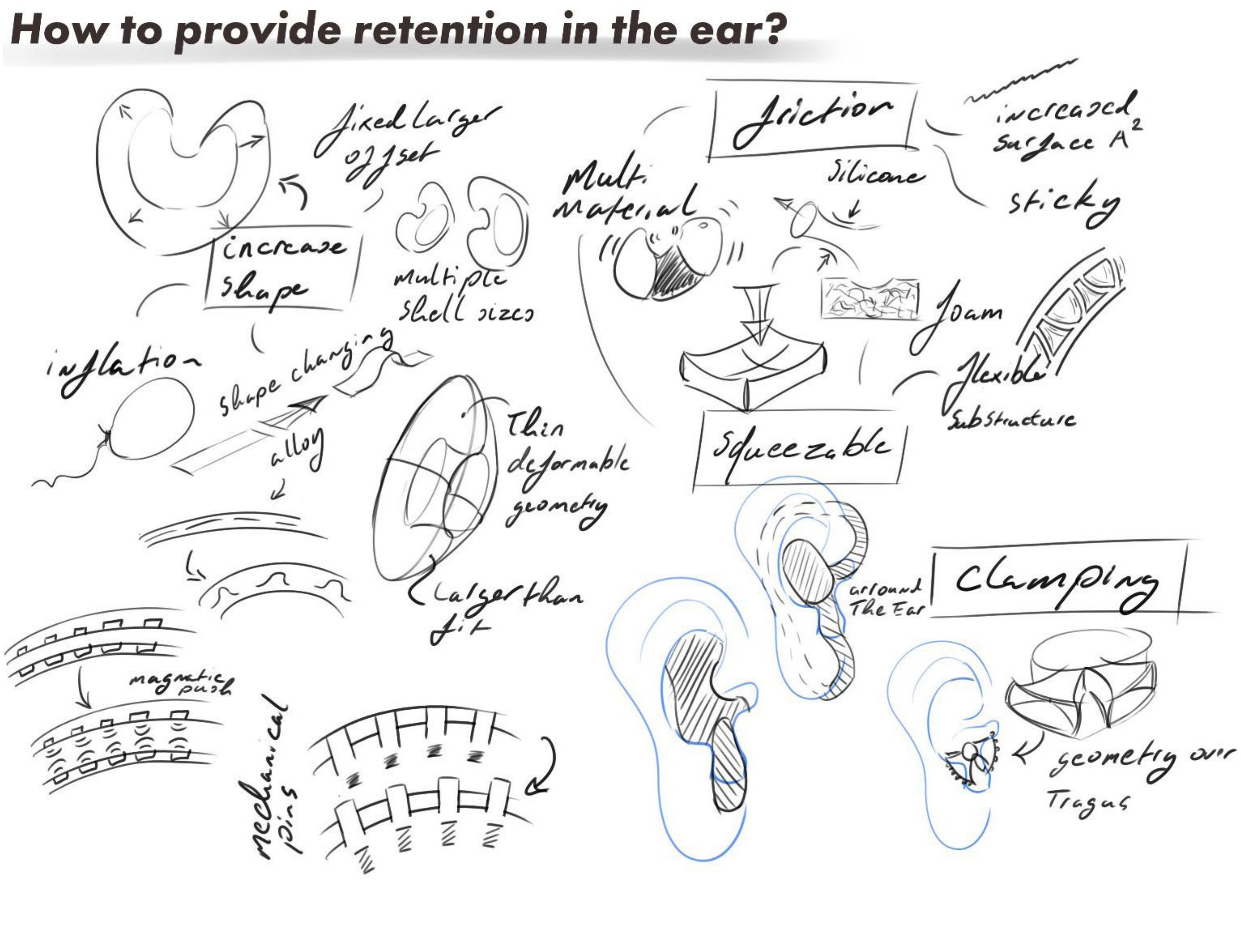


Figure 84: Ideation sketches on how to provide retention in the ear

7.2 Converge: C – Box

The C-box is a method to rate ideas on their feasibility and originality (van Boeijen & Zijlstra, 2020). Some ideas might be very innovative but difficult to realise at this time. Other ideas might not be as innovative but have the advantage that they can be implemented relatively easy. This C-Box maps the ideas of the How-To brainstorm: “How to provide retention to the ear?” (see figure 85).

For the feasibility axis, both the feasibility of the production technique and the ease of implementation are considered. On the originality axis, the ideas are judged on their originality in relation to the field of earphones. After analysing the ideas, the upper right quadrant consists of the following ideas:

- *Magnetic shape changing materials;*
- *Shape changing alloys;*
- *Inflation;*
- *Flexible substructures.*

The ideas around shape changing materials are currently not feasible (see chapter 6.3.5). The techniques, although proven in theory, are still in research and development. For example, long term effects of the materials on exposure to human skin are not yet known. Furthermore, the production techniques are not yet optimised. Therefore, they are currently hard to integrate into

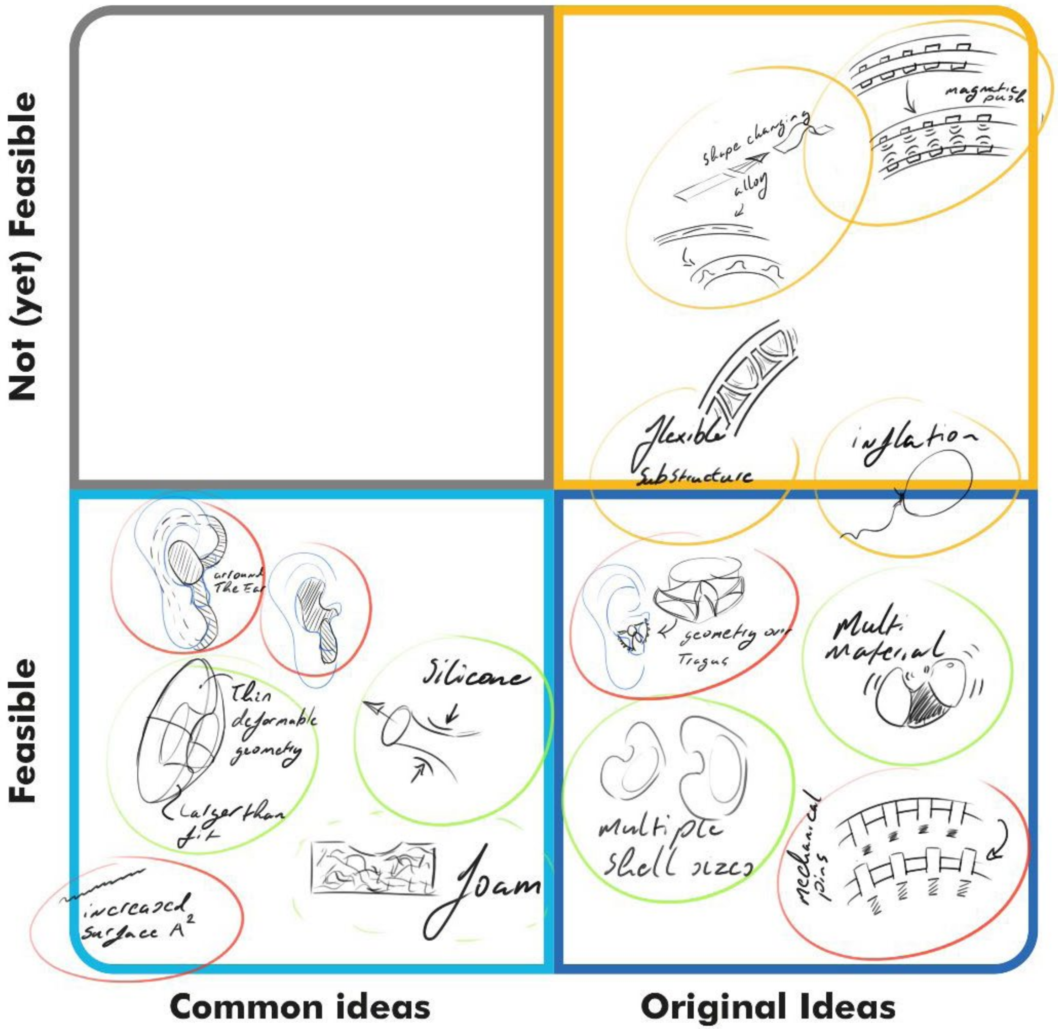


Figure 85: Clustering the ideas using the C-box

Figure 86: ADEL Earbud Balloon (Toor, 2011)

the production. However, when these techniques mature, they could offer a great opportunity in the context of earphones. Due to their shape changing abilities they could be used for personalisation for capabilities. The user might change the retention and sealing levels themselves.

Implementing a flexible substructure in the design, for example with a multi jet printer, is already possible. However, it is currently very difficult to print small 3D substructures due to the need for supports structures. New techniques such as liquid printing solve this issue, but the technique is not yet widely available.

The idea of inflation to improve retention is used in other fields. The idea of being able of inflate parts of the outer shell to provide extra retention and sealing in the ear sounds would be a great feature. However, it is difficult to integrate it at the scale of an earphone. The company Asius has developed miniaturized technology which they named an Asius Diaphonic Pump™ (Toor, 2011). It is used to inflate a medical-grade polymer membrane using sound waves. This technology is again very specialised and not yet widespread available (see figure 86).

Due to the complexity of this project, it would be better to implement a more feasible solution for the retention and sealing of the earphones.
Feasible yet uncommon solutions could be to implement multi material prints. The printers do not only provide flexible material properties but also add friction of the soft material.

Although current tube-shaped generic tips generally put a lot of pressure on the auditory canal of the users (see questionnaire 2). The pressure on the walls of the auditory canal can be reduced, when the size of the tips and the direction is matched with the scan data. The generic tips could therefore still offer a good and feasible solution.
A way to increase the retention, would be to increase the offset of the surface of the models,

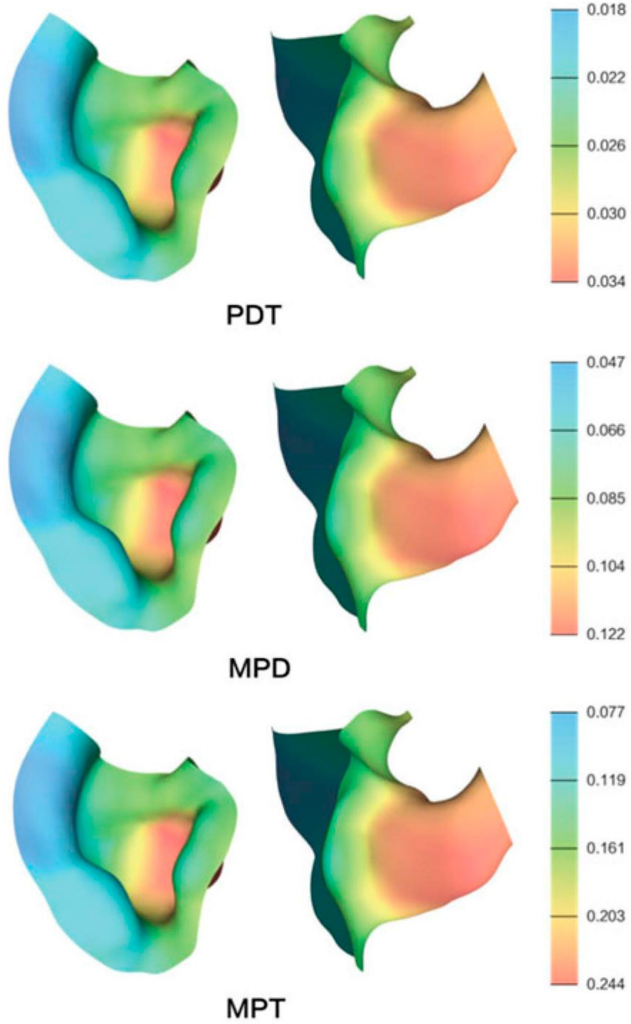


Figure 87: Sensitive regions of the ear by Yan et al. (2022) (PDT: pressure discomfort threshold; MPD: moderate pressure detection; MPT: maximum pressure threshold)

slightly more than the 0.5 mm to, for example, the 0.75 mm evaluated in the models. By making the whole design of flexible silicone, the shape can be deformed, providing retention while the earphones still feel comfortable in the ears.

Modular shells could be implemented to allow the users to switch between levels of retention for different use cases.

Not all the ideas that are feasible are worth exploring further. These ideas either conflict with earlier results found while evaluating models bring extra complexity or do not comply with the requirements. For example, methods for encasing and/or clamping the tragus are both feasible and uncommon, but not desired as it would put extra pressure on these areas which will result in discomfort since this area is quite sensitive (Yan et al., 2022) (see Figure 87). In the pressure maps (see Appendix E), the tragus is often marked by the participants.

Having a model with a high surface roughness will provide more friction in the ear and therefore more retention but was found to be uncomfortable when moving the jaw.

7.3. Conclusion

The most promising ideas are both simple and feasible. By combining the ideas of multi material printing, silicones, multiple sizes, and generic tube-shaped tips with the findings of the model evaluation, four concepts were developed.
Since the earphone should not stick out and be as flush to the ear as possible, a solution of going around the Pinna does not adhere to the requirements. The solution should be limited to the concha.

8. Concept Directions

Based on insights of the programme of requirements, the model evaluations and the design explorations, the following four concepts are developed.

8.1. Hermit crab

What
The users can take out the E-module out of its shell and place it into another shell. A brim around the cavity for the E-module will be printed in flexible material to increase the clamping force on the E-module. The clamping force should be high enough to withstand the shock of a drop test at 1.80 m.

Why
To accommodate the user better for multiple use scenario's, the E-module can be switched between shells. Therefore, the users themselves can switch between the preferred amount of retention for different activities, such as running or working. For more retention, a longer audio canal is preferred. Therefore, the auditory canal should be flexible. The brim should be made from flexible material so it can be slightly compressed when pushing in the E-module.

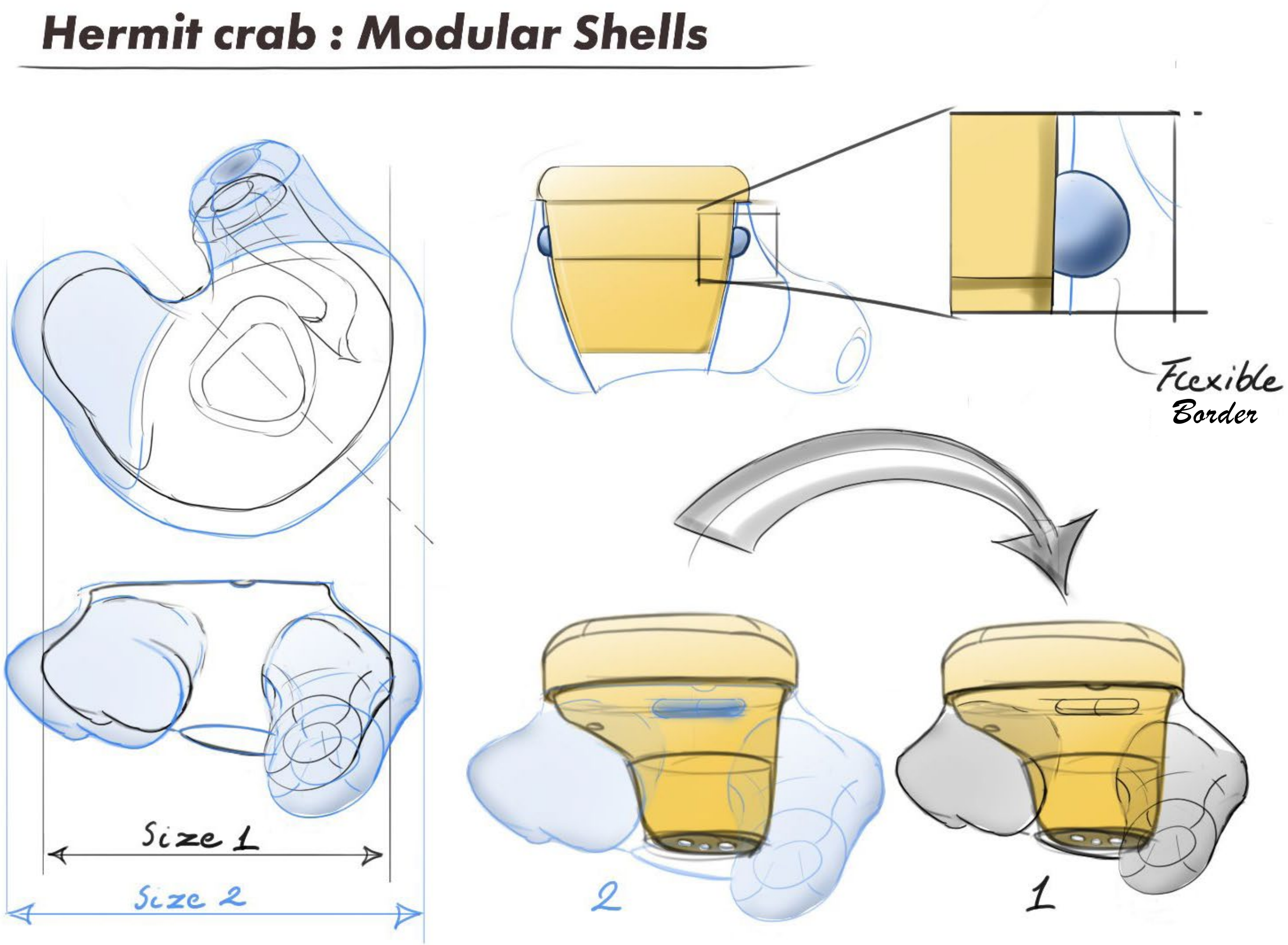


Figure 88: Concept 1: Hermit Crab

8.2. Squid

What
The shell of the squid is made completely out of silicone to maximally deform according to the shape of the concha. The E-module is encased by the whole shell instead of being fastened by a screw as screws will likely rip the material. Therefore, the E-module will be pushed into the cavity of the shell.

Why
The flexibility provided by the fully silicone exterior will make the model more accommodating to uncertainties of the scans. Therefore, it is possible to slightly extend the audio canal further into the auditory canal (6.5 mm, see Chapter 6.5).

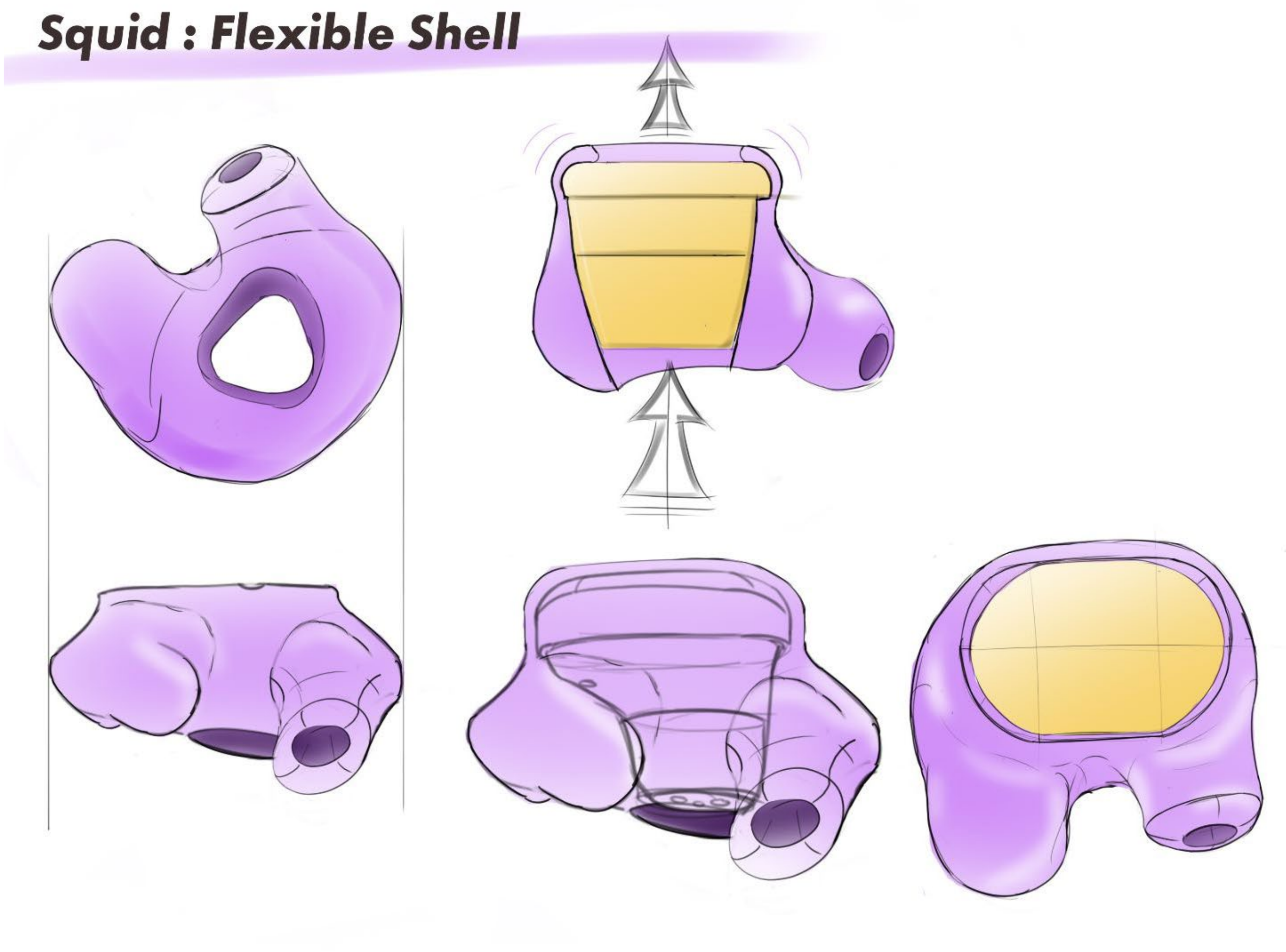


Figure 89: Concept 2: Squid

8.3 Turtle

What
The turtle consists of a hardshell and a generic tip. At the entrance of the auditory canal, a connection part will be modelled to hold a generic tube-shaped tip. Therefore, the inner diameter of the tips will be generic but the outer dimensions can be varied.

Why
When the tip is placed in an orientation based on the estimation of the entrance, a better fitting tube-shaped tip can be provided. The main problem with the generic tips is that earphone producers blindly deliver 3-5 standard tips, hoping that one of the tips will fit in the ear of the user. The tips themselves work quite well when they fit in the auditory canal. Therefore, when the ear data is known, a more accurate estimate of the tips size can be provided. Therefore, sealing with standard tips based on scan data can be more effective.

Turtle : Standard tips

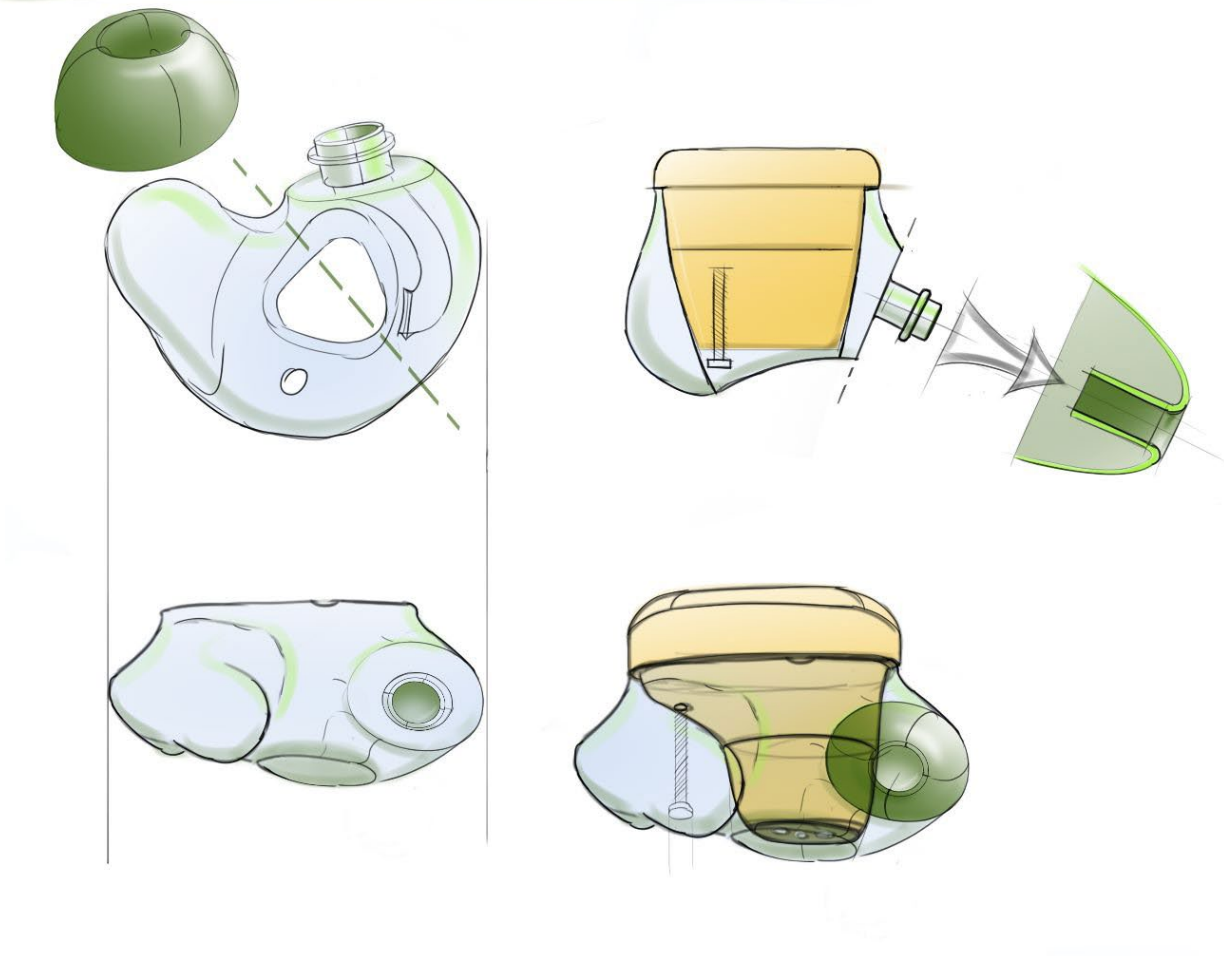


Figure 90: Concept 3: Turtle

8.4 Seal

Squishable collar

What

The seal has a very short audio canal which stops just behind the entrance of the auditory canal (of the scan data (see Chapter … FIXME ears). This provides a seal at the entrance. The seal is created by a collar of flexible material. The collar is made as an additional part and press fitted around the entrance. The collar can either be made of foam or silicone.

Why

By providing a seal at the entrance of the audio canal, the concept stays true to the data provided by the 3D scanner. This reduces the need to estimate how the auditory canal is shaped.

Seal : Enterance Sealing

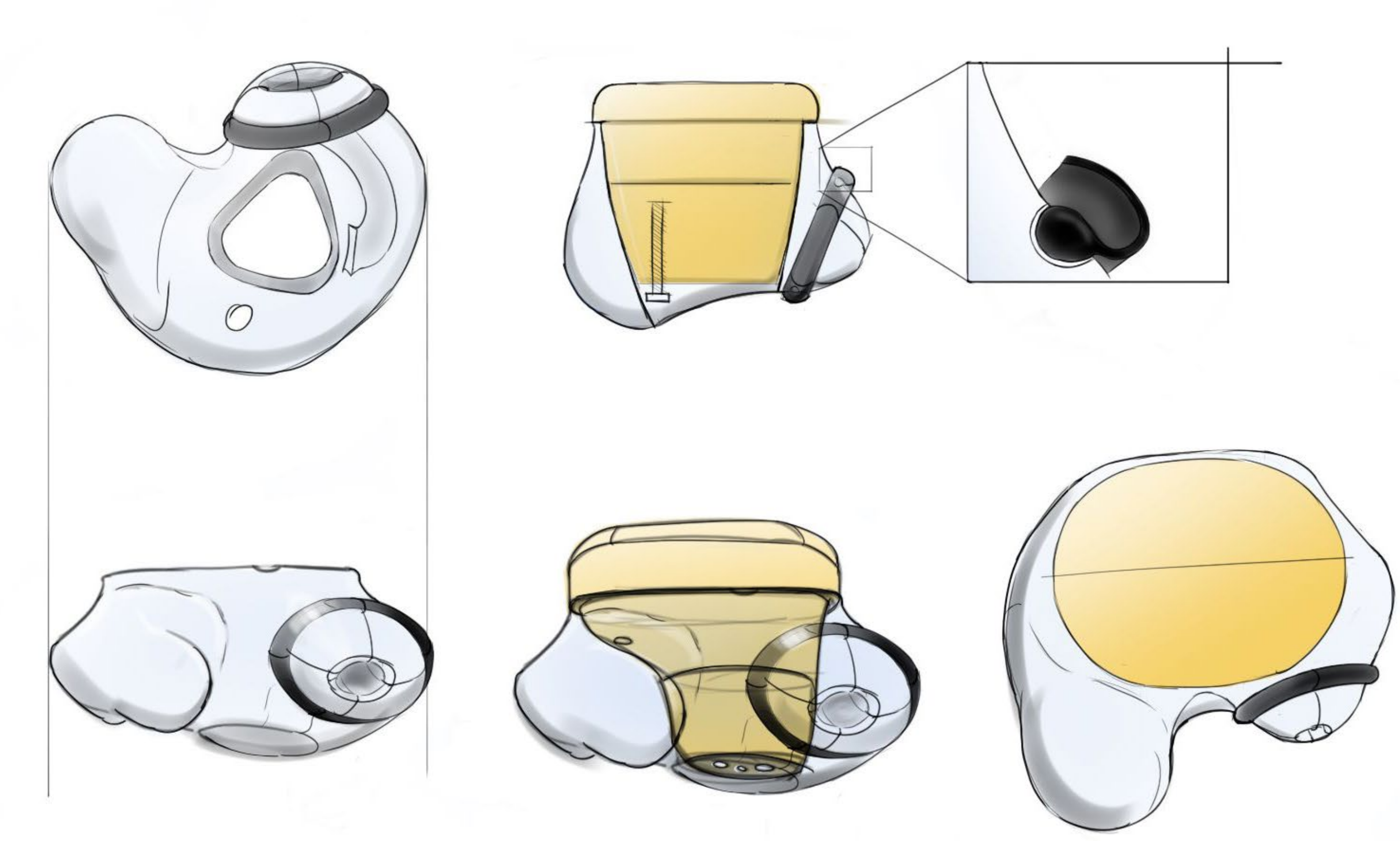


Figure 91: Concept 4: Seal

9. Concept Choice

After identifying the concepts, it is essential to prioritize them to focus on the concept that can have a significant impact on the customers' experience. The Harris profile is a way to visualize the rating of the concepts. The concepts are rated on the list of wishes, of which the most important wish is placed first. After ranking the criteria, weight is added in the Harris profile. When the weight is further removed from the rotation point below, the weight will exert a larger force and determine which concept will rotate to the positive side. It is therefore important to rank the wishes in order of importance.

9.1. Concept choice

The wishes were ranked in collaboration with three experts from Dopple as they could provide knowledge on their expertise with previous products. Although an order was decided upon in collaboration, I decided to give more precedence to the wish of predictable functionality. The reason for this is that the wish expresses whether the concept is expected to function well in relation to the retention, sealing and comfort based on the available scan data.

The prototypes will be rated by on the following wishes in this order :

1. *The earphone is as comfortable for as long as possible.*
2. *The earphones look personalised.*
3. *The functionality/performance of the earphones is predictable.*
4. *The earphone stays in the ear of the user re-gardless of their movements.*
5. *The earphone is easy to clean by the users themselves.*
6. *The earphone can easily be inserted in the ear of the user.*

After ranking, the products were rated by the experts in an open discussion. The ranked Harris profiles look as follows:

The preferred concept in both cases was concept "Seal" (See appendix F.2. for calculation).

The main difference between the seal and the other concepts is the score for function predictability. The seal concept scored full points, since the concept of the seal fabricates or estimate as little extra geometry as possible the concept scores higher on this wish than the hermit crab.

The concept of the hermit crab could still be combined with the concept of the seal. However, since all the models provided enough retention to remain in the ears during a shake test (see chapter 6.5.). The added value of the concept remains to be seen.

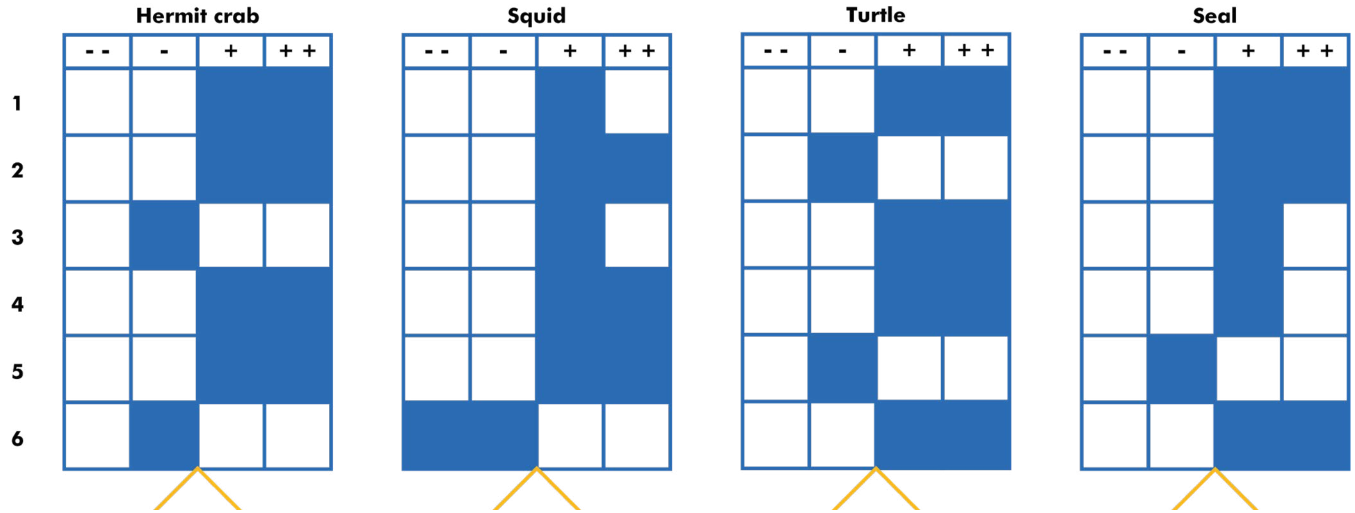


Figure 92: Harris profile ranked by Dopple

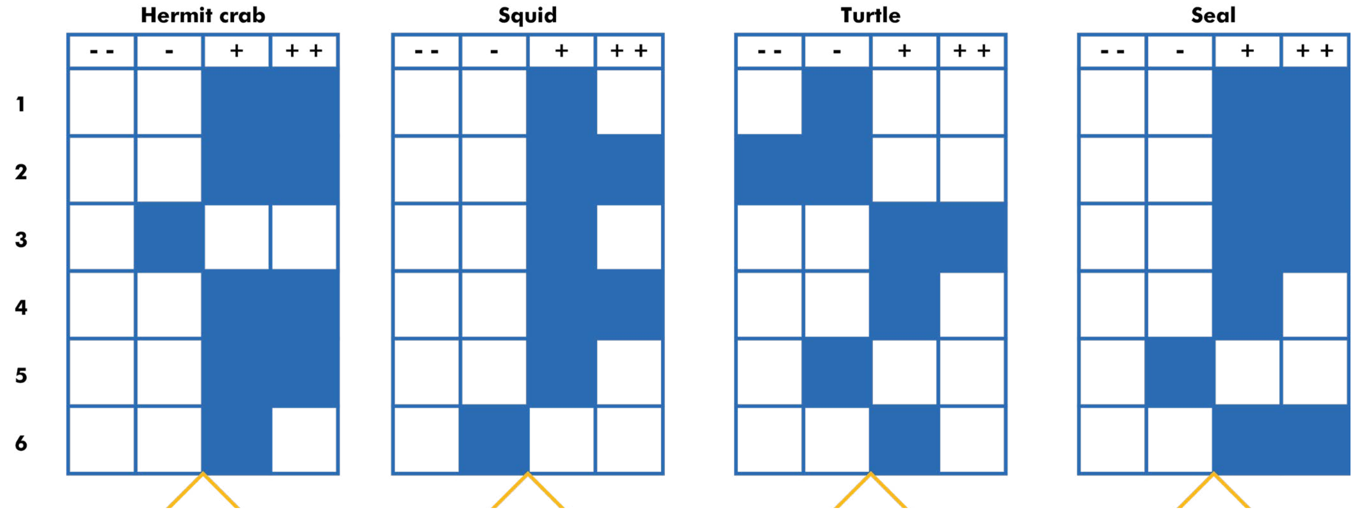


Figure 93: Harris profile ranked by myself

9.2 Conclusion

For the final evaluation, the Seal will be modelled using the same grasshopper script for each of the participants. To provide more comfort, the cymba concha will be printed with flexible material while the rest of the body will be printed in the hard material (like the test in chapter 6) in the multilateral printer. The flexible border around orifice of the audio canal, which provides extra seal and a better fit at the entrance of the auditory canal, will be made from a soft foam material, and glued to the model.

10. Parametric design process

The models in this master thesis are built using the visual programming software Grasshopper, which is an additional programme to the CAD software Rhinoceros. Grasshopper is a tool that allows designers to build 3D models using standard blocks of code or even custom code written in Python. When creating personalised products, the personal data of an individual is taken as a start point. The data is then manipulated and adapted in a series of steps to fit the functions of what the product aims to accomplish. The functions and quality of the personalised product should be the same for each individual. To automate the design process, each of the adaptations should work automatically for the same type of scan. This part should therefore be modelled in a modifiable template. The template should process the user data to implement the features and output a finalised design (Minnoye et al., 2022). Grasshopper allows the user to switch between scan input, which runs through the code and delivers a result accordingly, after which the results are visualised in Rhinoceros.

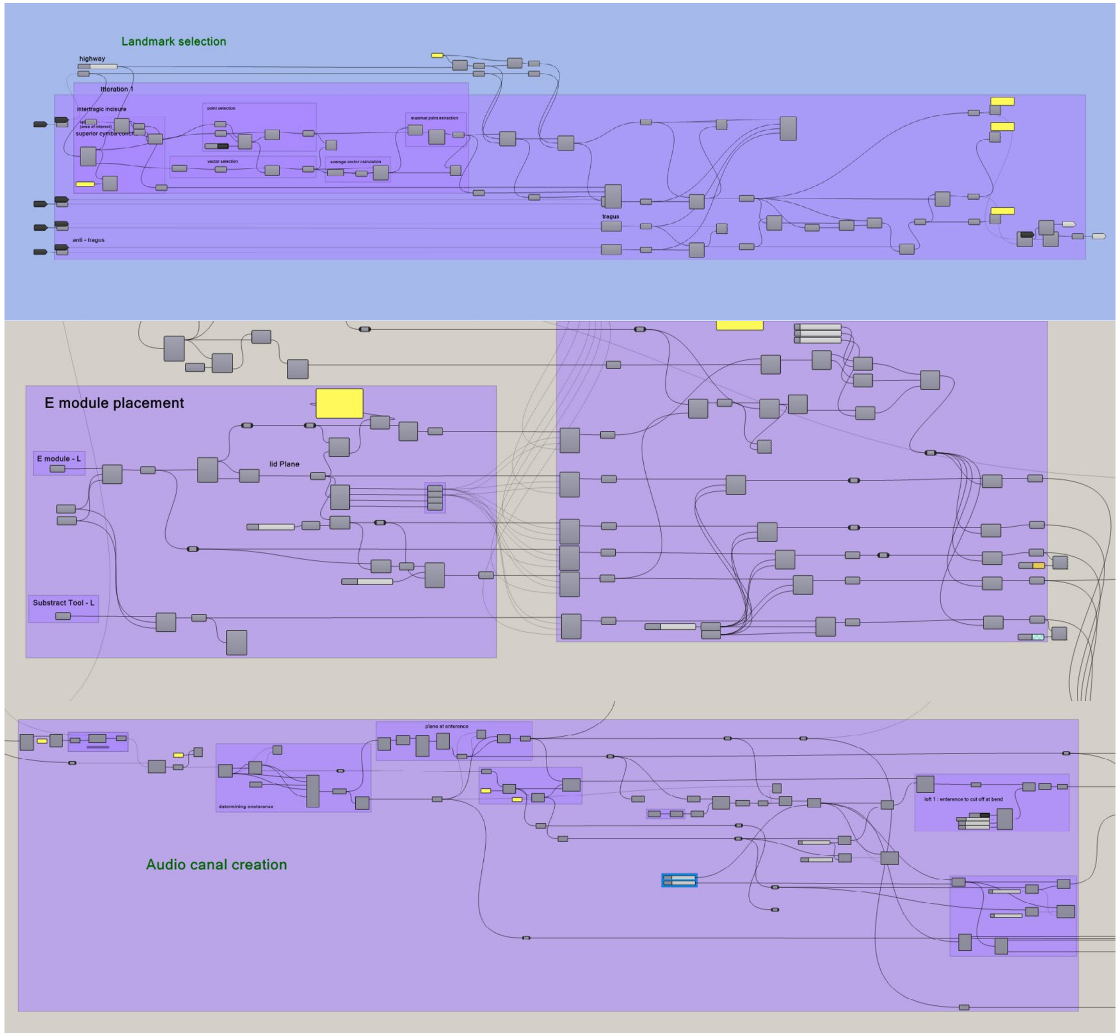


Figure 94: Sections of the Grasshopper script

10.1 Model build-up

The build-up can be split into five different sections. First, the model needs to be analysed and prepped for future adaptations. Secondly, the audio canal is added. Thirdly, the E-module is placed. (4) Fourth, general shape of the model will be built up. As a final action, the crux of the helix structure, the audio tube and the outer shape of the E-module are subtracted from the shell.

10.1.1 Analysis

The first stap into make a parametric earphone design is to interpret the scan data. Like the 3D mould ears of the database, the scans also capture the extreme geometries (to some extent) as can be seen in chapter 6. As a first step, each scan should be translated to a similar orientation and placed in the virtual space. For this thesis, the placement is done by using the relation between the following four landmarks:

- *Tragus*
- *Antitragus*
- *Superior Cymba Concha*
- *Intertragic incesure*

The location of the landmarks is determined using the same method as chapter 3.2 landmark selection.
Once the scan is realigned, the edges of the mesh need to be trimmed to form a homogenous curve (preferably in the same plane). If not, the loft function to enclose the E-module cannot be generated. Meaning that the shape cannot enclose the E-module.

The audio canal generated by the wrapping software did not have any scan data to rely on. Therefore, the entrance needs to be determined using the following landmarks:

- *Intertragic incesure*
- *Superior Cavum Concha*

The entrance is determined by the smallest circumference, using the same method as steps 1- 7 (see figure 28). At this location, the mesh of the scan data is split and the auditory canal is automatically removed by judging the surface area of the created meshes (see figure 95).

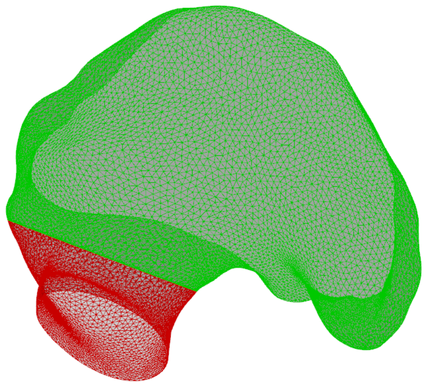


Figure 95: Splitting the auditory canal in CAD

10.1.2 The audio canal

The audio canal is created as a separate body which is later added to the main body (see figure 96). To create the shape, the circumference, the mid-point and orientation of the normal vector of the entrance are used as input for the start of the audio canal. At the midpoint, an oval is created using this input which is lofted to a second oval at 3.5 mm distance in the direction of the normal vector of the entrance. The second curve Is a circle, with the same radius as half of the diameter at the smallest section of the First oval. The orientation is determined by the multiplying the direction vector of the enterance with the unit vector of the y-axis (see chapter 3) . The edges of the audio canal are filleted to ensure that there are no sharp edges which could harm the ear of the user.

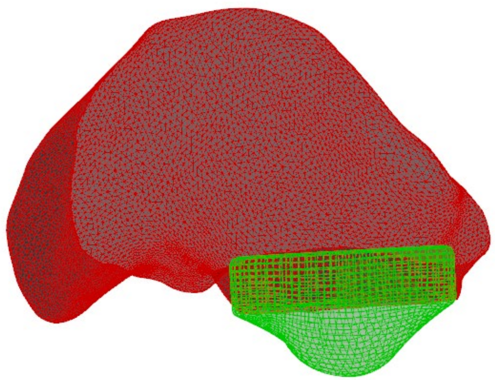


Figure 96: The creation of the audio canal in CAD

10.1.3 Placement of the E-module

The landmarks of the medial concha, posterior concha and superior cavum concha can be used for the placement of the E-module. In larger ears, the placement is relatively easy to automate. However, when the size of the ears becomes smaller, the translations for the placement of the E-module become more complex. The constrain that the charging pins need to be able to fit freely in the model without the interference of the audio canal adds an extra layer of complexity to the model (see figure 97).

Figure 97: Placement of the E-module in the scan data

10.1.4 General shape

After placing the E-module in its correct orientation, a loft can be generated between the cap of the E-module and the edge of the concha. Secondly, the shape of the audio canal is merged with the main body. As discussed in chapter 6, the scan data is inaccurate. Therefore, an overall surface offset is of approximately 0.5 mm is used to account for inaccuracy of the 3D scan. However, an offset over the whole surface means a decreases of the crux of the helix (see explanation of 6.4). Therefore, before creating the offset, a swept body is created. The guide of the sweep runs over the top of the valley of the crux of the helix (see figure 99). The profile of the sweep is determined between the following landmarks :

- *Cymba Concha*
- *Superior Cavum Concha*

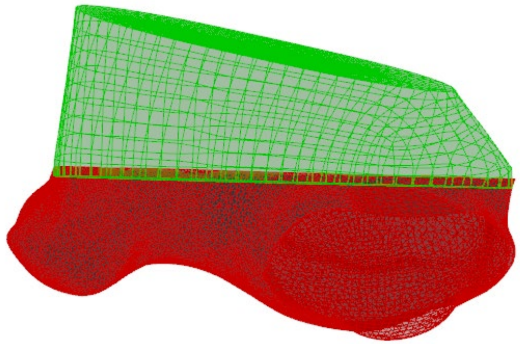


Figure 98: Creation of the loft in CAD

10.1.5 Subtracting

After the final shape is generated, audio tube needs to be generated from the tip of the model to the audio-exit on the E-module. The E-module itself also needs to be subtracted from the shell, while also cutting out a part at the bottom to allow for docking and charging in the cradle (see figure 98).

Finally, the sweep from the crux of the helix will be subtracted from the offset shell, to revert this part of the earphone to the original shape (see figure 99).

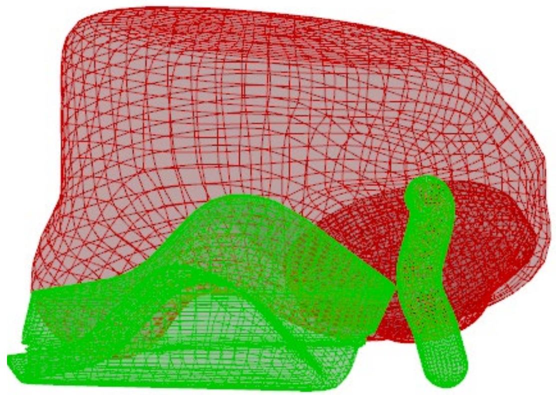


Figure 99: Subtracting geometries for the final Shape

10.2. Conclusion

Unfortunately, it was not possible to generate a fully parametrical script, without human intervention. There are a few weak spots in the script which cause it to fail.

The wrapping software which is currently used is an SSM of a moulded ear. The shape therefore includes the auditory canal. when the software is used to wrap the SSM around the Scan data there is no data available to wrap the auditory canal. Therefore, the auditory canal cannot be used for the model and should be cut off at its entrance. Because the entrances of the ear are located at different positions, cutting the auditor canal means changing the number of vertices and order of the mesh. This means that after this point it becomes even more unreliable to pick a specific vertex in the surround in of the landmark. This issue increases, when the cut of the auditory canal is also in line with part of the cymba concha. At this point the cut does not distinguish between the first part of the mesh and a second (or sometimes third) cut. When the cuts splits the mesh, it again changes the vertices of the mesh again making it not possible to pick a stable vertex point which will work for each scan.

Cutting off the audio canal of the wrap, cuts through all shapes on its path, therefor also through the cymba concha. Cutting the mesh means that number and order of indices of the mesh are changed (see figure 100).

In some cases, the orientation of the plane at the entrance of the Auditory canal will be created in a different orientation. In some cases, only the normal vector is flipped, however at other times, the whole plane was rotated around the normal vector as well. When this happens the loft of the audio canal is either flipped or cannot be created until the axis is realigned.

Comparing the landmarks with the dimensions of the E-Module, will only give an indication on how difficult the placement of the module will be. However due to complex organic shape (see figure 101). The placement was often more difficult then expected. Height differences between the cymba concha and the concha as well as the shape of the crux of the helix make it difficult to place the whole module inside of the ear, without needing a higher displacement out of the ear. It becomes increasingly more difficult to obtain a correct placement when

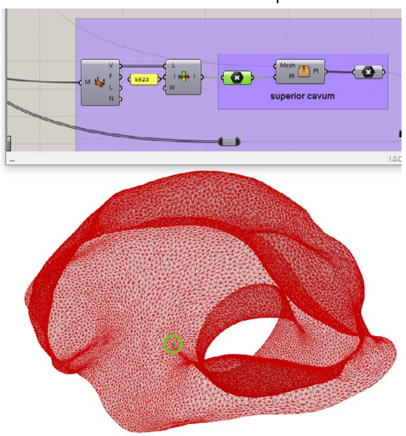


Figure 100: Representation of the script and the wrapped scan data

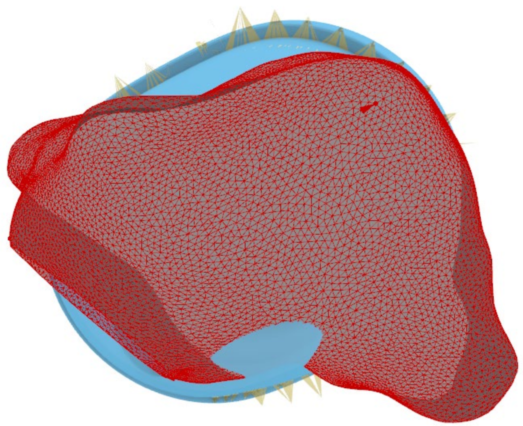


Figure 102: representation of a small ear shape with the E- module

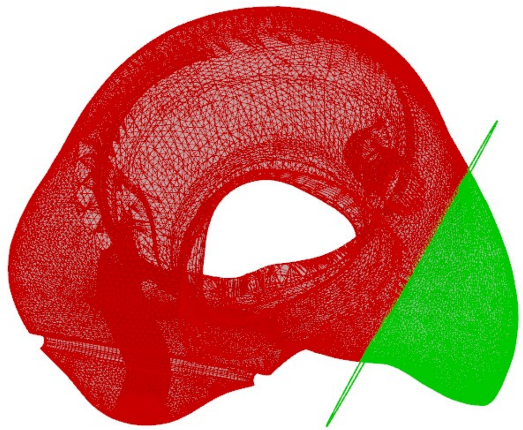


Figure 101:Rrepresentation of the script and 3D representation of cut off cymba concha

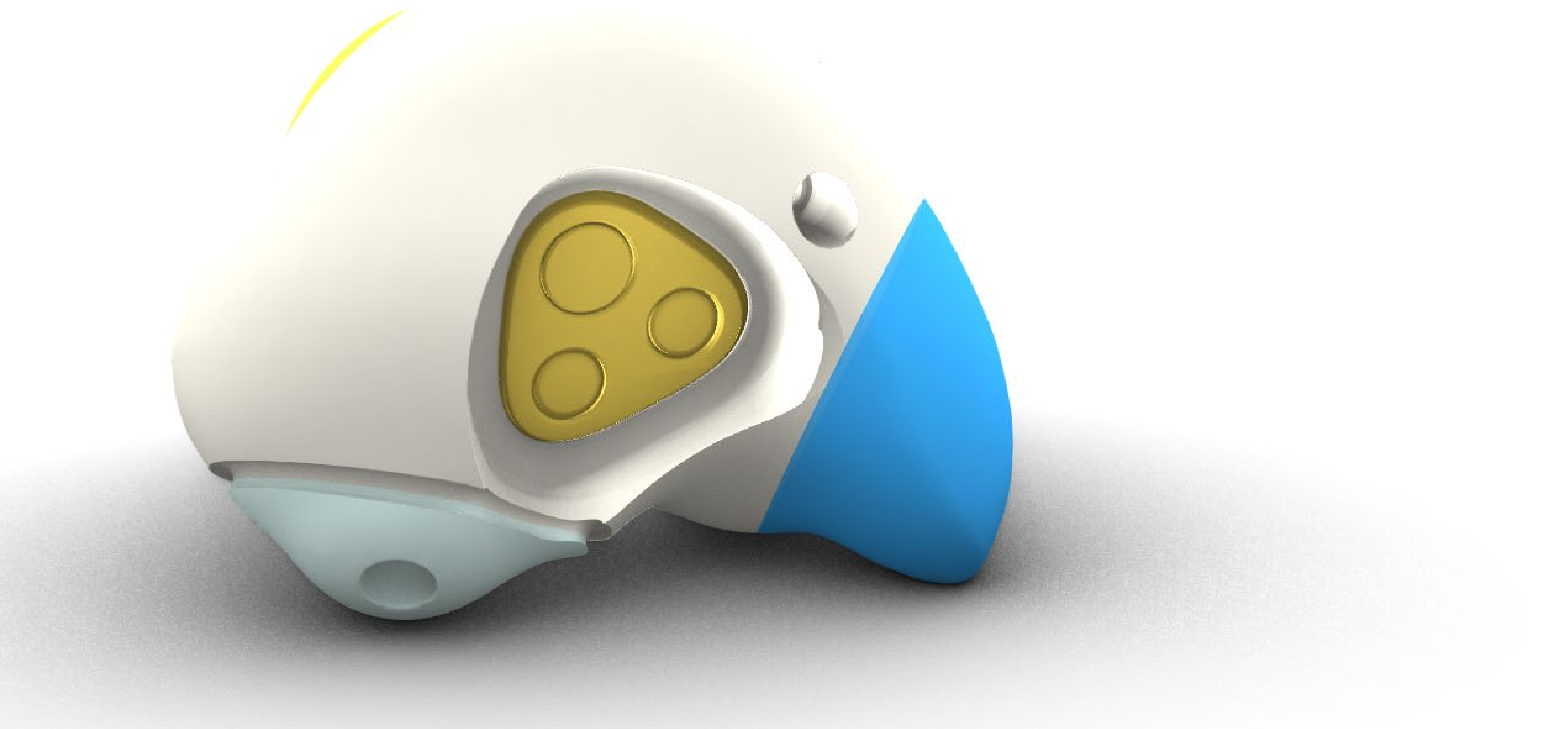
ears are smaller, in comparison with average and larger ears. If the E-module is not well aligned the loft cannot be made properly. In some this results in an error after which the loft is not created. In other cases, the loft is created but the loft does not fully enclose the E-module, leaving holes in the model.

During the evaluation it was remarked that adding flexibility to the cymba concha, added to the feeling of comfort. therfore a large part of the cymba concha is split in order to create a separate part file for the MJ printer (see figure 102).

10.3. Main takeaways

- *Cutting off the auditory canal changes the vertices of the mesh.*
- *The creation of the entrance plane always needs to have the same general alignment of axis.*
- *Smaller ears provide difficulty with placement of the E-module.*
- *The overall automation of the placement of the E-module needs to be optimised to find a good fit in an iterative manner.*
- *The location of the audio exit at the E-module and orientation of the charging pins increases the difficulty of placement (especially in small ears).*

Figure 103: Render of final prototype



11. Prototype evaluation

The final concept will be evaluated with the ears of participants that are not in the database and can therefore, not be checked against ear mould data. This way, the robustness of the parametrical model can be tested. Participants will receive a prototype for each ear which is equipped with the E-module from Dopple. This way, the prototypes can be evaluated while listening to music, providing a user experience as close as possible to the intended use scenario. This helps the participants to better judge the performance of the prototype.

The following research questions gave guidance in validating of the prototypes with customers.

- *Is the design comfortable for long time use of 6 hours (concentration use-case)?*
- *Does the design provide enough retention to keep its position in the ear during an extreme scenario (a lot of head movement e.g. dancing)?*
- *Is the design fit for both extreme use-cases (dancing and concentrating)?*

11.1. Method

Five participants will evaluate the models through 2 scenario's, using the perceived pressure scale for both ears. The map needs to be filled out for both ears immediately placing the earphones in at the start of each scenario.

11.1.1 Procedure

The participant will execute the following scenario's:

1. *The concentration test will take place over the course of a working day. Participants are allowed to take out the earphones, but they are asked to keep track of the time in which the earphones are removed.*
2. *To test if the design provides enough retention the participants will rehearse and perform a dance routine of roughly 20 minutes.*

Scenario 1 can be executed by the participants themselves in their own time. Scenario 2 will be conducted in one session with available participants.

As an extra scenario, two of the participant wore the earphones during their run to evaluate if they would experience the earphones differently than during the dancing activity. This activity could unfortunately not be performed by other participants due to sports injuries and was there for optional.

11.1.2 Participants

For the evaluation of the concepts, five participants are asked to participate in the activities. For each, a unique set of prototypes is developed (and printed with a multi material printer) based on the scan data of both their right and left ear. In addition, the ears of a dance expert were scanned whom would lead a dance choreography session for the participants, as well as the ears of the expert engineers of Dopple. The expert opinion will evaluate the prototypes in relation to the UE Drops, which are the full custom earphones developed by Dopple.

11.1.3 Data collection

In addition to filling out the pressure maps during the duration test, the participants are also asked to reflect on how they were feeling during the test. When taking out the earphones, the pressure map needs to be filled out again. This means that if the earphones are removed during the test the pressure map needs to be filled in again.
As a final assignment, participants will be asked to fill out an online questionnaire to rate the descriptors of comfort and discomfort (see questions below) on a CP-50 scale.

11.2. Results

The heatmaps show some cluster formation around the entrance of the auditory canal and the Superior Cymba Concha.

In some spots, the perceived pressure increases towards the end of the tests (see figure 104). where ass in other locations it has disappeared. As expected, the maps of the dancing and concentrating use cases look quite similar. In both cases some of the highest recorded values are in the cymba concha and at the entrance of the auditory canal.

11.2.1 Dancing

The retention of each of the models was high enough to remain fixed in the ears of the user. while performing the head shake movements in the dance.

11.2.2 Concentrating

The results vary from widely from person to person and ear to ear. In some Ears the models become very unpleasant over time, others do not notice a significant difference between the start and end of the test. In most cases the earphones were removed for communicating with others, not because of irritation.

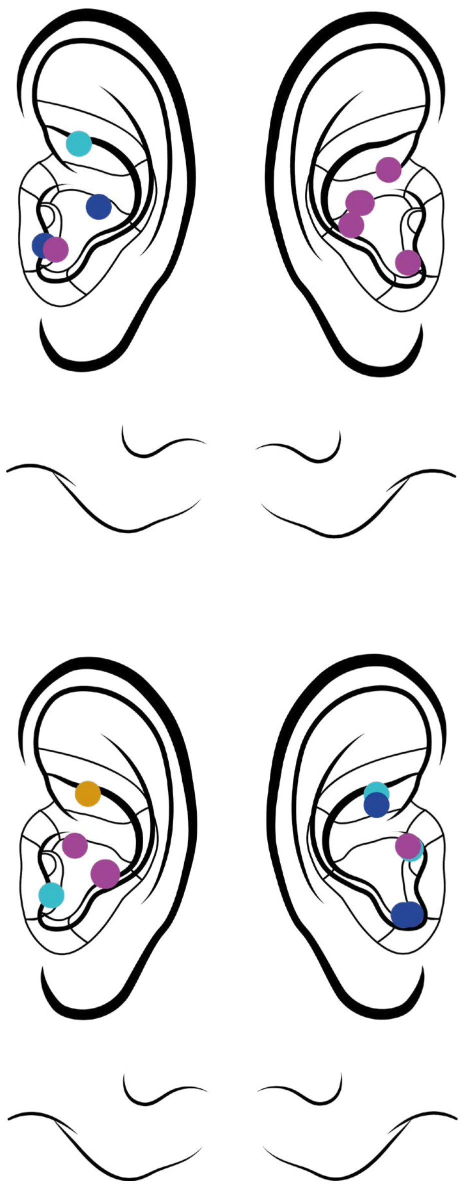


Figure 104: Heatmap of perceived pressure after dancing

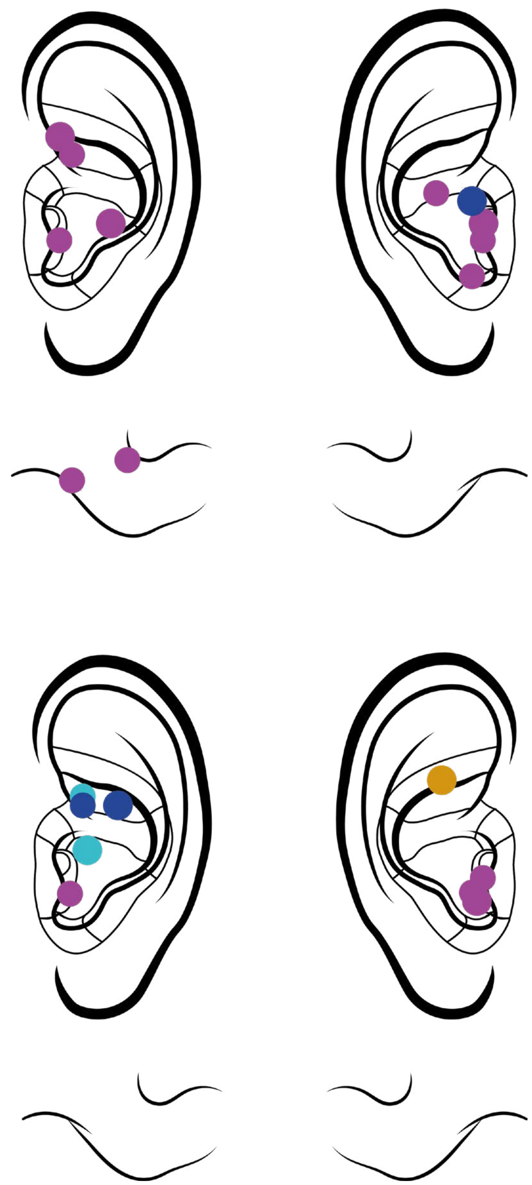


Figure 105: Heatmap of perceived pressure after concentrating

11.2.3. Comfort and discomfort scores

To validate the earphones on comfort, the participants are asked to fill out the CP-50 scale while wearing the earphones. On average, the participants agreed that the prototypes were somewhat comfortable (36/50) (see appendix G.4.). At the same time, they disagree to strongly disagree with the statement that the prototypes cause discomfort (12/50) (see appendix G.3. for scale).

The left ear of participant P2 and the right ear of participant P5 were given the worst scores on the questions of the questionnaire. On average P2 and P5 gave these prototypes an average comfort score of 24, which is on the lower side of the range of neither agree nor disagree towards disagree. For P5 the right ear also scored a 28 (the high side of the range of neither agree or disagree towards agree) on discomfort. In both cases this a hint is given at question 17, in which the participants indicated that the pressure is not equally divided over the ear. This can also be seen in the pressure map of P5 (see appendix G.1. & G.2.). The participant indicated a perceived pressure point of six out of seven near the Superior Cymba Concha.

What is interesting to see is that Right ear of P2 is rated above average on both comfort and discomfort.

Figure 106 (top): image of the evaluation session of the dancing use case
Figure 107 (below): Image of a concentration session at Dopple

11.3. Conclusions

In most cases, the prototypes were positively rated and described as comfortable (see appendix G.5.). The prototypes were in most cases removed from the ears, not because the models caused pain, but rather to talk to other people. Even when testing the prototypes myself, in which I pushed myself to keep wearing the earphones, the longest consecutive use was around 4 hours. Therefore, the 8 hour use case might be an extreme overestimation and not necessary to obtain.

Not all the models provided the participants with comfort. As mentioned in the results, the left earphone of P2, the right Earphone of P5 and left earphone of the dancer instructor gave these participants a high concentration of pressure around the Superior Cymba Concha. It is not possible to conclusively say what caused this discomfort since there are multiple factors which play a part in this. The expected cause is one of the three following reasons : (1) The ear was not scanned accurately enough, creating inconsistencies; (2) the placement of the E-module in to the CAD data is wrong; (3) The foam collar pushes the shell out of its intended position up to the superior cymba concha. It is likely that the reason is either option 2 or 3 (or a combination of both), since there were no anomalies noticed in the scan data. The placement of the E-module proved difficult in some cases. The module needed the be manually repositioned closer to the Crux of the helix. This placement caused could have caused the loft function to put more strain on the Superior Cymba Concha, the area which the participants indicated on the pressure maps.

Most of the given perceived pressure scores remained on the lower side of the scale. This indicates ghat the participants felt the prototypes, but they did not perceive them as discomfortable.

Below, some quotes about the (dis)comfort of the earphones are mentioned.

Quotes
P1: *"You almost have the feeling that it is not in your ear, very light. The foam could have been glued to the model with a bit more care."*

P2 : *"I have the feeling that my left ear is slightly to small, I feel a concentrated pressure in one point (superior cymba concha). It gives the impression that it could fall out at any moment. My Right ear on the other hand fits great, I do not feel any pressure at all! It feels especially good during sports. "*

P3 : *"The prototype feels nice in my ear, because of the soft texture to my skin and it does not exert pressure onto my ears. Furthermore, the earphones feel light and I hardly notice them when they are in my ears."*

P4 : *"The way the prototype feels in my ear is comfortable and light, because the prototype fit really well in my ears. The right earphone does fit slightly less, as I feel it more in the upper part of my ear. It does however not hurt."*

P5: *"My left ear felt good and I could have used it for longer. I am quite sensitive with things in and around my ear and my right ear started to hurt quite fast."*

Expert Dopple : *"The prototype feels good, comfortable and secure, because the fit is good. Plus I have a seal on both sides, however the seal on the right*

11.4. Discussion

When the earphones needed to be removed to talk to a colleague or friend the test was disrupted. This can be seen as a reset, since it allows the ears to rest. If this happened frequently, the participant might not have reached a representative consecutive use time. This could have skewed the results to be more favourable. To test the prototypes more rigorously, the prototypes should be tested in a better controlled environment, in which the participants are for instance not interrupted during the test.

The heatmaps indicated perceived pressure areas at the start of the test while they disappeared at the end of the test. These pressure points at the start could be caused by the participants, when placing the earphones in the ear. Another explanation could be that the models slowly shift position while wearing which influences the perceived pressure.

Figure 108: Four participants with their prototype

12. Recommendations

For future research, there are certain aspects in this thesis that should be evaluated and improved to design a more robust design that will be easier to implement as a new product by Dopple.

12.1. CAD software: Rhinoceros and grasshopper

Although I believe that the software combination of Rhinoceros and grasshopper is very suitable for generating parametric designs, not every function can be implemented by using the standard commands in Grasshopper. However, I was unable to use one of the key advantages of Grasshopper. The software allows for custom python scripts to be integrated as a component in the scripts (see figure 109).

12.2. Database evaluation

Therefore, the evaluation of the database could be improved by, for example, implementing a machine learning algorithm that recognises the position of each landmark better than the current model based on the shape of the ear. In the current evaluation of the data from the 3D database, it is still very hard to conclude which of the outliers are caused by incorrect landmark placements and which outliers are because of the geometry of the ear. To be sure which of the two is the case, the individual model needs to be evaluated. Currently, it could also be that certain outliers are not detected by

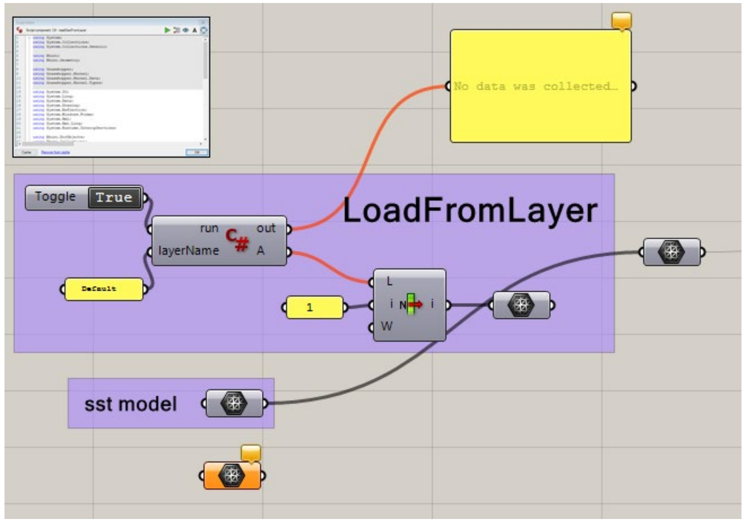


Figure 109: integration of a python script in Grasshopper.

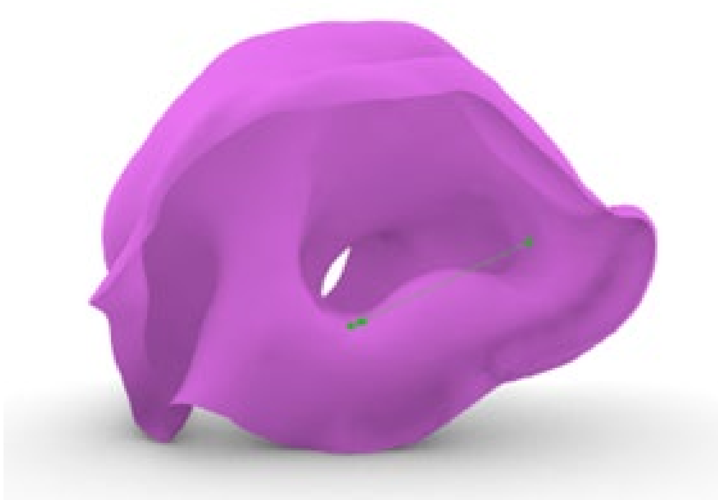


Figure 110: Outlier based on wrong landmark selection (repeated)

the Mahalanobis distance. There could be cases in which only one of the landmarks causes an outlying measurement (either by faulty landmark or atypical shape), but the other measurements might still be within the normal bounds. This ear will not appear in the list of outliers overall. To be certain of that the generated data is correct, each ear should be inspected individually and the faulty landmarks should be corrected manually to ensure the outlier of the measurements are caused by the variance of the ear shapes.

12.3. Parametric design build-up

As discussed in chapter 11, the current script still requires some human assistance depending on the shape of the ear. Even when the placement of the landmarks is improved, the script would still require some adjustments to generate the design without human intervention. One of the adjustments which will make it easier to edit each mesh in the same way is to keep the number of indices and the order of the points assigned to the mesh constant. This means that once the mesh is deconstructed after loading in the ear shape into Grasshopper, the indices do not get reassigned, even when a part is removed for instance. This would also ensure that each mesh has the same quality, even after remeshing.

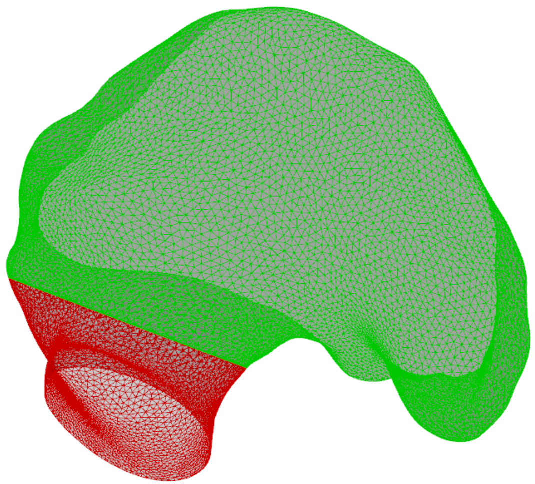


Figure 111: mesh of the earscan after Splitting

The positioning of the E-module was the largest manual task in the current script. After each slight adjustment the model needed to update itself, after which the model needed to be manually checked whether the new position of the E-module would fit in the shell. Instead of doing this manually, a code should be written that checks whether the E-module (and the orientation of the charging pins) are enclosed in the shape of the shell. If the requirements are not met, the script should translate the E-module into a different position. This process should be repeated until the requirements are met.

12.4. Concept

As a further elaboration on the concept, the collar of the shell could be changed to one which is integrated in the multi jet printer. Due to the time constraints, the current solution is made from foam, but, if possible, the personalised look of the product would be improved if the collar can be printed in the model (see figure 112).

12.5. Sealing

The seal of the earphones cannot be guaranteed based on the scan data. The scanners cannot reach behind the tragus and therefore there is a data gap in the wrapping software. In the concept, this area of uncertainty is covered by a placing a flexible collar around the entrance. To guarantee a good seal, more tests should be done to integrate a suitable seal at the entrance.

12.6. Validation

As the time constraints of this thesis are limited to 20 weeks, the validation of the concept was done with a small group of participants. In the future, the proposed improvements should be tested with at least 50 participants. This amount will provide more quantitative data on the functionality of the design. The current test set ups are defined to stay close to the actual use environment. However, the test set up could also be approached to test the limits of the prototype, by providing a set up for example in which the prototypes need to be worn uninterrupted for as long as possible (in the case of the concentration use case).

Figure 112: Current Seal on the prototype

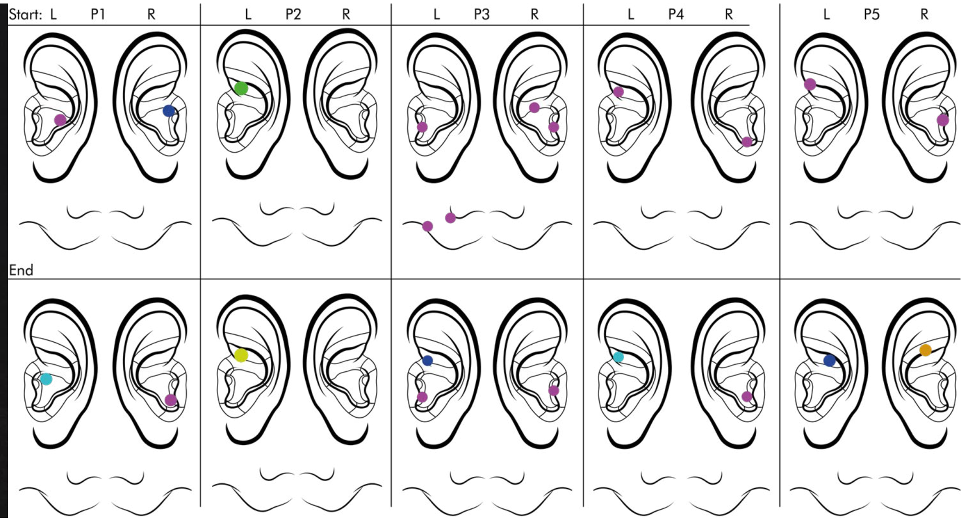


Figure 113 : Percieved pressure maps of the concentration evaluation

12.7. Offset

The offset of 0.5 mm was determined through testing models with an increasing interval of 0.25 mm. When more use cases are clearly defined, the exact relationship between retention, comfort and sealing should be determined for the concerned use case. In this case, Dopple can provide small nuances in offsets in the shells to tailor more precisely for a specific use case and thus providing not only personalisation in fit, but also in capabilities with the shell (Minnoye et al., 2022).

Figure 114: Collection of models used for the offset audio canal evaluation

13. Reflection

This chapter will reflect on the outcome of the project by evaluating desirability, viability and feasibility (pages FIXME & FIXME). It ends with a reflection on my own learning journey (p. FIXME).

13.1 Reflection on the outcome of the project

To reflect on the outcome of the project, feasibility, viability, desirability and future implications are highlighted.

13.1.1 Feasibility

The models and the prototypes show that it is possible to design earphones based on scanned data that are gathered by a smartphone or tablet. This provides the customer with new listening experiences.

Although the design is currently not fully parametric, it is likely that this will be possible in the future for most ears. The three largest hurdles for the feasibility of this concept are: 1) The adaptation of 3D scanners into other smartphone brands; 2) The improvements on the reliability of the landmark selection; 3) A solution for the uniformity of the mesh.

On the first hurdle, Dopple does not have any influence. So far, other phones brands besides Apple have not adapted their phones with 3D scanners. One of the reasons for this could be that Apple currently has a patent on the Truedepth technology. Therefore, other brands need to develop their own technology, pay Apple for the rights or wait until the patent is no longer valid.

Dopple could have an influence on the second and third hurdle. They could invest time and resources either by developing the model themselves or outsourcing it to a software company.

13.1.2 Viability

As mentioned in feasibility, the success of the concept partly depends on the availability and quality of scanners. Since this is hard to predict, Dopple will need to consider the risks of moving forward with the concept by investing time to solve the other hurdles.

In the current concept, sealing is not considered. This topic requires further research as indicated in recommendations see (chapter 12.7.). Therefore, the concept is currently better equipped as a sports earphone. These types of earphones generally have little sealing to account for changes in the shape of the auditory canal due to movement. When the auditory canal is blocked, it will cause the air pressure to fluctuate which will exert more force on the ears. Sport earphones allow for the air to pass through. Therefore, it is proposed that this concept should be marketed as sport earphones.

13.1.3 Desirability

Assuming that the scanners will be implemented, I believe that the concept offers a desirable alternative to customers who need and/or want more retention and comfort from their wireless earphones. The semi-personalised earphones have shown that they can provide a better fit to their users while being easier to obtain than a fully personalised earphone. As one of the experts from Dopple said:

“specifically the combination of the ear canal entrance plus sealing collar looks better than a current Bamboo (E-module)”

13.1.4 Future implications

Apart from the concept, the generated data of the 3D ear database, when the data is evaluated, will serve as an input for other designers. With the implementation of the data in Dined, an online software tool developed by the TU Delft to provide statistical data on the human body, the data will provide insights on the shape and measurements of the ear to create designs that better fit users in the future.

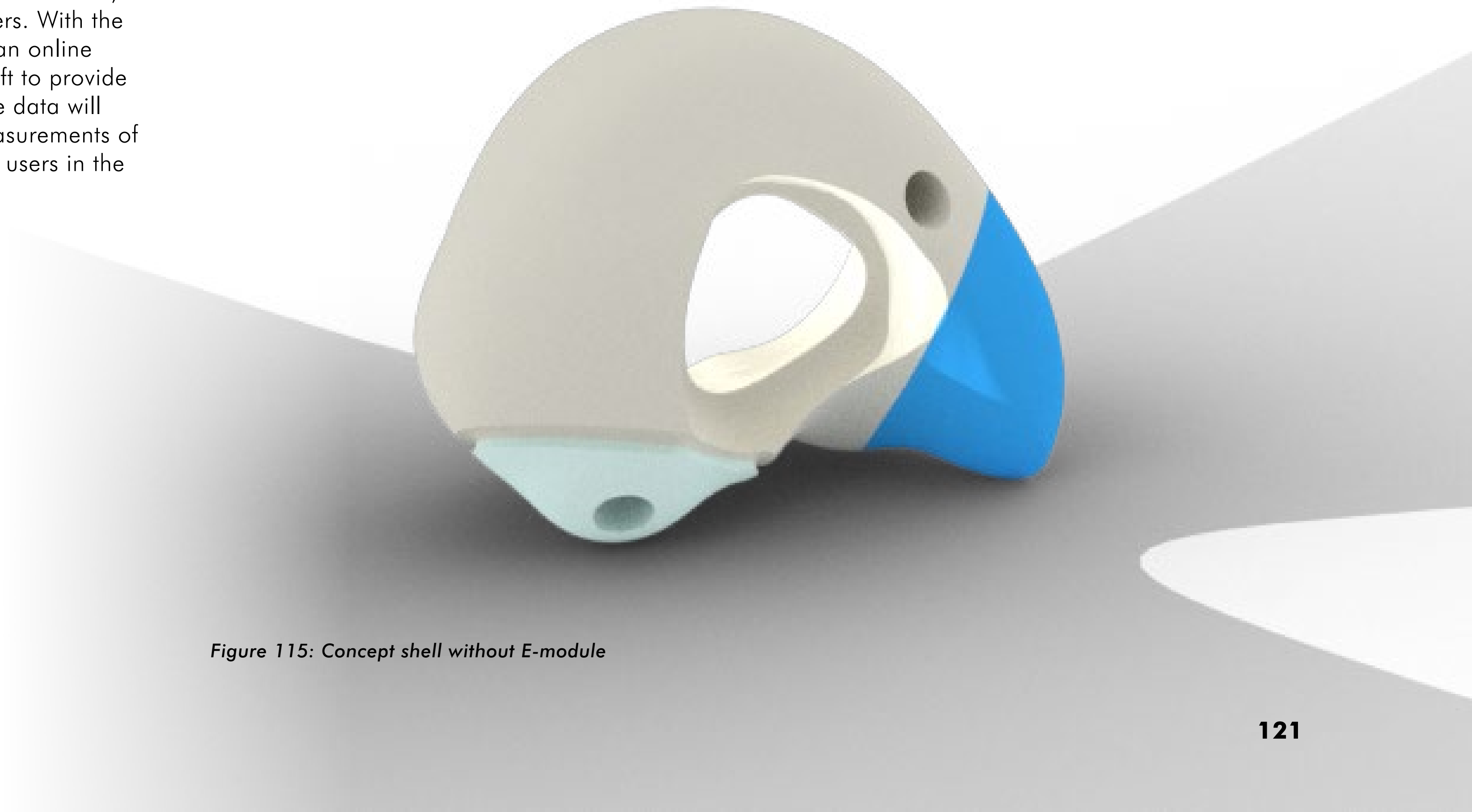


Figure 115: Concept shell without E-module

13.2. Reflection on my own learning process

At the start of this project, I have set myself an ambitious goal: to develop a concept for a semi-personalised earbud, which (1) integrates the in-ear database, the individual 3D "scan" data and the electronical module from Dopple (2) The model should be easy to adapt for every individual and (3) feel comfortable within the ear of the user, while keeping a sufficient amount of retention and providing enough sealing form sound. To add to the challenge, I had to teach myself multiple new 3D modelling tools which could make it possible to set up a parametric design.

(1). The evaluation of the data of the database provided some key insights for the developments of the auditory canal and the concha. The selection of the landmarks plays a vital role in the placement of the models and make it possible to evaluate each design similarly. The measurements of the entrance and direction of the auditory canal are used to design the final audio canal. The final design was based on participants which were not included in the database. Therefore, I could only rely on the scan data to build the final prototypes. I successfully created seven pairs of ears that fit each of the participants. Every prototype was able to fit the E-module and charge in their cradle. Unfortunately, for one participant, I was not able to create a shell, since the dimensions of the E-module were too large for their ears.

(2). The model is not yet as easily adaptable as I would like it to be. Depending on the shape and size of the ear, it was sometimes difficult to find a correct placement of the E-module. In large ears, the placements were quite easy. Small ears were more challenging since space is limited by the size of the E-module. With more time, some of the issues could have been solved in the next iteration of the model, such as the standard orientation of the entrance plane. However, knowledge of Python was required to make customised scripts. Unfortunately, I have yet to acquire this knowledge and could therefore not do it myself.

(3) Although not every earphone provided the participants with the aimed comfort, the consensus between the participants was positive. The prototypes did not fall out of the ears during the evaluation of the extreme use case of dancing. Therefore, I believe that I was able deliver a final concept which was overall comfortable and provided enough retention. As discussed before, sealing could not be guaranteed due to the scanning method and was therefore regarded as out of scope for this project.

Overall, I am proud with the results of the project. I was able gain new skills and knowledge in a new area of design. In the future, I hope to continue to use these methods and techniques in other projects to create personalised designs that are comfortable to wear.

Figure 116: Personal prototype

Bibliography

Alpine Oordoppen Op Maat. Alpine Hearing Protection. (n.d.). Retrieved May 8, 2023, from https://www.alpine.nl/collections/op-maat

Ahmed, A. A., & Omer, N. (2015). Estimation of sex from the anthropometric ear measurements of a Sudanese population. Legal Medicine (Tokyo, Japan), 17(5), 313–319. https://doi.org/10.1016/j.legalmed.2015.03.002

Anjani, S., Kühne, M., Naddeo, A., Frohriep, S., Mansfield, N., Song, Y., & Vink, P. (2021). PCQ: Preferred Comfort Questionnaires for product design. Work, 68(s1), S19–S28. https://doi.org/10.3233/WOR-208002

Asius' ADEL earbud balloon promises to take some pressure off your poor eardrums. (n.d.). Engadget. Retrieved 18 July 2023, from https://www.engadget.com/2011-05-18-asius-adel-earbud-balloon-promises-to-take-some-pressure-off-yo.html

Bhanu, B. (2011). Ear Shape for Biometric Identification. In H. C. A. van Tilborg & S. Jajodia (Eds.), Encyclopedia of Cryptography and Security (pp. 372–378). Springer US. https://doi.org/10.1007/978-1-4419-5906-5_738

Bozali, B., Ghodrat, S., & Jansen, K. M. B. (2023). Design of Wearable Finger Sensors for Rehabilitation Applications. Micromachines, 14(4), Article 4. https://doi.org/10.3390/mi14040710

Chiu, H.-P., Chiang, H.-Y., Liu, C.-H., Wang, M.-H., & Chiou, W.-K. (2014). Surveying the comfort perception of the ergonomic design of bluetooth earphones. Work, 49(2), 235–243. https://doi.org/10.3233/WOR-131723

De Looze, M. P., Kuijt-Evers, L. F. M., & Van Dieën, J. (2003). Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46(10), 985–997. https://doi.org/10.1080/0014013031000121977

Fan, H., Yu, S., Chu, J., Wang, M., Chen, D., Zhang, S., Wang, W., Wu, T., & Wang, N. (2019). Anthropometric characteristics and product categorization of Chinese auricles for ergonomic design. International Journal of Industrial Ergonomics, 69, 118–141. https://doi.org/10.1016/j.ergon.2018.11.002

Fernández-de-las-Peñas, C., Madeleine, P., Martínez-Perez, A., Arendt-Nielsen, L., Jiménez-García, R., & Pareja, J. A. (2010). Pressure pain sensitivity topographical maps reveal bilateral hyperalgesia of the hands in patients with unilateral carpal tunnel syndrome. Arthritis Care & Research, 62(8), 1055–1064. https://doi.org/10.1002/acr.20189

Gefen, D., Karahanna, E., & Straub, D. W. (2003). Trust and TAM in Online Shopping: An Integrated Model. MIS Quarterly, 27(1), 51–90. https://doi.org/10.2307/30036519

Gibson, I., Rosen, D., Stucker, B., & Khorasani, M. (2021). Additive Manufacturing Technologies. Springer International Publishing. https://doi.org/10.1007/978-3-030-56127-7

Guberan, C., & MIT, self-assembly lab. (n.d.). Liquid to Air: Pneumatic Objects. Self-Assembly Lab. Retrieved 13 April 2023, from https://selfassemblylab.mit.edu/liquid-to-air

Helander, M. G., & Zhang, L. (1997). Field studies of comfort and discomfort in sitting. Ergonomics, 40(9), 895–915. https://doi.org/10.1080/001401397187739

Huang, X., Wang, Y., Liu, Y., Ni, B., Zhang, W., Liu, J., & Li, T. (2023). AudioEar: Single-View Ear Reconstruction for Personalized Spatial Audio (arXiv:2301.12613). arXiv. http://arxiv.org/abs/2301.12613

Japatti, S. R., Engineer, P. J., Reddy, B. M., Tiwari, A. U., Siddegowda, C. Y.,

& Hammannavar, R. B. (2018). Anthropometric Assessment of the Normal Adult Human Ear. Annals of Maxillofacial Surgery, 8(1), 42–50. https://doi.org/10.4103/ams.ams_183_17

Jordan, P. W. (2000). Designing Pleasurable Products: An Introduction to the New Human Factors. CRC Press.

Kerstenetzky, A. (2022). PolyJet Materials Reference Guide Presentation. Stratasys.

Koninkrijksrelaties, M. van B. Z. en. (n.d.). Burgerlijk Wetboek Boek 6 [Wet]. Retrieved 25 April 2023, from https://wetten.overheid.nl/BWBR0005289/2023-01-01

Lee, W., Jung, H., Bok, I., Kim, C., Kwon, O., Choi, T., & You, H. (2016). Measurement and Application of 3D Ear Images For Earphone Design. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 60(1), 1053–1057. https://doi.org/10.1177/1541931213601244

Lee, W., Yang, X., Jung, H., Bok, I., Kim, C., Kwon, O., & You, H. (2018). Anthropometric analysis of 3D ear scans of Koreans and Caucasians for ear product design. Ergonomics, 61(11), 1480–1495. https://doi.org/10.1080/00140139.2018.1493150

Lundquist, P., Holmberg, K., Burström, L., & Landström, U. (2003). Sound Levels in Classrooms and Effects on Self-Reported Mood among School Children. Perceptual and Motor Skills, 96(3_suppl), 1289–1299. https://doi.org/10.2466/pms.2003.96.3c.1289

Maddikunta, P. K. R., Pham, Q.-V., B, P., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., & Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications. Journal of Industrial Information Integration, 26, 100257. https://doi.org/10.1016/j.jii.2021.100257

Mikalai, Z., Andrey, D., Hawas, H. S., Ttiana, ., & Oleksandr, S. (2022). Human body measurement with the iPhone 12 Pro LiDAR scanner. 090009. https://doi.org/10.1063/5.0078310

Minnoye, A. (Sander) L. M., Tajdari, F., Doubrovski, E. (Zjenja) L., Wu, J., Kwa, F., Elkhuizen, W. S., Huysmans, T., & Song, Y. (Wolf). (2022). Personalized Product Design Through Digital Fabrication. Volume 2: 42nd Computers and Information in Engineering Conference (CIE), V002T02A054. https://doi.org/10.1115/DETC2022-91173

Mugge, R., Schoormans, J. P. L., & Schifferstein, H. N. J. (2009). Emotional bonding with personalised products. Journal of Engineering Design, 20(5), 467–476. https://doi.org/10.1080/09544820802698550

Neumann, E. S. (2001). Measurement of Socket Discomfort???Part I: Pressure Sensation: JPO Journal of Prosthetics and Orthotics, 13(4), 99–110. https://doi.org/10.1097/00008526-200112000-00010

Niemitz, C., Nibbrig, M., & Zacher, V. (2007). Human ears grow throughout the entire lifetime according to complicated and sexually dimorphic patterns—Conclusions from a cross-sectional analysis. Anthropologischer Anzeiger, 65(4), 391–413.

Nikolina Sajn. (2022). Right to repair. European Parlaimentary Research Service (EPRS). https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf

Rossing, L., Scharff, R. B. N., Chömpff, B., Wang, C. C. L., & Doubrovski, E. L. (2020). Bonding between silicones and thermoplastics using 3D printed mechanical interlocking. Materials & Design, 186, 108254. https://doi.

org/10.1016/j.matdes.2019.108254

Scheiber, G. (2020). Bluetooth Applicability in High-Fidelity Audio Systems.

Shen, W., & Parsons, K. C. (1997). Validity and reliability of rating scales for seated pressure discomfort. International Journal of Industrial Ergonomics, 20(6), 441–461. https://doi.org/10.1016/S0169-8141(96)00068-6
Song, H., Shin, G. W., Yoon, Y., & Bahn, S. (2020). The Effects of Ear Dimensions and Product Attributes on the Wearing Comfort of Wireless Earphones. Applied Sciences, 10(24), 8890. https://doi.org/10.3390/app10248890

Sony, M. (2018). Industry 4.0 and lean management: A proposed integration model and research propositions. Production & Manufacturing Research, 6(1), 416–432. https://doi.org/10.1080/21693277.2018.1540949

Sundar, R., Balaji, A. N., & Kumar, R. M. S. (2014). A Review on Lean Manufacturing Implementation Techniques. Procedia Engineering, 97, 1875–1885. https://doi.org/10.1016/j.proeng.2014.12.341

Tan, W., Xu, Y., Xu, W., Xu, L., Zhao, X., Wang, L., & Fu, L. (2010). A methodology toward manufacturing grid-based virtual enterprise operation platform. Enterprise Information Systems, 4(3), 283–309. https://doi.org/10.1080/17517575.2010.504888

Technology 3D FIT. 64 Audio. (n.d.). https://www.64audio.com/pages/3d-fit

Technology Readiness Levels (TRL). (n.d.). RVO.nl. Retrieved 9 August 2023, from https://www.rvo.nl/onderwerpen/trl

van Boeijen, A. G. C., & Zijlstra, J. (2020). Delft Design Guide (2nd ed.). BIS Publishers.
van Vilsteren, S. J. M., Yarmand, H., & Ghodrat, S. (2021). Review of Magnetic Shape Memory Polymers and Magnetic Soft Materials. Magnetochemistry, 7(9), Article 9. https://doi.org/10.3390/magnetochemistry7090123

Verma, P. (2016). Morphological Variations and Biometrics of Ear: An Aid to Personal Identification. JOURNAL OF CLINICAL AND DIAGNOSTIC RESEARCH. https://doi.org/10.7860/JCDR/2016/18265.7876

Vink, P., & Hallbeck, S. (2012). Editorial: Comfort and discomfort studies demonstrate the need for a new model. Applied Ergonomics, 43(2), 271–276. https://doi.org/10.1016/j.apergo.2011.06.001

Vogt, M., Rips, A., & Emmelmann, C. (2021). Comparison of iPad Pro®'s LiDAR and TrueDepth Capabilities with an Industrial 3D Scanning Solution. Technologies, 9(2), Article 2. https://doi.org/10.3390/technologies9020025

Watching an Eartech Monitor being made | Audiofool Reviews. (2018, August 13). https://audiofool.reviews/building-a-custom-in-ear-monitor/

Yan, Y., Liu, Y., Rui, J., Liu, K., Du, Y., & Wang, H. (2022). In-ear earphone design-oriented pressure sensitivity evaluation on the external ear. Ergonomics, 1–15. https://doi.org/10.1080/00140139.2022.2146759

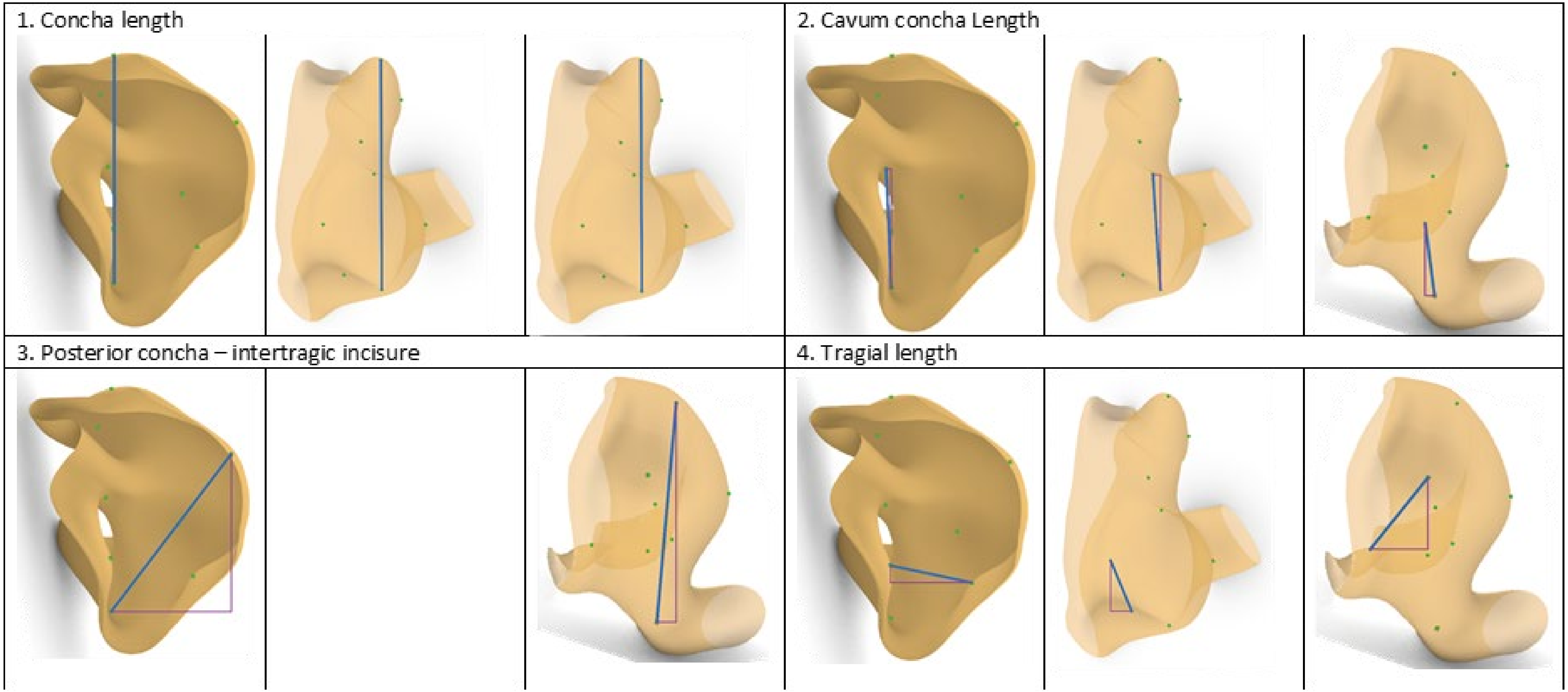
Yun, M. H., Kotani, K., & Ellis, D. (1992). Using Force Sensitive Resistors to Evaluate Hand Tool Grip Design. Proceedings of the Human Factors Society Annual Meeting, 36(10), 806–810. https://doi.org/10.1177/154193129203601036

Zhang, L., Helander, M., & Drury, C. (1996). Identifying Factors of Comfort and Discomfort in Sitting. Human Factors, 38, 377–389. https://doi.org/10.1518/001872096778701962
Zhi, X., Yuexin, S., Jin, M., Lujie, Z., & Zijian, D. (2017). Research on the Pearson correlation coefficient evaluation method of analog signal in the

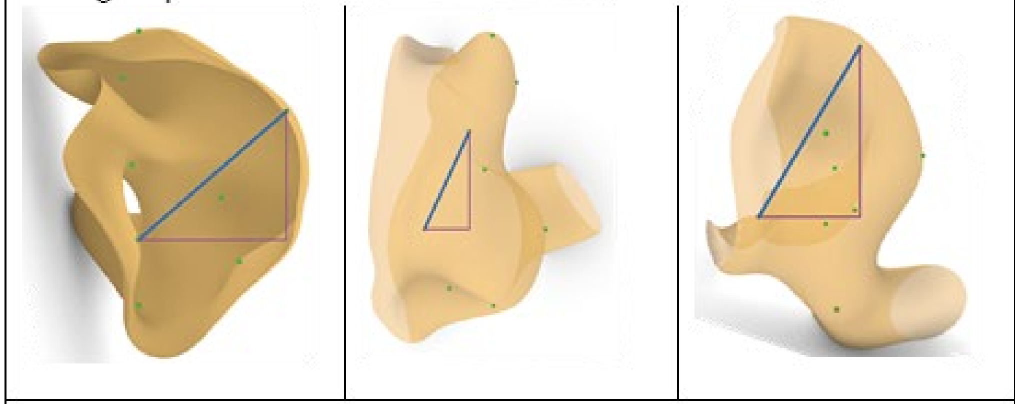
process of unit peak load regulation. 2017 13th IEEE International Conference on Electronic Measurement & Instruments (ICEMI), 522–527. https://doi.org/10.1109/ICEMI.2017.8265997

Appendix A : Ear measurements

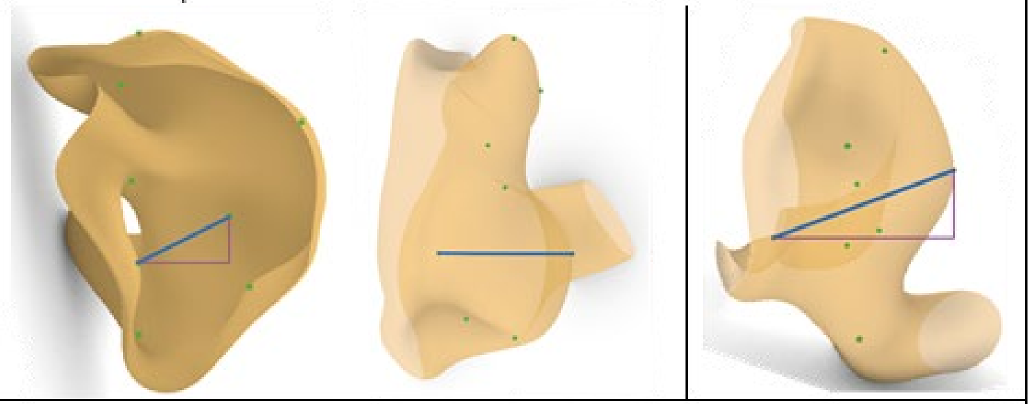
A.1. Distances



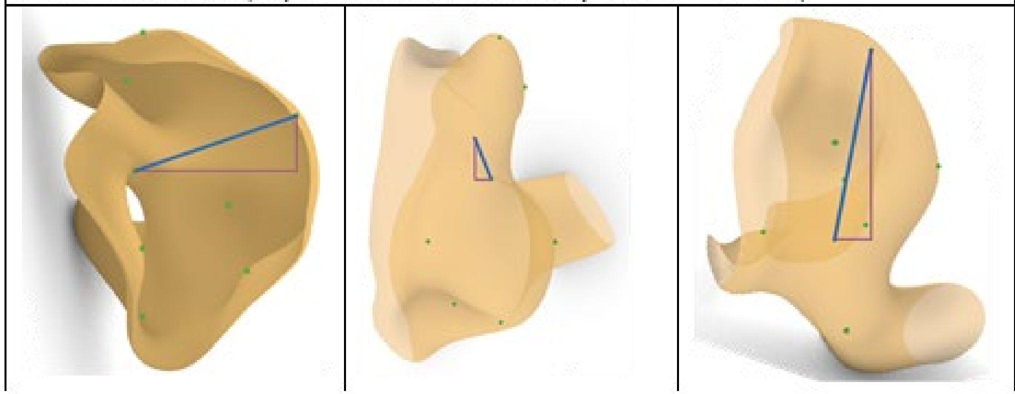
5. Tragus - posterior concha



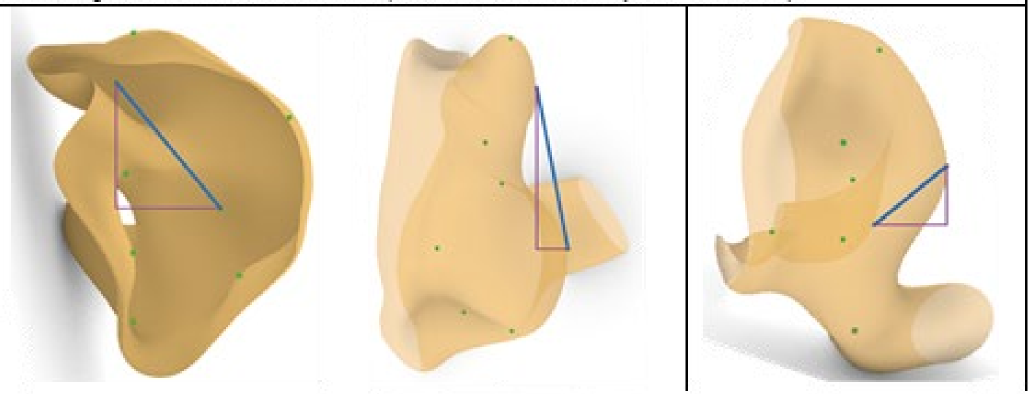
6. Concha depth



7 . concha width (superior cavum concha - posterior concha)



8 . length between concha's (medial concha - cymba cavum)



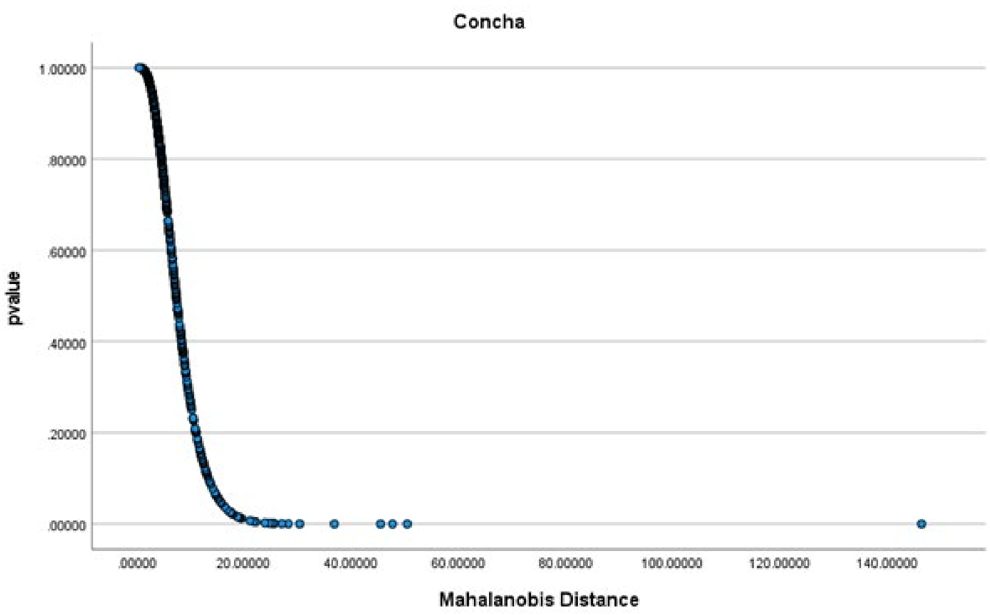
A.2. Outliers

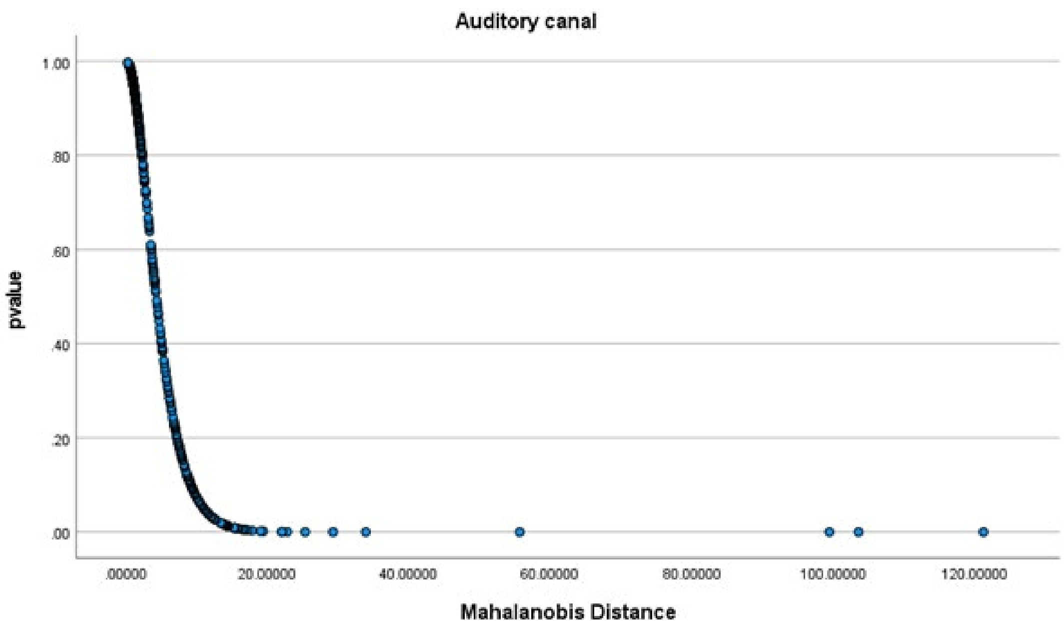
Distance	Concha : length	Auditory canal : circumference and vector component Ny
0.01	LR_cropped__001.txt	LR_cropped_Auditory_244.txt
	LR_cropped__106.txt	LR_cropped_Auditory_066.txt
	LR_cropped__225.txt	LR_cropped_Auditory_469.txt
	LR_cropped__311.txt	LR_cropped_Auditory_071.txt
	LR_cropped__167.txt	LR_cropped_Auditory_139.txt
	LR_cropped__443.txt	LR_cropped_Auditory_156.txt
	LR_cropped__339.txt	LR_cropped_Auditory_365.txt
	LR_cropped__025.txt	LR_cropped_Auditory_330.txt
	LR_cropped__374.txt	LR_cropped_Auditory_508.txt
	LR_cropped__528.txt	LR_cropped_Auditory_193.txt
	LR_cropped__435.txt	LR_cropped_Auditory_101.txt
	LR_cropped__047.txt	LR_cropped_Auditory_085.txt
	LR_cropped__524.txt	LR_cropped_Auditory_523.txt
	LR_cropped__031.txt	LR_cropped_Auditory_401.txt
	LR_cropped__333.txt	LR_cropped_Auditory_419.txt
		LR_cropped_Auditory_084.txt
		LR_cropped_Auditory_499.txt
		LR_cropped_Auditory_239.txt
		LR_cropped_Auditory_363.txt
		LR_cropped_Auditory_241.txt
		LR_cropped_Auditory_238.txt
		LR_cropped_Auditory_404.txt
		LR_cropped_Auditory_274.txt
		LR_cropped_Auditory_240.txt
		LR_cropped_Auditory_300.txt
0.05	LR_cropped__474.txt	LR_cropped_Auditory_111.txt
	LR_cropped__438.txt	LR_cropped_Auditory_081.txt
	LR_cropped__121.txt	LR_cropped_Auditory_402.txt
	LR_cropped__485.txt	LR_cropped_Auditory_222.txt
	LR_cropped__317.txt	LR_cropped_Auditory_427.txt
	LR_cropped__132.txt	LR_cropped_Auditory_486.txt
	LR_cropped__421.txt	LR_cropped_Auditory_369.txt
	LR_cropped__506.txt	LR_cropped_Auditory_046.txt
	LR_cropped__135.txt	LR_cropped_Auditory_126.txt

LR_cropped__510.txt	LR_cropped_Auditory_204.txt
LR_cropped__274.txt	LR_cropped_Auditory_309.txt
LR_cropped__092.txt	LR_cropped_Auditory_026.txt
LR_cropped__014.txt	LR_cropped_Auditory_428.txt
LR_cropped__387.txt	LR_cropped_Auditory_411.txt
LR_cropped__345.txt	LR_cropped_Auditory_503.txt
LR_cropped__197.txt	LR_cropped_Auditory_259.txt
	LR_cropped_Auditory_294.txt
	LR_cropped_Auditory_335.txt
	LR_cropped_Auditory_262.txt
	LR_cropped_Auditory_261.txt
	LR_cropped_Auditory_408.txt
	LR_cropped_Auditory_206.txt
	LR_cropped_Auditory_014.txt
	LR_cropped_Auditory_200.txt
	LR_cropped_Auditory_324.txt
	LR_cropped_Auditory_237.txt
	LR_cropped_Auditory_174.txt
	LR_cropped_Auditory_417.txt

A.3. Statsistical data

Mahalanobis distance :





Descriptives:

Descriptives for Concha				
			Statistic	Std. Error
concha length	Mean		27.9873445	.08511005
	95% Confidence Interval for Mean	Lower Bound	27.8201543	
		Upper Bound	28.1545346	
	5% Trimmed Mean		27.9717687	
	Median		27.9602120	
	Variance		3.890	
	Std. Deviation		1.97227739	
	Minimum		22.75309	
	Maximum		34.88956	
	Range		12.13648	
	Interquartile Range		2.53680	
	Skewness		.119	.105
	Kurtosis		.154	.210
Cavum concha length	Mean		13.7545098	.06335503
	95% Confidence Interval for Mean	Lower Bound	13.6300552	
		Upper Bound	13.8789644	
	5% Trimmed Mean		13.7695408	
	Median		13.8487060	
	Variance		2.155	
	Std. Deviation		1.46814254	
	Minimum		7.91272	
	Maximum		19.00993	
	Range		11.09721	
	Interquartile Range		1.87614	
	Skewness		-.174	.105
	Kurtosis		.681	.210
tragus - anti tragus	Mean		1.2106300	.03883449
	95% Confidence Interval for Mean	Lower Bound	1.1343436	
		Upper Bound	1.2869165	
	5% Trimmed Mean		1.1480589	
	Median		1.0317370	
	Variance		.810	
	Std. Deviation		.89992164	
	Minimum		.01419	
	Maximum		4.50655	
	Range		4.49237	
	Interquartile Range		1.30682	
	Skewness		.967	.105
	Kurtosis		.738	.210
concha width (tragus - posterior concha)	Mean		10.4614365	.14897172
	95% Confidence Interval for Mean	Lower Bound	10.1687964	
		Upper Bound	10.7540765	
	5% Trimmed Mean		10.5305142	
	Median		10.5768130	
	Variance		11.917	
	Std. Deviation		3.45216055	
	Minimum		1.71014	
	Maximum		19.84950	
	Range		18.13936	
	Interquartile Range		4.88023	
	Skewness		-.295	.105
	Kurtosis		-.445	.210

			Statistic	Std. Error
concha depth (medial concha - tragus)	Mean		3.4201863	.05569131
	95% Confidence Interval for Mean	Lower Bound	3.3107864	
		Upper Bound	3.5295863	
	5% Trimmed Mean		3.4221775	
	Median		3.4813250	
	Variance		1.666	
	Std. Deviation		1.29054921	
	Minimum		.06860	
	Maximum		10.01036	
	Range		9.94176	
	Interquartile Range		1.61563	
	Skewness		.167	.105
	Kurtosis		1.255	.210
superior cavum concha - posterior concha	Mean		4.5225502	.11699456
	95% Confidence Interval for Mean	Lower Bound	4.2927261	
		Upper Bound	4.7523742	
	5% Trimmed Mean		4.4590774	
	Median		4.2242420	
	Variance		7.350	
	Std. Deviation		2.71114538	
	Minimum		.00674	
	Maximum		12.71405	
	Range		12.70731	
	Interquartile Range		4.36695	
	Skewness		.285	.105
	Kurtosis		-.833	.210
m	Mean		11.7282811	.04588624
	95% Confidence Interval for Mean	Lower Bound	11.6381422	
		Upper Bound	11.8184200	
	5% Trimmed Mean		11.7411953	
	Median		11.7224120	
	Variance		1.131	
	Std. Deviation		1.06333382	
	Minimum		1.00000	
	Maximum		14.93132	
	Range		13.93132	
	Interquartile Range		1.30469	
	Skewness		-1.820	.105
	Kurtosis		18.575	.210

Descriptive of Auditory canal

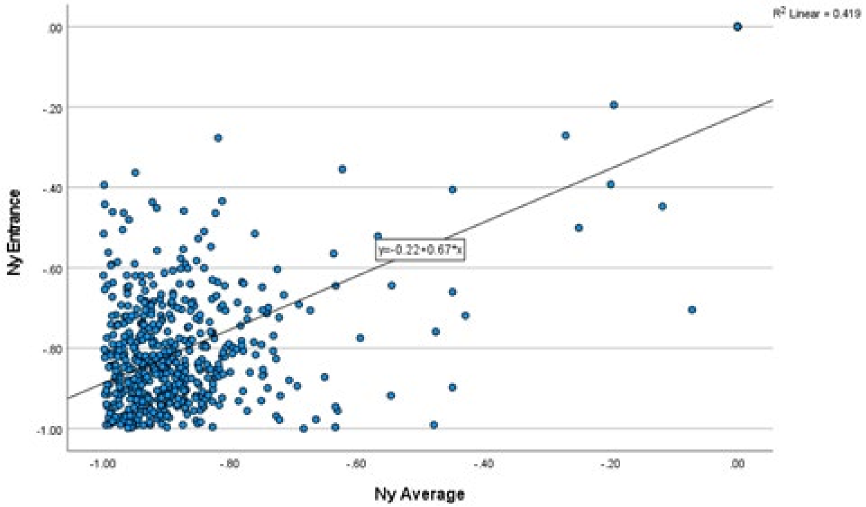
			Statistic (mm)	Std. Error
Circomference E	Mean		32.95284	.541175
	95% Confidence Interval for Mean	Lower Bound	31.88974	
		Upper Bound	34.01593	
	5% Trimmed Mean		31.87064	
	Median		30.33093	
	Variance		156.393	
	Std. Deviation		12.505700	
	Minimum		3.710	
	Maximum		100.289	
	Range		96.579	
	Interquartile Range		8.321	
	Skewness		2.047	.106
	Kurtosis		6.889	.211

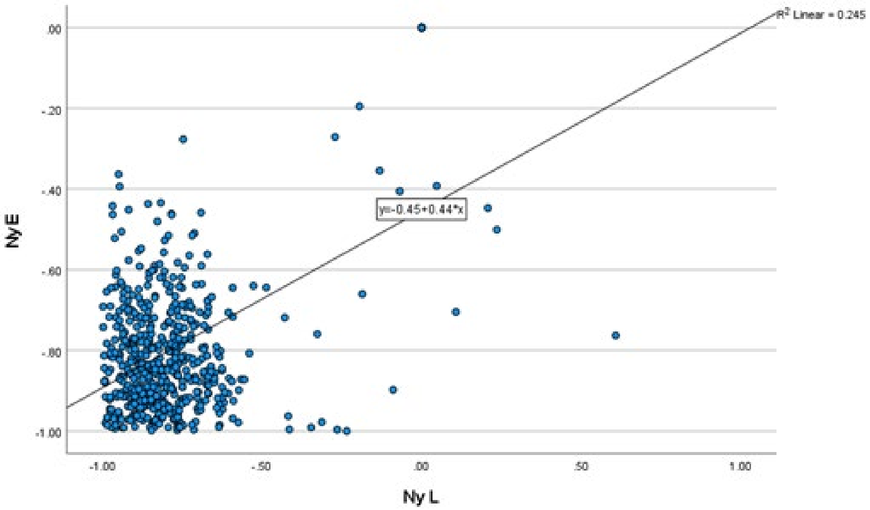
Circomference A	Mean		37.96314	1.065465
	95% Confidence Interval for Mean	Lower Bound	35.87011	
		Upper Bound	40.05616	
	5% Trimmed Mean		36.01940	
	Median		26.74099	
	Variance		606.205	
	Std. Deviation		24.621232	
	Minimum		1.488	
	Maximum		106.207	
	Range		104.720	
	Interquartile Range		10.730	
	Skewness		1.440	.106
	Kurtosis		.517	.211
Circomference L	Mean		34.06406	.801036
	95% Confidence Interval for Mean	Lower Bound	32.49049	
		Upper Bound	35.63764	
	5% Trimmed Mean		31.53955	
	Median		27.79367	
	Variance		342.646	
	Std. Deviation		18.510702	
	Minimum		4.263	
	Maximum		105.881	
	Range		101.618	
	Interquartile Range		6.612	
	Skewness		2.429	.106
	Kurtosis		4.862	.211

Length O - E	Mean		10.70665	.150680
	95% Confidence Interval for Mean	Lower Bound	10.41065	
		Upper Bound	11.00265	
	5% Trimmed Mean		10.52065	
	Median		10.12582	
	Variance		12.124	
	Std. Deviation		3.481981	
	Minimum		4.947	
	Maximum		22.085	
	Range		17.138	
	Interquartile Range		4.312	
	Skewness		.861	.106
	Kurtosis		.039	.211
Length E - A	Mean		4.85305	.162851
	95% Confidence Interval for Mean	Lower Bound	4.53314	
		Upper Bound	5.17296	
	5% Trimmed Mean		4.50047	
	Median		3.58863	
	Variance		14.162	
	Std. Deviation		3.763225	
	Minimum		.000	
	Maximum		19.451	
	Range		19.451	
	Interquartile Range		3.259	
	Skewness		1.619	.106
	Kurtosis		2.274	.211

Length A - L	Mean		4.83637	.164680
	95% Confidence Interval for Mean	Lower Bound	4.51286	
		Upper Bound	5.15987	
	5% Trimmed Mean		4.49175	
	Median		3.85293	
	Variance		14.482	
	Std. Deviation		3.805503	
	Minimum		.000	
	Maximum		19.850	
	Range		19.850	
	Interquartile Range		3.073	
	Skewness		1.600	.106
	Kurtosis		2.348	.211

Correlation :





Correlations

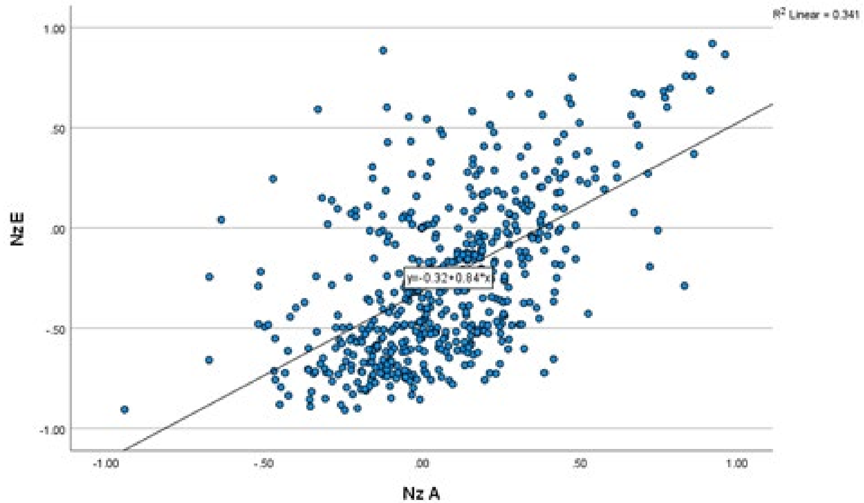
		Ny E	Ny A
Ny E	Pearson Correlation	1	.647**
	Sig. (2-tailed)		<.001
	N	537	537
Ny A	Pearson Correlation	.647**	1
	Sig. (2-tailed)	<.001	
	N	537	537

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

		Ny E	Ny L
Ny E	Pearson Correlation	1	.495**
	Sig. (2-tailed)		<.001
	N	537	537
Ny L	Pearson Correlation	.495**	1
	Sig. (2-tailed)	<.001	
	N	537	537

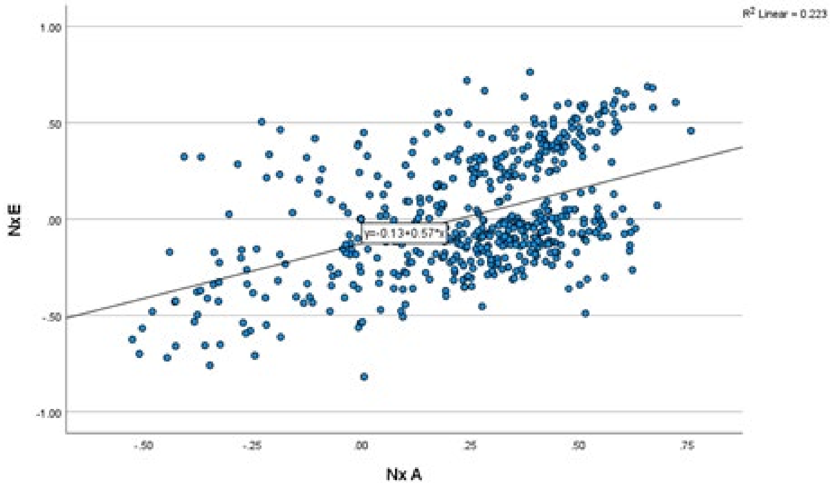
**. Correlation is significant at the 0.01 level (2-tailed).



Correlations

		Nz E	Nz A
Nz E	Pearson Correlation	1	.584**
	Sig. (2-tailed)		<.001
	N	537	537
Nz A	Pearson Correlation	.584**	1
	Sig. (2-tailed)	<.001	
	N	537	537

**. Correlation is significant at the 0.01 level (2-tailed).

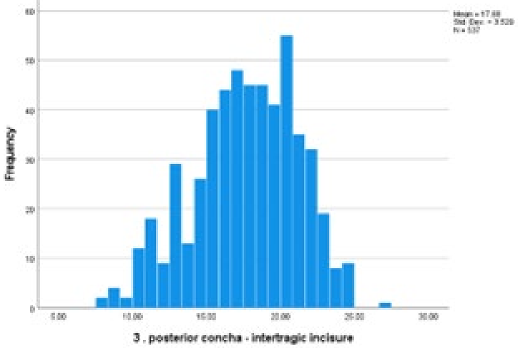


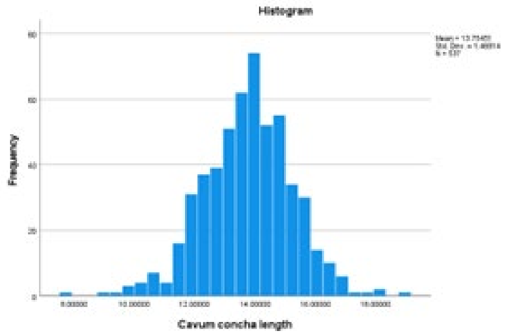
Correlations

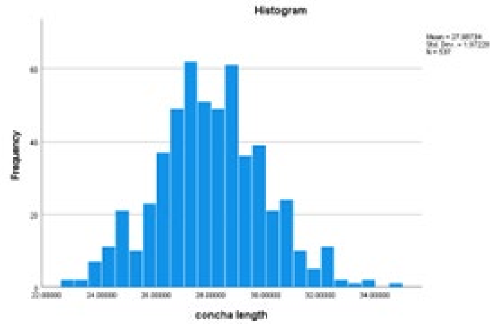
		Nx E	Nx A
Nx E	Pearson Correlation	1	.472**
	Sig. (2-tailed)		<.001
	N	537	537
Nx A	Pearson Correlation	.472**	1
	Sig. (2-tailed)	<.001	
	N	537	537

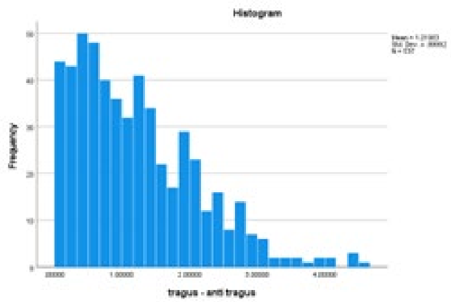
**. Correlation is significant at the 0.01 level (2-tailed).

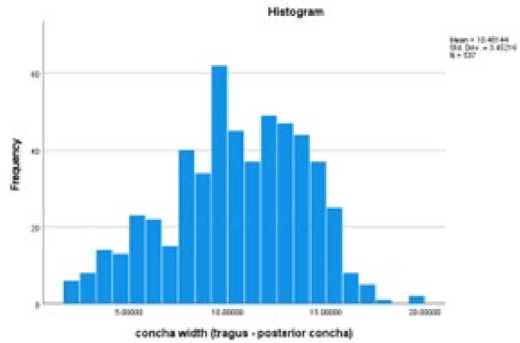
Standard deviation:

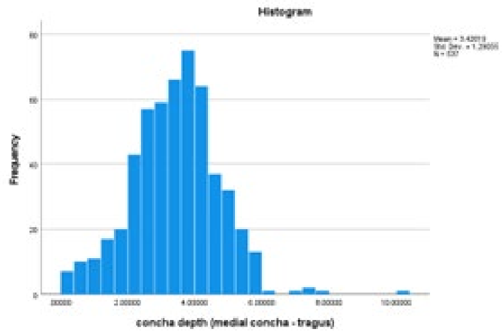


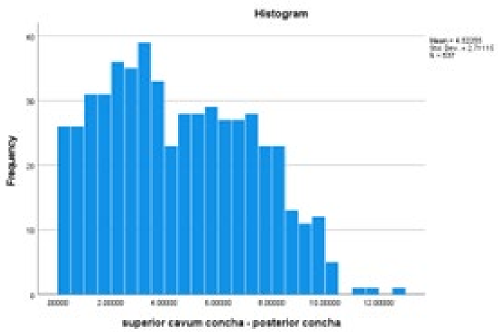


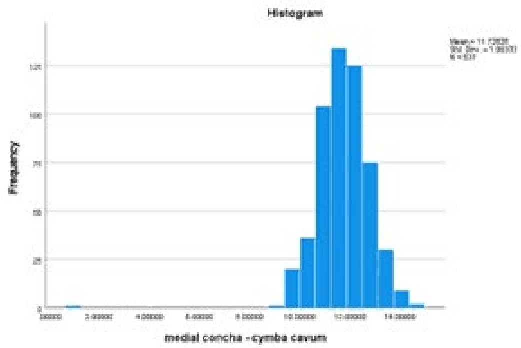


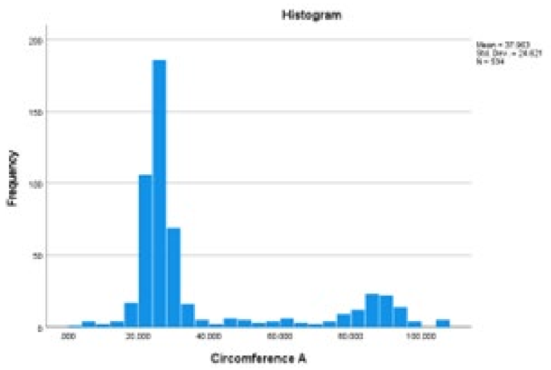


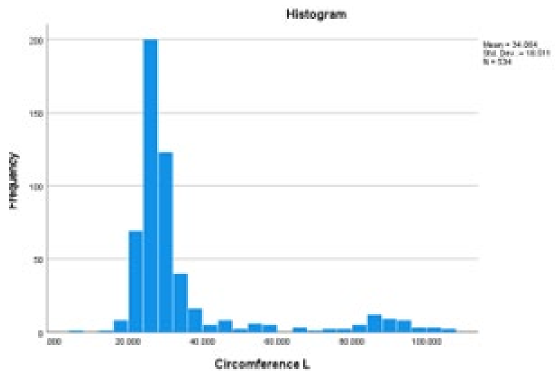


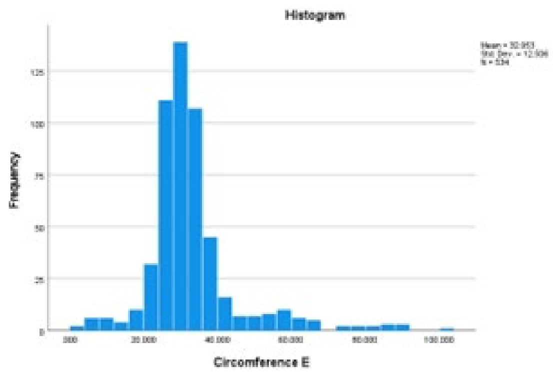






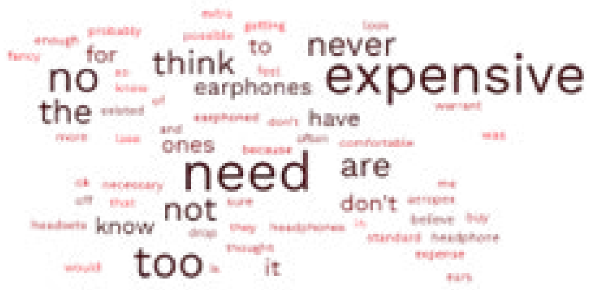

Histogram
Frequency
Circumference A


Histogram
Frequency
Circumference L


Histogram
Frequency
Circumference E

Appendix B : Questionnaires

B.1. Questionnaire earphones



- *depending on initial amount spent, the amount people willing to spend on personalised fit would be higher or lower in correlation with the first amount.*
    - *People In the cheaper scale earphones, often did not know what to expect/ ask in the scenario questions of €400,-.*
    - *Good audio quality was mentioned as a factor of importance even among users spending less than €60,-.*
- *When asked for the reason why users were satisfied or dissatisfied with their current earphones, a the most common reply on both sides had to do with the retention of the earphone. Form this it can be concluded that good retention is one of the main reasons for user satisfaction for earphones. This also shows the opportunity and the need for more optimised in earpiece designs. With fully personalised earphones the entire shape is considered. The design therefor does not only rely on the clamping of the hearing canal for grip but rather the entire concha.*
- *Main reasons for using earphones apart form enjoying music : Calling, exercising and concentrating.*
- *Most important attributes listed for earphones are: sound quality and comfort retention.*

B.2. Questionnaire wireless earphones

On averaged participants are prepared to pay 137% more for a personalised fit product of the same audio quality, this resulted in an average of €226.52. For further personalisation participants would on average like to pay €40,58 more, however in many cases participants did not want to spend any money on further personalisation.

Satisfaction rate

- *Not possible to conclude due to the small data set.*
- *People also tend to relevant the price of purchasing to the quality. Therefor if the product delivers good quality for a relatively cheap price the customer will perceive it as good quality.*

Attribute ranking

- *Comfort, sound quality and retention were ranked the most in the top 3.*
- *Out of these, comfort was ranked 1st 10 times. None of the highest priced products had comfort in the top 1 (price range 80- 230).*
- *In the highest range (7 participants above 300), sound quality was the most marked attribute ranked 1st.*
- *Overall sound quality was ranked 21 times in the top 3. Meaning that in every price category sound quality was deemed important. However, when conducting interviews. It became clear that the perception of sound quality varies*

heavily on the past experiences. Mainly which earphones has the user had before and to what was he able to experience somewhere else. A hint to this could be that that sound quality was not only the most first ranked attribute in the highest range but also in the cheaper price range from €100 – 130.

Attributes satisfaction

- *The users paying a higher were more critical in general.*
- *Active noise cancelling and sealing was rated as bad in the range between € 100- 135.*

Tip type

- *Silicone tips can be found in any price category.*
- *Foam tips are only used by the higher price range, 270 – 450.*
- *The kennel type earphones (for example apple earpods) are mostly found in the range between €100- 200.*
- *Lack of data of personalised prices*
- *Users of the silicon and foam tips generally get extra tips provided.*
- *Hours listening*
- *No clear distinction can be made; however a larger quantity of the higher priced products can be found listening more hours per day to their earphone. More data is needed to confirm a clear distinction.*

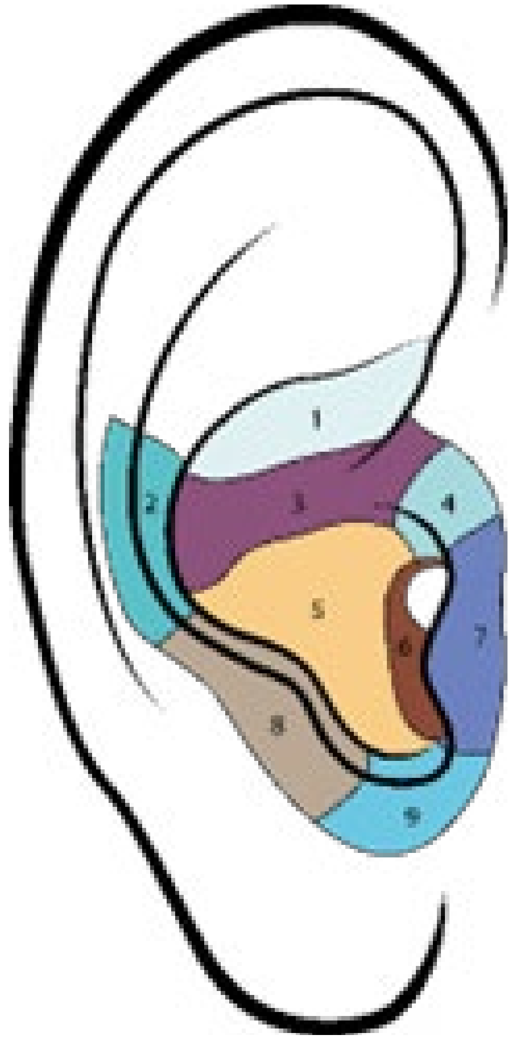
Hours listening compared to

Discomfort:

- *The hearing cannel is indicated as the zone in which irritations most often start to rise. After which comes the concha.*
- *This however does not seem to have a connection with the number of hours listening per day, nor the purchasing price of the price of the earphones.*
- *The tip type which causes the most discomfort in the ear canal does mainly consist out of silicon or foam. It is hard to make a definitive conclusion based on this data set since silicone tips was the most named response. However, it is logical since it is the characteristic of both tip types to expand within the hearing canal and exert pressure on its walls. While open-type product such as the ear pods (2 questionnaire) are designed to not touch the hearing canal while wearing. This was also concluded by (Song et al., 2020) in which four types of wireless earphones were compared on their comfort, with regard to ear size. For the study 2 open type products and 2 kernel-type (with a silicon or foam tip) products were compared.*

Occupation compared to:

- *Spread is too limited to draw any conclusions. A large part of the survey is a student. Other job types were singular occurring.*



Age compared to

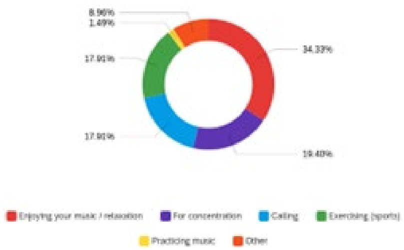
- *Does not seem to influence the price too much.*
- *Using earphones for sports was also not limited to an age*

What are the earbuds generally used for :

21 of the 27 participants listed at least 2 reasons for using earphones, indicating that earphones should full fill multiple use cases. The reasons for use can be translated directly to scenarios and functions of the earphones. In case of calling users can stand in busy environments, in which they need to hear the person on the other end clearly. Therefor surrounding sound needs to be shut out; however, the user should still be able to respond, therefor the earphones need to filter out the voice of the user out of the noise. In case the user uses the earphones for exercising, the earphones need to be resistant to sweat and regulate air pressure within between the tip and the eardrum. The movement made during exercising, exert larger forces on the earphones, which therefor need to be designed to have more retention. For users who use the earphones for concentration, are usually working or studying for multiple hours on end. For them higher retention is not needed, since they do not move around a lot. However, they do prefer better active and passive noise cancelling, to filter a way environmental noise which could distract from the task at hand.

- *Enjoyment and relaxation were in nearly all cases named for listening and is the primary function of the earphone.*
- *Concentration is the second most mentioned reason for use. Which also takes up a lot of hours of many users during the day. 8 of the 15 Participants who filled in concentration as reason of use, also ranked active noise cancelling and sealing in their top 3.*
- *In case participants indicated to wear the earphones while exercising, retention was placed 6 times (out of 14) in the top 3, never at first place however.*
- *As exercise participants listed either the gym, Running or Cycling.*
- *Main reasons for using earphones while traveling is to shut out other noise and to make the trip more enjoyable*

Reasons for choosing Personalised options



What :

- *Earplugs*
- *Wired earphone*

Why :

- *Non-standard body size*
- *Ease of use*
- *For comfort / reduction of irritation*

Reasons for not buying wireless headphones.

- *They tend to fall out of the ears Fall out.*
- *In the participants opinion, Headphones produce better sound quality, and closed off the surrounding better.*
- *Losing an earphone is a problem.*
- *Forgetting to charge the earphones.*
- *Better bass levels.*

Reason for buying / satisfaction:

- *Convenience.*
- *The earphones break down less since the cords do not get tangled.*
- *Easy to use.*
- *Personalised sound options.*

Reason for owning multiple earphones:

- *Inside – outside*
- *Noise cancelling – no noise cancelling*
- *Work – private*
- *Airpods : “fall out less easily and are nice for a run since they are essentially open back”*
- *“Wireless earphones with ANC, deep fit isolation tips and a neck cable that I use while working with noisy tools, riding motorcycles, etc.”*
- *Reserve pair while charging the wireless ones*
- *Cheap(er) – better but (more) expensive when the risk of losing/damage is greater.*

Appendix C : Other use cases

Medical Student
Listening habit : [8h / day]
Maximum expected noise levels : 30 – 80 dB
(Directive 2003/10/EC - noise)

Needs for using wireless earphones:

- *Concentration during hospital shift*
    - *Awareness of audio cues of alarms*
- *Watching lectures*
    - *2h uninterrupted*
- *running / gym*
    - *Should be resistant to sweat and rain. (option for cleaning)*
- *One earphone for multiple situations*
    - *Does not want to spend a lot of money for multiple devices.*
- *Likes to keep track of performance.*
- *Afraid of losing the earphones*
    - *Tracking sensor*

… is studying medicine. This means that as part of their studies, they needs to do hospital shifts, which can have a huge time variance. When scheduled for a night shift, they like to keep the focus on non-medical-related tasks by listening to music. In this case, it remains vital for the care of the patient that they can hear the alarm of a monitor going off. Before their shift begins, they try to go running at least 3 times a week to keep in shape. When it is raining, instead of running … goes to the gym next to the hospital, however, they do not like the taste of the person in charge of the music. In both cases, they are interested to keep track of his heart rate.

Musician
Age : 30
Listening habit : [4 – 12 h/ day]

Reason for use :

- *Plays the drums in a band.*
- *The band is well known in the region and performs live concerts.*
- *On the side he started his own Drum school to teach kids the joy of playing music.*
- *Was early on aware of the danger of tinnitus and therefor already uses personalised hearing protection.*
    - *Owns a pair of personalised wired IEM for live performances.*
    - *Uses personalised hearing protection when teaching and practicing tobe able to listen to the sound of his student/ other band members (and music from the boxes)*

Blue collar worker
Age : 56
Listening habit : [4 h/day]

Reasons for use:
- *Surrounded by noise on daily a basis.*
- *Needs hearing protection.*
- *Does repetitive tasks and likes to listen to music/radio to keep entertained.*
- *Hearing is beginning to be diminished.*
- *Still needs to be able to talk to co-workers in the noisy environment.*
- *Drives a motorcycle.*
    - *Needs good sealing as a shield for outside noise.*

High-end audio
Age : 61
Listening habit : [2]

Reason for use :

- *Main purpose is to enjoy music.*
- *Takes time out of the day to sit down music.*
- *Spends large sums of money on earphones.*
- *Expects the highest quality of audio and comfort*
    - *Prefer wired earphones due to quality (source Ears unlimited)*

Appendix D : General requirements

Performance

- *The earphones should be able to survive 5 years . (Dopple)*
- *After 5 years the*
- *The earphones should be able to survive 10 x 1820 use cycles (1 use cycle = putting the earphone in and out the ear). (reasoning : use 5 days a week, 10 use cycles / day)*
- *Hours of use … FIXME for flexible materials*
- *The E-module does not separate from the shell after a fall of 1.80 m. (requirement dopple)*
- *The shell of the product does not damage after dropping 17 times from a hight of 180 m.*
- *After 5 years of use the product still does not damage after dropping from a height of 1.80 m.*
- *The battery should last at least 8 h on one charge when playing music. (UE drop)*
- *The Battery should last at least 4 h voice call time. (UE drop)*
- *After 5 minutes charging the earphones should be able to play music for 1 h. (UE drops)*
- *The connection is not interrupted while listening, within a radius of 10 m of the streaming device. [Check UE]*
- *The maximum sound pressure is 110 db at 500 Hz. (UE drops)*
- *The earphones can be connected to 2 devices at the same time. (UE drops)*

Environmental influences

- *The earphones dissipate enough heat to prevent the user from feeling discomfort. (Vink & Hallbeck, 2012). ((Yan et al., 2022) : "thermal comfort of the external ear is yet to be examined out of scope)*
- *Should be watertight up to IP 57 (dust protected & temporary emersion in water for 30 min)*
- *The product is rinsible. (Requirement By Dopple)*
- *The product can be cleaned by the user themselves. (Requirement By Dopple)*

Maintenance

- *The Electric components can be separated from the shell. (EU legislation: repairability)*
- *The shell can be replaced.*

Target costs

- *The cost price of the Earphones is €400,-. (Requirement Dopple)*

Quantity

- *The earphone shell can be generated in the parametric model using scan data or AI prediction.*

Size and weight

- *The earphone must fit in the cradle. (Requirement Dopple)*
- *The earphone must make contact with the charging pins in the cradle. (requirement Dopple)*
- *The earphones have a minimal offset of 0.5 mm.*
- *The earphones have a maximal audio canal length of 6.5 mm.*

Aesthetics

- *Does not stick out of the ear more than 5 mm above the tragus point.*
- *Surface look can be determined by the user. (Requirement Dopple)*

Materials

- *Restriction of the use of certain Hazardous Substances Directive (RoHS/RoHS2) (2011/65/EU)*
- *General Product Safety Directive (2001/95/EC)*
- *The materials should be biocompatible.*

Ergonomics

- *The earphones distribute the pressure evenly over the concha. (comfort)*
- *It is clear to the user how the earphones should be positioned in the ears.*
- *Difference between the Left and Right is clear. (Cognitive ergonomics)*
- *The orientation from the top and bottom of the product is clear.*
- *After 5 uses cases, the user is able to place the product in the ear without complications.*

User requirements

- *The earphones provide active noise cancelling at least to 15 dB of (mid to high range) sound.*
- *In a standard office the average noise is between 50-60 dB. For concentration noise level of maximum 40 dB is preferred. (Lundquist et al., 2003)*
- *The earphones have a transparency mode for hearing the surrounding sounds.*
- *The earphones should still comply with the use case after 5 years of use. (ear growth)*

- *The earphones do not exceed the pressure discomfort level on the wall of hearing canal of the user. (28 N/m^2) (Yan et al., 2022)*
- *The earphones do not exceed the pressure discomfort level on the wall the concha of the user. (34 N/m^2) (Yan et al., 2022)*
- *The earphones do not exceed the pressure discomfort level on the wall the anti- helix of the user. (18 N/m^2) (Yan et al., 2022)*

Office worker

- *Earphones cause no noticeable discomfort after 2 hours of consecutive wearing. (Average concentration use questionnaire)*
- *The earbuds do not shift position during 20 minutes of walking. (Persona)*

Dancer

- *The earphone allows for a constant pressure within the hearing canal.*
- *The earphone allows the user to dance for 30 minutes without the earphones losing their retention (falling out of the ear). (Persona)*
- *The earphones are sweat resistant. (Persona)*
- *The earphones allow for control on device. (Persona)*

(EU) Standards, Rules & regulations

- *The earphones shall not generate or be affected by any electromagnetic disturbances. (standard : EN 301 489-17)*
- *Compliant with Radio Equipment Directive (RED). (2014/53/EU)*

Programme of wishes :

1. *The earphone is as comfortable for as long as possible.*
2. *The earphones look personalised.*
3. *The earphone stays in the ear of the user regardless of their movements.*
4. *The Functionality/performance of the earphones is predictable.*
5. *The earphone is easy to clean by the users themselves.*
6. *The earphone can easily be inserted in the ear of the user.*

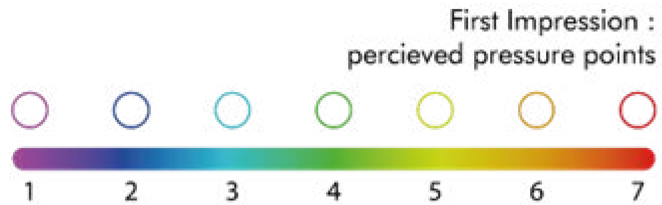
General wishes :

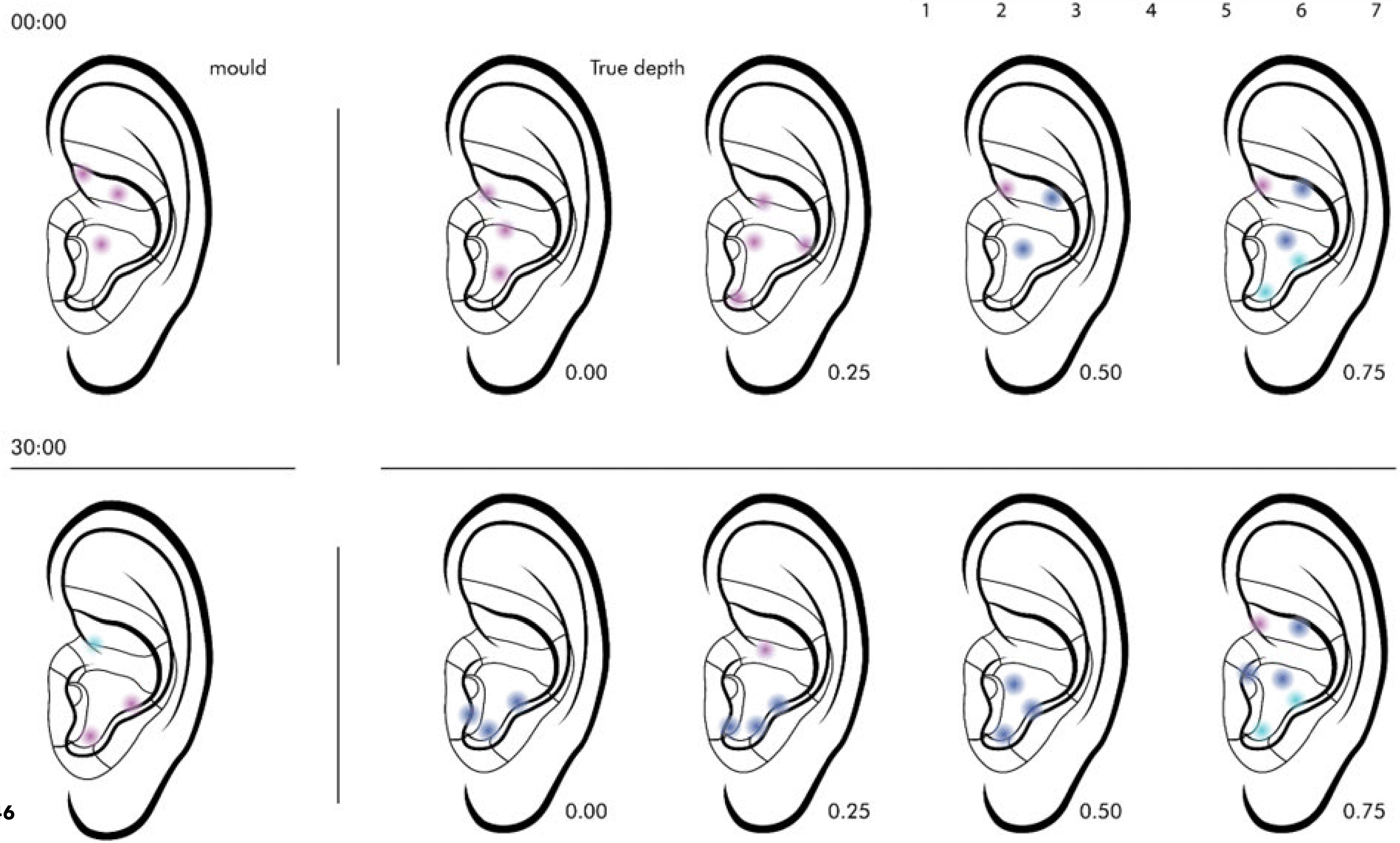
1. *The shell / tip can be changed by the users themselves.*
2. *The earphones are as light as possible. (Song et al., 2020)*
3. *(no particular influence, materials are roughly the same, main weight is determined by the e module)*
4. *The E-module is as flush as possible with the outer edges of the ear as possible. (Wish Dopple)*
5. *The concepts focus on the connection to the audio canal therefor this wish does not influence the decision for the concepts.*
6. *The earphones provide enough noise cancellation in any use case.*
7. *(future recommendation with the current prototyping possibility it was not possible to fabricate a representative seal tip for the short. Therefore, sealing could not be properly evaluated for the concepts. this should be done in future research.)*
8. *The earphones provide the user with as much passive Sealing as possible.*
9. *(also for future recommendations)*
10. *Customers can change the retention of the earphones. (Use cases) (currently redundant)*

Appendix E : Pressure maps

SLA prints

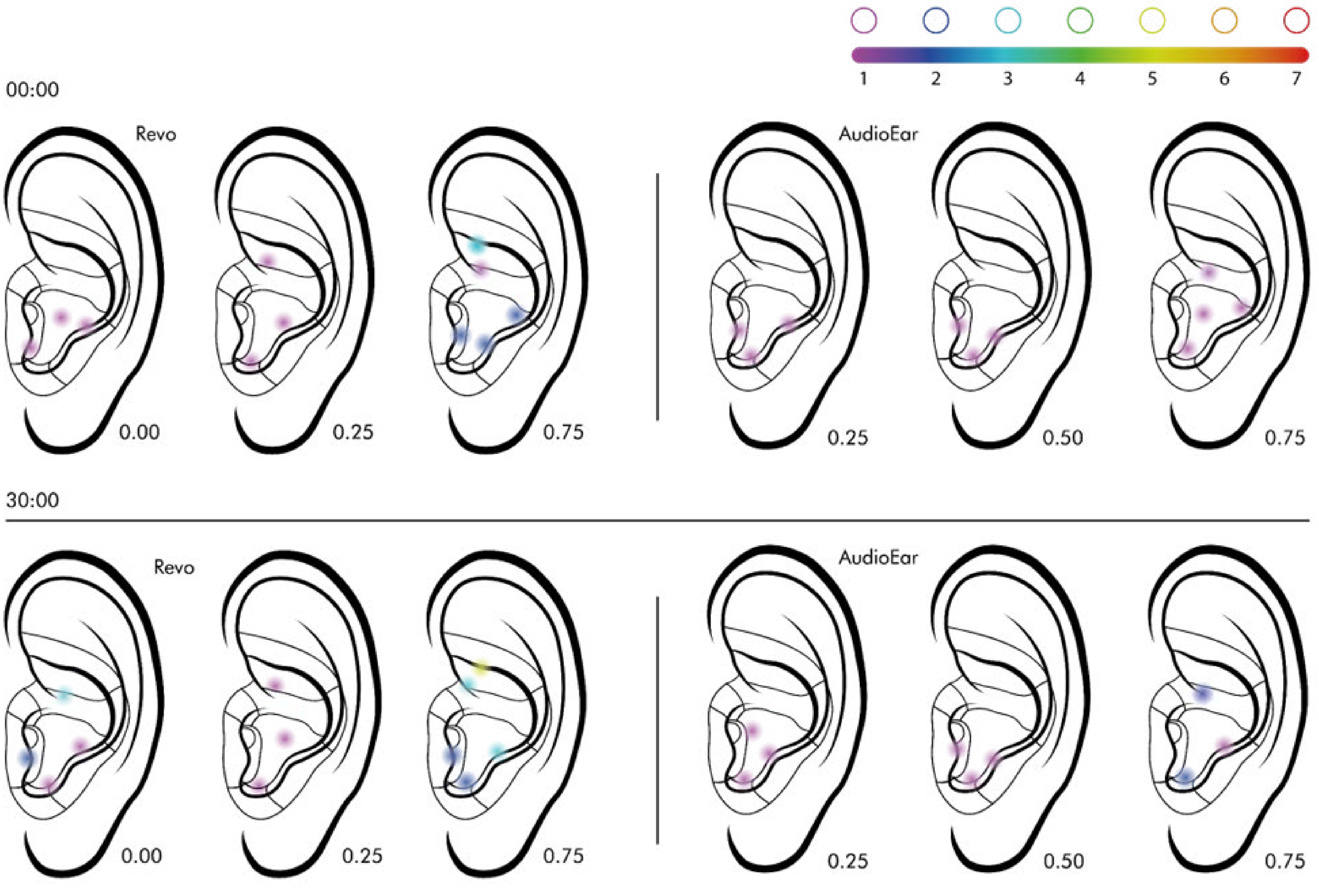
E.1. Pressure maps of different offsets



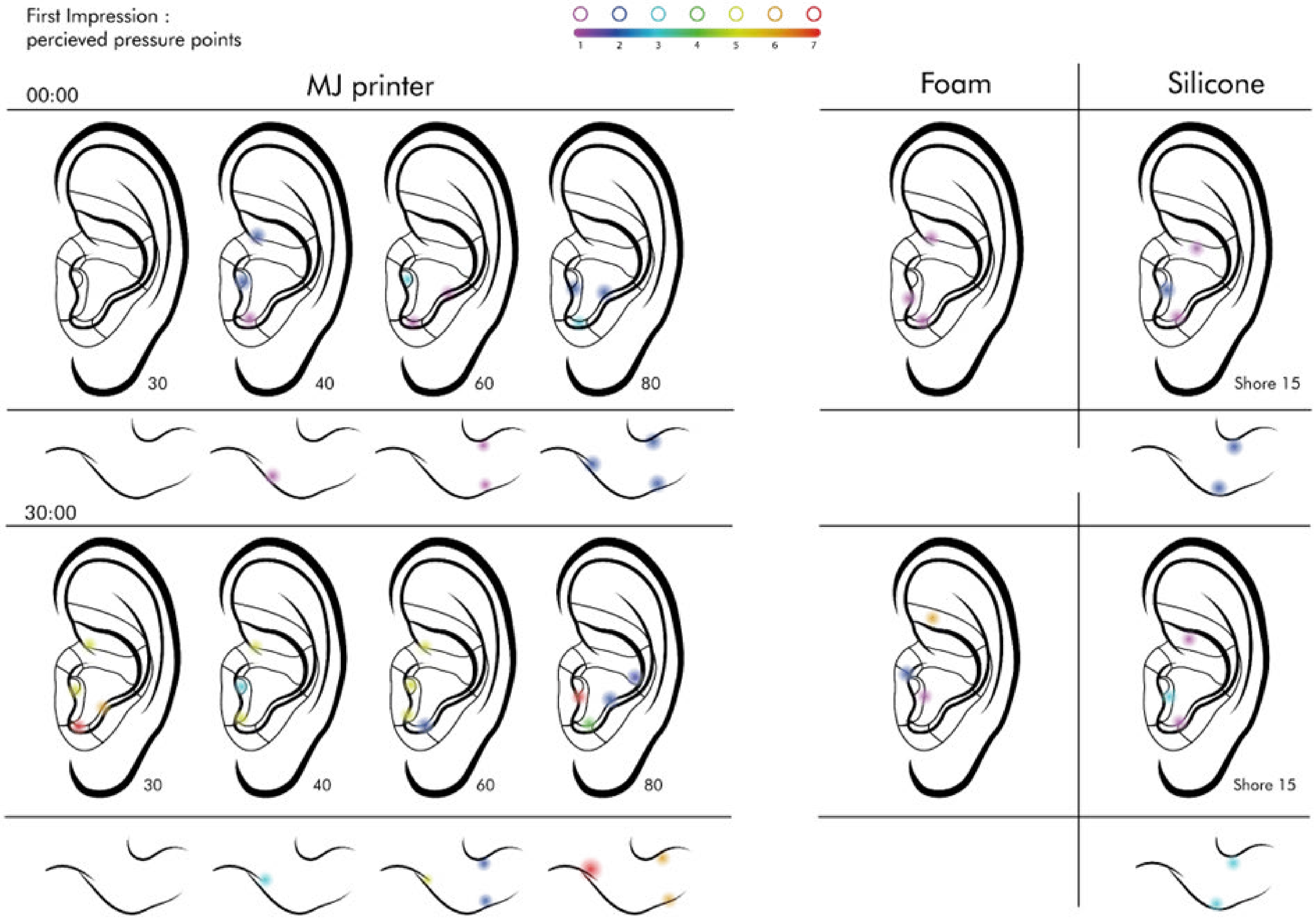


SLA prints

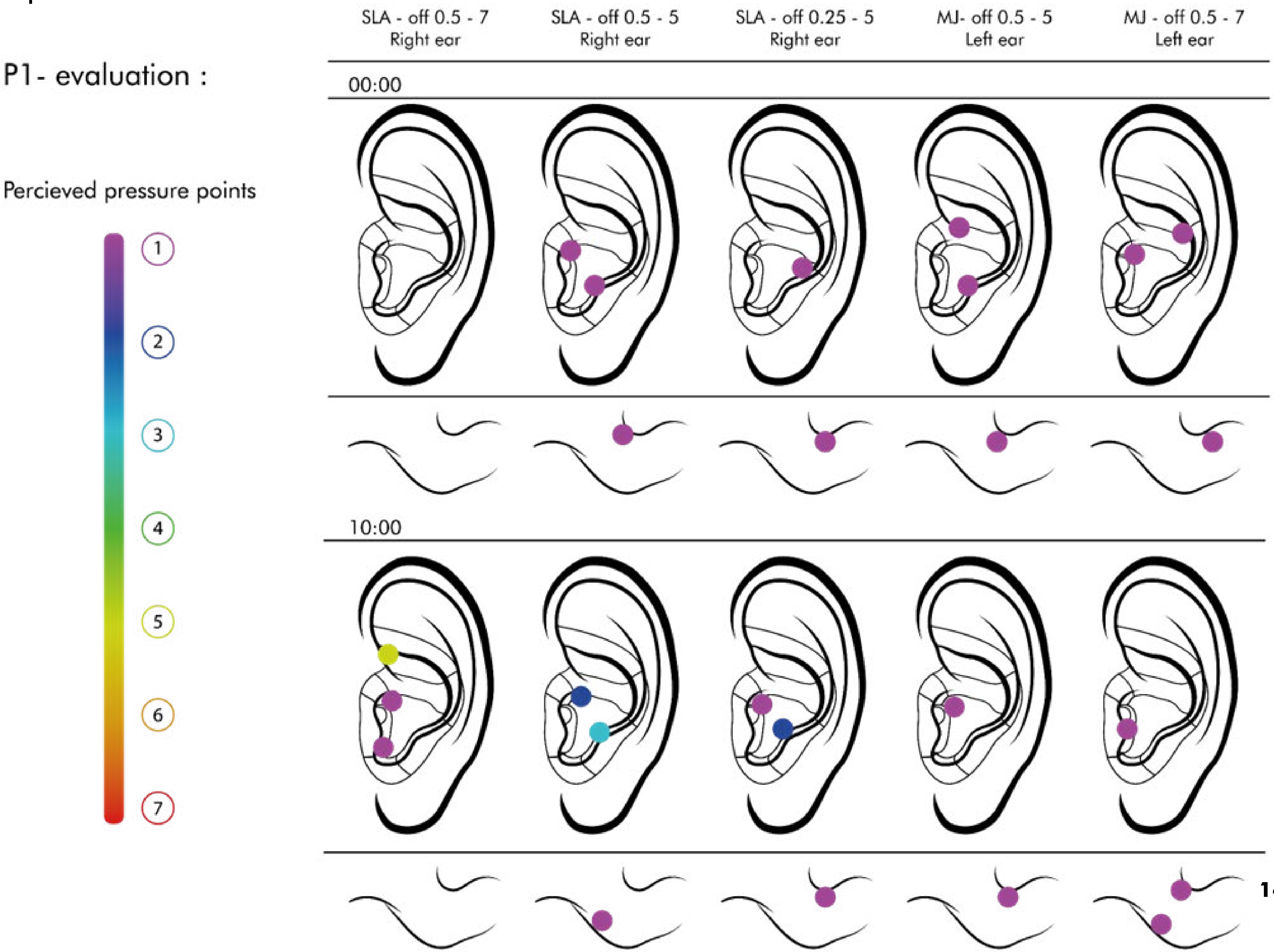
First Impression :
percieved pressure points

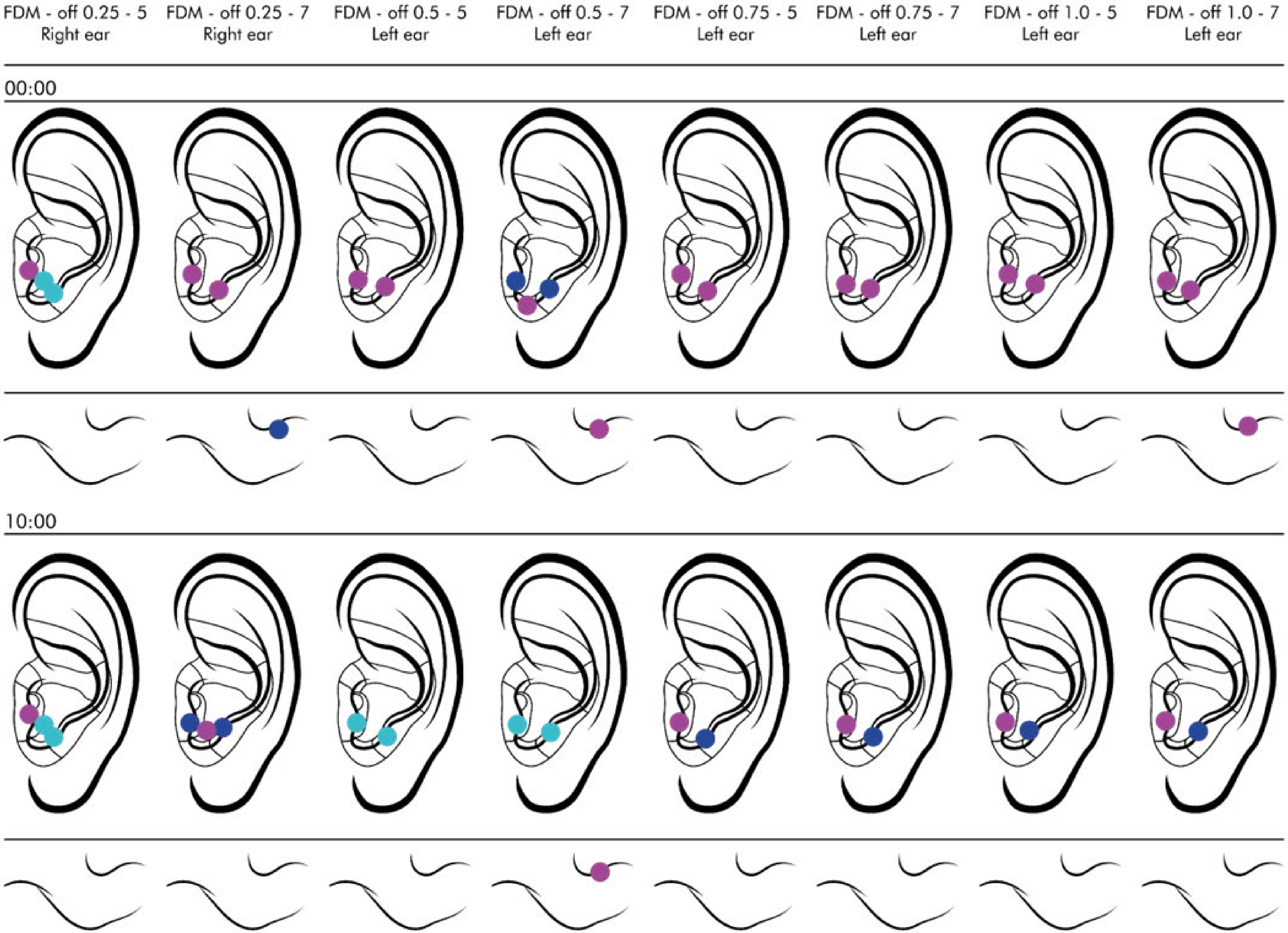


E.2. Pressure maps of different materials



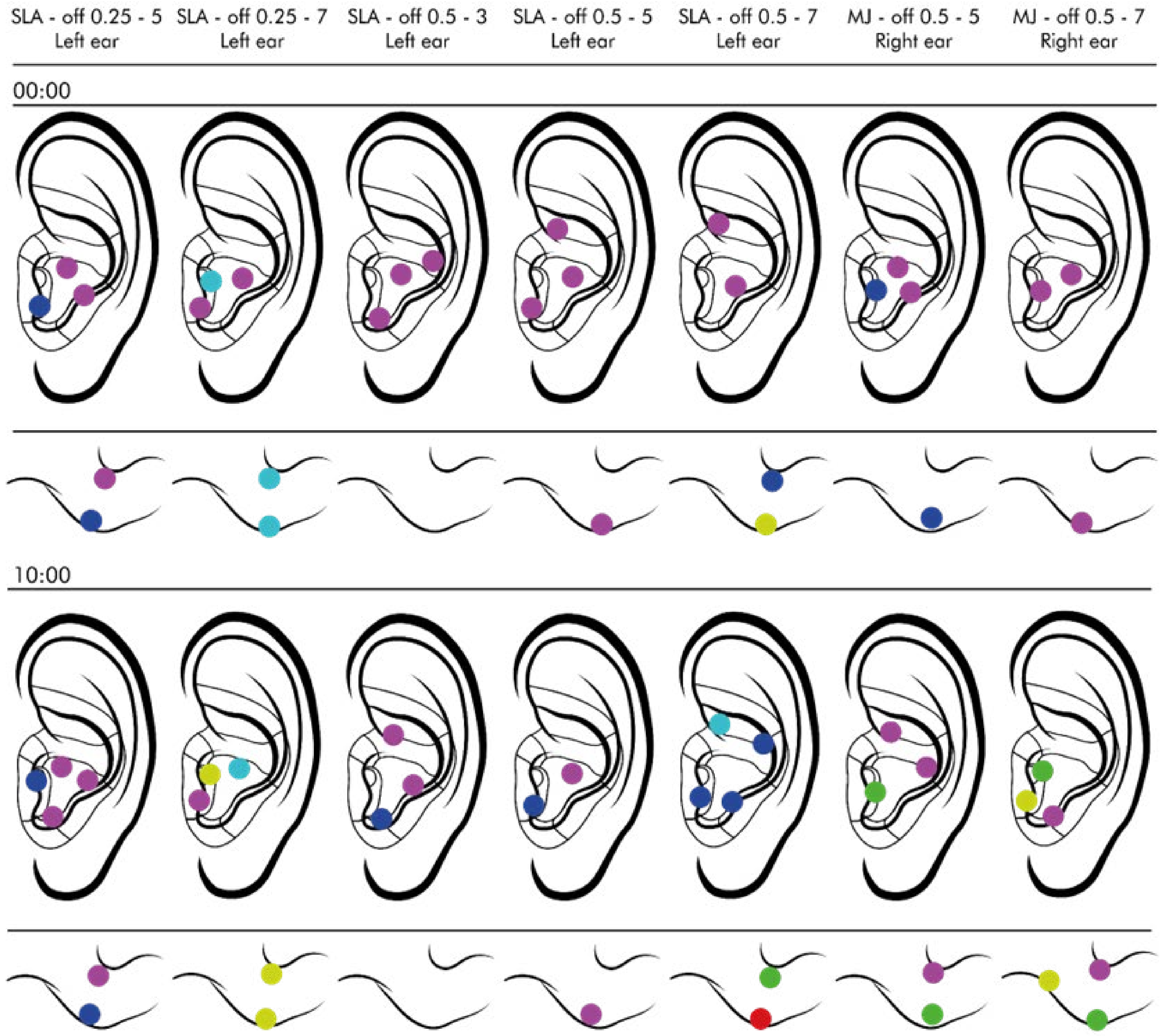
E.3. Pressure maps of different scan methods




FDM - off 0.25 - 5 Right ear
FDM - off 0.25 - 7 Right ear
FDM - off 0.5 - 5 Left ear
FDM - off 0.5 - 7 Left ear
FDM - off 0.75 - 5 Left ear
FDM - off 0.75 - 7 Left ear
FDM - off 1.0 - 5 Left ear
FDM - off 1.0 - 7 Left ear
00:00
10:00

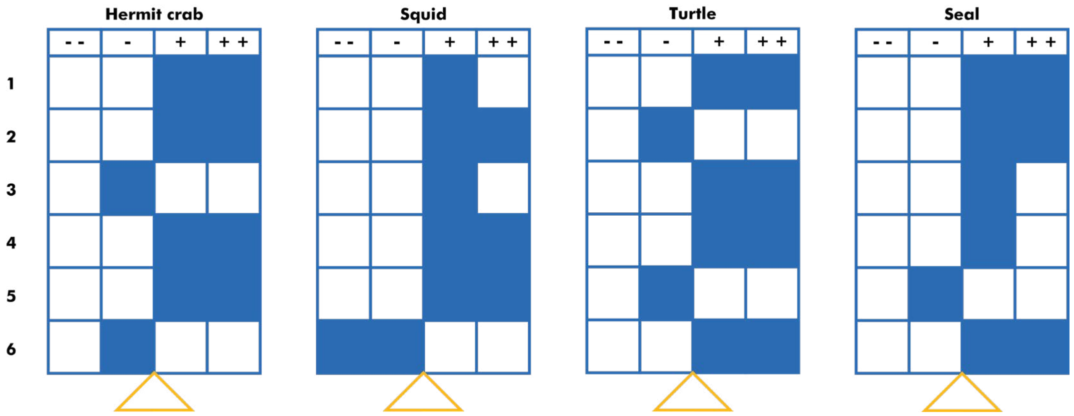
P3 - evaluation :

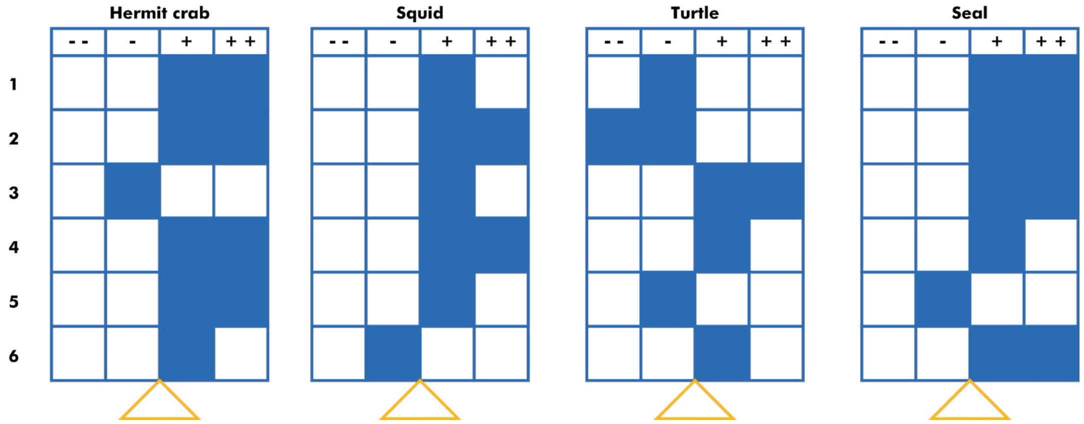
Percieved pressure points



Appendix F : Concept Choice

F.1. Harris profile





F.2. Weighted calculation

Dopple

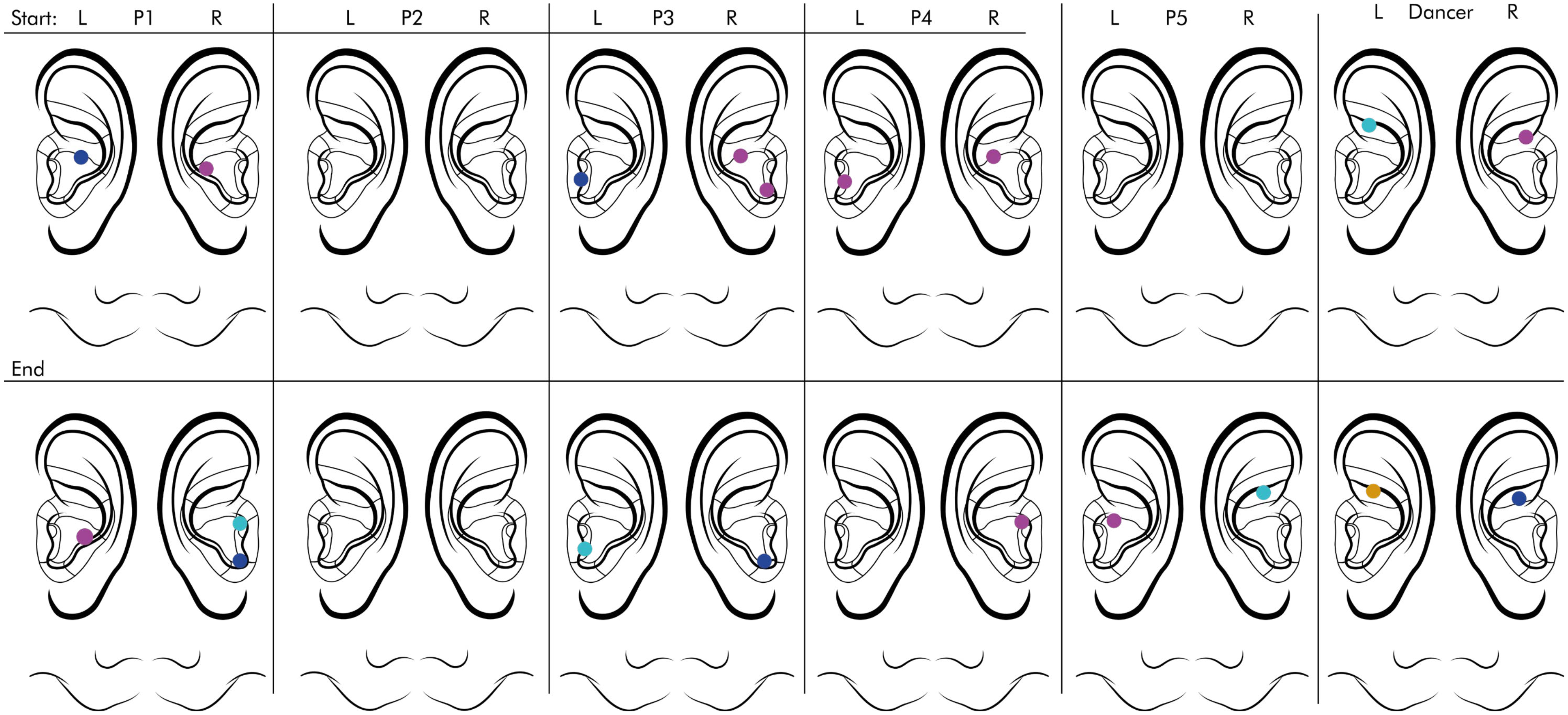
weight	hermit		squid		turtle		seal	
1.00	2	2.0	1	1.00	2	2.00	2	2.00
0.83	2	1.7	2	1.67	-1	-0.83	2	1.67
0.67	-1	-0.7	1	0.67	2	1.33	1	0.67
0.50	2	1.0	2	1.00	2	1.00	1	0.50
0.33	2	0.7	2	0.67	-1	-0.33	-1	-0.33
0.17	-1	-0.2	-2	-0.33	2	0.33	2	0.33
	6	4.5	6	4.67	6	3.50	7	4.83

Ruben

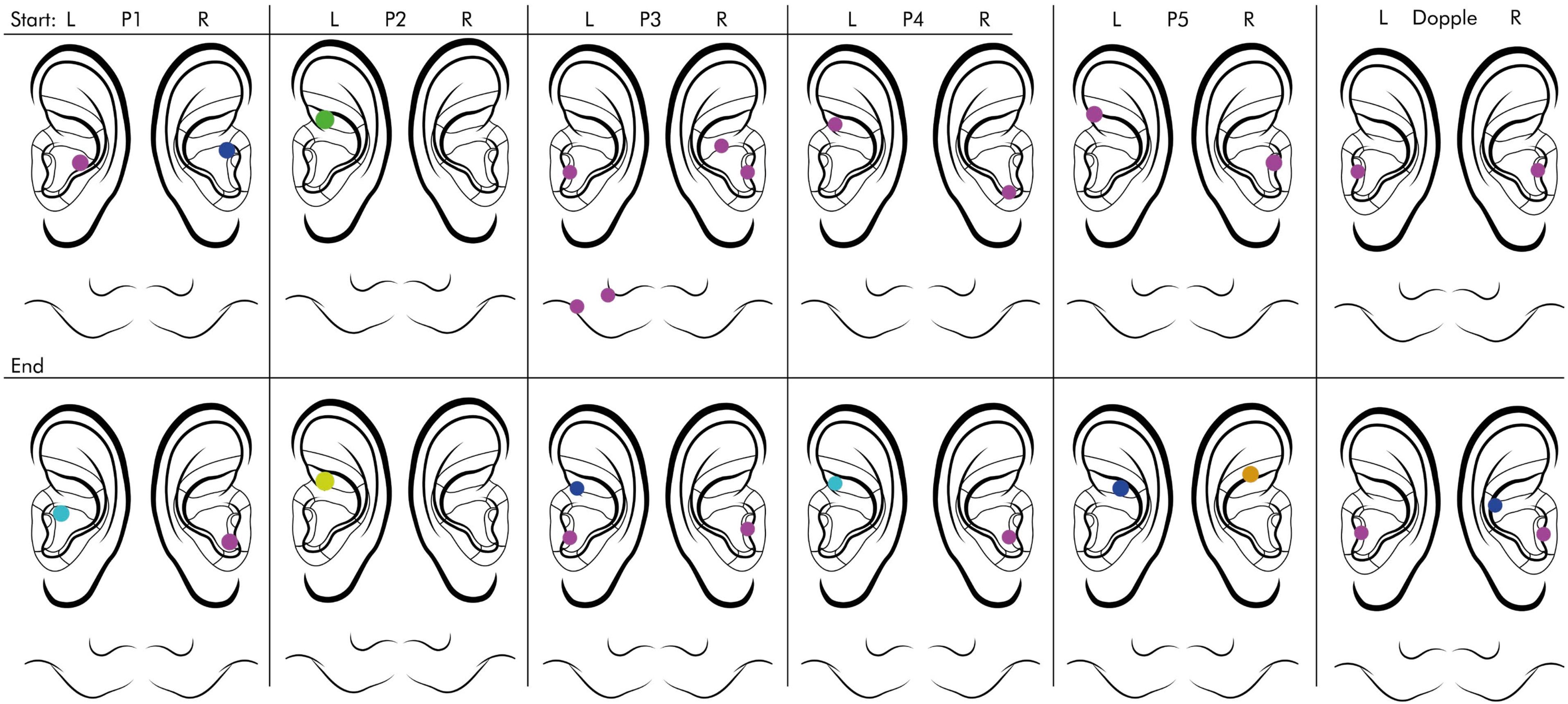
weight	hermit		squid		turtle		seal	
1.00	2	2.00	1	1.00	-1	-1.00	2	2.00
0.83	2	1.67	2	1.67	-2	-1.67	2	1.67
0.67	-1	-0.67	1	0.67	2	1.33	2	1.33
0.50	2	1.00	2	1.00	1	0.50	1	0.50
0.33	2	0.67	1	0.33	-1	-0.33	-1	-0.33
0.17	1	0.17	-1	-0.17	1	0.17	2	0.33
	8	4.83	6	4.50	0	-1.00	8	5.50

Appendix G : Prototype evaluation

G.3. Heat maps - Dancing



G.4. Heat map - Concentration



G.4. CP 50 scale

Absolutely agree	.
	52
	51
Strongly agree	50
	49
	48
	47
	46
	45
	44
	43
	42
	41
Somewhat agree	40
	39
	38
	37
	36
	35
	34
	33
	32
	31
Neither agree nor disagree	30
	29
	28
	27
	26
	25
	24
	23
	22
	21
Somewhat Disagree	20
	19
	18
	17
	16
	15
	14
	13
	12
	11
Strongly disagree	10
	9
	8
	7
	6
	5
	4
	3
	2
	1
Absolutely disagree	0

G.5. Comfort Scores

	Select the start Letter(s) of your Name to identify your self:	Y	Ro	Ro	T	T	Ru	Ru	L	L				
	Do you notice a significant difference between your left and right	no	yes	yes	yes	yes	yes	yes	yes	yes				
	Indicate Which Ear you are evaluating :		Right	Left	Left	Right	Left	Right	Left	Right	over all avg.		avg left	avg right
1	The prototype feels soft to the skin.	35.00	42.00	42.00	40.00	41.00	46.00	46.00	33.00	37.00	40.22	between "somewhat agee" and "strongly agree"	39.20	40.20
2	I feel that the prototype is luxurious	36.00	37.00	26.00	37.00	32.00	31.00	31.00	25.00	22.00	30.78	between "somewhat agree" and "neither	31.00	31.60
3	The prototype feels relaxed in my ear.	47.00	41.00	20.00	27.00	42.00	37.00	44.00	36.00	26.00	35.56	middle of "somewhat agree"	33.40	40.00
4	The prototype feels refreshing in the ear.	46.00	27.00	26.00	31.00	36.00	42.00	43.00	26.00	19.00	32.89	lower side of "somewhat agree"	34.20	34.20
5	The prototype feels pleasant in my ear.	45.00	46.00	15.00	22.00	41.00	40.00	46.00	38.00	14.00	34.11	middle of "somewhat agree"	32.00	38.40
6	I am content with the prototype.	41.00	44.00	13.00	33.00	44.00	38.00	48.00	40.00	19.00	35.56	middle of "somewhat agree"	33.00	39.20
7	I feel at ease while wearing the prototype.	46.00	40.00	11.00	40.00	44.00	43.00	46.00	36.00	15.00	35.67	middle of "somewhat agree"	35.20	38.20
8	The prototype feels comfortable in the concha.	37.00	42.00	43.00	19.00	38.00	48.00	43.00	35.00	36.00	37.89	higher side of "somewhat agree"	36.40	39.20
9	The prototype feels comfortable in the Cymba concha.	31.00	42.00	15.00	43.00	42.00	38.00	48.00	35.00	11.00	33.89	middle of "somewhat agree"	32.40	34.80
10	The prototype feels comfortable in the auditory canal.	46.00	39.00	26.00	40.00	43.00	47.00	46.00	35.00	40.00	40.22	between "somewhat agee" and "strongly agree"	38.80	42.80
11	I feel restless because of the Prototype.	17.00	9.00	30.00	9.00	6.00	16.00	4.00	11.00	35.00	15.22	middle of "somewhat disagree"	16.60	14.20
12	I feel fatigued because of the prototype.	4.00	5.00	11.00	13.00	1.00	14.00	5.00	6.00	30.00	9.89	between "somewhat disagee" and "strongly disagree"	9.60	9.00
13	I feel a strain on my ear because of the prototype.	17.00	8.00	10.00	32.00	2.00	12.00	9.00	10.00	33.00	14.78	middle of "somewhat disagree"	16.20	13.80
14	The prototype causes my ears to ache.	12.00	4.00	8.00	32.00	10.00	34.00	8.00	18.00	35.00	17.89	higher side of "somewhat disagree"	20.80	13.80
15	The prototype makes my ears feel numb.	11.00	5.00	6.00	5.00	1.00	5.00	6.00	3.00	15.00	6.33	middle of "strongly disagree"	6.00	7.60
16	The earphones feel heavy.	2.00	3.00	29.00	1.00	4.00	4.00	3.00	8.00	12.00	7.33	higher side of "strongly disagree"	8.80	4.80
17	The pressure is evenly distributed over my ear	31.00	45.00	8.00	4.00	40.00	21.00	47.00	36.00	9.00	26.78	middel of "neither"	20.00	34.40
18	The prototype hurts my ear.	8.00	4.00	3.00	24.00	1.00	20.00	0.00	5.00	39.00	11.56	lower side of "somewhat disagree"	12.00	10.40
19	The product feels secure within my ear for the given use case.	45.00	45.00	15.00	44.00	41.00	50.00	50.00	39.00	35.00	40.44	between "somewhat agee" and "strongly agree"	38.60	43.20
20	The prototype gives me the feeling that it will stay in my ear when	40.00	48.00	13.00	39.00	43.00	50.00	48.00	42.00	38.00	40.11	between "somewhat agee" and "strongly agree"	36.80	43.40
21	The contact between the prototype and my skin feels appropriate	45.00	46.00	15.00	43.00	41.00	40.00	44.00	43.00	40.00	39.67	between "somewhat agee" and "strongly agree"	37.20	43.20
22	The size of the shell feels appropriate in my concha (&cymba con	47.00	43.00	15.00	42.00	44.00	44.00	47.00	30.00	25.00	37.44	higher side of "somewhat agree"	35.60	41.20
23	The sealing collar feels appropriate in my ear.	31.00	47.00	26.00	37.00	42.00	37.00	38.00	34.00	40.00	36.89	higher side of "somewhat agree"	33.00	39.60
		41.00	40.00	23.70	33.20	40.30	41.00	44.10	33.90	23.90	35.68		34.56	37.86
		10.14	5.43	13.86	16.57	3.57	15.00	5.00	8.71	28.43	11.86		13.75	13.50
		41.60	45.80	16.80	41.00	42.20	44.20	45.40	37.60	35.60	38.91		36.24	42.12

G.6. Reflection

Reasons for taking out the earphones :

P1 : +-20 "I took the earphones out every time I talked to someone"

P3 : 3 "once at lunch time, the other times I removed the earphones in order to have conversations with friends."

P4 : 2 "Just to have a conversation with a colleague and to go to the restroom, not because of discomfort."

P5 : 1 "After a while, the right ear started to hurt a bit so I wanted to see if I could move it a bit to stop this feeling"

Expert Dopple : 4 "I needed to talk to colleagues, there were no real problems with the prototype."

General Feeling towards the earphone :

P1: "You almost have the feeling that it is not in your ear, very light. The foam could have been glued to the model with a bit more care."

P3 : "The prototype feels nice in my ear, because of the soft texture to my skin and it does not exert pressure onto my ears. Furthermore, the earphones feel light and I hardly notice them when they are in my ears."

P4 : "The way the prototype feels in my ear is comfortable and light, because the prototype fit really well in my ears. The right earphone does fit slightly less, as I feel it more in the upper part of my ear. It does however not hurt."

P5: "My left ear felt good and I could have used it for longer. I am quite sensitive with things in and around my ear and my right ear started to hurt quite fast."

Expert Dopple : "The prototype feels good, comfortable and secure, because the fit is good, + I have a seal on both sides, however the seal on the right is better than the seal on the left. (--> Difficult to judge how much seal I actually have, however it feels similar as having 2 fingers in my ears.)"

Overall opinion :

P1 : "-"

P3: "The feel of the prototype is comfortable and little discomfort is generated. The prototypes lack sealing, therefor the bass is less powerful than I would like it to be and surrounding sounds are still audible. Compared to the UE Drops the audio quality is therefore less."

P4 : "The prototype fits my ears very well. These earphones are by far the most comfortable earphones that I've ever worn. Especially the fact that the prototype does not hurt my ears after extensively listening to music for more than 3 hours + is a big difference with my previous earphones."

P5: "I like that they are really steady but for my right ear there was just one point where it was hurting so in real life, maybe it has to be fitted with even more detail."

Expert Dopple : " Pleasantly surprised, feels good in fit and comfort.
"It provides a secure fit"
"Also good looking prototype."
"specifically the combo of the ear canal entrance + sealing collar,
better looks than a current Bamboo (E-module)"

Remarks :

P3 : "The foam boarder tickles a bit. The audio lacks in base."

P4 : "I think I have two remarks to the prototype. First of all, because regular airphones often use buds that you push into your hearing canal the sound is a lot closer. Therefore, with the prototype you automatically have to set the volume slightly higher. With the volume set higher, the audio quality sometimes is less than I'm used to with regular airphones (currently using Sony).
Secondly, as the airphones are a lot lighter than I'm used to I find it scary sometimes to wear them as I'm afraid to lose them"

P5: "the quality of the sound is not too good."

Expert Dopple : "When heavily moving / nodding my head, it seems like the right earphone is moving a little, however it does not fall out and the seal remains!
It is more difficult to fit the left earphone. The right one fits immediately in its position. The left earphone only obtains a seal after additional adjustments (pulling at the back of the ear).
the seal seems to remain also when chewing."

TU Delft

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair Toon Huysmans date - - signature Toon Huysmans Digitally signed by Toon Huysmans Date: 2023.03.18 07:03:11 +01'00'

CHECK STUDY PROGRESS
To be filled in by the SSC E&SA (Shared Service Center, 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: 25 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 25 EC

List of electives obtained before the third semester without approval of the BoE

★ YES all 1st year master courses passed

NO missing 1st year master courses are:

name Robin den Braber date 27 - 03 - 2023 signature Robin den Braber Digitaal ondertekend door Robin den Braber Datum: 2023.03.27 08:37:06 +02'00'

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED NOT APPROVED

Procedure: ★ APPROVED NOT APPROVED

comments

name Monique von Morgen date 04 - 04 - 2023 signature

Initials & Name R. H. R. van Es 6371 Student number 4540786

Title of Project Design automation of semi-custom In ear monitors

Design automation of semi-custom In ear monitors — project title

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

start date 07 - 03 - 2023 — 08 - 08 - 2023 end date

INTRODUCTION **

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

Dopple focuses on providing mass customisation solutions for other companies. Through the means of translating products to AR and 3D experiences, customers can personalise products on the website and view them in their own homes. One of the products which Dopple has helped to develop are the EU drop wireless earphones. These wireless earbuds are fully personalised. This is done by creating a silicone mould of the outer ear with the hearing channel. For their new concept, Dopple wants to explore a new type of earbud which will be semi-personalised. The aim is to replace the physical mould with pictures of the customers' ear. With AI, the images(s) will be translated to a 3D model of the ear of the customer. By generating the model with an AI, the customer can directly see a preview of how the earphones will fit in their ear, before making the decision to purchase. Another advantage is that the scan data will already consist of virtual data points and can therefore be easier implemented into a parametrical CAD model.

More technologies are adopted into the everyday workflow of companies including AI, computer simulations and digital models. Therefore, it is becoming easier to produce personalised products for a large audience. Due to more automation in design processes and improvements in Additive Manufacturing (AM) techniques, it is possible to produce complex products in small to unique batch sizes. Furthermore, there is no delay to switch between the production of various products. This is not feasible with injection moulding that require high investment costs to produce specific tools. It even allows for a different approach to supply chain. Instead of producing large batches of a product and estimating the demand, an order driven approach can be taken. Selling products in low quantity batches or products that allow for customisation by the customer reduces wasting resources and risks. New AM techniques are being developed for printing flexible materials, such as silicones and printing multiple materials within the same print (Rossing et al., 2020), allowing a larger scale of design properties.

Personalization for products can be split up in three types: (1) Identity, which focuses on perception; (2) Capabilities, which focuses on functionality; (3) Fit, which focuses on the physical interactions (Minnoye et al., 2022). In this project, the focus will be on personalisation in fit, since it will focus on the shape and ergonomics of the product. Because the earbud will follow the contours and shapes of the body of the user, the product will not force its own form on the user and will thus feel more natural and comfortable to wear.

First, to get to a personalised model, the relevant parameters of the human body need to be collected. This data can either come directly from the customer by scanning or it could be generated using a digital model (Minnoye et al., 2022). The model can either be based on anthropometric measurements, 3D scanning, or a statistical shape model which finds overlapping geometries and compiles the models to an average shape and finds shape variations. A new way to generate personalised 3D data consists of AI trained with a database of 3D scans. By giving the programme 2D pictures (of an ear), it can approximate a 3D model based on the knowledge of the database (Huang et al., 2023). The second step is to generate a design based on the parametric human data, which is done with CAD programmes to help designers to visualise and define their design in 3D.

Most earbuds on the market fall into two categories. Earbuds with generic tips, often made of silicon or foam, are round and come into standard sizes. The standard size to fit most of the population well enough so the earbud will stay in the entrance of the hearing channel. Therefore, the tips can be mass produced with injection moulding. Personalized earbuds are expensive and time consuming because they require multiple steps (moulding and modelling). They are mainly used by musicians, people with hearing aids and people who are exposed to (loud) noise (above 85dB) over an extended period of time. However, it would be interesting to explore how personalized earbuds could provide a solution for a larger/different target group when the process efficiency will be improved through AI generated ear scans.

space available for images / figures on next page

Personal Project Brief - IDE Master Graduation

introduction (continued): space for images

image / figure 1: creation of a silicon in-ear mould

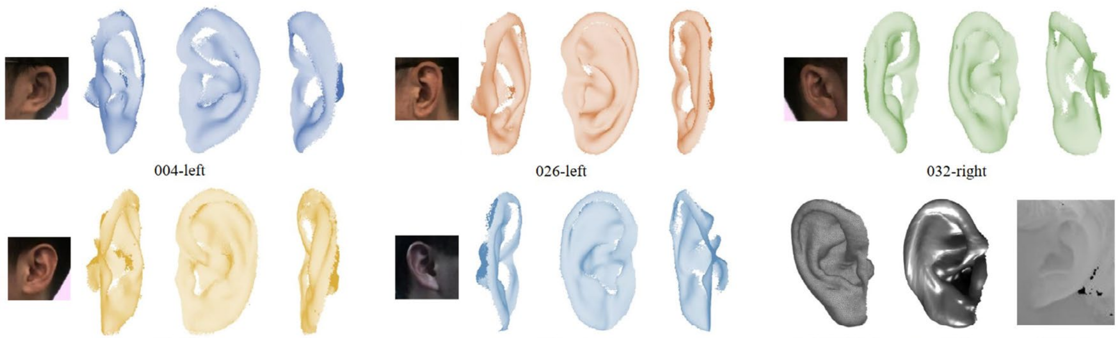


image / figure 2: AI generated ear scans of AudioEar3D

Initials & Name R. H. R. van Es 6371 Student number 4540786

Title of Project Design automation of semi-custom In ear monitors

PROBLEM DEFINITION **

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

Using AI to generate the 3D models of the ears will never give a perfect representation of the ear of the user. Pictures can give a good representation of the auricle, but it cannot provide information on the hearing channel. The generated model of the auricle also has limitations. Although the algorithm can be trained and improved to become more accurate over time, it remains an interpretation.
Currently, Dopple uses physical moulds to design the fully personalised earbuds. This is time and energy intensive. while automated digital representations of the ears could offer a solution for a quicker design process for (semi-) personalized earbuds.
The new concept needs to integrate the data of the Statistical ear model (TU/dopple), the 3D-scan data of an individual, which is generated based on the pictures made by the end user, and the electronics module with sensors from Dopple. This is the basis for a parametrical model in Rhino and Grasshopper. The model should fit comfortable to the ear of the individual customer.
The difference in representation of the generated model and the real ears, can be compared with the 3D-database of the TU based on the exact ear moulds. In comparing the outcomes, a rough margin of error can be determined. As a solution to mitigate the margin such as of soft materials, shape morphing, or multiple material will be implemented to provide the customer with comfort. The ear of the customer needs to be sufficiently sealed off from outside noise, while sitting comfortably in the ear of the user for long periods of time. Since the concept will integrate personalised data, the parametrical model should be set up in such a way that the scans can be easily interchangeable with one another. By making the design parametric the design which can interchange 3D models of different customers, the design process can be automated reducing the work load of the engineers. This would mean that the product and be produced cheaper. By including AM, human intervention could even be obsolete. In
However, due to the uncertainties within the AI generated model, solutions might make use of soft or multi-material, but methods of producing these materials with AM are still being researched and developed.

ASSIGNMENT **

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

The goal of the thesis will be to develop a concept for a semi-personalised earbud, which integrates the in-ear database, the individual 3D "scan" data and the electronical module from Dopple. The model should be easy to adapt for every individual and feel comfortable within the ear of the user, while keeping a sufficient amount of retention and providing enough sealing form sound.

Overall, I will approach the project iteratively, meaning that I will make use of short design loops which includes prototyping in the early stages of the project. Prototypes will be a key factor to evaluate and incorporate findings for the result. In early stages, prototypes will mainly be tested on my own ears to provide quick feedback loops. When the concepts mature, I will test the ergonomic comfort, retention and sealing with 10 – 15 participants (depending on the target audience).

I will compare the generated ear data with actual scans of the same ear to determine how reliable the generated data is and how to mitigate these unreliability's with the design. Some interesting area's I would like to explore are shape morphing materials and multi-material 3D – printing.

The deliverables will include a prototype of the final concept, a report with the findings of my research and test results on the ergonomic comfort, and a parametrical model in Rhino and Grasshopper.

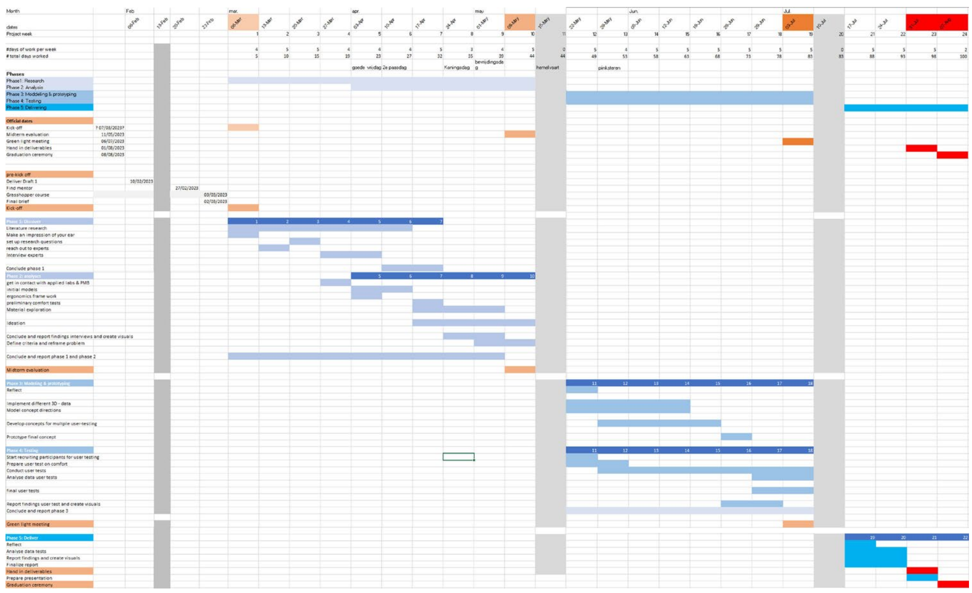
Initials & Name R. H. R. van Es 6371 Student number 4540786

Title of Project Design automation of semi-custom In ear monitors

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and 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 activities.

start date 7 - 3 - 2023 | 8 - 8 - 2023 end date



The start of the project is divided into two phases, which run to a certain extend parallel to one another. In the discovery phase, I will focus on gathering information through desk research, interviews and familiarizing myself with the software or grasshopper and Rhino. During the analysis phase, I will start with the first prototypes and tests. This will be done in short iterative feedback loops in the form of the double diamond method.

After the midterm I will continue to use physical prototypes to validate the shapes. However, during these phases I will use the input of multiple persons for modelling and validation of the shapes. Depending on my findings on ergonomic comfort, sealing and retention, I want to use different materials and production techniques to prototype, taking a material driven design approach.

The final phase will consist mainly of concluding all the findings into a written report.

Initials & Name R. H. R. van Es 6371 Student number 4540786

Title of Project Design automation of semi-custom In ear monitors

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

In primary school I started playing drums for the first time. I discovered the fun of playing along with the songs I love to listen to. It meant that I started to listen more to music in my spare time, while practicing new rhythms and beats. Therefor, I was more frequently exposed to loud music. Therefore, hearing protection also became more important. As protection I have used general earplugs of alpine. These reusable plugs consist out of silicone exterior with a hard plastic tube at the end. Although the plugs seal off the walls of the hearing channel, the plastic tube has a small hole to allow some sound to get through. This way the quality of the sound is better, but the level of noise is reduced. However, it often happened that my earplugs were not correctly inserted, and or became loose while plying. The round generalised shape of the plugs did not fit well enough within my ears.

The same thing happens when listening to music via earbuds. When listening to music I like to fully emerge myself in the music. But after a while my earbuds, all with generic tips, would loosen, allowing surrounding sounds to become more audible. For me this is a huge loss in listening experience. In that sense I often like my headphone better. However, headphones have other disadvantages, they are big and therefore harder to store and noticeable, they close off the ears completely, which over time causes discomfort due to heat, and due to their weight, they are not practical for running or other sports either. Therefore, I personally still prefer earbuds over headphones, due to their convenience.

During my minor in Hong Kong, I first came into contact with using 3D-scan data of body parts within design. Through this course, I became more interested in which way the products can be made to fit perfectly to the human body. I especially became interested in the combination of using Additive manufacturing for personalised products. This project will give me the opportunity to work on a design which will incorporate personalised 3D data, to be used in a parametric model, for which I will a new CAD software (rhino and grasshopper), and test different solutions and materials, such as for example AM technologies and shape morphing materials.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.