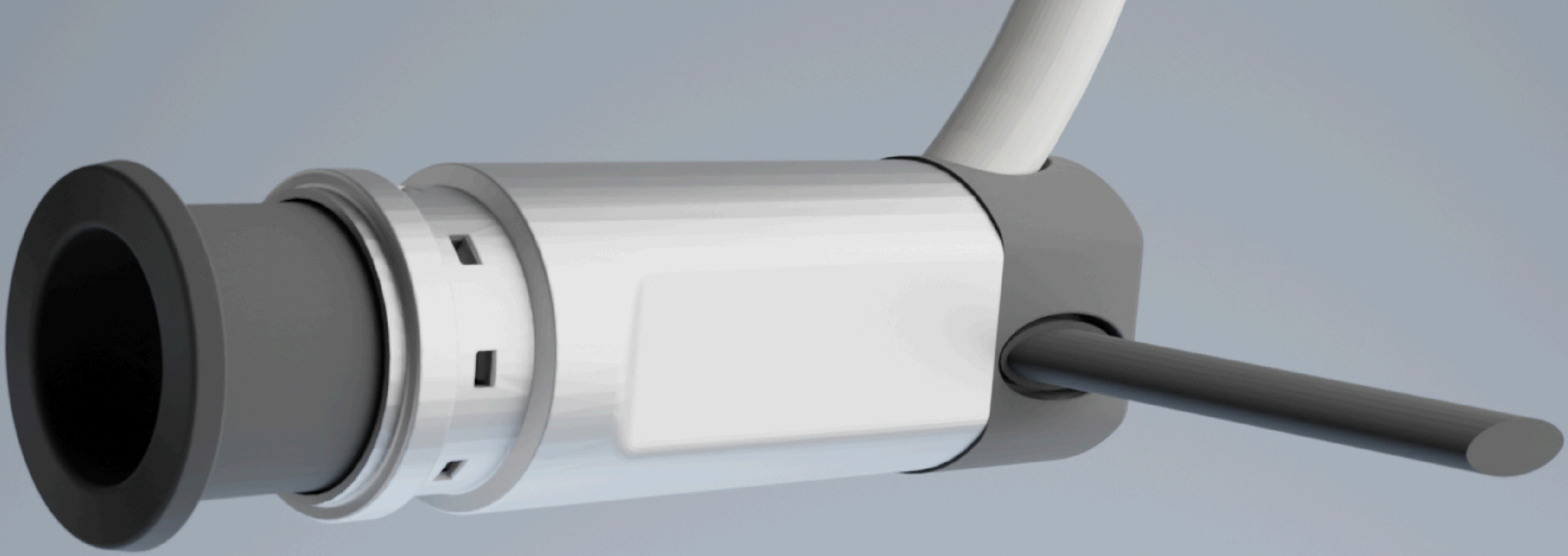
Adaptive Venting in Hearing Aids

Design of a Manual-Driven RIC Venting Mechanism



MSc. Thesis Report

Job Nuijen

Author

Job Nuijen
MSc. Graduation Thesis
March 2026

Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Graduation Committee

Dr. René van Egmond | Chair
Faculty of Industrial Design Engineering
Department of Human-Centered Design

Ir. Eur. Erg. Gonny Hoekstra | Mentor
Faculty of Industrial Design Engineering
Department of Human-Centered Design

Ir. Pieter Hermsen | Company Mentor
Principal Product Development Engineer
Sonion Netherlands

Preface

Dear reader,

I am proud to present my graduation report. This project was exactly what I was looking for, as it combined two areas I like working in; niche product development and user-centred design. Although I found it quite challenging to work within a confined design context, I enjoyed every second of it, and am proud to share that it resulted in an interesting, innovative solution for Sonion for future development.

Throughout this project, I created more miniature 3D-printed components than I ever did before. 3D printing small parts with a thickness of less than 0.50 mm continued to amaze me, both when these prints succeeded or accidentally failed.

I hope this report not only sparks your interest in niche product development or miniature design, but also offers a fresh perspective on hearing aids, as it did for me. Because for me, hearing aids are no longer designed solely for elderly people, but represent a complex and evolving field of design innovation.

Enjoy reading this graduation report, cheers!

Delft, March 2026
Job Nuijen

Acknowledgement

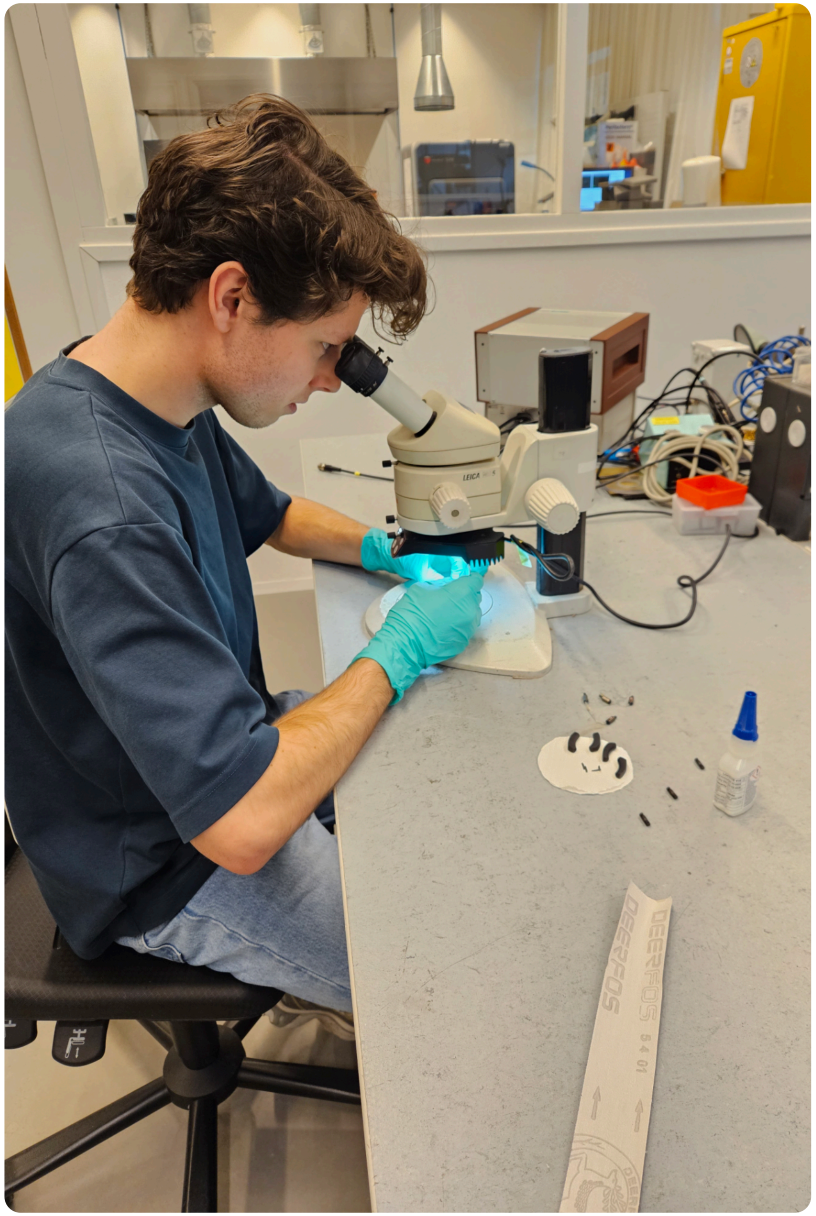
This result would not have been possible without the support of those who accompanied me throughout this project.

First, I would like to thank my TU Delft supervisors, René van Egmond and Gonny Hoekstra, for guiding me through this project. Your support during moments of uncertainty, along with your critical questions and constructive feedback, continuously challenged me and helped me push the project forward.

I would also like to express my gratitude to my colleagues at Sonion, in particular Pieter Hermsen, for welcoming me at Sonion and supporting me throughout the research and development process. Special thanks to my fellow interns at Sonion, Vijay, Nidia, and Max, for making my time there even more enjoyable and for the valuable sparring sessions. Vijay, thank you for the countless 3D-printed parts you produced for me, and for all the fun Ping-pong games shared together with Max, Bas, Jeroen, and Daniel.

Finally, I would like to thank my parents and brother for their continuous support and encouragement throughout this journey. I am also grateful to my friends and roommates, for the distracting conversations and discussions, the countless cups of coffee, and the moments of unwinding at ID Kafee.

Thank you all!



Me assembling 3D-printed parts for 1:1 scale prototypes at Sonion.

Table of contents

ABSTRACT

Today's hearing aids are more advanced than ever before. In addition to their primary function of selectively amplifying specific frequencies to improve speech intelligibility, modern devices increasingly suppress unwanted background noise and enable phone calls and music streaming via Bluetooth connectivity with smartphones.

Despite these advancements, hearing aids still require a trade-off between wearing comfort and acoustic performance. Soft, open-fit domes reduce the occlusion effect and improve wearing comfort and perceived sound naturalness. However, they allow low-frequency sound leakage, which negatively affects bass response during music streaming and reduces speech intelligibility in noisy environments. In contrast, closed systems enhance low-frequency amplification and noise control, but often cause discomfort due to occlusion.

The only commercialised product currently addressing this challenge is the Phonak ActiveVent, which automatically switches between open and closed vent states based on environmental sound analysis. Despite its innovative approach, the electronic miniature components required for the automated mechanism reduce cost-effectiveness and durability, while limiting user control. This graduation project addresses these limitations through the development of a more robust, user-friendly, manual open/closed venting mechanism for Receiver-in-Canal (RIC) hearing aids.

Through desk research, user interviews, iterative prototyping and testing, an innovative manual alternative was developed. Fugai, the final proposed concept, is a RIC hearing aid featuring a manual adaptive venting mechanism that allows users to actively control their listening experience across different acoustic environments. By integrating a manual mechanism rather than an automated one, the design enhances robustness and durability while improving cost efficiency. Providing direct user control further increases perceived reliability and usability.

As a result, Fugai presents an innovative RIC solution that balances user autonomy, ease of use, robustness and cost-effectiveness, without compromising acoustic performance.

Use of AI

This graduation project made use of AI tools, such as ChatGPT and Vizcom to help improve language and text flow, conduct quick initial research, organise ideas, and generate images. All content and conclusions remain the author's own, and critical analysis was conducted independently.

SET THE TONE

PROJECT INTRODUCTION

This chapter introduces the challenge this graduation project focuses on and provides the scientific background to understand its context and relevance. It outlines the project’s goal, scope and the corresponding research question. In addition, the chosen design approach and methodology that structure the research and development process are defined.

1

1.1 Project introduction

This graduation project focuses on the research and development of a user-friendly, manual-driven, open/closed venting mechanism for Receiver-in-Canal (RIC) hearing aids. The purpose of this mechanism is to provide users with direct and intuitive control over vent openness, enabling them to manually switch between two distinct acoustic states: (i) a closed, occluded state, optimised for music streaming, speech clarity and/or noise reduction, (ii) and an open state, which reduces occlusion effects and improves listening comfort in quieter environments.

1.1.1 The Receiver-in-Canal

The RIC is the most common hearing aid in today's market (Xu et al., 2017). Traditional Behind-the-Ear (BTE) hearing aids contain an earmould and house the microphone, receiver (also known as the speaker), amplifier, and battery behind the ear. Unlike the BTE hearing aids, RIC devices separate the receiver (1) from the main body (Figure 1.1). The receiver sits inside the ear canal, connected by a thin cable to the housing behind the ear (Figure 1.2). This allows the receiver to send amplified sound directly to the eardrum, improving listening comfort. (Natalizia et al., 2010). The thin cable and in-canal receiver make RICs both discrete and lightweight, which makes the wearing comfort feel more natural.

Furthermore, the receiver is typically capped with a open soft dome (2) or a vented earmould (Figure 1.1). This open-fit design improves ventilation as it allows low-frequency sound waves to travel naturally through the ear canal. In addition, it provides flexibility during jaw movement (Estes, 2020). The open-fit design therefore mitigates the occlusion effect; the effect where an individual feels 'plugged up', perceiving their own voice as hollow (Estes, 2020). This effect is more common with In-Ear devices, which house all components in the ear, where all components are located inside the ear, as they seal the ear canal more completely (Figure 1.3) (Estes, 2020).

However, creating a vent results in an open acoustic system, meaning low frequencies can enter and escape the ear canal due to their long sound waves. This leakage reduces low-frequency output, especially during music streaming where a closed system, with no ventilation, is more desired for better bass response.

Figure 1.1 RIC hearing aid (Phonak Audeo Fit, n.d.).

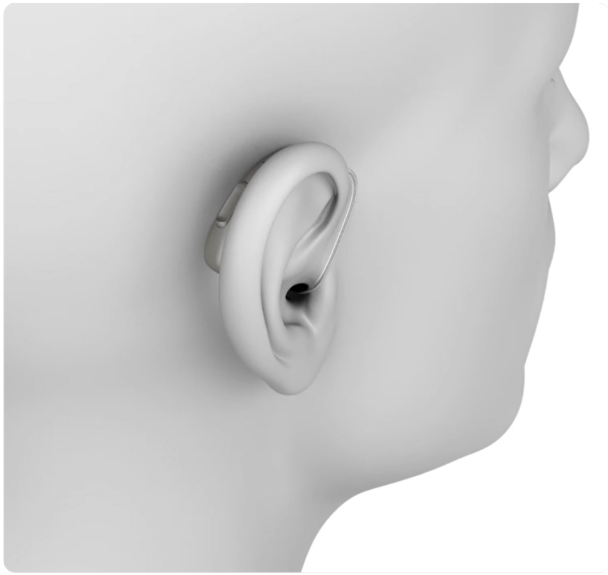


Figure 1.2 RIC hearing aid wearing position (Audio Service Hearing Aids, 2022).

Figure 1.3 In-Ear hearing aid blocking ear canal more completely (Oticon Canada, 2013).

1.2 Project scope and goal

This graduation project has been conducted in collaboration with Sonion (Sonion.com), a leading company in the research, development, and production of miniature components for hearing aids. Together with its competitor Knowles, Sonion plays a crucial role in advanced hearing aid technology, with their core business focusing on microphones and receivers.

The project specifically focus on the Phonak ActiveVent, developed by Sonion in collaboration with Sonova, one of the five largest hearing aids suppliers globally. The ActiveVent is a Valve-Receiver-in-Canal (VRIC), an advanced version of the traditional RIC, featuring an automatic valve mechanism in the RIC to dynamically switch between an open and closed system based on environmental sound conditions. This feature allows the hearing aid to balance wearing comfort when in open state, and sound performance when in closed state.

However, feedback from early adopters indicates that this solution still faces several limitations. It is relatively ***expensive*** and exhibits increased susceptibility to earwax and moisture due to its mechanism, making it more ***fragile*** and ***less reliable over time.*** Additionally, users report a ***lack of control*** over the autonomous behaviour, noting ***hearing discomfort*** and ***annoyance*** when the mechanism switches modes unexpectedly with an audible click; it distracts the users.

Ultimately, this reveals a clear gap in current hearing aid technology. There is a clear opportunity for improved venting solutions that maintain the benefits of ActiveVent while addressing its weaknesses: ***user autonomy, cost-efficiency, and reliability.*** This graduation project aims to explore and develop new design opportunities for adaptive venting mechanisms that enhance both the acoustic performance and everyday usability of VRIC hearing aids.

1.3 Project objective and design challenge

As a guideline for the research and development of this project, a research question has been formulated to define the project scope and objective. It provides a framework to ensure that technical performance, cost efficiency, user experience, and manufacturability are considered throughout the project. The research question is as follows:

Which manually operated opening/closing mechanism for VRIC hearing aids offers the best balance between user autonomy, ease of use, reliability and cost-effectiveness, without compromising acoustic performance?

1.4 Design approach

This project applied the Double Diamond methodology to structure the research and development process, which can be divided into four phases (van Boeijen et al., 2020). First, the context was discovered and explored through desktop research. Secondly, in the Define phase, these insights, together with insights from interviews with hearing aid users were drawn and structured the project's target group, design vision, and its functional and ergonomic requirements. Next, an explorative development phase involving ideation, and iterative concept prototyping was conducted. Finally, in the Deliver phase, the selected concept is presented and detailed. The final design outcome is validated to demonstrate its technical feasibility, usability, and desirability. Figure 1.4 shows the project's build-up with its relevant chapters.

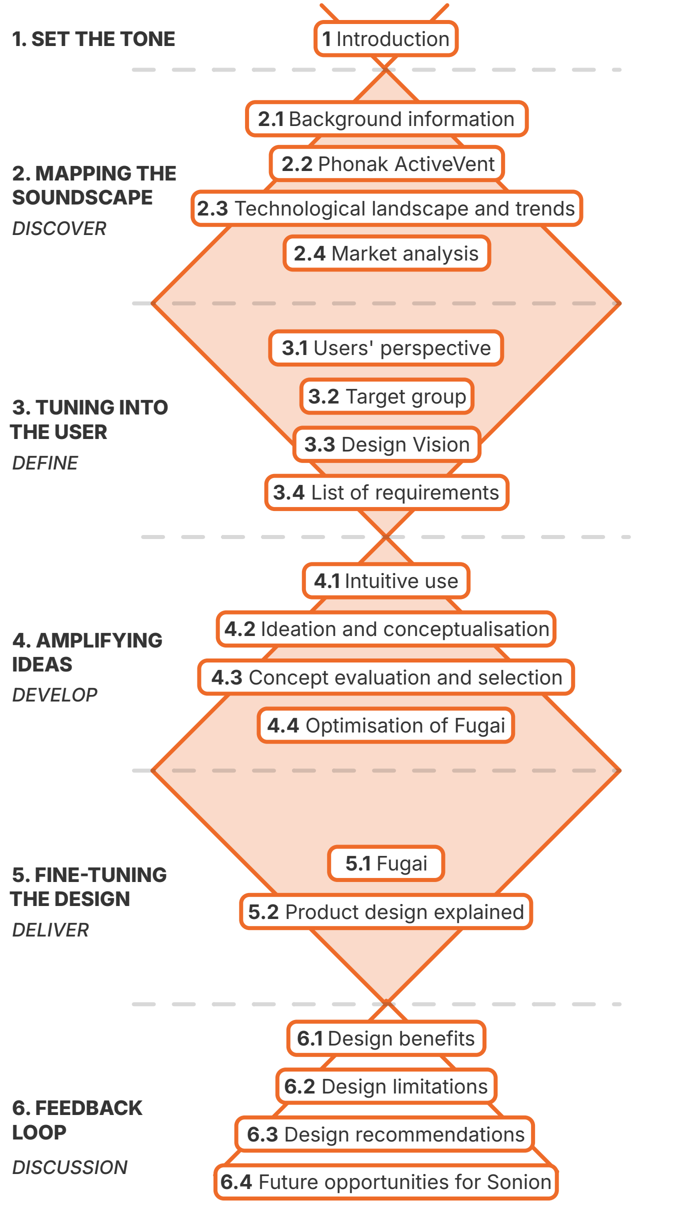


Figure 1.4 Structure of the design project using the Double Diamond design approach, highlighting the phases and corresponding (sub)chapters.

MAPPING THE SOUNDSCAPE

CONTEXT ANALYSIS

2

This chapter provides a concise overview of background information relevant to the hearing context. It then introduces the current Valve-Receiver-in-Canal (VRIC) design, the Phonak ActiveVent, and discusses the technological landscape and emerging trends in hearing aid technology. Finally, a market analysis is conducted.

2.1 Background information

To understand how hearing aids function, it is important to first understand the basic principles of human hearing; how sound is transmitted through the ear, the different types of hearing loss, and which types of hearing aids are suited to each condition. Finally, a general overview is given of the basic components contained in a hearing aid.

2.1.1 The human auditory system

The human auditory system is divided into three sections; the outer ear, the middle ear, and the inner ear, see Figure 2.1. The outer ear consists of the external ear, the pinna, and the ear canal. In the middle ear the ossicles are located. In the inner ear the cochlea is located. Each of these sections play a specific and vital role in capturing, transmitting and interpreting sound.

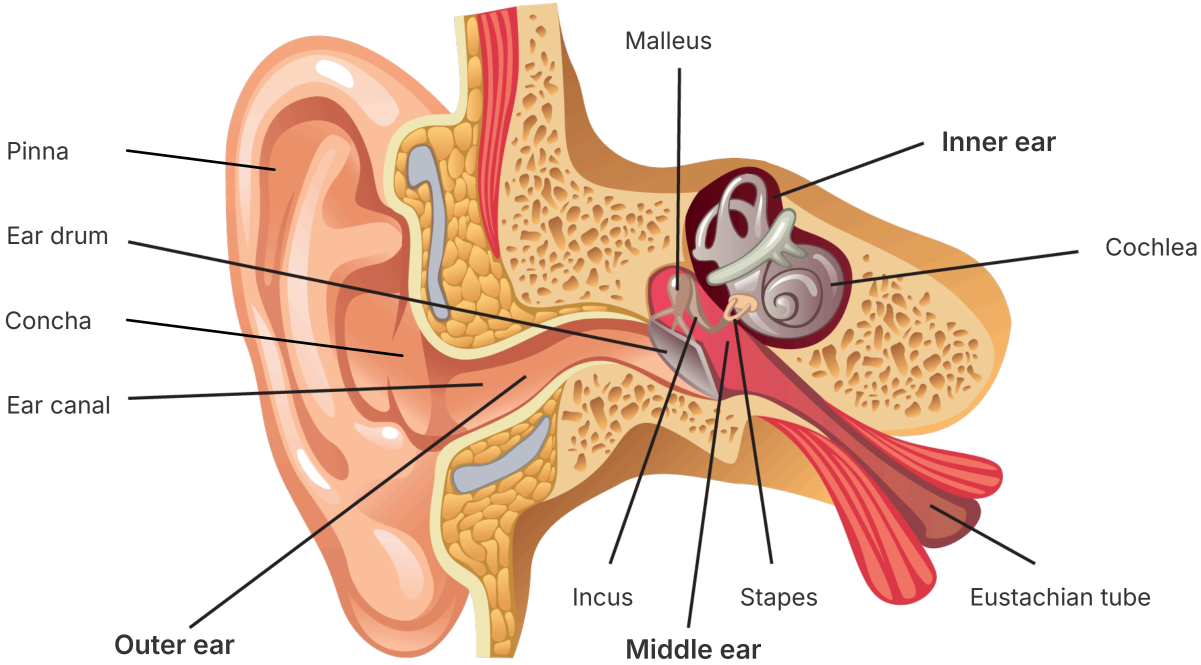


Figure 2.1 Three sections of the human auditory system. Adapted from Davidson Hearing Aid Centres (2015).

The outer ear

As mentioned before, the outer ear consists of the external ear, often referred to as pinna or auricle, and the ear canal with at its end the eardrum. The entrance to the ear canal is the concha (Figure 2.1). One of the two main functions of the outer ear is to maximise the sound pressure at the eardrum. The other is to localise the sound (Hermes, 2023). Due to its asymmetrical shape, the pinna concentrates the sound waves at the concha, where they arrive at the ear canal. Here, they interact depending on the direction of the sounds come from. As a result, we can identify whether the sound comes from behind, below or in front of us (Hermes, 2023).

The ear canal not only collects and funnels the sound waves. The ear canal amplifies sound in a specific frequency range due to its resonance properties and its asymmetrical shape. These effects explain why certain frequency ranges are perceived more clearly than others (Hermes, 2023). Figure 2.2 from Moore et al. (1997) shows a graph where the average power of an acoustic wave at the eardrum is drawn relative to its power when entering the canal.

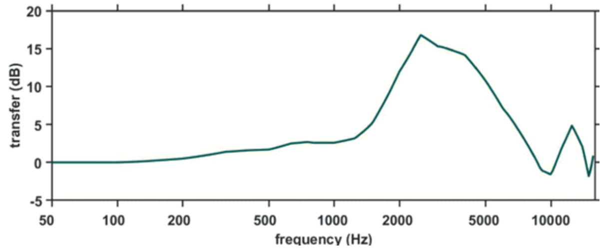


Figure 2.2 The average power of an acoustic wave at the eardrum when entering the ear canal (Moore et al., 1997).

As can be seen in Figure 2.2, there is a wide peak with a maximum at ~3kHz. This range is particularly important because it corresponds with frequencies which are most relevant for human speech perception. From this can be drawn that humans are most sensitive to the mid-range frequency band, frequencies between 2 and 5 kHz, while sensitivity decreases at lower and higher frequencies. These sensitivity characteristics are summarised in the human hearing curve, which shows the threshold of hearing, the pain threshold, and the speech frequency range across the audible spectrum (Figure

2.3). Here, the light blue line represents the threshold of hearing; the minimum Sound Pressure Level (SPL) that is required for a tone at each frequency to be barely audible to an average human ear. Consequently, from this Figure can be drawn that perceived loudness is frequency dependent; sounds with the same SPLs can be perceived as having different loudness depending on their frequency.

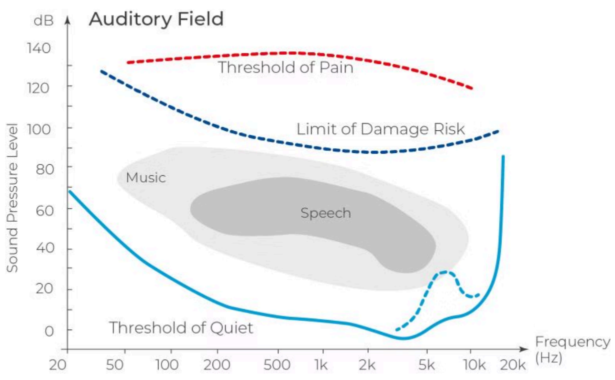


Figure 2.3 Human hearing curve illustrating the human hearing range, with Sound Pressure Level (dB) plotted against Frequency (Hz) (Svantek, n.d.).

The middle ear

The middle ear plays a crucial role in transmitting sound from the outer ear to the inner ear. It is an air-filled cavity (the tympanic cavity) located behind the eardrum that contains three tiny bones known as the ossicles: malleus, incus, and stapes (Figure 2.4). The malleus is attached to the eardrum, while the stapes connects to the oval window, the entrance to the inner ear. The ossicles are kept in place by three ligaments (Hermes, 2023).

When sound waves enter the ear canal, its resonance builds up pressure, causing the eardrum to vibrate. These vibrations are then transferred through the ossicles, whose main function is to convert the pressure waves from the air-filled canal into mechanical vibrations in the fluid-filled inner ear (Hermes, 2023). In doing so, the ossicles amplify and adjust the sound so that it can effectively travel through the fluid. This amplification is essential because sound vibrations move much less efficiently in fluid than in air, similar to how speech becomes muffled when heard underwater. As the inner ear fluid is displaced by these vibrations, the round window acts as a pressure release mechanism, ensuring that the incompressible fluid can move properly (Hermes, 2023).

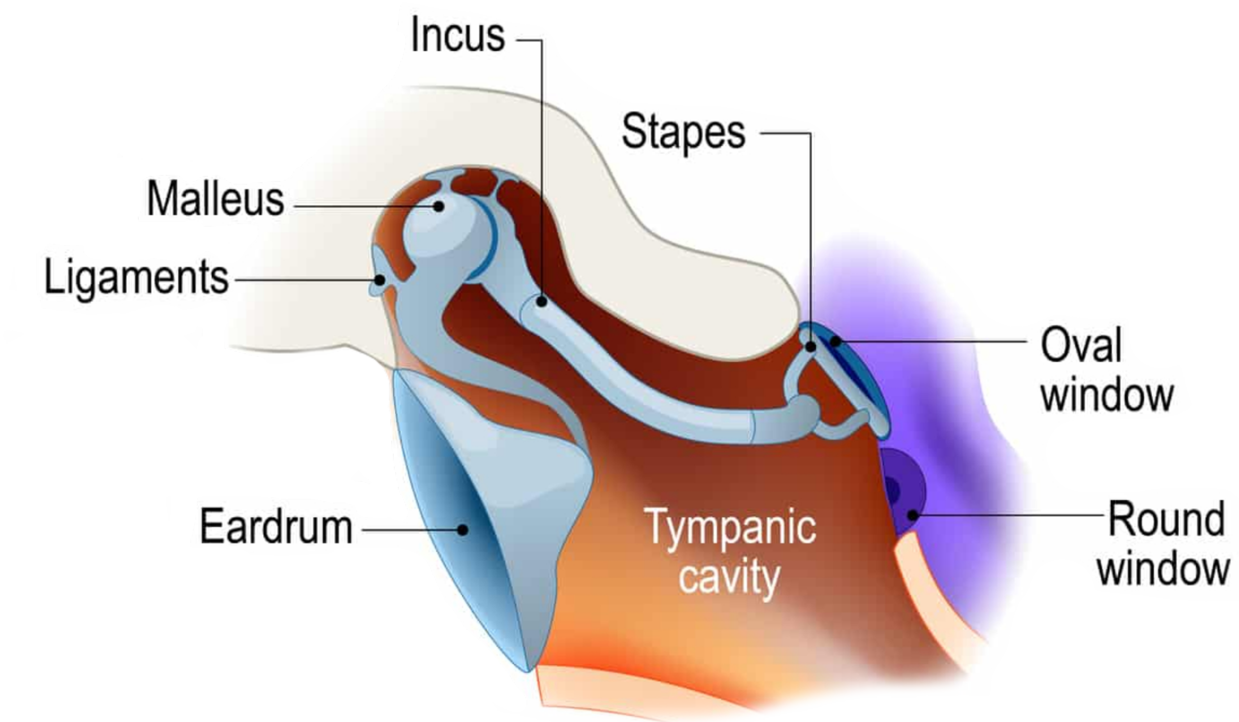


Figure 2.4 A detailed illustration of the middle ear showing the ossicles, tympanic cavity, and associated openings (AudioCardio, 2020).

The inner ear

The inner ear is the final section and is responsible for converting the vibrations into neural signals that the brain interprets as sound. The auditory part in the inner ear is the cochlea, which consists of a spiral structure (Figure 2.5).

When the stapes pushes on the oval window, it sets the fluid inside the cochlea into motion. This fluid movement causes the basilar membrane, which runs along the length of the cochlea, to vibrate. Near the oval window, the membrane is narrow and stiff, responding to high-frequency sounds, while toward the apex it becomes wider and more flexible where it resonates with low frequencies. In this way, the basilar membrane separates incoming sound vibrations into their individual frequency components (Hermes, 2023). The ear thus functions as a biological frequency filter, breaking down sound into its various frequency components. This breakdown is known as tonotopy; each specific frequency corresponds to a position on the Sandra membrane.

The organ of Corti, placed on the basilar membrane, contains, amongst others, two kinds of sensory cells; a single row of inner hair cells and three rows of outer hair cells (Figure 2.5). The inner hair cells are primarily responsible for converting mechanical vibrations into electrical signals that are transmitted to the brain, whereas the outer hair cells amplify and fine-tune the vibrations of the basilar membrane. This amplification enhances sensitivity to soft sounds and improves the precision of pitch perception (Hermes, 2023).

Each hair cell has an outward pointing bundle of hair-like structures, the stereocilia. As the cochlear fluid moves, it bends the stereocilia, opening tiny channels that create electrical signals (Hermes, 2023). These signals travel through the auditory nerve to the brain, where they are interpreted as sound.

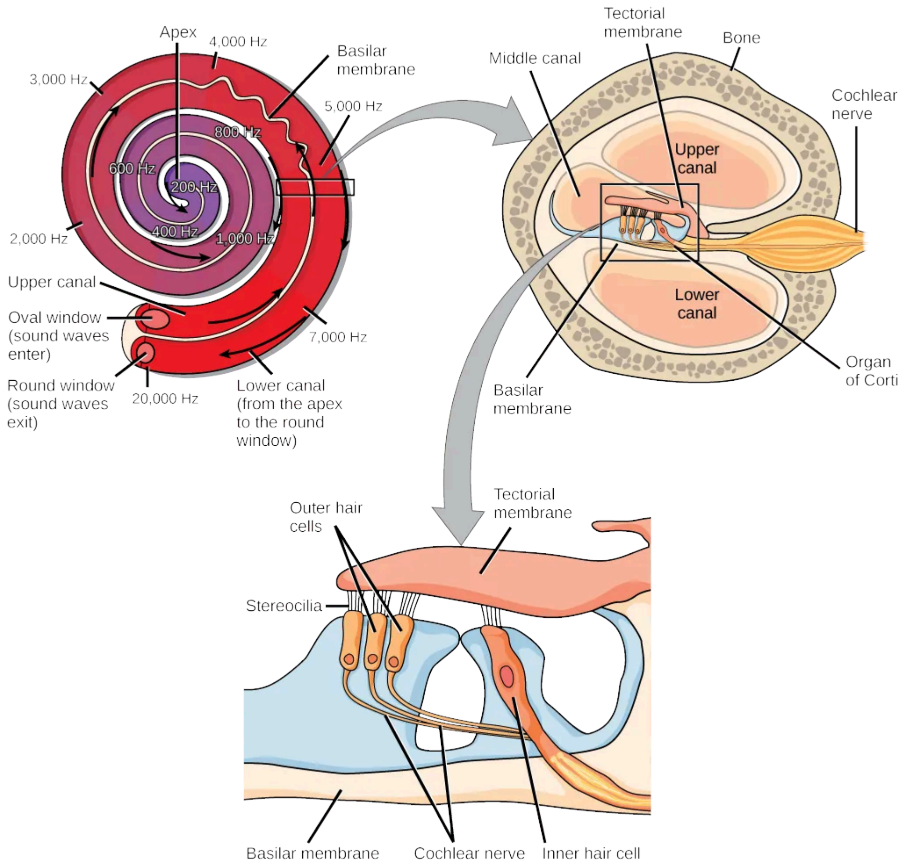


Figure 2.5 Schematic illustration of the Cochlea, showing how different sound frequencies are processed along the spiral structure and how this relates to the anatomy of the cochlear duct and organ of Corti (Zedalis & Eggebrecht, 2018).

Each part of the human auditory system has a distinct and sensitive function, where the outer and middle ear capture and amplify sound vibrations and the inner ear converts them into electrical signals for the brain. Damage or dysfunction in any of these parts can disrupt the transmission or perception of sound, resulting in hearing loss. Before diving into the different types of hearing loss and their characteristics, an introduction to hearing loss is given in the following subchapter.

Takeaways 2.1.1

- People are most sensitive to the mid-range frequency band, frequencies between 2 and 5 kHz. This means that sounds in this range are perceived as louder and clearer than sounds at other frequencies, even when the sound pressure level is the same.

2.1.2 Introduction to hearing loss

Hearing loss is the partial or complete inability to perceive sound in one or both ears. It is a larger global problem than one might think, with one in five people of the world's population, around 1.5 billion people, having some form of hearing impairment (Wilson & Tucci, 2021). Of the world population, more than 5%, or 430 million people, including 34 million children, experience moderate-to-complete hearing loss that affects their ability to communicate without assistance (e.g. a hearing aid) and therefore require rehabilitation (World Health Organization, 2025). Moreover, the World Health Organization (WHO) predicts and warns that nearly 2.5 billion people, or 1 in 4 people, will be having some degree of hearing loss by 2050, with at least 700 million of these people will require access to ear and hearing care (World Health Organization, 2021).

Hearing loss can especially have major consequences in two age groups. For infants and young children, hearing loss can hinder in understanding speech, language development, education, cognitive growth and mental health, and may persist into adulthood (Livingston et al., 2017, & Lieu et al., 2020). For adults, especially for people older than 65 years, hearing loss can lead to social isolation, an increased risk in dementia, depression, affecting quality of life and falls (Sterkens, 2024, & Lieu et al., 2020). Beyond individual effects, hearing loss could also place a burden on families and caregivers.

The WHO (2013) describes hearing loss as an invisible disability, not just because it cannot be seen, but the long-term impact and damage on the patient and society is not proportional to the attention and financial support it receives. The WHO (2017) even estimates that hearing loss costs the global economy $750 billion USD annually due to healthcare costs, costs of educational support, loss of productivity and broader societal costs.

Despite this, awareness and access to hearing care remain limited. In many regions, hearing aids are still perceived as luxury medical products rather than essentials. The major barriers are stigma and affordability, especially in low- and middle-income countries. However, even in high-income countries, many individuals are hesitant in seeking support after noticing hearing difficulties, mainly due to denial, stigma, or misconceptions on hearing aids (World Health Organization, 2021).

Population growth and ageing are one of the main contributors to the increased prevalence of hearing loss nationally, regionally and globally (Jiang et al., 2023), although elderly hearing loss cannot be considered to be caused by ageing alone. Instead, it is a result of combination of factors such as genetics, health status, lifestyle and environment (Davis et al., 2016). Additionally, the increasing use of head- and earphones while studying, working, exercising, playing video games or commuting, plays also a major role in the risk of hearing loss for Gen Z and Millennials (Ostrowski, 2025).

Given the growing prevalence of global hearing loss and its social and economic consequences, hearing aids are one of the most important solutions in global hearing care. However, the effectiveness of hearing aids depends not only on availability, but also on their usability, reliability and acceptance by users across different age groups and lifestyles. If hearing aids are perceived as uncomfortable, unreliable or socially stigmatising, their potential to mitigate wide-spread hearing loss is reduced. As a result, continuous improvement of hearing aid designs remains crucial to ensure that hearing care can meet current and future global demands.

To address this growing concern, the WHO aims to ensure timely and appropriate global access to ear and hearing care to prevent hearing loss, by using strategies such as early detection and screening programs, greater availability access to ear and hearing care, and the integration of hearing care into primary healthcare systems. Moreover, the WHO emphasises the normalisation of hearing health to reduce stigma, alongside the improved availability of ear, nose, and throat specialists and audiologists to meet the growing demand (World Health Organization, 2021).

Takeaways 2.1.2

- Hearing loss is increasing worldwide
- Many people delay adoption of hearing aids due to denial, stigma, or misconceptions on hearing aids. The design should therefore not contribute to stigmatisation in order to prevent delays in adoption **(R6.1)**

2.1.3 Types of hearing loss

Hearing loss can appear sudden or develop progressive over time, and it can be mild or severe, temporary or permanent. Although hearing loss is often considered stable, it may be fluctuating where it improves or is getting worse over time (Alshuaib et al., 2015). As described in the previous subchapter, there is a range of causes which may lead to hearing loss, such as genetics, age, long exposure to noise, illness, and physical trauma to the head and/or ear (Alshuaib et al., 2015). Hearing loss can be unilateral, where one ear is affected, and bilateral, which affects both ears. There are four main types of hearing loss. These will be described in the following paragraphs. Figures 2.6 - 2.9 show schematic cross-sections of the human ear illustrating the anatomical sites involved in different types of hearing loss.

Conductive hearing Loss

Conductive hearing loss (CHL) (Figure 2.6) occurs when the vibrations cannot pass in the outer or middle ear, often due to blockages or structural issues, such as the build-up of earwax, an infection of the outer ear, or damage to the eardrum or ossicles (Zahnert, 2011). This results in softer sounds, but can be heard more clearly when amplified.

Sensorineural hearing loss

Sensorineural hearing loss (SNHL) (Figure 2.7) happens when the inner ear does not work properly, and results from damage often to the organ of Corti, or when the hair cells are not capable of stimulating the auditory nerve (Alshuaib et al., 2015). These damages are often caused by different factors, including long exposure to noise and sudden exposure to a loud noise, e.g. an explosion. Others are perinatal infections, postnatal infections, ageing, illness, genetics or malformation of the inner ear (Alshuaib et al., 2015). Once damaged, the cells are not able to repair themselves, making SNHL a permanent condition (Burns & Corwin, 2013).

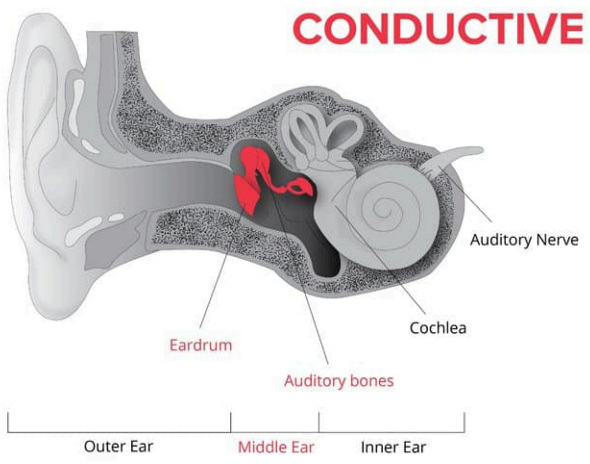


Figure 2.6 Anatomical sites involved in Conductive Hearing Loss (Speech & Hearing Associates, 2021).

Mixed hearing loss

Mixed hearing loss (MHL) (Figure 2.8) is a combination of conductive and sensorineural damage in the same ear.

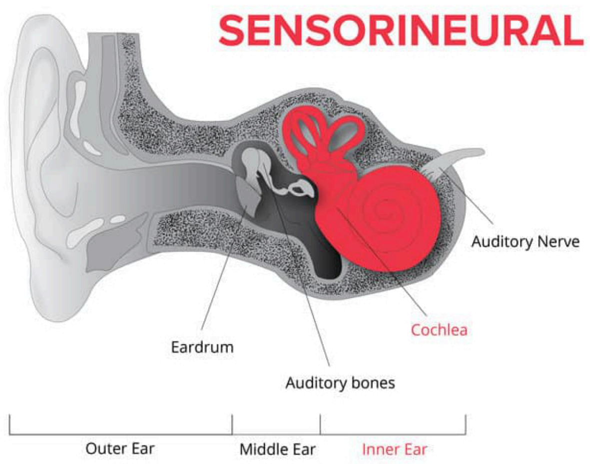


Figure 2.7 Anatomical sites involved in Sensorineural Hearing Loss (Speech & Hearing Associates, 2021).

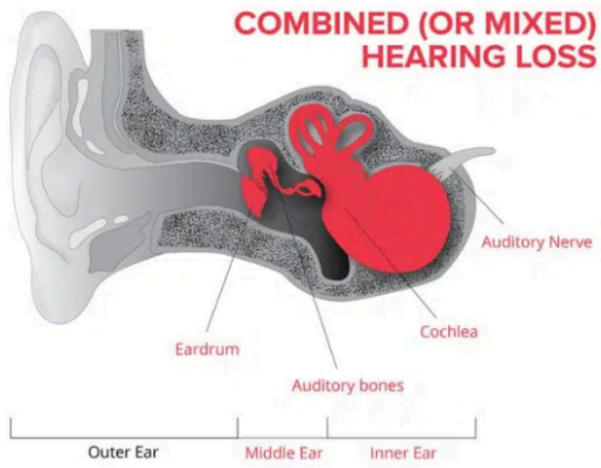


Figure 2.8 Anatomical sites involved in Mixed Hearing Loss (Speech & Hearing Associates, 2021).

Auditory Neuropathy

The fourth type, Auditory Neuropathy Spectrum Disorder (ANSD) (Figure 2.9), is different than the previous three. Here, sound vibrations are able to enter the inner ear, but the electric signal processing along the auditory nerve is distorted, or there is a lacking transmission of this signal to the auditory nerve by the inner hair cells (De Siati et al., 2020). Individuals with ANSD are able to hear sounds, but have trouble understanding and recognising speech (NIDCD, 2018). Here too are several factors that cause ANSD. In some cases, inner hair cells are damaged or auditory neurons, which transmit sound information to the brain, may be damaged. Other causes include genetic mutations, failed connections between the inner hair cells and the auditory nerve, or the nerve itself (NIDCD, 2018).

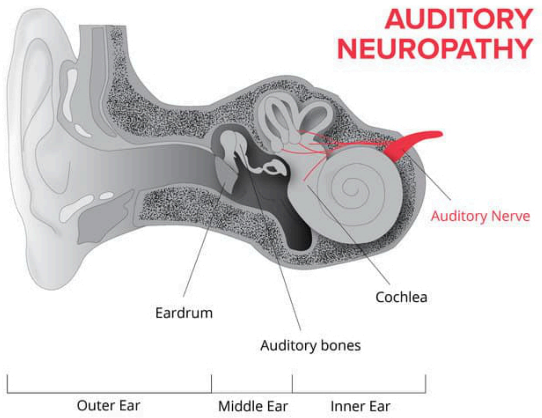


Figure 2.9 Anatomical sites involved in Auditory Neuropathy Spectrum Disorder (Speech & Hearing Associates, 2021).

To understand if an individual is suffering from a conductive or a sensorineural hearing loss, an audiometer is used to measure the individual's hearing threshold; the dB level of a sound before it becomes inaudible, where the normal threshold for adults is between 0 and 25 dB, and 0 and 15 dB for children (Alshuaib et al., 2015). The threshold is

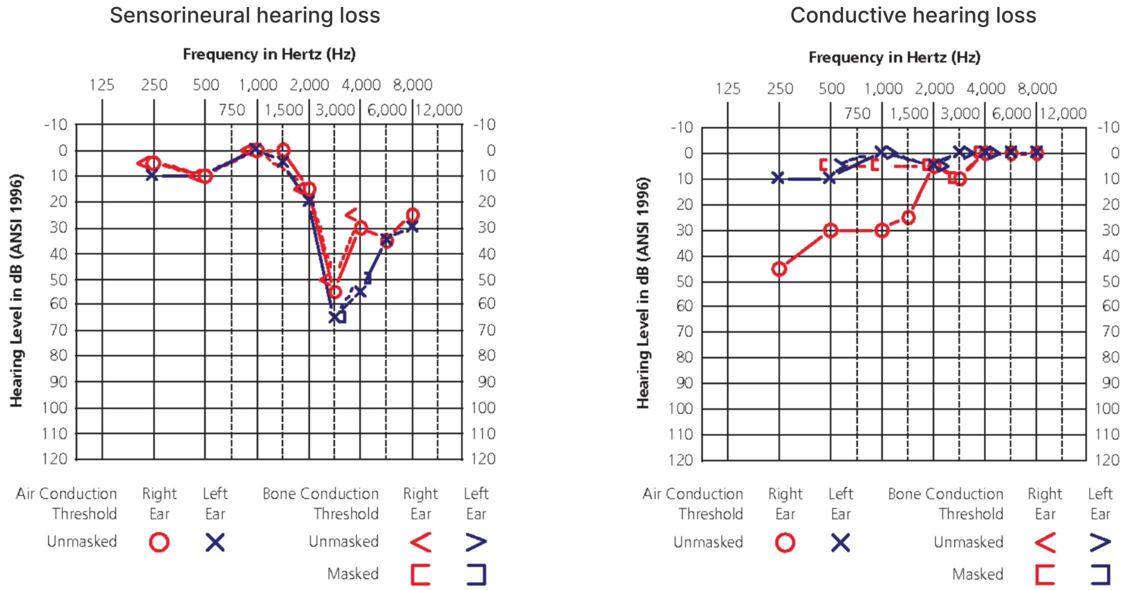


Figure 2.10 Audiograms indicating sensorineural (left) and conductive hearing loss (right), with Hearing Level (dB) plotted against Frequency (Hz) (Walker et al., 2013).

shown on a graph, the audiogram, where the sound frequency and the dB's of the sound are plotted against each other (Figure 2.10). The measurement is done in two ways; through an air conduction test and a bone conduction test. At the air conduction test, pure tone signals are sent to the individual through a pair of headphones, meaning that these thresholds measure the entire auditory pathway (outer, middle, and inner ear and auditory nerve) and thus can indicate if a CHL is present. On the contrary, a bone conduction test surpasses the outer and middle ear, by placing a bone conductor on the mastoid process, a bony projection located behind the ear lump, which sends tiny vibrations to the inner ear to find the inner ear threshold. The results, by comparing the outcomes the air conduction and bone conduction, show which type of hearing loss the individual is suffering from.

If both air and bone conduction are reduced by the same amount, it suggests a sensorineural hearing loss (SNHL). When the bone conduction is normal but the air conduction is poor, this indicates a conductive hearing loss (CHL) (Figure 2.10). However, if both are reduced but air conduction is worse than bone conduction, the pattern is consistent with a mixed hearing loss (MHL).

Since different parts of the auditory system can be affected, hearing aids are designed to compensate by amplifying sound vibrations in such a way, tailored to the individual's needs. In essence, hearing aids compensate or replace the natural processes of the outer, middle and/or inner ear, depending on the type of hearing loss. By boosting all frequencies, it compensates part of the amplification role of the outer ear. By increasing the efficiency of sound entering the inner ear, it can replace the transform role of the ossicles, and by selectively amplifying certain frequencies, it can substitute for the fine-tuning of the cochlea's hair cells.

As mentioned before, different types of hearing loss each require different amplification needs. For CHL, since the cochlea is not affected, it can process the sound vibrations normally if amplified sufficiently by the hearing aid. Therefore the hearing aid replaces the blocked or damaged outer and middle ear. However, if an individual is suffering from severe CHL, bone-anchored hearing aid (BAHA) devices are often the way to go. BAHA devices consist of three main components: a sound processor (1), an osseointegrated titanium implant (3) (which forms a direct biological connection with the bone), and an abutment (2) that connects the two (Figure 2.11). The processor attaches to the implant in the temporal bone, where the cochlea is located. By transmitting vibrations through the temporal bone, the device delivers sound directly to the cochlea, providing sound perception (Dickinson, 2010).

Hearing aids are most commonly used for SNHL (Wardenga et al., 2020). For SNHL, hearing aids provide a targeted frequency amplification and dynamic range compression to mimic the lost function of the outer hair cells; amplifying soft sounds to make them audible, amplifying loud noise less to prevent hearing discomfort, and amplifying moderate sounds appropriate.

For MHL, hearing aids must aim both the CHL and SNHL elements. It becomes complex to balance these elements. If the hearing aid amplifies all frequencies equally to overcome CHL, frequencies that the cochlea still processes well may be experienced too loud or distorted. In contrast, if amplification only aims SNHL affected frequencies, CHL will still remain, resulting in a perceived muffled sound.

In the case of ANSD, hearing aids do have limited capabilities, as the challenge lies not with sound amplification, but with neural transmissions.

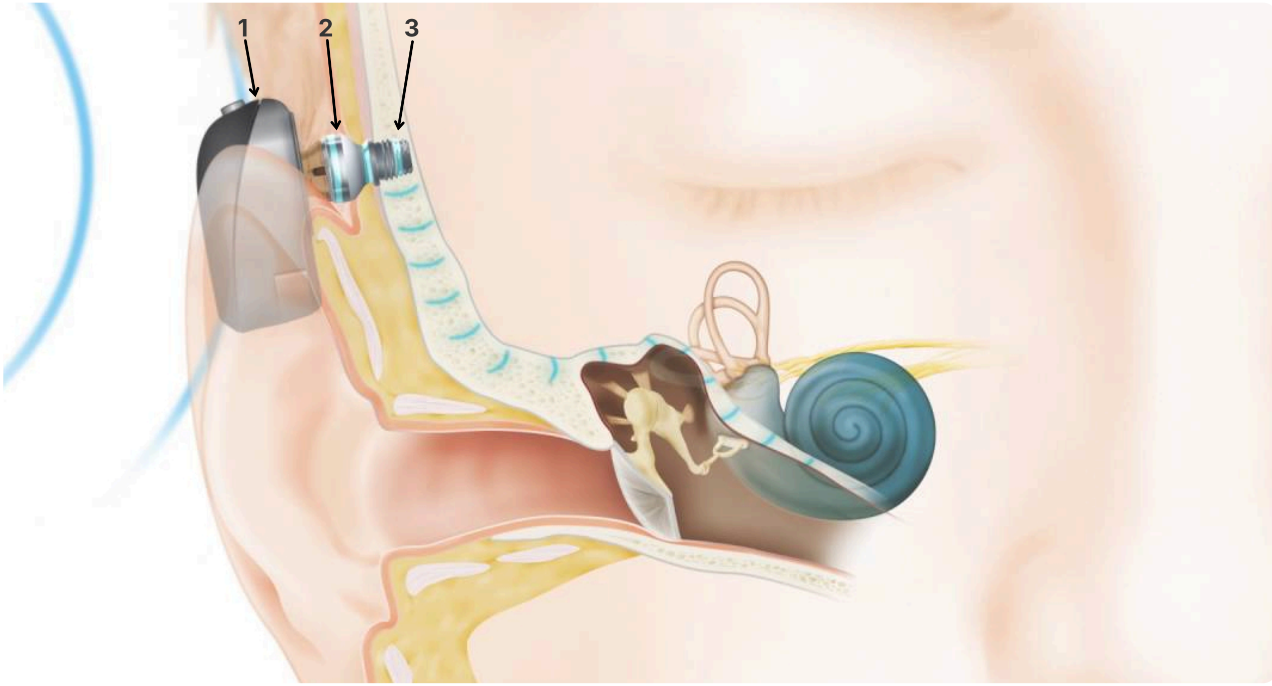


Figure 2.11 Illustration of the human ear showing a BAHA device transmitting sound vibrations directly to the inner ear (Cochlear Australia, n.d.).

Therefore, other solutions, such as cochlear implants, are more effective (Verhaert et al., 2013).

So, while the amplification differs for CHL, SNHL, MHL or ANSD, the physical form and placement of the hearing aid also plays a critical role in meeting the needs of the users. Modern hearing aids are designed not only to provide the necessary amplification and frequency-specific adjustments, but also to accommodate wearing comfort and usability. Depending on the user's profile, lifestyle and degree of hearing loss, different models are available. An elaboration of these models is given in the following subchapter.

Takeaways 2.1.3

- Different types of hearing loss require different amplification strategies, dependent on the frequencies where hearing loss occurs

- Hearing aids are most commonly used by people with SNHL

2.1.4 Types of hearing aids

Today's modern hearing aids can be categorised in two main models, behind-the-ear (BTE) and in-the-ear (ITE) (Celikgun et al., 2024).

BTE models

BTE hearing aids are worn behind the ear and transmit sound to the ear through either an earmould or a dome. They are available in several types, mainly by their power output (which also affects their size) and the method of sound delivery. Receiver-in-Canal (RIC) models represent a more advanced BTE design, where the receiver is placed directly in the ear canal rather than within the housing. This provides several benefits; it delivers sound more directly into the ear canal, causing an improved sound quality (Prabhu & Barman, 2016). Additionally, the BTE housing is smaller and lighter, making it more discrete and comfortable to wear. This design has made RICs the most popular hearing aid type (Celikgun et al., 2024), establishing a new subcategory within BTE devices.

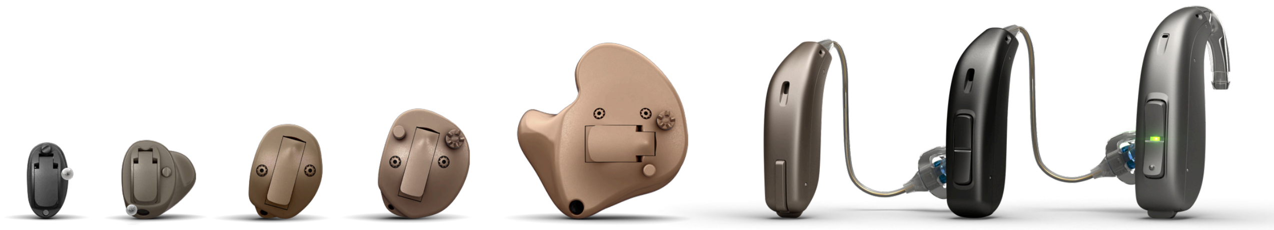


Figure 2.12 Types of hearing aids. Adapted from Hidden Hearing Hearing Centre (n.d.)

ITE models

ITE models are made according to the individual's ear and are placed in the ear. The types ITE models come in are, from smallest to largest: Invisible in the Canal (IIC), Completely in the Canal (CIC), In the Canal (ITC), and In the Ear (ITE) (Figure 2.12), where the full shell model fills the complete ear shell. Although the IIC and CIC models are considered to give a better appealing than ITCs and ITE's while wearing (as they are less visible), they have lower speaker performance and contain a single microphone which makes them less effective in filtering out background noise and focusing on specific sounds (Celikgun et al., 2024).

Less common hearing aids

Next to the well-known BTE and ITE models, other less common hearing aids are available. Headband, headset and spectacle hearing aids, which are designed for CHL, have a vibrating receiver that stimulates bone conduction, and may be preferred to individuals that are not suitable for, or do not wish to wear a BAHA (Celikgun et al., 2024). In addition, cochlear implants (CIs) can provide a sense of sound to a patient who is profoundly deaf or extremely hard-of-hearing (NIDCD, 2024). CIs consists of an external part and an internal part, which is placed under the skin through surgery, bypassing damaged portions of the ear and directly stimulating the auditory nerve (NIDCD, 2024). For patients who have severe hearing loss but do not want to undergo surgery, pocket (body worn) hearing aids may be used (Celikgun et al., 2024).

Takeaways 2.1.4

- RICs are advanced BTE models in terms of sound quality, size and wearing comfort
- Smaller devices improve aesthetics but are less effective in signal-processing and reduce sound quality

2.1.5 Basic hearing aid components

In general, hearing aid components include the microphone, amplifier, receiver (speaker), and an earmould or a dome (Figure 2.13). Each of these play an important role in enhancing the user's ability to hear sounds clearly.

Microphones

The microphones (1) are responsible for capturing sound waves from the environment and converting them into electrical signals. Since the 1960s, electret condenser microphones (ECMs) were the ideal option for hearing aid due to their size and their accurate frequency response. However, ECMs are sensitive to ambient temperature and stability problems, which led to the development and adaption of micro-electromechanical systems (MEMS) microphones (Celikgun et al., 2024). Although MEMS are less in quality, it is the preferred choice of manufacturers, as MEMS are good enough according to audiologists, and decrease the amount of the total costs (personal communication Sonion employee, 2025).

Modern hearing aids typically feature either omnidirectional or directional microphones. Omnidirectional microphones capture sound waves equally from all directions, providing a natural and balanced sound environment. On the contrary, directional microphones capture sound waves from a specific direction, often from in front of the user, aiming to improve, for example, speech recognition in noisy environments. The sensitivity of the microphone determines the amount of sound that is captured, affecting the overall hearing experience.

Amplifier

Next, the amplifier (2) increases the strength of the electrical signals transmitted by the microphone, tailoring both current and voltage levels according to the individual's needs. The amplifier ensures frequency-specific amplification, while maintaining a small design, low power-use and low distortion systems (Celikgun et al., 2024).

Figure 2.13 Exploded view of a typical RIC hearing aid, showing the microphones (1), amplifier (2), battery (3), receiver (4) and dome (5). (Bed Bath & Beyond, n.d.)

Battery

The battery (3) provides the required power needed for the hearing aid to operate. Modern batteries balance long-lasting performance with low power consumption, to ensure the device can function throughout daily use. Their small size, efficiency, and ease of replacement or recharging make them well suited for continuous use.

Receiver (speaker)

The receiver (4) converts the amplified electric signals back into sound waves, creating sound the individual can hear. There are different receiver technologies, with two dominant types used in commercial receivers today: moving coil (MC) receivers (also known as dynamic receivers) and balanced armature (BA) receivers, see Figures 2.14a and 2.14b (Sanga, 2018). For the dynamic receiver (Figure 2.14a), the coil (1) receives electronic signals, is getting magnetised, and starts to move between the magnets (2). The movement of the coil creates a vibration in the membrane (3), which then pressures the air above the membrane (4). This creates sound pressure which is let through the sound outlet (5).

For the BA (Figure 2.14b), the coil (1) receives electronic signals, creating a flux into the armature and starts to vibrate in the magnetic field (2). This vibration causes the drive pin (3) to move up and down, resulting in a vibration in the membrane (4). Next, the membrane pressures the air above the membrane (5), creating a sound pressure which is let out through the outlet (6) (Sanga, 2018).

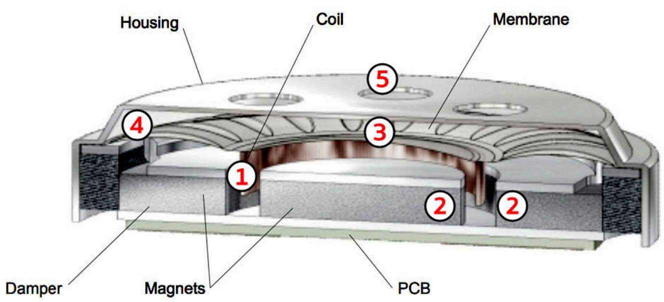


Figure 2.14a Illustration of a moving coil receiver (Sanga, 2018)

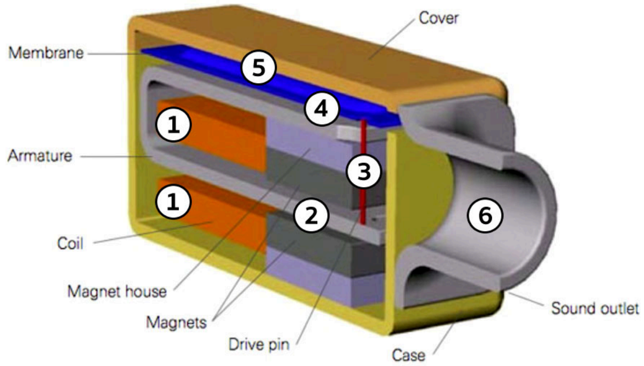


Figure 2.14b Illustration of a BA receiver (Sanga, 2018)

In general, for more powerful BTE devices larger receivers are used and thus placed in the housing. This is not only limited to their dimensions but also to the acoustic properties of the receiver.

Pro's and cons of MC's and BA's

When comparing MC and BA receivers, the fundamental trade-offs centre on size, efficiency, acoustic performance, and system integration.

Typically, MC receivers are larger due to the coil and membrane assembly which limits their suitability for miniaturised devices. However, the greater membrane results in a stronger low-frequency output, making MC receivers well suited for applications requiring high acoustic power. Nevertheless, MC's are less electrical efficient, leading to a higher current consumption, which drains the battery life quicker.

BA receivers are optimised for efficiency and compactness. Due to their small size, it is able to integrate BA's in discrete products, e.g. RIC hearing aids. BA's typically achieve high sound pressure levels with a significant low power use, making them ideal for all-day wear and small battery capacities (leading to small BTE housings). Moreover, they offer great high-frequency performance, which is critical for speech intelligibility. However, the primary limitation is reduced low-frequency output. Additionally, BA's tend to have a higher unit cost due to precision manufacturing requirements.

In conclusion, BA's are the preferred receivers for RICs, due to their size, electrical efficiency and high-frequency performance. However, possible future breakthroughs in the battery technology, such as higher energy density or reduced form factors, could mitigate power limitations. In addition, breakthroughs in MC design, such as miniaturisation, enhanced membrane engineering could mitigate current disadvantages. If such developments take place, MC receivers could become a strong alternative for RIC applications by offering improved low-frequency performance without compromising discreteness and battery life. Consequently, the optimal receiver for RICs may change in the future.

Earmoulds and domes

The main function of earmoulds and domes (5, Fig) is to ensure the hearing aids on the ear (or the RIC in the ear) remain in place, and that the amplified sound are transmitted to the inner ear. Important to note is that any changes to the earmoulds or domes will affect the acoustic performance of the hearing aid, so any acoustic property of the designs should be considered (Xu et al., 2017). Earmoulds and domes are available in soft and hard materials, where soft materials are more tailored to prevent acoustic leakage, and hard materials are better in preserving acoustic properties.

The design of earmoulds and domes not only ensures secure placement, but also directly impacts sound quality and hearing performance. By selecting the appropriate dome type or vent size, a balance is involved in sound transmission, wearing and hearing comfort, and amplification needs. The balance between openness, for natural sound, and closure, for optimal sound performance, is central to venting design.

Takeaways 2.1.5

- The required amplification power determines the placement and size of the receiver
- Vent openness vs. closure is the central trade-off in hearing aid design

Closing summary on 2.1 Background information

The insights and takeaways shape how hearing aids must perform and why their design involves constant trade-offs for hearing care professionals and users. The way humans naturally process sound, the diverse profiles of hearing loss, and the function of hearing aid components all converge toward a key challenge: ***delivering amplified sound that is both effective and comfortable in diverse acoustic environments.***

Current Receiver-in-Canal hearing aids highlight this challenge most clearly through venting; balancing (natural) sound quality, and wearing and listening comfort. The key challenge between openness and acoustic performance sets the tone for the design problem of this graduation project. The broader context therefore provides a foundation for the research, exploration and development for new improvements in Valve-Receiver-in-Canal systems, such as the Phonak ActiveVent.

The following chapter describes how the Phonak ActiveVent addresses the key trade-off of openness and acoustic performance by dynamically balancing open and closed venting systems.

Design requirements

R6.1: The product should not contribute to stigmatisation

2.2 Phonak ActiveVent

The Phonak ActiveVent is a Valve-Receiver-in-Canal (VRIC), an advanced version of the traditional RIC, featuring an automatic valve mechanism in the RIC to dynamically switch between an open and closed system based on environmental sound conditions. This chapter outlines how the ActiveVent (Figure 2.15) fits within the broader hearing aid context. It begins by discussing the importance of venting for hearing aid users and the challenges associated with achieving optimal sound performance. This is followed by an explanation of the working principle of the Valve Receiver-in-Canal (VRIC) system, its influence on acoustic performance, and a detailed description of its key components and the candidacy requirements to wear a Phonak ActiveVent.

Figure 2.16 shows how the ActiveVent has been integrated with the BTE housings and the earmoulds.

Figure 2.15 Phonak ActiveVent for the right ear (ASH Audiology, n.d.).

Figure 2.16 A set of Phonak ActiveVent hearing aids (Phonak, 2021).

2.2.1 Why venting is important

Programming a set of hearing aids is the process of adjusting the device's settings to an individual's hearing needs. Audiologists modify parameters such as volume and frequency response using specialised software to ensure optimal hearing comfort, clarity and speech understanding. An important challenge during this process is balancing the choice of dome and vent size, with options such as open, vented or closed domes, respectively from top to bottom (Figure 2.17), each affecting sound reproduction and feedback control (Olson, 2021). Here, vent size is defined as the diameter of the vent opening in the earmould, or, in the Valve-Receiver-in-Canal (VRIC) design, as the diameter of the VRIC nozzle, to which the dome is attached.

In the context of hearing aids, low-frequency sounds typically are within the range of approximately 250 - 750 Hz and contribute primarily to volume of speech, while high-frequency sounds range from 2 - 8 kHz and provide clarity to speech. Open domes are great for individuals with good low-frequency hearing, but less high-frequency hearing, as the low frequencies are able to enter their ear canal naturally through the open dome, due to their long wavelengths, and mix with the amplified sound. Vented domes are for those who have a bit more low-frequency loss or have a more significant high-frequency loss, as it traps more sound inside the ear canal. Closed domes are an ideal option if an individual has a significant low-frequency loss, or more hearing loss in general (Olson, 2021).

When a custom earmould is required, there is still a need to select the proper vent size diameter. The vent diameter can range between no vent (closed system) and a large vent (open system). Table 2.1 shows the recommended vent diameter according to the degree of hearing loss at 500 Hz (Kuk & Baekgaard, 2008). The main challenge when programming is that any of these options does not always guarantee maximum hearing performance in all different situations. A closed system could create the occlusion effect, and an open system could lead to leakage, a reduction of the directionality and noise reduction effects of a hearing aid (Olson, 2021). This results, for the hearing care professional, in making a trade-off to what hearing situation is most crucial for the patient, but optimising for that situation could lead to taking away the individual's hearing ability from another situation (Olson, 2021).

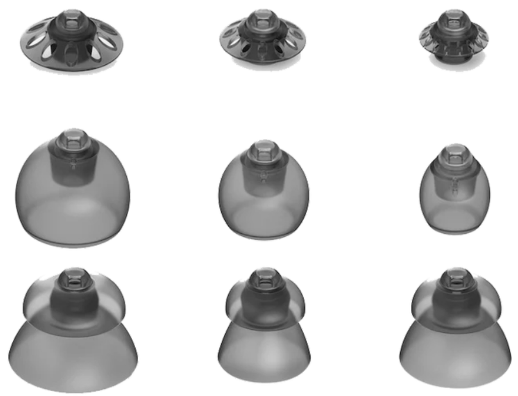


Figure 2.17 Different sizes of open, vented and closed domes (from top to bottom) (hearingaidhero, n.d.).

Table 2.1 Recommended vent diameters (in mm) based on the hearing loss at 500 Hz (in dBHL). Adapted from Kuk & Baekgaard (2008).

Degree of hearing loss at 500 Hz (in dBHL)	Recommended vent diameter (solid mold)
<20 dB	open
20-29 dB	3-4 mm
30-39 dB	2-3 mm
40-49 dB	1-2 mm
50-60 dB	0.5-1 mm

Each decision between the programming and the fit of a hearing aid has a great impact on the performance of hearing aids, especially regarding to earmould vent size. If the wrong venting is chosen, the hearing aid is not able to transfer the right amount of amplification into the ear canal (Olson, 2019). Vent size has impact on four aspects: occlusion effect, sound quality, risk of feedback, and the ability to amplify low frequencies.

Occlusion effect

The occlusion effect is the perception of one's own voice, chewing, or other internally generated sounds being transmitted via bone conduction through the jaw and skull. This effect can occur while wearing a hearing aid that either has a dome that closes off the ear canal completely, or uses a mould that doesn't have a large enough vent size (Olson, 2019). When the ear canal is blocked, these sound vibrations become trapped and reflected back toward the eardrum, creating a muffled, hollow, or 'boomy' sound (Carillo et al., 2021). Options to reduce this effect could be, but are not limited to, open fittings or ventilation holes in the earpiece (Liebich & Vary, 2021). It is also crucial that vent holes are positioned close to the dome. By doing so, the length of the vent is shorter, resulting in less acoustic resistance, and allowing air and sound to pass more freely. As a result, the vent functions more effectively, improving user comfort and creating a more natural listening experience (Cubick et al., 2022).

Sound quality

Most people with hearing loss have good low-frequency and bad high-frequency hearing. Low frequency sound waves are relatively long compared to high-frequency waves, which results that open vents allow low frequencies from the environment to enter the ear naturally. With the right amount of amplification, these low frequencies will blend well and improve natural sound quality. However, if the vent size is too small, it will reduce low-frequency hearing, resulting in poor natural sound quality. How larger the vent size, the more natural sound can enter the ear canal.

Risk of feedback

On the other hand, a larger vent size increases the risk of feedback; the whistling sound. Larger vent sizes results in more amplified sound leakages, which could return back through the microphone, causing the feedback.

Ability to amplify low frequencies

On top of that, too large vent sizes make it impossible to sufficiently amplify low frequencies. These must be trapped inside the ear canal to vibrate through the eardrum appropriately. Too large vent sizes result in low-frequency leakages as they go right out the ear canal.

Due to these trade-offs, no single dome or vent size can create an optimal acoustic performance in all sound environment. This is where the Valve-Receiver-in-Canal (VRIC) hearing aid becomes relevant, where it has an open and closed vent system at the same time. In the VRIC design, the vent size is defined by the diameter of the VRIC nozzle.

As discussed previously, the recommended vent diameter is dependent on the degree of hearing loss. Consequently, designing a fixed vent diameter would limit the suitability of the VRIC to a smaller user group. To serve a broader target group, the redesign could incorporate an adjustable vent diameter, to support a wider range of hearing losses. While such a functionality may be desirable from a clinical and market perspective, it is not part of the scope and goal of this graduation project.

The valve in the current VRIC design automatically switches between the open and closed system, depending on the environment that the individual is in. By doing so, the individual experiences an optimal sound quality across a wide range of situations. The next subchapter describes the working principle of the VRIC in more detail.

Takeaways 2.2.1

- In an optimal scenario, vent size can be adjusted **(R1.2)**

- Vent size has impact on occlusion effect, sound quality, risk of feedback and the ability to amplify low frequencies

- Vent openings must be placed close to the dome **(R1.3)**

2.2.2 Working principle of the valve

Figure 2.18 shows a cross-section of the VRIC hearing aid, including the valve (1) and its mechanism. The valve is transported through a moving magnet (2) technology. When the BTE housing detects music is being streamed or the user is entering a noisy environment, an electric signal is sent to the coil (3), creating an electromagnetic field. This field interacts with the moving magnet. Depending on the direction of the current through the coil, the ring magnet is moving forward or backward, including the valve, allowing to create an open or closed system, by opening or blocking the vent openings (4). On one end of the valve system, a latching ring is placed (5), to keep the valve in place when in a closed position.

For the outlet tube design (6), it is crucial that the sound outlet is positioned after the vent openings (4), as shown in Figure 2.18, and that the tube is not too narrow. If the outlet is located before the vent openings, the amplified sound can easily escape from the ear canal, which reduces efficiency. If the tube is too narrow, low-frequency sounds struggle to escape through the vent openings, resulting in less openness: the difference in output between an open and a closed state would be less significant. This diminishes the difference in output between an open and a closed system, making it harder for the user to hear the difference (personal communication Sonion employee, 2025).

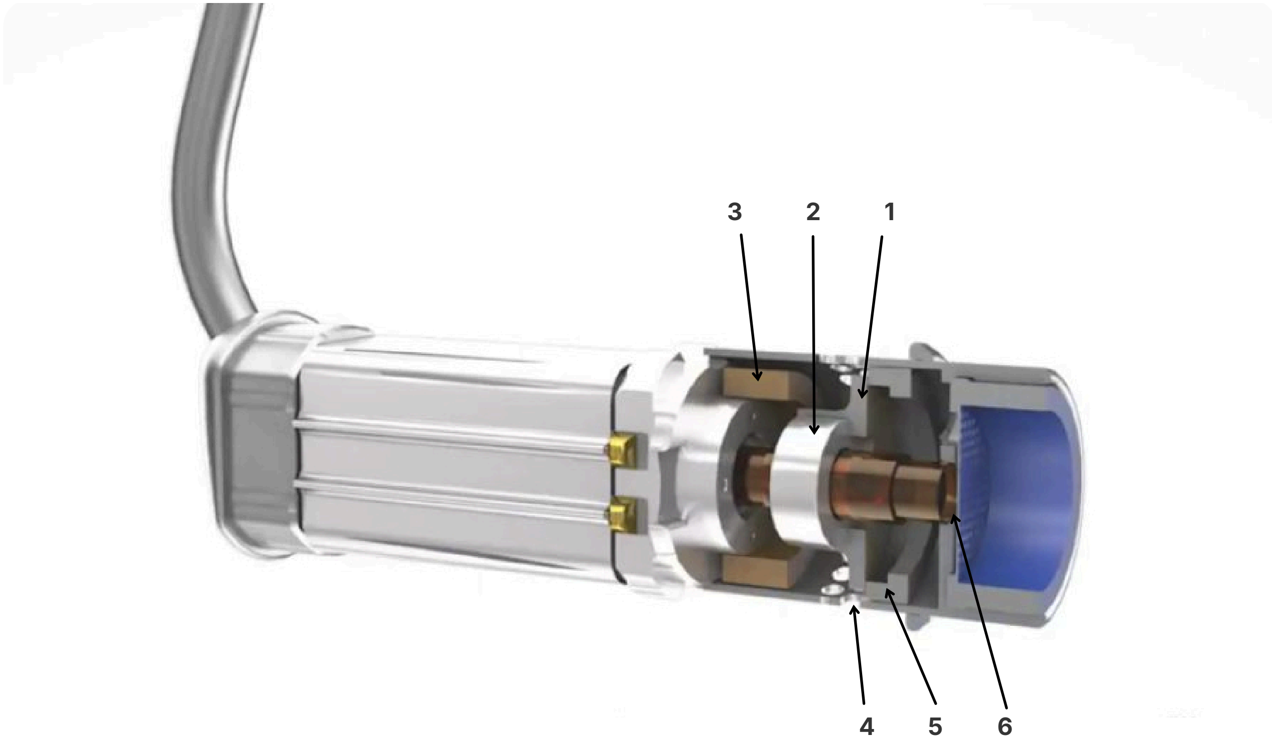


Figure 2.18 Cross-section view of the VRIC hearing aid in a closed vent position, showing the valve (1), moving magnet (2), coil (3), vent holes (4), latching ring (5) and sound outlet tube (6) (Cooling, 2020).

Why a valve is desired for streaming music

The valve is particularly valuable for optimising music streaming through a hearing aid. During music streaming, the valve closes the vent, creating a more sealed acoustic system that prevents streamed audio from leaking out of the ear canal and limits external sounds from interfering with the streamed audio. A closed vent allows the receiver to deliver a cleaner and controlled sound, which improves low-frequency response, perceived fullness, and overall streamed music performance. Without the valve, an open vent would allow low frequencies to escape and environmental sounds to mix with the streamed audio, which impacts the bass response and clarity.

Takeaways 2.2.2

- Phonak ActiveVent uses an electromagnetic actuation system to open/close the venting pathway
- For the redesign, incorporating the manual mechanism, it must include a reliable locking feature to keep the vent open or closed **(R3.1)**
- Sound outlet must be positioned after the vent openings **(R1.5)**
- The redesign must maintain the cross-section of the sound outlet tube **(R1.6)**

2.2.3 Understanding the effect of venting on hearing aid acoustics

Both lines of the graph (Figure 2.19), show how the Valve-Receiver-in-Canal (VRIC) with an open (3.5 mm) and closed vent amplifies sound across frequencies, represented in dB's and Hz. Here can clearly be seen that especially low frequencies (frequencies ≤1 kHz) are less amplified in an open vent system because low-frequency sound waves escape through the vent. In a closed vent system, a more consistent amplification can be noted, providing a better sound quality.

It is worth mentioning that a resonance effect is visible in the open vent system, indicated with the peak around 1 kHz. This can be considered as a typical acoustic consequence of venting, where sound leakage interacts with the amplified signal, creating standing wave resonances; the frequencies are reinforced. With a closed vent, the amplification is controlled, resulting in a smoother curve. For the closed vent graph, two noticeable peaks are shown. These peaks show the resonance of the membrane placed in the receiver; same for when moving up and down a ruler, on a given moment it moves more easily without much more force. High-frequency waves are less affected by venting, as these wave vibrations do not escape as easily.

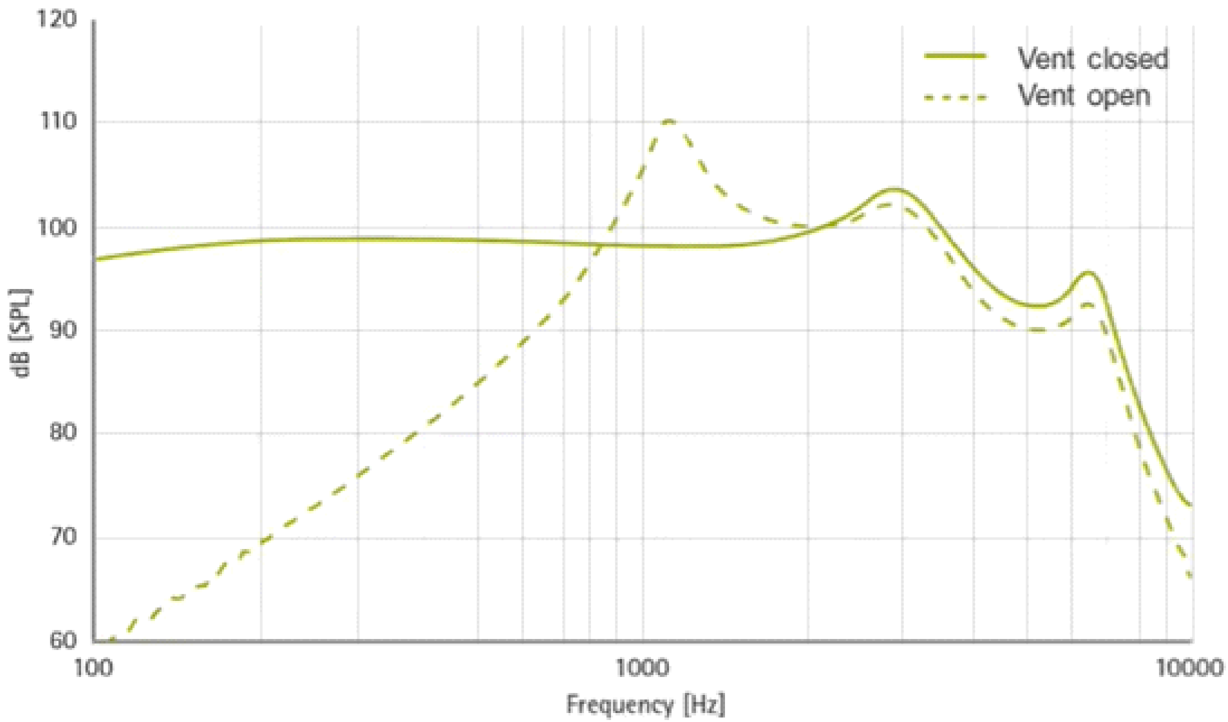


Figure 2.19 Frequency response of the VRIC with an open and closed venting system, with the Sound Pressure Level (dB) plotted against Frequency (Hz) (Olson, 2021).

Takeaways 2.2.3

- Open vent significantly reduces low-frequency amplification
- Venting mainly influences frequencies below ≤1 kHz

2.2.4 Components of the VRIC

By gaining insight into the current Valve-Receiver-in-Canal (VRIC) components, a clearer understanding is obtained of which elements may be simplified or eliminated to enable the integration of a manual mechanism without relying on electrical components. This analysis helps identify opportunities to reduce internal complexity and free up design space within the RIC, which is essential for accommodating a manual, mechanically actuated venting system.

The VRIC consists of various miniature components (Figure 2.20). It includes:

1. Nozzle tube
2. Nozzle filter ring
3. Valve seat
4. Sound outlet tube
5. Latching ring
6. Sliding tube
7. Valve
8. Moving magnet
9. Coil
10. Suspension
11. Housing
12. Electrical tape
13. Receiver (speaker)
14. Electric wires
15. Plastic insert
16. Cable to BTE housing

Through the cable (16) that is connected to the BTE housing, an electrical signal is sent to the receiver (13), which is secured in place using glue and electrical tape (12). The receiver (13) converts this signal into sound vibrations, which are then transmitted via the sound outlet tube (4) toward the eardrum.

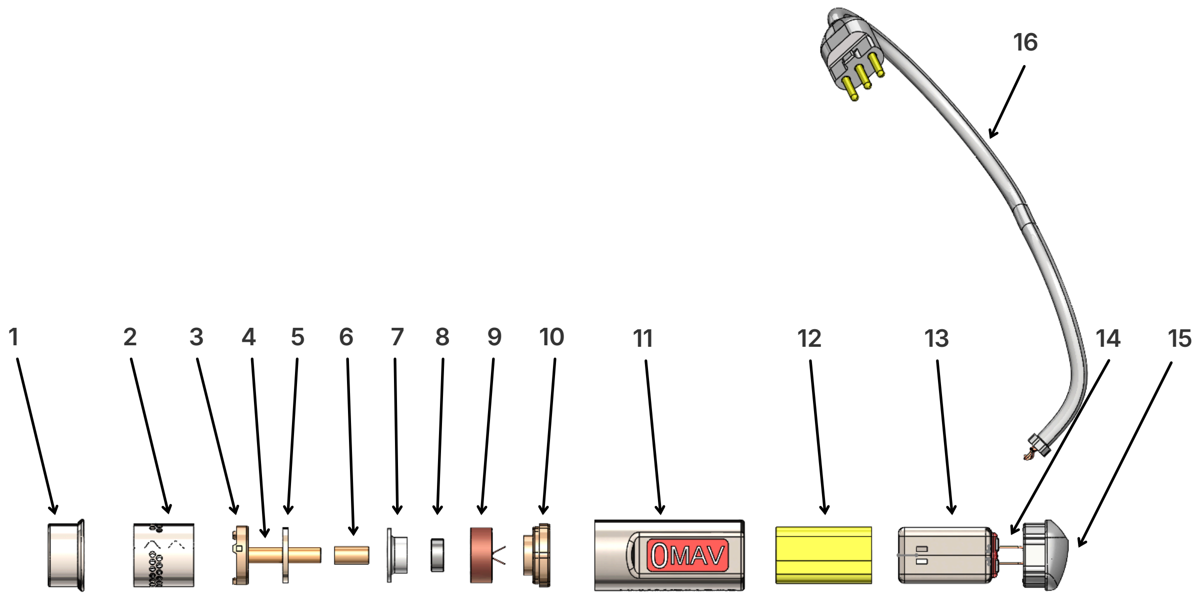


Figure 2.20 Side view of an exploded view of the VRIC.

Furthermore, the nozzle tube (1) is important for the interaction with the dome/earmould, to ensure it connects well. The suspension (10) forms the structural body of the automatic mechanism, existing of components such as the valve (7), the moving magnet (8) with the slide tube (6) sliding over the sound outlet tube (4), and the coil (9).

Takeaways 2.2.4

- For a manual VRIC design, the valve seat, latching ring, sliding tube, valve, moving magnet, coil, and suspension could be eliminated, reducing assembly steps and with that manufacturing costs

2.2.5 Candidacy requirement

Currently, the ActiveVent receiver is only compatible with all Phonak Audéo Paradise and Audéo Lumity rechargeable hearing aids, because they require their own powered connection to operate the mechanical valve, meaning it won't work with Audéo hearing aids with batteries or with other Phonak hearing aids (personal communication Sonion employee, 2025). In addition, not every individual with hearing impairment is suited for a Phonak ActiveVent hearing aid. Amongst others, the individual's hearing thresholds needs to be within an appropriate range, has sufficient dexterity for changing wax filters, doesn't report problematic tinnitus and the ears are free of excess moisture and earwax (Sonova, 2021a). On top of that, if the client is unable or not willing to take appropriate measures and care of the receiver, such as wiping away any earwax or debris, changing wax filters, or to disable audio notifications on their phone (to prevent unnecessary vent switching), Phonak recommends to continue the fitting with a standard receiver (Sonova, 2021a). These requirements show the VRIC is a technically advanced but selective solution, which restricts its accessibility. This highlights an opportunity for a venting system with a broader range of hearing aid users, by making it more universally applicable and less dependent on precise maintenance routines.

Takeaways 2.2.5

- Phonak ActiveVent works with a limited range of Phonak devices
- Phonak ActiveVent is a highly user-selective product
- Phonak ActiveVent requires frequent maintenance for the proper functioning of the vent mechanism

Closing summary on 2.2 Phonak ActiveVent

This chapter demonstrates how venting lies at the core of hearing aid performance. It shapes ***user listening and wearing comfort, sound quality, and overall effectiveness.*** The Phonak ActiveVent shows that dynamic venting can offer clear acoustic benefits by switching between openness and closedness. However, it also reveals limitations, such as ***mechanical complexity, candidacy requirements, frequent maintenance and reliability***. As a result, the ActiveVent is not only a technological reference point, but also evidence of the opportunity for ***simpler, more accessible venting mechanisms***. Understanding the role and function of its components, how venting affects acoustics, and the current constrains of the ActiveVent provide the foundation for developing a manual, more reliable, improved alternative.

While the Phonak ActiveVent represents an innovation in the hearing aid market, it is only one example of the broader technological evolution within the industry. To better understand how such developments fit into modern hearing aids, an exploration of the technical landscape and trends is given in the following subchapter.

Design requirements

R1.2: Vent size diameter could be adjusted
R1.3: Vent holes should be placed close to the dome
R1.5: Sound outlet must be positioned after the vent holes
R1.6: The design must preserve the current tube's cross section
R3.1: The design must ensure reliable vent locking

2.3 Technological landscape and trends

The technological landscape of hearing aids has advanced rapidly. Today's modern hearing aids are no longer 'simple' amplification devices, but systems that combine digital signal processing (DSP), wireless connectivity and artificial intelligence (AI). These innovations aim to improve sound quality, hearing comfort and adaptability across a wide range of acoustic environments.

2.3.1 Analogue vs. Digital aids

The previous chapters described a general overview of basic hearing aid components and those of a VRIC system. However, a distinction between an analogue and digital hearing aid has not been given. Both hearing aids share the basic hardware components (microphone, amplifier, receiver, earmould/dome), but they differ in signal processing. Analogue hearing aids amplify incoming sound continuously, whereas digital hearing aids first convert sound into digital signals that can be analysed and adjusted before being converted back into sound. Almost all hearing aids sold today are based on digital signal processing (DSP) (Ryan et al., 2025).

DSP hearing aids have provided significant advances and improvements compared to analogue hearing aids, such as improved noise reduction, improved algorithms in directional microphones, speech enhancement and improved feedback cancellation, a technique that eliminates a high-pitch caused by the microphone picking up its own amplified output (Kerckhoff et al., 2008).

In RIC hearing aids, multiple directional microphones are often integrated along with intelligent signal processing algorithms. Such systems dynamically adjust the microphone focus, prioritising speech while suppressing background noise. This results in an improved hearing performance in complex and challenging acoustic environments, to provide users with enhanced clarity, and hearing comfort (Bissmeyer & Goldsworthy, 2017).

2.3.2 Connectivity and User Interaction

Wireless connectivity has also become a major trend and important advance in hearing aid technology. By offering Bluetooth functionality, hearing aids can connect to devices such as mobile telephones or car audio systems for streaming music or picking up phone calls. This wireless connection improves the signal-to-noise ratio (SNR), meaning it improves sound quality and improves the ability to understand speech, by bypassing the microphone and sending sound directly to the processor (Mecklenburger & Groth, 2016).

Furthermore, a smartphone-connected hearing aid through an app offers several advantages. The app helps users to understand hearing aid controls and encourages them to take charge of their own hearing loss management, leading to a confidence boost in daily life (Gomez et al., 2021). On top of that, the ability to adjust, personalise and interact with the hearing aid is what empowered users most (Gomez et al., 2021). This means that smartphone-connected hearing aids could shift the relationship between audiologists and the patient, where patients are offered greater independence and control over their hearing, while audiologists take the role of guiding and supporting the patients.

2.3.3 AI in hearing aids

As hearing aids have evolved from standalone devices to connected systems, the next step in their technological development is the integration of AI. It enables hearing aids not only to enhance real-time sound processing, but also to improve personalisation; to learn, adapt and make decisions based on the user's listening environment and behaviour.

Still, a major challenge for hearing aids is background noise. AI addresses this by automatically distinguishing speech from unwanted noise through advanced noise cancellation techniques. This improves the ability to focus on the person a user want to hear, while enhancing overall sound clarity (Sygrove, 2025).

Beyond noise cancellation, AI offers additional capabilities, such as personalised learning, health tracking and real-time translation (Sygrove, 2025).

Technological advancements in digital signal processing, wireless connectivity, and AI are transforming hearing aids into highly personalised, user-friendly devices. These innovations are driving market growth, and creating opportunities for new product segments. The next chapter provides an analysis of the hearing aid market.

Takeaways 2.3

- The ability to adjust, personalise and interact with the hearing aid is what users empower most **(R2.2)**

- The industry is moving toward more automated and intelligent systems that adapt in real time to the users' environment and behaviour, to improve personalisation and user independence

Closing summary on 2.3 Technological landscape and trends

This chapter shows how hearing aids have transformed into advanced, interconnected products through digital processing, connectivity and Artificial Intelligence. These innovations stimulate the need for ***personalisation, sound adaptability and user control***; trends that influence both product performance and user expectations. The shift toward such technologies show that, even though software-driven features are growing, the acoustic performance and user autonomy define wearing and hearing comfort in daily use.

Design requirements

R2.2: The design must allow the user to adjust the sound to their preference

2.4 Market analysis

According to Wani and Faizullabhoy (2025), the global hearing aids market size was valued at USD 8.3 billion in 2024 (Figure 2.21), with the forecast that the market will grow with 6.5% each year, resulting in a market size of USD 15.5 billion in 2034. Key drivers of this growing trend include the increase in prevalence of hearing loss, a rising ageing population, a growing awareness of hearing loss treatment options, and an increase in supportive government policies (Wani & Faizullabhoy, 2025).

From a product perspective, Behind-the-Ear models are still the dominant hearing aids in the market, accounting for 34.9% in 2024, due to their ability to deliver a greater amplification for those with profound hearing loss, and are easier to use for elderly with dexterity issues. However, the Receiver-in-Canal hearing aids are expected to grow fastest, with an annual growth of 7.3%, due to their compact design and natural sound quality. Completely-in-Canal and Invisible-in-Canal hearing aids are expected to gain an annual growth of 6.9%, due to their increasing popularity for their invisible fit, which addresses aesthetic concerns among patients (Wani & Faizullabhoy, 2025).

The top players in the market, the Big Five, include Demant, GN Store Nord, Sonova, Starkey and WS Audiology, with the last leading with a 26.9% market share, together have a collective market share in 2024 of 92.4% (Wani & Faizullabhoy, 2025). Four out of five have adopted a newly growing hearing aid segment, the Over-the-Counter (OTC) hearing aids. OTC hearing aids are tailored for adults with mild to moderate hearing loss. These aids are self-fitted, allowing users to tailor amplification and sound quality to their needs, and are available without an audiologist, intended to increase accessibility (Chung & Zeng, 2024). Logically, this results in an increase of competitors trying to enter the huge health market. For example Apple is putting earphones (AirPods) on the market which can be used as a clinical-grade hearing aid (Apple, 2025).

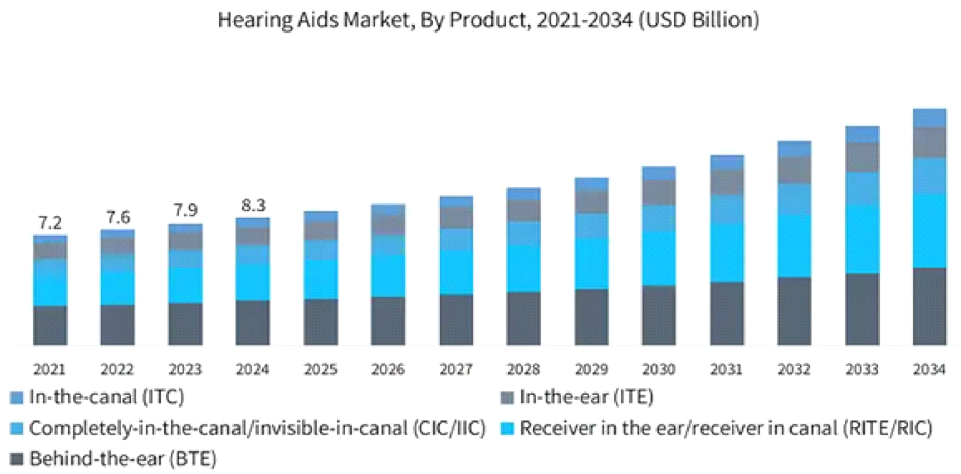


Figure 2.21 Hearing aids market size and its forecast (Wani & Faizullabhoy, 2025).

When it comes down to the market of intelligent RICs, the ActiveVent hearing aid is the world's first and currently only product that automatically opens and closes a venting system based on the acoustic environment (Sonova, 2021b). This creates an unique value proposition. Although no direct comparable dynamic venting systems have been offered, the rapid innovation in hearing aids technology indicate that similar solutions may pop-up.

Takeaways 2.4

- The hearing aid market is expected to grow 6.5% each year
- OTC hearing aids are emerging as a major new category

Closing summary on 2.4 Market analysis

With Receiver-in-Canal hearing aids becoming the fastest growing market, it highlights that users' demand increasingly focuses on comfort and natural sound quality, which are influenced by venting. The ActiveVent shows that dynamic venting has a strong market potential, however its uniqueness exposes a clear gap, as no simpler dynamic venting options currently exist. As competition increases, especially with Over-the-Counter aids entering the market, a manually adjustable Valve-Receiver-in-Canal concept could offer the Big Five a differentiated feature that aligns with the expected market growth.

TUNING INTO THE USER

USER & DESIGN FOUNDATIONS

3

In this phase, insights from user interviews are presented to provide a deeper understanding of hearing aid users’ experiences and perspectives. These insights, including findings from the context analysis, are used and translated into two personas. These personas help illustrate the diverse needs, wishes and behaviours within the hearing aid context. Next, the specific target group for this project will be defined that will help shape the design vision, design requirements, and ideation and development phase of the project.

3.1 Users' perspective

Although today's hearing aids have various modern features and functionalities such as Bluetooth, wireless streaming and AI-driven support, research from Manchaiah et al. (2021) suggests that the most favourably hearing aid attributes are more practical. This research suggests most desirable aspects are the physical comfort and reliability of a hearing aid, and the ability to understand friends and family in quiet and noisy environments. To complement these findings, qualitative interviews were conducted with a diverse group of hearing aid users to gain a better understanding of their daily experiences, their values, and how they interact with hearing aids.

3.1.1 Research method

The study involved twelve hearing aid users between 19 and 65 years old. The sample consisted of seven male and five female participants. Two participants were aged 65 or older, two were between 45 and 55 years old, and the remaining eight were 25 years old or younger. Both Phonak ActiveVent users and non-ActiveVent users were included to ensure a diverse range of experiences and perspectives.

The primary stimuli consisted of semi-structured interview questions to explore participants' experiences with hearing aids. These questions covered themes such as day-to-day use, hearing and wearing comfort, reliability, and speech challenges in diverse acoustic environments. Next to the formulated questions, follow-up questions were asked depending on participants' responses for a deeper understanding of users' motivations, values, and frustrations. The full list of prepared questions and gathered insights are shown in Appendix A and B respectively.

Interviews were conducted either in-person or through Microsoft Teams for remote sessions. A standard smartphone was used to record the in-person interviews, and Microsoft Teams to record online interviews, when permitted.

Participants were first informed about the purpose of the study and the focus on understanding hearing aid use in everyday contexts. After providing consent, participants engaged in a semi-structured interview.

The primary goal of the interviews was to identify and clarify user needs, preferences, benefits, challenges, as well as situations that may cause frustration or discomfort during their use. These insights provide guidance for designing solutions that align with real-life users. Additionally, interviews helped uncover struggles that might not be noticeable through observations or quantitative research alone. Responses were documented and later analysed qualitatively.

3.1.2 Insights from interviews

Interviews offered a clear understanding of how users experience hearing aids in daily life. The findings highlight the main benefits users value, and the challenges they face.

Participants consistently described benefits that enhance their daily lives. These benefits show why hearing aids are considered essential rather than optional tools.

Main benefits users value

1 Understanding friends and family

The most frequent cited benefit is the ability to reconnect with friends and family. All twelve participants noted that hearing aids allow them to follow conversations in quiet settings, and feel socially included. Several participants highlighted that without their devices, they would miss interactions, feel isolated, or avoid social situations.

2 Adaptive sound balance

Users value the ability to adapt the sound environment to their needs. By adjusting volume or temporarily turning off the device, they can manage sensory overload, maintain focus, or limit fatigue caused by ambient noise. This functionality provide users with a sense of control and autonomy over their listening experience.

3 Seamless media connectivity

Eight out of twelve participants use their hearing aids to stream music and radio, phone calls, and podcasts. They treat their hearing aids as substitutes for wireless ear-/headphones. This shows that hearing aids have become multifunctional devices that are integrated into users' daily digital lives.

While these benefits enhance social participation and listening comfort, users also described challenges that affect the ease and satisfaction of daily hearing aid use. Understanding these challenges is critical for designing solutions that align with users' needs and values.

Main challenges users face

1 Understanding speech in noise

All twelve participants reported having difficulty following conversations in noisy environments such as restaurants, bars, auditoriums, and social gatherings. Current hearing aids are not yet effective enough in noise reduction, which makes it challenging for users to focus on relevant sounds.

2 Unclear program distinction

Most participants rely on only one or two pre-installed programs because clear differences between diverse modes are difficult to perceive. Users express a need for clearer program differentiation and simpler, more intuitive switching, which would enhance autonomy and confidence in managing their device(s).

3 Cumbersome phone interaction

Adjusting pre-installed programs or volume through smartphone apps is described as slow and inconvenient by eight out of twelve participants. They expressed a preference for physical buttons on the device, which allow for quick, intuitive control without disruptions.

3.1.3 Discussion

The interviews highlight that the use of hearing aids is shaped by a combination of sound performance and the type of interaction. Although participants differed in age, experience and expectations, their perspectives consistently show a need for hearing aids that not only delivers well amplified, clear sound but also integrate smoothly into daily routines and align with users' sense of control; hearing aids are experienced not only as medical devices but as essential, intuitive tools.

The results align with prior research (Manchaiah et al., 2021) suggesting that practical functionalities remain more critical to users than advanced technological features alone. Participants emphasised that the broad ability to manage and control sound in complex environments is highly valued. Three central topics emerged in the interviews; understanding speech in noise, the ability to adapt their surrounding sounds, and seamless media connectivity. These collectively represent the overarching theme of noise and sound control. This ability to regulate incoming audio, whether by reducing unwanted noise or streaming music, gives users a sense of control and clarity in daily life. This support user autonomy, as it determines how comfortably and confidently users can participate in conversations, crowded environments, and how seamlessly they can switch between social, work-related, and personal listening environments. In addition, the preference for tactile controls over smartphone-based interactions emphasises this connection. Users value interactions that are immediate, unobtrusive, and user-centred, which allows them to adjust their auditory environment intuitively with minimal effort.

While smart features such as streaming or smartphone-based settings are appreciated, there is a strong desire for hearing aids that "just work", as the interaction with smartphones is considered to be cumbersome. Users are seeking for less technological friction, less complexity, and support users on their daily activities without having to rely on an external tool that interferes with their activities.

Although age differences were not the main focus of the study, they did emerge as interesting contextual insights. Younger adults (≤25 years old) value media connectivity, as they integrate hearing aids into their digital lives and value instant tactile, intuitive control. Middle-aged users (40-55 years old) prioritise speech clarity and reliability across professional and social contexts without technological friction. Older adults (65+ years old) focus on simplicity, wearing comfort and predictability, viewing hearing aids as medical devices rather than lifestyle products.

Overall, insights revealed that effective hearing aid design requires a balance between advanced functionality and intuitive usability. Users show appreciation that reduce effort and enhance communication, however their frustration comes from interruptions in their daily lives that draws attention to their device(s). To avoid these moments of disruption, users show a need for clarity, autonomy and control, valuing quick, intuitive adjustments that allow them to manage how they hear and engage with their surroundings.

Takeaways 3.1

- For users, the main benefit of hearing aids is reconnecting with friends and family, which avoids social exclusion.

- Users highly value having control over their hearing aids, allowing them to adjust or mute the device to manage how they engage with their surroundings **(R2.2)**

- Users value having the ability to stream music and podcasts, and make phone calls with their devices

- Understanding speech, especially in noisy environments, is the top priority for all participants

- Hearing aids should have a more effective noise reduction to preserve a clear sound quality to understand speech, and to reduce unwanted noise (e.g. wind or crowd noise)

- Switching programs using a phone is considered too slow and inconvenient

- Hearing aid users want immediate access to, easy-to-use, physical controls **(R2.3 & R2.4)**

- Most users end up using one or two programs, despite many available functionalities

- Hearing aids are seen as daily-life essentials

Closing summary on 3.1 Users' perspectives

Findings from the study emphasise a key design challenge relevant to this graduation project: users want hearing aids that support ***autonomy, minimise disruptions***, and offers ***the ability to quick adapt*** to changing acoustic situations without requiring complex interaction. The user frustrations highlight design opportunities for more user-responsive solutions. These insights directly inform the development of Valve-Receiver-in-Canal systems and adaptive venting solutions to better meet users' expectations.

Design requirements

R2.2: The design must offer the ability to the user to adjust their perceived sound
R2.3: The design mechanism should have an instant switch
R2.4: The mechanism should be intuitive to use

3.2 Target group

To define the target group for this project, personas were created. To develop personas, it is important to look back at the main insights and themes that emerged from the research. Users consistently emphasised the importance of understanding speech, especially in noisy environments, and expressed a strong wish for autonomy through adaptive sound control and effective noise reduction. In addition, users experience confusion around the distinction in pre-installed programs and frustrations with smartphone-use, which highlight a preference for simple, quick, tactile controls. While younger adults often appreciate advanced features, older users tend to prioritise simplicity and predictability without demanding attention.

For this project, the target group will be represented by two personas (Figures 3.1 and 3.2), Robin and Sandra, as they represent the user group that benefits most from innovation in venting mechanisms and interactive hearing aids. The two personas show the growing demographic of younger and middle-aged, tech-comfortable hearing aid users, whose lifestyles and hearing needs differ significantly from older-aged (elderly) hearing aid users. Where Robin represents the younger users showing the need for adaptability and seamless integration, Sandra represents the professional, socially engaged adult who prioritises clarity, reliability, and usability.

Both personas seek adaptive sound balance and autonomy in their hearing aid, which seamless integrates into their digital lifestyles. Therefore, the target group benefits most from a manually driven mechanism, as it gives them direct, intuitive control over how open or closed they want their acoustic environment to be. Unlike the current, fully automatic system, a manual mechanism empowers these users to adapt their hearing experience instantly and deliberately to changing situations, e.g. to focus on a conversation, reduce noise, or tune into their surroundings. This direct interaction aligns with their desire for autonomy, immediacy, and a tangible sense of control.

Persona Robin

Figure 3.1 Persona Robin - Photo by Noman Khan on Unsplash.

Profile

Age:	23
Gender:	Male
Location:	Rotterdam, the Netherlands

Hobbies

Enjoys team sports, loves music and playlists during workouts, and spends time with friends at concerts or cafes.

Needs and motivations

Robin wants to be able to understand friends and family in all sound environments, from quiet one-on-one conversations to noisy environments. Robin values sound quality and wants control over when to open up to his surroundings or tune them out. Quick, intuitive controls to adapt sound are important, as app interactions are too slow. Moreover, Robin appreciates streaming capabilities to listen to music and podcasts.

Frustrations

- Struggles to understand speech in noisy settings
- Experiences unclear differences between preset programs
- App-based control is too slow; prefers direct physical interaction

“I want to hear people clearly no matter where I am, and I need simple, instant control to adjust my sound without pulling out my phone, especially when I’m with friends.”

Persona Sandra

Figure 3.2 Persona Sandra - Photo by Maria Lupan on Unsplash.

Profile

Age:	53
Gender:	Female
Location:	The Hague, the Netherlands

Hobbies

Loves going for long walks, listens to audiobooks and music while being on the bike or train, and enjoys cooking with friends.

Needs and motivations

Sandra's main priority is speech clarity and hearing comfort, especially in group conversations or work meetings. She appreciates Bluetooth connectivity for phone calls and online meetings, but also to listen to music or podcasts. She prefers seamless switching between modes over complex smart features; a single, quick action to switch modes is desired.

Frustrations

- Difficulty understanding speech in noisy settings

- Prefers predictability over constant digital interaction

"I love that I can call and listen to music through my hearing aids, but what really matters is I'm able to understand people again, without having to strain all the time."

3.3 Design vision

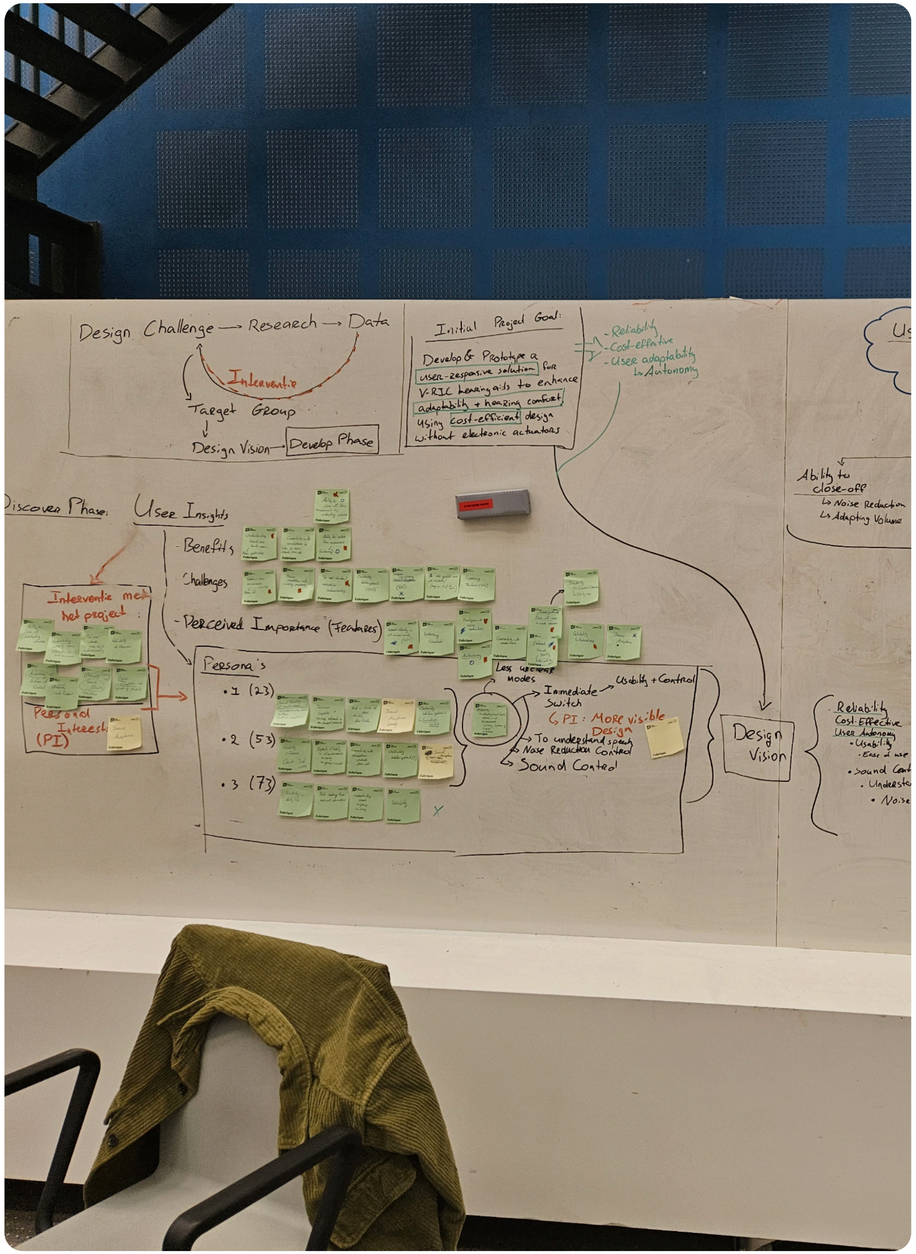
With the project's scope, the research conducted and the identification of the target group, a more precise design vision statement has been formulated. The design vision is stated as followed:

"Elevating hearing experience for hearing aid users,

by offering an easy-to-use, user-responsive manual driven venting solution

for intuitive control, adaptive sound balance and effective noise reduction,

to increase user autonomy, while improving robustness and cost-efficiency of the Phonak ActiveVent."



3.4 List of requirements

From all insights and takeaways from the Discover phase, a list of requirements has been created. The full list can be found in Appendix C. Here, requirements from research, Sonion Netherlands and the author are categorised in the following sections:

- Performance
- User comfort & Ergonomics
- Design constraints
- Durability & Reliability
- Manufacturability
- Aesthetics
- Sustainability
- Storage & Transport

The most important requirements are shown on the right (Table 3.1) and structured according to the MoSCoW method (Must, Should, Could, Will Not). Each requirement is linked to its tracking source, and requirement number that corresponds with the full list of requirements.

Table 3.1 List of requirements, indicating the tracking source, the number that corresponds with the full list, and the corresponding section.

	Tracking source	# Req. (App. C)	Section (App. C)
Must			
The design must contain a mechanism that provides an open vent (3-4 mm) and a closed vent (0 mm) system	Sonion Netherlands	R1.1 & R1.4	Performance
The vent must be placed close to the dome	Ch. 2.2.1	R1.3	Performance
The user has manual control over the product	Sonion Netherlands	R2.1	User comfort & Ergonomics
The design must ensure reliable vent locking	Ch. 2.2.3	R3.1	Design Constraints
The mechanism must be robust to insertion and removal forces	Sonion Netherlands	R4.1	Durability & Reliability
Sound outlet must be positioned after the vent holes	Ch. 2.2.4	R1.5	Performance
Should			
The mechanism should have an instant switch	Ch. 2.5.2	R2.3	User comfort & Ergonomics
The mechanism should be intuitive to use	Ch. 2.5.2	R2.4	User comfort & Ergonomics
The product should not create wearing discomfort to users	Sonion Netherlands & Author	R2.5	User comfort & Ergonomics
The product should be moisture and earwax resistant	Sonion Netherlands	R4.2	Durability & Reliability
The product should not contribute to stigmatisation	Ch. 2.1.2	R6.1	Aesthetics
Could			
The vent size diameter could be adjustable	Ch. 2.2.1	R1.2	Performance

AMPLIFYING IDEAS

MECHANISM DESIGN & OPTIMISATION

This phase presents the iterative process of ideation and conceptualisation. Explorative prototypes, including 1:1 scale 3D prints, were developed to gain an understanding and a feeling of using a mechanism at a miniature scale. In the later stage, more detailed prototypes were developed, including five 10:1 scale 3D prints. These concepts were evaluated through tools and methods to make informed design decisions. Ultimately, an iteration on the chosen concept has been performed.

4

4.1 Intuitive use

Before developing ideas and concepts of manual mechanisms, It is important to decide which interaction with the product is most intuitive for users. In light of intuitive use, two locations for placing the aid were spotted as main possibilities; either interacting with the Behind-The-Ear (BTE) housing or directly with the Receiver-In-Canal (RIC) component placed in the ear. To evaluate these possibilities, an intuitive user interaction study was conducted with the aim of understanding which interactions users perceive as easy to perform and acceptable for daily use, and which controls are perceived as comfortable to wear and easy to reach.

For the controls, four interaction types were selected: pressing, twisting, pulling and switching (using a lever or switch). To make these actions tangible, seven physical dummy models were developed (Figures 4.1 - 4.4). These models replicated different control concepts on both the BTE housing and the RIC component. The BTE Upper and Lower models featured a lever mechanism to switch between two states, while the BTE switch incorporated a light-switch-type interaction.

These models were 3D printed from a bio-compatible material to avoid skin irritation when tested in and around the ear.

4.1.1 Research method

The study was conducted with six participants between the ages of 20 and 47. Both users with and without hearing aid experience were recruited to capture a variety of interaction habits. All testing took place in person. Since the dummy models were designed for the right ear, only right-handed participants were selected for the study. Each

Figure 4.1 BTE Upper.

Figure 4.2 BTE Switch.

Figure 4.3 BTE Lower.

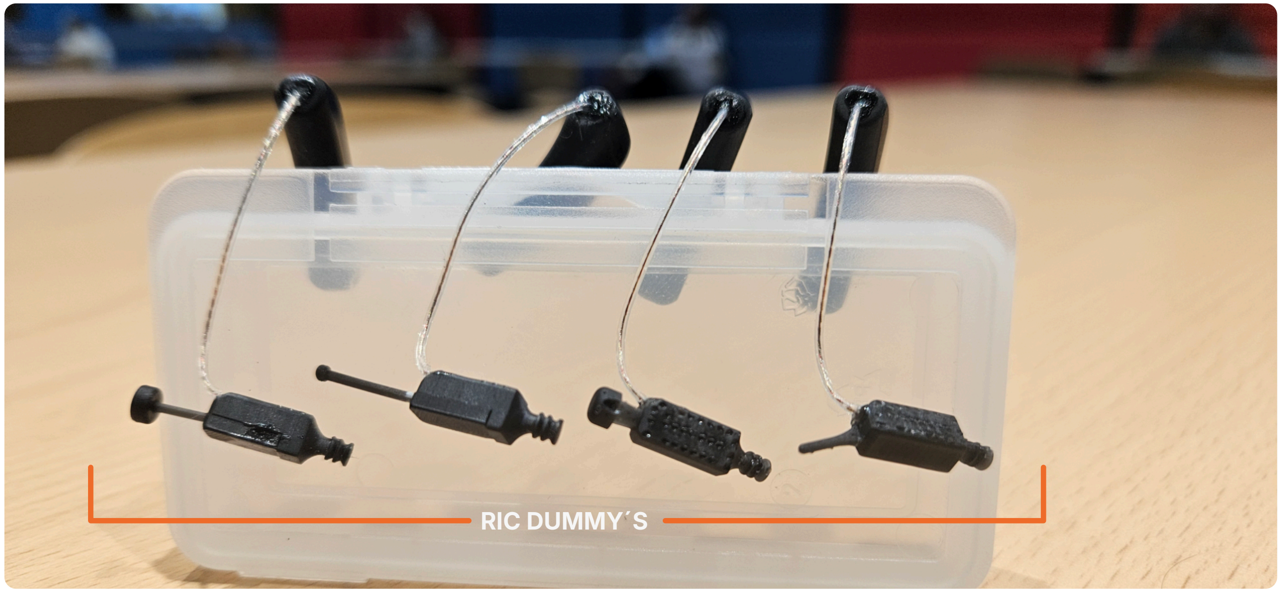


Figure 4.4 From left to right, RIC Twist, RIC Pull, RIC Push and RIC Handle.

participant was presented with the dummy models one at a time and was encouraged to handle them freely. They were informed on the type of interaction, and asked to perform the action several times, both standing and sitting, with pauses in between, to mimic real-life situations.

During these sessions, participants were encouraged to think out loud, to describe how intuitive each action felt, and whether they would consider the type of interaction as comfortable or practical. Follow-up questions were asked to further explore their reasoning and whether they encounter any difficulties due to hand position, ear anatomy, or physical constraints of the prototypes. In addition to verbal feedback, participants also evaluated each control on aspects such as fit, reachability, and ease of performing the action. These assessments were captured using a questionnaire with a 1–5 rating scale (1 = very negative, 5 = very positive).

The collected data was analysed and visualised in graphs, to provide insight into the strengths and limitations of each interaction type. These findings provide input for identifying the most desired interaction type and most suitable location for the manual mechanism for further concept development.

4.1.2 Key findings

The results from the intuitive use test revealed clear preferences and insights on how users perceive different control types and placements. Among the seven dummy models, the BTE Lower emerged as the most preferred, having the best scores on the four assessments (Figure 4.5). Participants reported that this position felt natural, as the movement follows a familiar motion of running their fingers through their hair (Figure 4.6). In addition, the location of the control is logical to them, as current volume buttons are also placed on the same position. Moreover, it was perceived as subtle and unobtrusive, as it interferes minimally with hair or glasses (Figures 4.7 and 4.8).

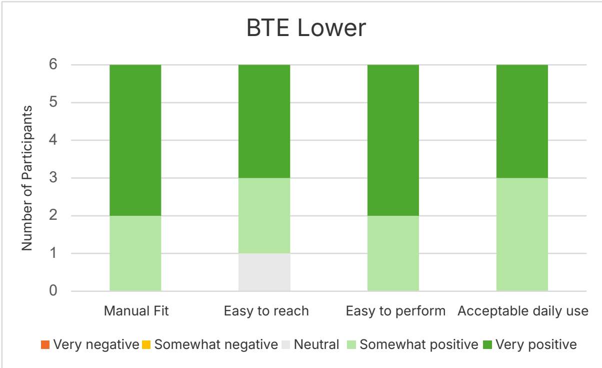


Figure 4.5 Results of the BTE Lower Intuitive Interaction test.

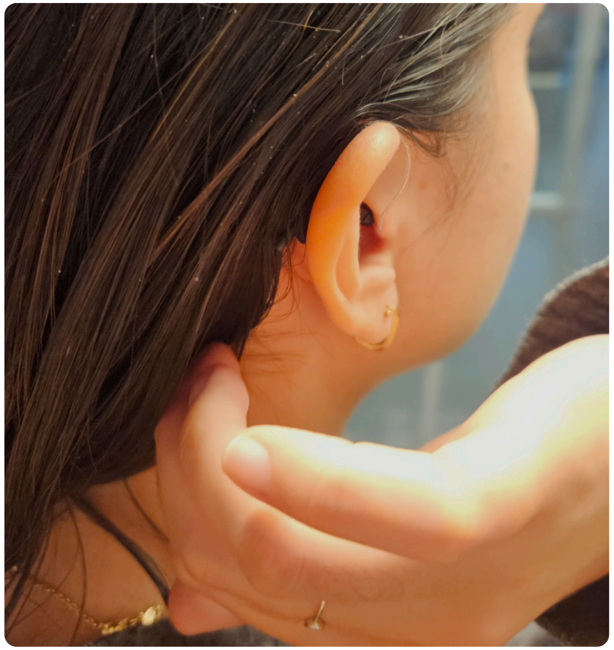


Figure 4.6 Participant running through her hair, following a similar movement when interacting with the BTE Lower.

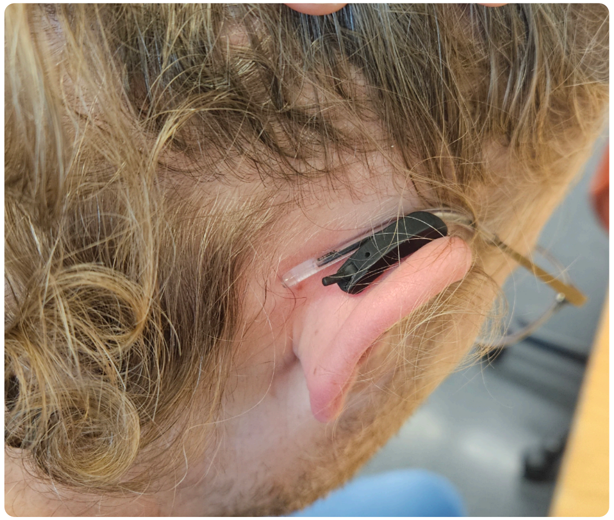


Figure 4.7 BTE Lower interferes minimally with participant's glasses

Figure 4.8 BTE Switch interferes with participant's glasses

Within the RIC options, the RIC Handle scored great on ease of performing (Figure 4.9), but was considered less intuitive. Participants indicated the handle interfered with inserting the device. Some participants noted that they expected to have a lever positioned on the BTE rather than on the RIC. Although it was appreciated that the interaction was discrete, it did not outweigh the sense of intuition or lack of naturalness.

Although the RIC Twist scored less on the ease of performing (Figure 4.10), it was regarded as the most intuitive interaction within the RIC options. Participants linked it to a volume knob, which enhanced the intuitive appearance. In addition, the control felt external rather than intrusive. Users noted that the device can be adjusted without having the fear of pressing the device further into the ear. Some participants noted limitations with the RIC Twist, such as experiencing obstruction by the tragus of the ear or larger hands, slightly longer adjustment time, and a feeling that the mechanism felt somewhat fragile. Despite these drawbacks, the twist provides the best sense of intuition and among the in-ear options.

In summary, the study shows that users respond most positively to interactions that afford familiar hand movements and existing habitual movements. The BTE Lower clearly stands out as the most intuitive and preferred option, while the RIC Twist represents the best compromise for having a control in-ear. Based on these findings, the BTE Lower and the RIC Twist will be used as the interaction controls for further concept development.

The remaining results from other dummy models are presented in Appendix D.

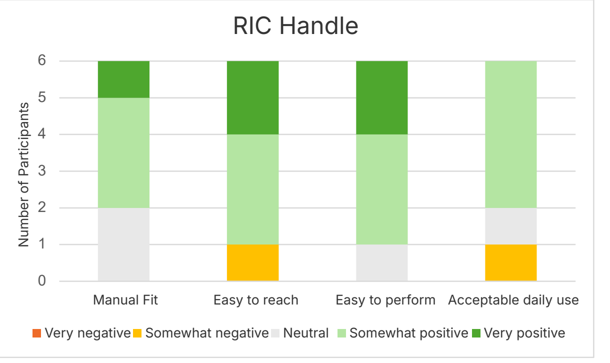


Figure 4.9 Results of the RIC Handle Intuitive Interaction test.

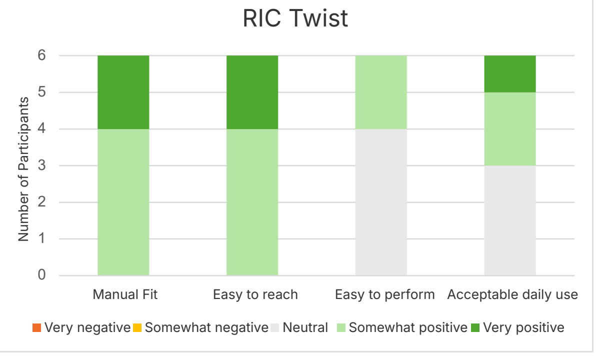
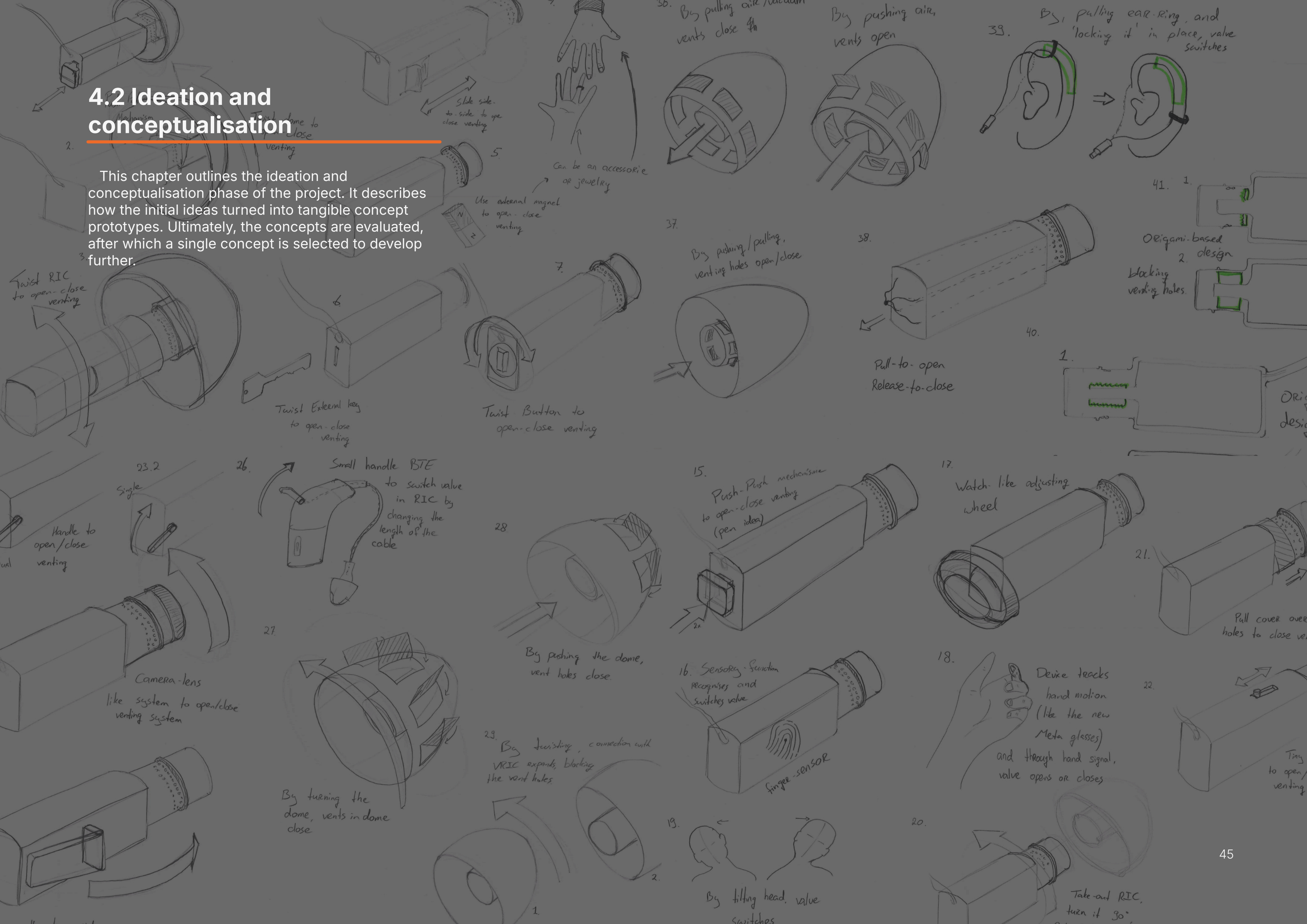


Figure 4.10 Results of the RIC Twist Intuitive Interaction test.

4.2 Ideation and conceptualisation

This chapter outlines the ideation and conceptualisation phase of the project. It describes how the initial ideas turned into tangible concept prototypes. Ultimately, the concepts are evaluated, after which a single concept is selected to develop further.



4.2.1 Conceptualisation BTE Lower

The development of a mechanism controlled from the lower part of the BTE housing initially started with design thinking and sketching. Since the BTE housing and the RIC component with the connection cable are manufactured separately and assembled at a later stage, any motion by the user interaction on the BTE would need to be mechanically transferred through the cable to the receiver.

Therefore, early sketches and ideation has been done, focusing on the existing connector system, to explore possibilities to transfer the motion from the BTE to the RIC through the cable (Figure 4.11). Based on these sketches, CAD models and 3D prints have been created. These mechanisms were inspired on existing cable-driven mechanisms, such as the brake cable system on a bicycle.

After the early ideation provided detailed mechanisms, the viability of these ideas was validated. After evaluations and discussion with experts from Sonion, it became evident that the mechanisms related to BTE Lower, although theoretically possible, were not viable in practice. Firstly, current BTE housings are already highly optimised in size with little space left for additional mechanical components. Integrating such a mechanism would increase the housing size and thus making it less discrete, an outcome which is not desired by the market (personal communication Sonion employee, 2025). Additionally, due to such a mechanism, a continuous tension in either of the cables (in the BTE or the cable itself) is present. During user interaction, the tension could cause unintended cable movement, which could cause the RIC to fall out of the ear. While this could be mitigated by making the cable more sturdy, it would again compromise discreteness and wearing comfort. On top of that, the extremely small components for such mechanisms would be fragile, increasing the risk of mechanical failures in both the RIC and BTE housing.

Based on these limitations, the design focus was shifted away from BTE-controlled solutions toward the RIC twist; an in-ear mechanism, controlled through a direct twist interaction.

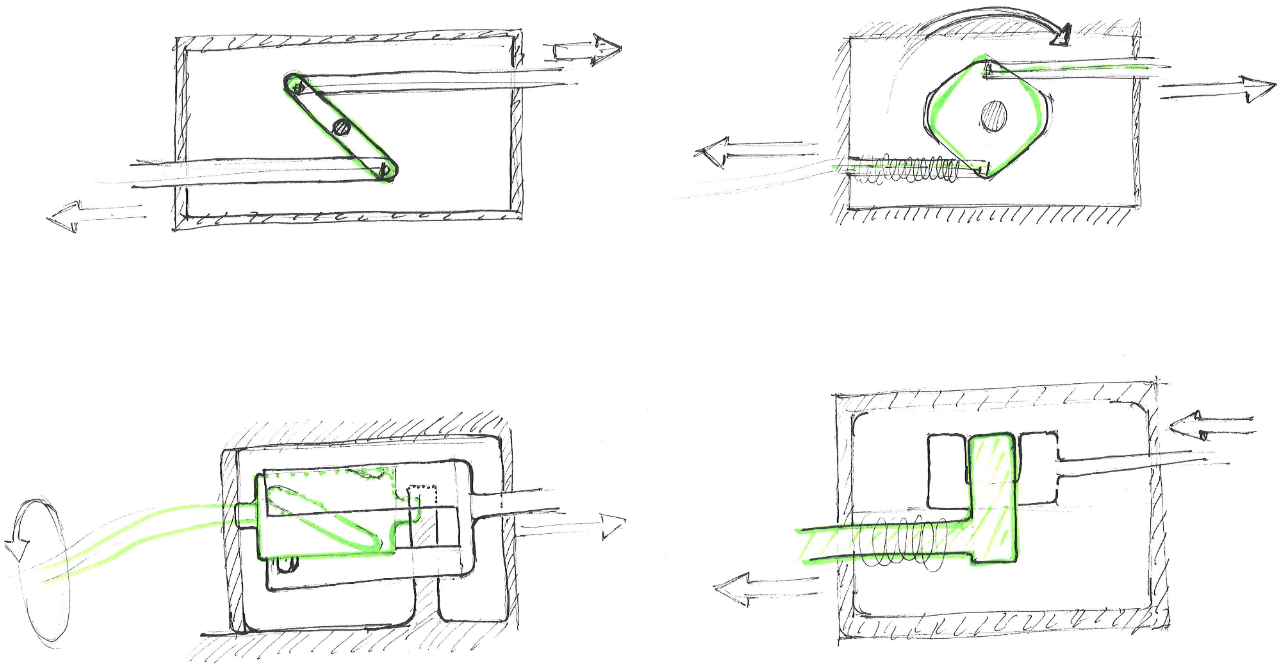


Figure 4.11 Ideation sketches on mechanical transfer system.

4.2.2 Conceptualisation RIC Twist

The development of a twist-controlled mechanism integrated into the RIC housing began by revisiting earlier ideation and sketches. A key constraint of the current RIC design is that its internal components are fully glued together, leaving minimal space left for additional mechanical components. To address this limitation, the design strategy shifted toward concepts in which the RIC housing itself rotates around the nozzle during user interaction.

By defining the nozzle, together with the dome, as a fixed point within the ear canal, more design freedom has been created for developing twist-based mechanisms. It enables mechanical actuation without requiring internal space within the RIC housing. From here, three main conceptual directions emerged for manually opening and closing the venting system.

These directions were further explored through five 10:1 scale prototypes. The enlarged scale was selected to visualise component interaction, the prototypes' motion, and its actuation. The prototypes are intended to validate the working principles of opening and closing the vent, by rotating the RIC housing, while maintaining a fixed nozzle position.

Figure 4.12 shows the five prototypes in a closed vent position, where Figure 4.13 shows the five prototypes in an open vent position. Each concept is presented in the following sections, outlining its working principle and highlighting the key distinctions between the alternatives to enable a structured comparison.

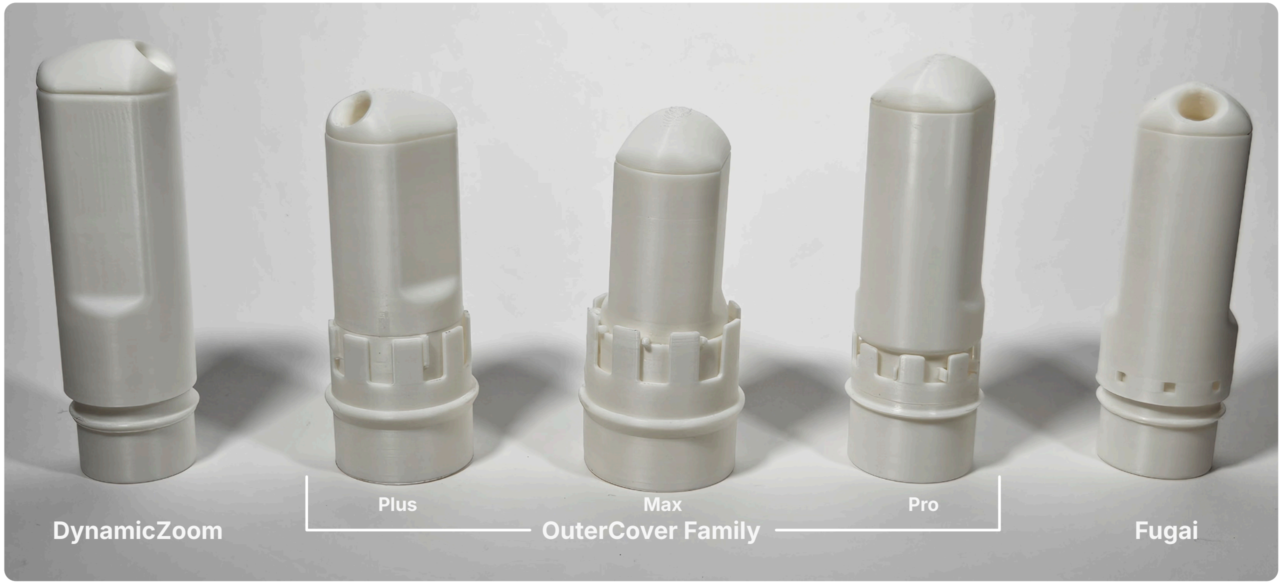


Figure 4.12 Five 10:1 scale prototypes in closed vent position.

Figure 4.13 Five 10:1 scale prototypes in open vent position.

Concept 1 - DynamicZoom

The DynamicZoom concept is inspired by the mechanical principle of a camera zoom lens, where a rotational input results in linear movement. Applying this principle to the RIC, rotating the housing causes the three-pointed star-shape, connected to the RIC housing, to follow a helical path (1) along the nozzle (shown in blue, Figure 4.16), over the sound outlet tube (3), resulting in axial displacement. A valve (2) is attached to the three-pointed star-shape, allowing it to move linearly as the housing rotates, thereby opening or closing the venting path, (Figures 4.14 and 4.15). A simplified model of a receiver connected to it is also shown in these figures.

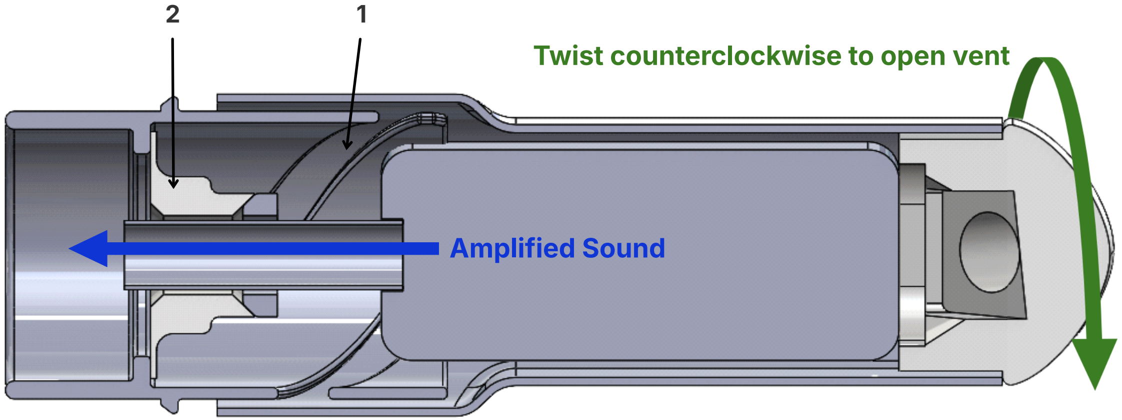


Figure 4.14 Cross-section view of DynamicZoom in closed vent position.

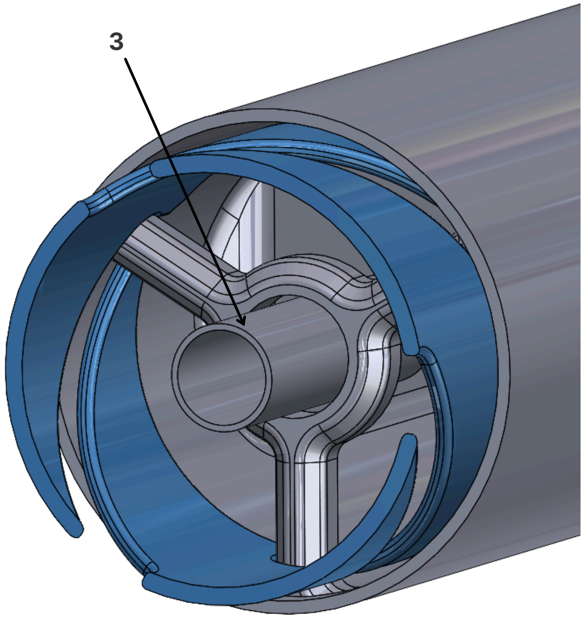


Figure 4.16 Partial cross section; the three-pointed star-shape following the helical path (valve is not shown in this picture for clarity).

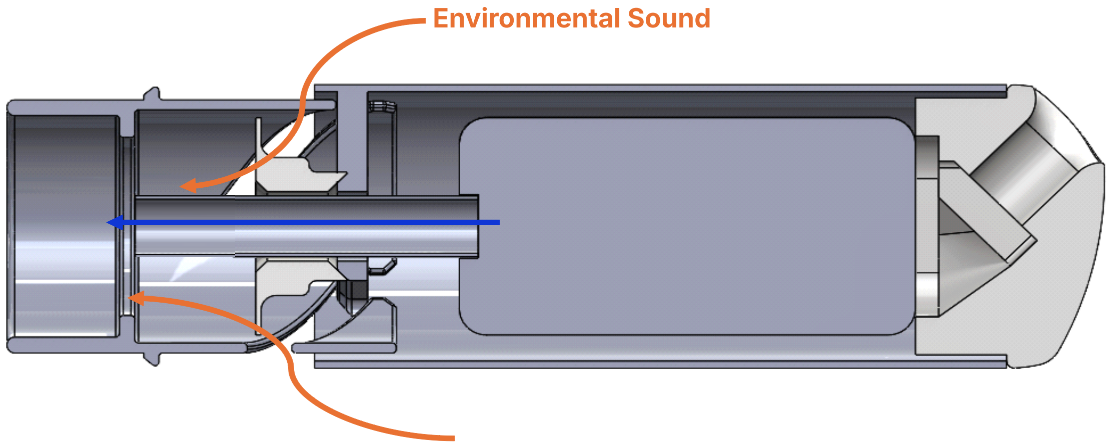


Figure 4.15 Cross-section view of DynamicZoom in open vent position.

A 10:1 scale prototype of the DynamicZoom has been created. The prototype is shown in a closed vent position (Figure 4.17), and in an open vent position (Figure 4.18) after twisting the RIC housing counterclockwise, while the nozzle stays in place, to evaluate a variation of the vent actuation principle described earlier.

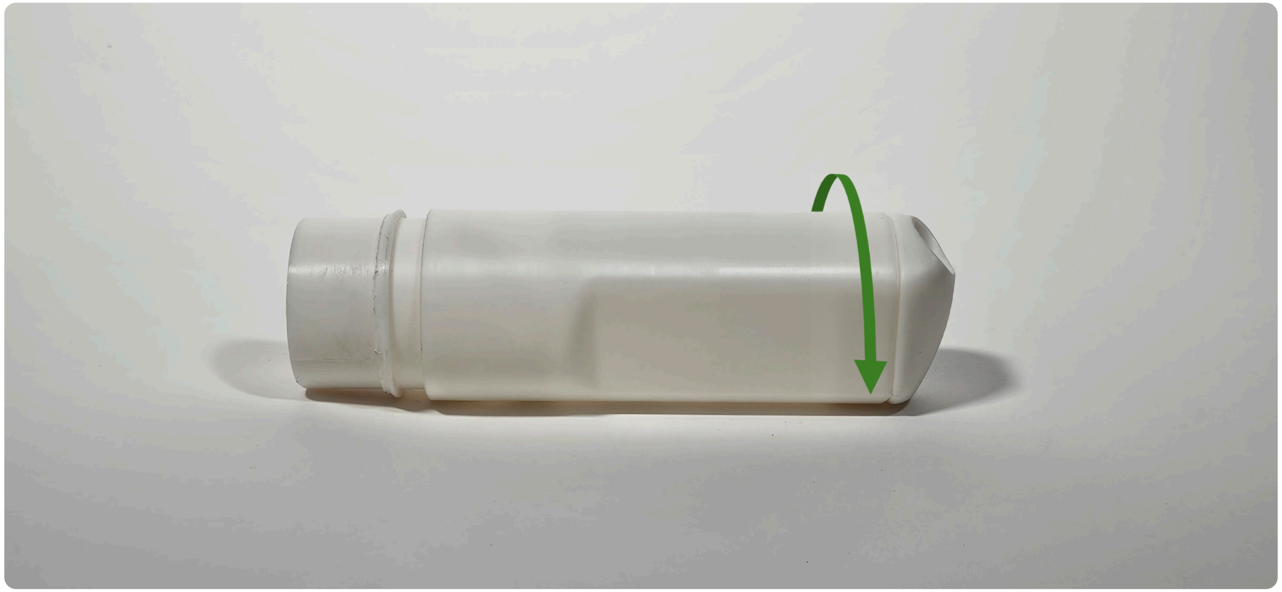


Figure 4.17 Prototype of DynamicZoom in closed vent position.

Figure 4.18 Prototype of DynamicZoom in open vent position.

Concept 2 - OuterCover

The OuterCover concepts share a common working principle in which venting is achieved by mechanically covering and uncovering vent holes. In these designs, the vent holes are positioned on the inner nozzle, while a secondary nozzle rotates over an inner nozzle. Several variations were developed to explore design opportunities and manufacturing constraints.

OuterCover Plus

In OuterCover Plus, the secondary outer nozzle (shown in blue, Figure 4.21) rotates over the inner nozzle along a guide rail (1) (Figures 4.19 and 4.20). OuterCover Plus incorporates small mechanical stops (2) (walls) on the nozzle to define clear end positions, to ensure that the vent holes are either fully open or fully closed, and to prevent over-rotation (Figure 4.21).

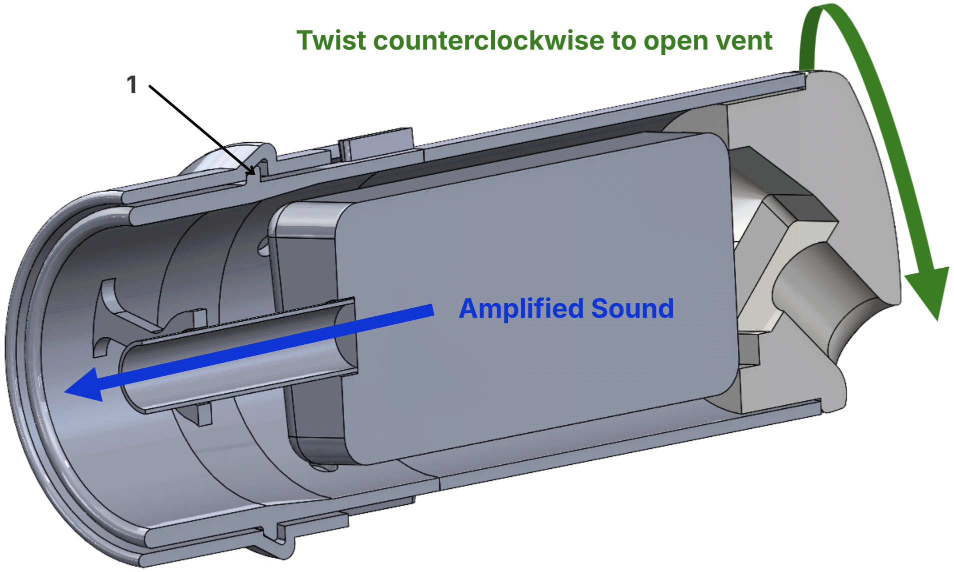


Figure 4.19 Section view of OuterCover Plus in closed vent position.

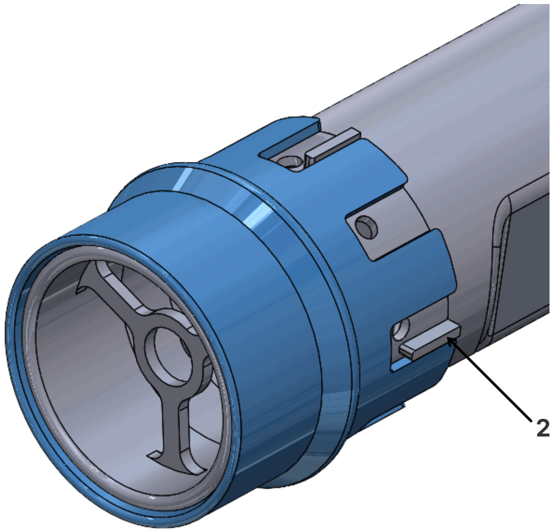


Figure 4.21 Walls preventing over-rotation and ensuring open and closed venting.

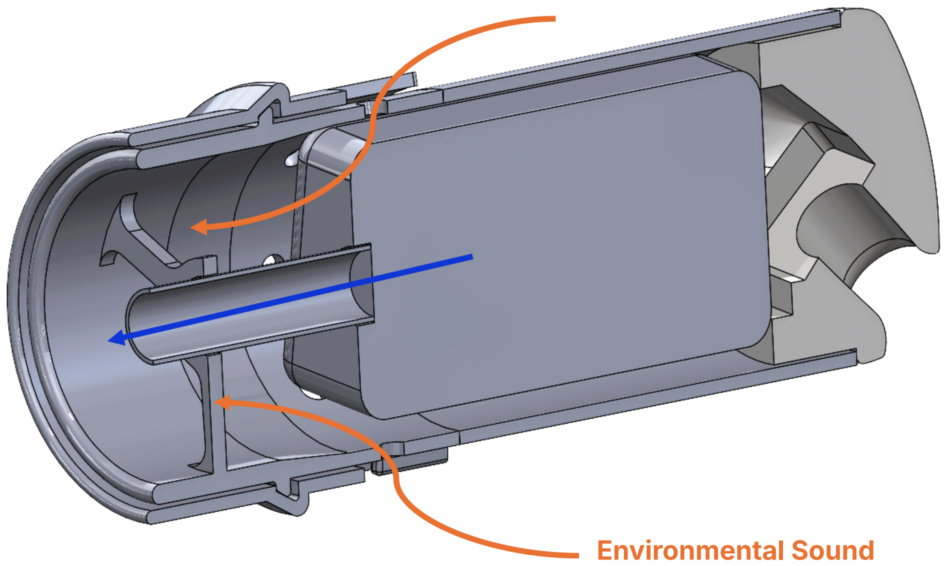


Figure 4.20 Section view of OuterCover Plus in open vent position.

A 10:1 scale prototype of the OuterCover Plus has been created. The prototype is shown in a closed vent position (Figure 4.22), and in an open vent position (Figure 4.23) after twisting the RIC housing counterclockwise, while the nozzle stays in place, to evaluate a variation of the vent actuation principle described earlier.

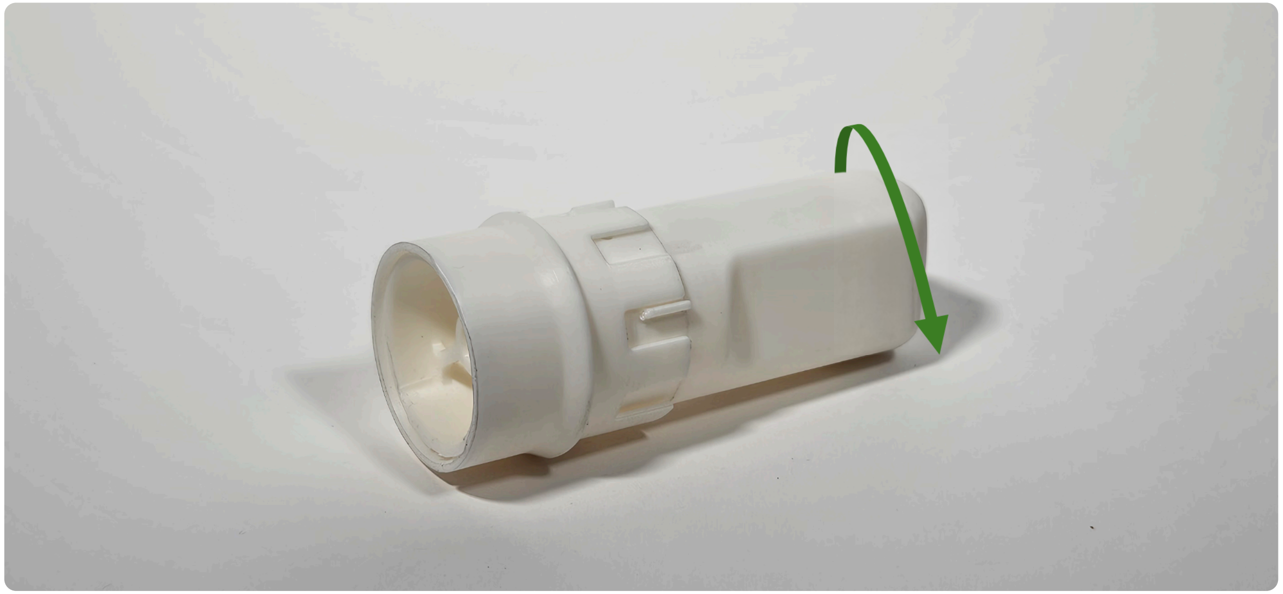


Figure 4.22 Prototype of OuterCover Plus in closed vent position.

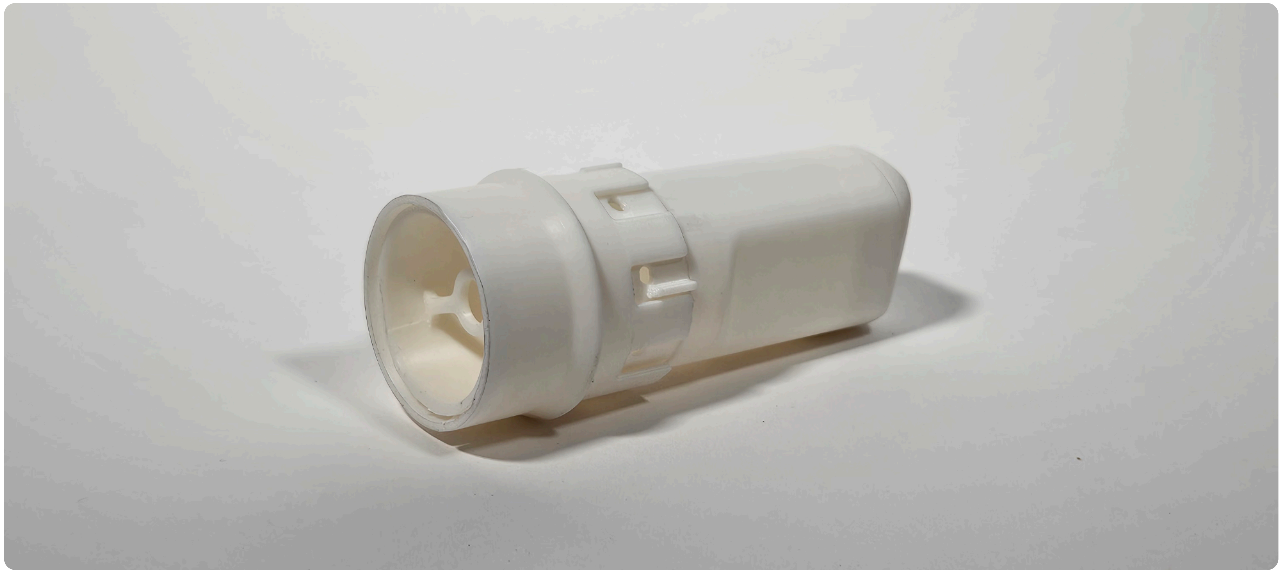


Figure 4.23 Prototype of OuterCover Plus in open vent position.

OuterCover Max

OuterCover Max builds on the same rotational logic as OuterCover Plus, a secondary outer nozzle rotates over the inner nozzle along a guide rail (Figures 4.24 and 4.25). However, it replaces welded mechanical stops with folded material features. By cutting and folding the nozzle material, rotational limits (1) are integrated into the geometry itself (Figure 4.26).

This iteration investigates how functional features such as stops can be incorporated directly into the part design, reducing the need for additional assembly steps. While this simplifies the manufacturing process, it results in a bulkier design, compared to OuterCover Plus.

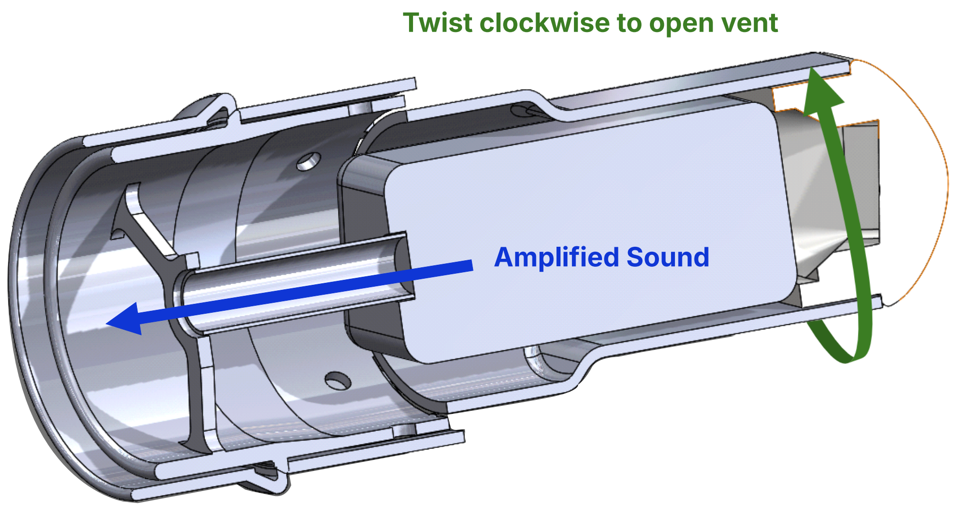


Figure 4.24 Section view of OuterCover Max in closed vent position.

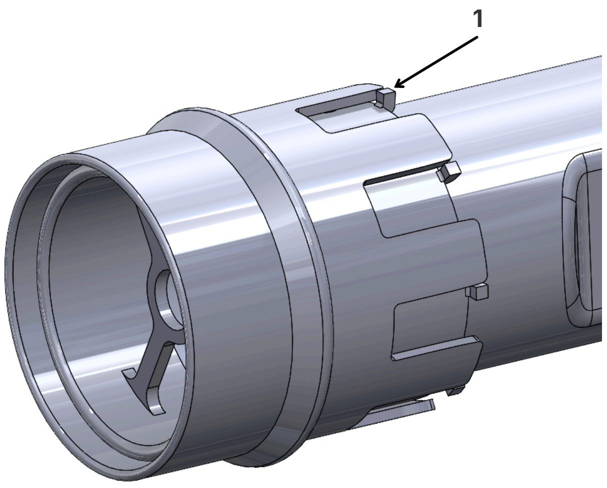


Figure 4.26 Walls preventing over-rotation and ensuring open and closed venting.

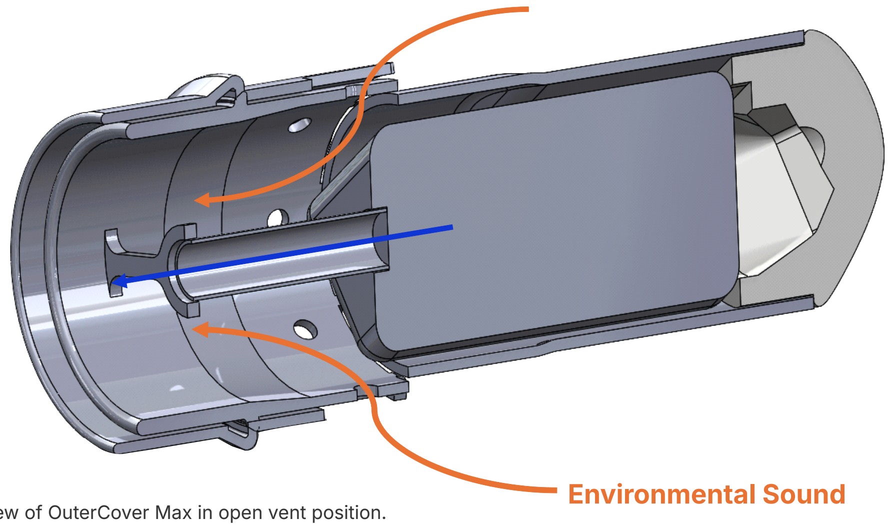


Figure 4.25 Section view of OuterCover Max in open vent position.

A 10:1 scale prototype of the OuterCover Max has been created. The prototype is shown in a closed vent position (Figure 4.27), and in an open vent position (Figure 4.28) after twisting the RIC housing clockwise, while the nozzle stays in place, to evaluate a variation of the vent actuation principle described earlier.

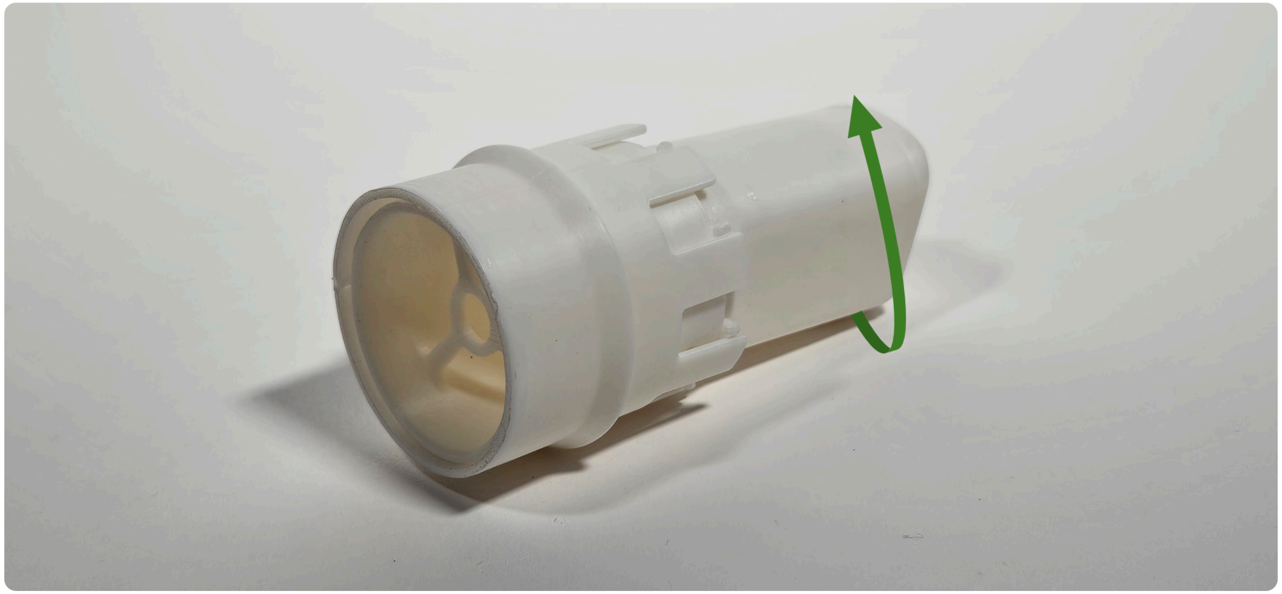


Figure 4.27 Prototype of OuterCover Max in closed vent position.

Figure 4.28 Prototype of OuterCover Max in open vent position.

OuterCover Pro

OuterCover Pro addresses the bulkiness of the previous iterations by reducing the diameter of the inner and outer nozzle to the diameter of the RIC housing, thus minimising overall size (Figures 4.29 and 4.30). In this iteration, the guide rail is replaced by two longitudinal cutting paths in the inner nozzle, with the outer nozzle rotating within it, as shown in blue in Figure 4.31, which shows a cross-section of one of these two paths (1).

The mechanical stops and vent holes are created simultaneously through U-shaped cuts (2, next page) in the RIC housing that are folded outward, creating both vent openings and rotation stops (Figure 4.32).

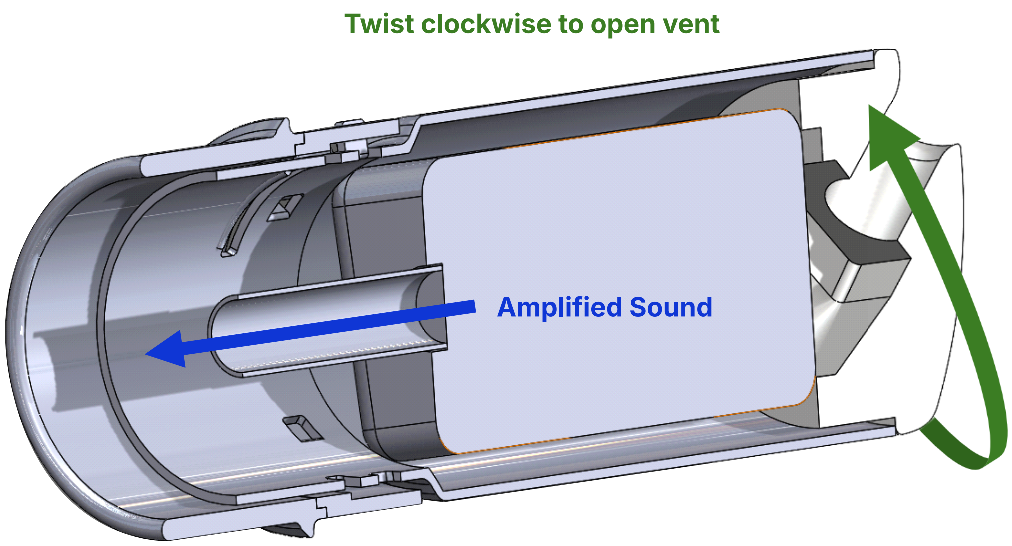


Figure 4.29 Section view of OuterCover Pro in closed vent position.

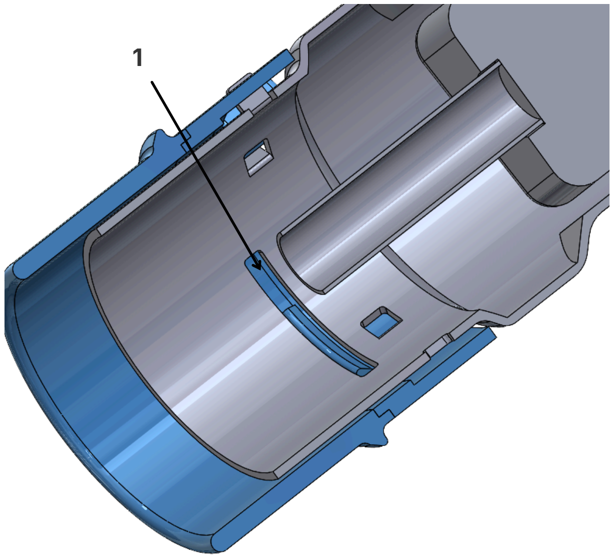


Figure 4.31 Section view, displaying one path in the inner nozzle.

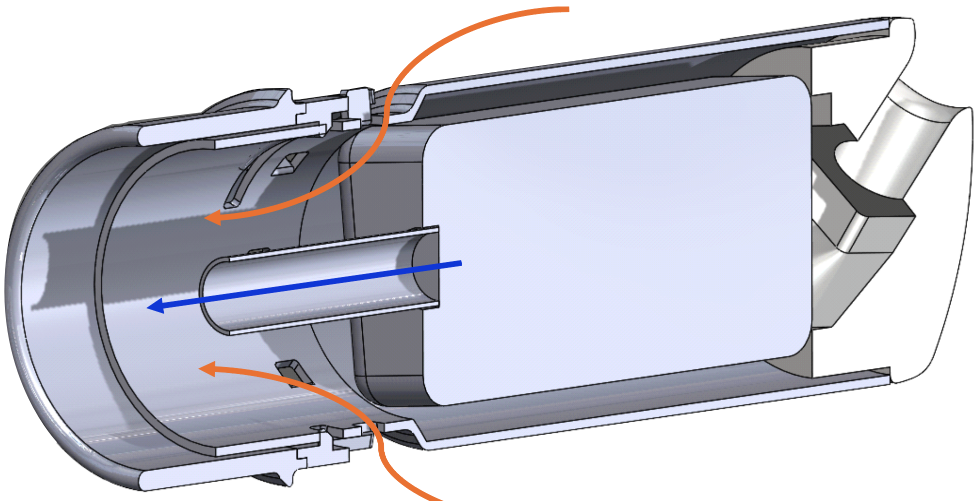


Figure 4.30 Section view of OuterCover Pro in open vent position.

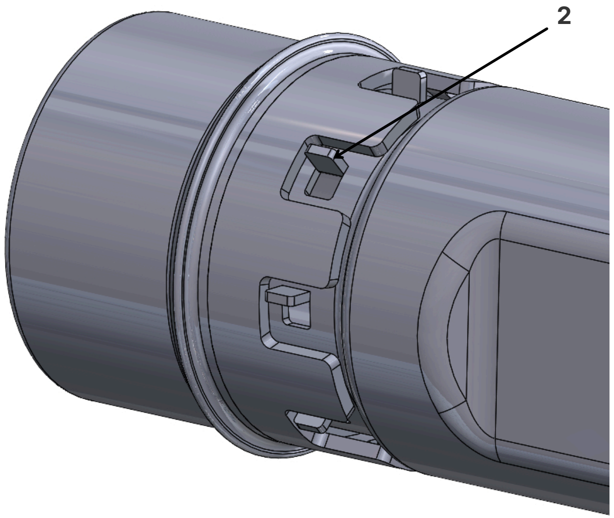


Figure 4.32 Close-up showing U-shaped cuts creating vent holes and rotation stops.

A 10:1 scale prototype of the OuterCover Pro has been created. The prototype is shown in a closed vent position (Figure 4.33), and in an open vent position (Figure 4.34) after twisting the RIC housing clockwise, while the nozzle stays in place, to evaluate a variation of the vent actuation principle described earlier.

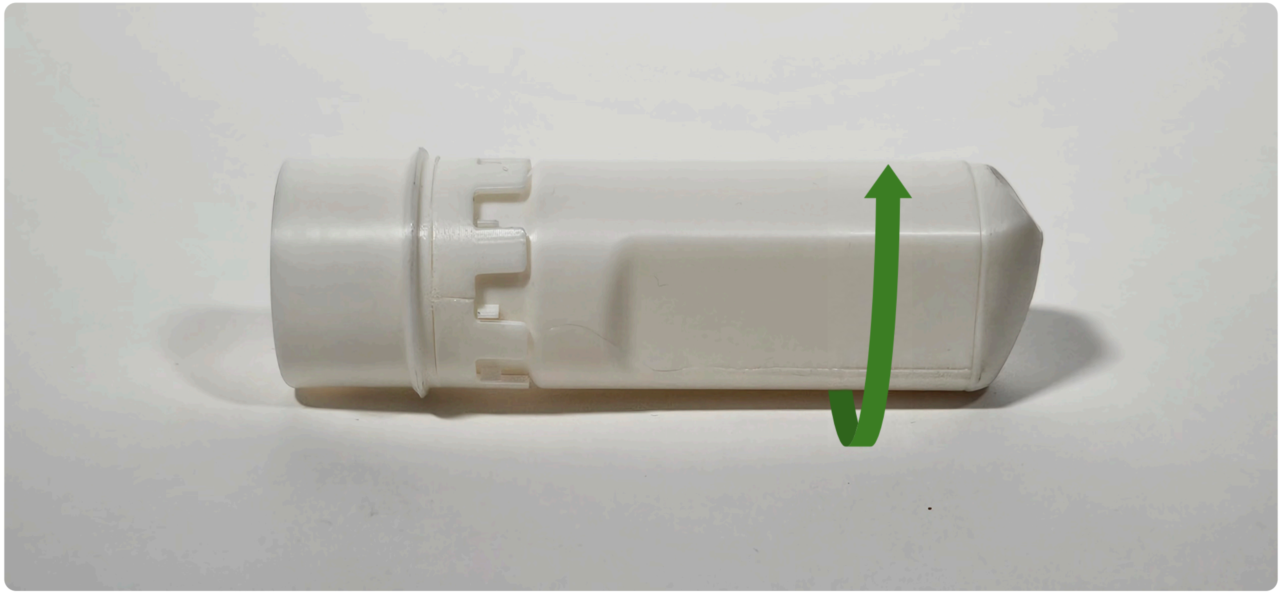


Figure 4.33 Prototype of OuterCover Pro in closed vent position.

Figure 4.34 Prototype of OuterCover Pro in open vent position.

Concept 3 - Fugai

Fugai applies the same covering principle as the OuterCover family but relocates the moving mechanism inside the RIC housing rather than around the nozzle externally (Figures 4.35 and 4.36). This allows the overall dimensions to remain the same to the Phonak ActiveVent.

Fugai contains a three-pointed star-shaped element that rotates along the sound outlet tube (Figure 4.37), while inward folded U-shaped cuts in the RIC housing simultaneously define the vent openings and act as rotation stops (1). Two retaining rings are mounted on the tube and function as rod clamps (2), to ensure that the mechanism remains securely in position during use.

By positioning the mechanism internally, the concept aims to preserve compatibility with the existing Phonak ActiveVent earmould geometries and minimise interference with surrounding ear anatomy.

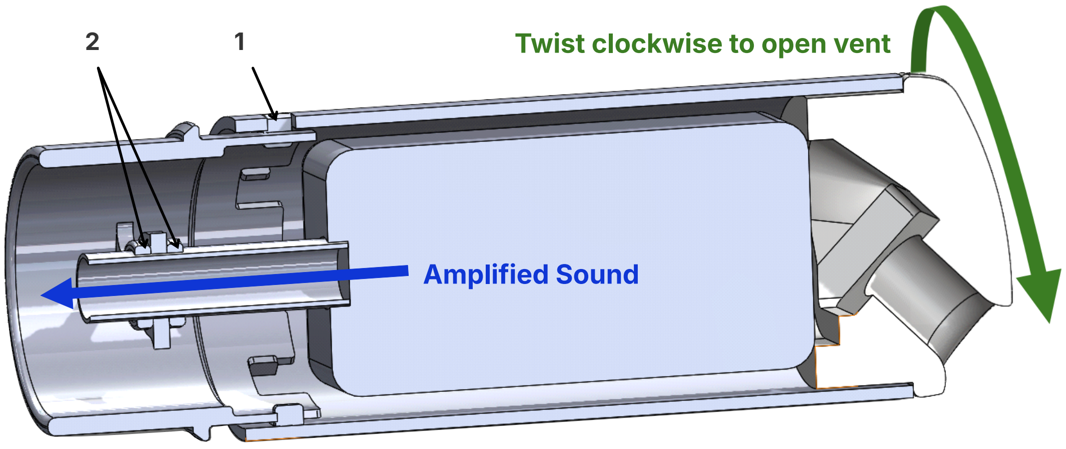


Figure 4.35 Section view of Fugai in closed vent position.

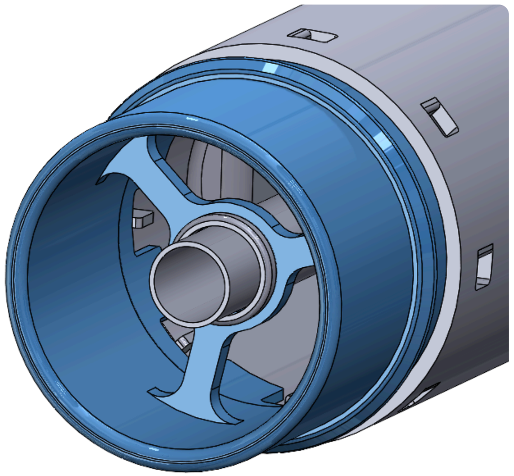


Figure 4.37 Three-pointed star-shape rotating over the sound outlet tube.

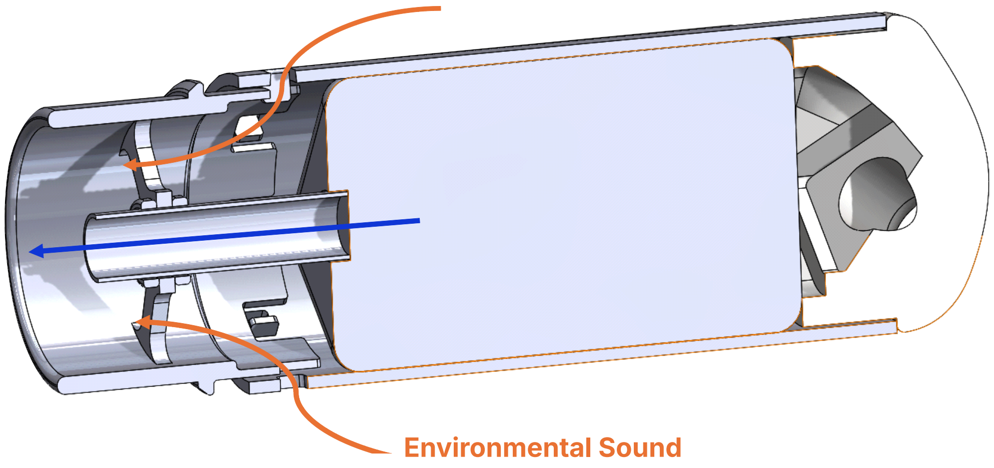


Figure 4.36 Section view of Fugai in open vent position.

A 10:1 scale prototype of Fugai has been created. The prototype is shown in a closed vent position (Figure 4.38), and in an open vent position (Figure 4.39) after twisting the RIC housing clockwise, while the nozzle stays in place, to evaluate a variation of the vent actuation principle described earlier.

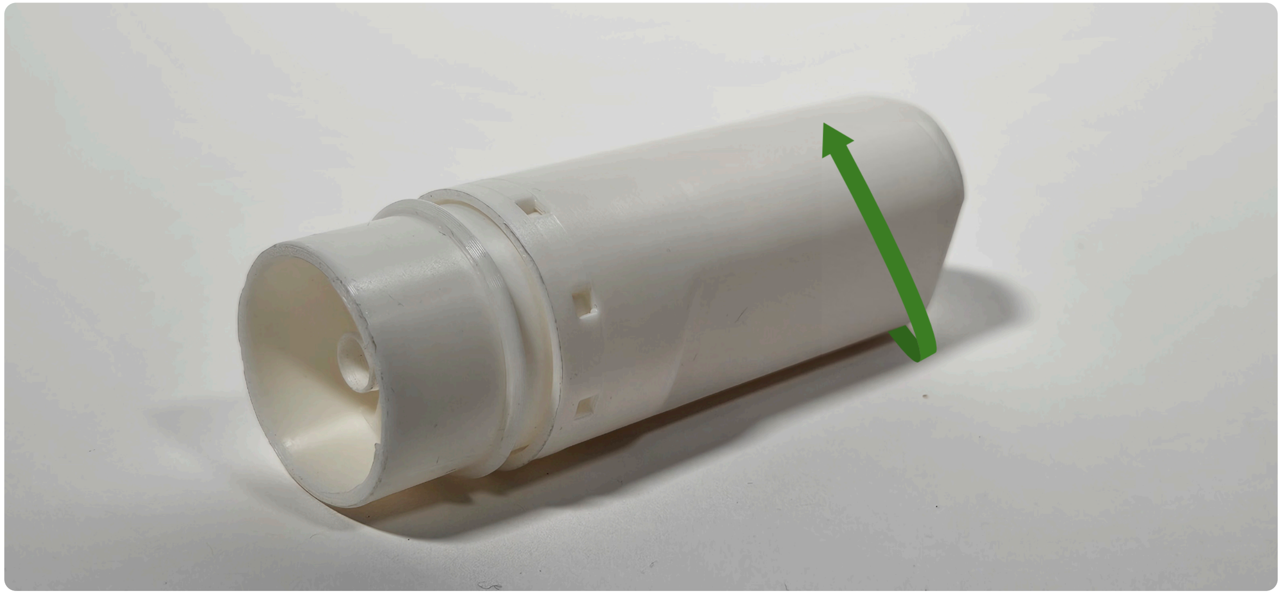


Figure 4.38 Prototype of Fugai in closed vent position.

Figure 4.39 Prototype of Fugai in open vent position.

4.3 Concept selection

After developing and prototyping the concepts, they were evaluated against the following core criteria: robustness ***(R4)***, manufacturability ***(R5)*** and dimensional compatibility ***(R3)***. Dimensional compatibility directly affects integration with existing dome designs as well as suitability for a wide range of ear canal anatomies. The scores of each concept on the evaluation and selection criteria are shown in the Harris Profile (Figure 4.40).

4.3.1 Evaluation of concepts

Based on the Harris Profile, Fugai has been selected as the most promising concept for further development, as it provides the most balanced performance according to the evaluation criteria. By internalising the venting mechanism, it preserves the current dimensions of the Phonak ActiveVent, meaning it maintains compatibility with current dome geometries. On top of that, an internal venting mechanism reduces exposure to earwax and debris, making it more robust, compared to the other concepts that rely on externally covered vent openings.

Although the DynamicZoom has the same dimensions as the Phonak ActiveVent, the axial displacement required to open the vent increases the overall length of the RIC during use. Additionally, the approximately 90-degree rotation of the housing results in a corresponding rotation of the cable. Given the stiffness of the cable, this movement of the cable introduces risks related to discomfort, skin irritation, and instability of the RIC during wear. Furthermore, cable stiffness may cause the housing to rotate back toward its original position, negatively affecting functional reliability. These dimensional, functional and ergonomic drawbacks outweigh the conceptual clarity of the mechanism and limits the suitability.

The OuterCover concept family was deprioritised primarily due to dimensional and integration limitations. All variants require an additional nozzle layer, leading to a significantly increased nozzle diameter compared to the Phonak ActiveVent. This increased bulk complicates integration with existing dome designs and limits compatibility with a broad range of ear canal anatomies (personal communication, Sonion employee, 2025). Furthermore, externally covering vent openings increases susceptibility to earwax and debris, negatively impacting robustness. While design iterations improved manufacturability and integration of rotation stops, the fundamental increase in nozzle size remained unresolved.

As mentioned before, Fugai contains a three-pointed star-shaped element and rod clamps for its mechanism. Although this is mechanically effective, it introduces increased manufacturing complexity. Moreover, despite its technical and ergonomic advantages, user reachability remains a key unresolved challenge. Because the interaction takes place within the ear, precise and comfortable use may be difficult for some users. Consequently, a redesign will be explored to simplify the construction and improve manufacturability, while ensuring intuitive, reliable user control without compromising wearing comfort.

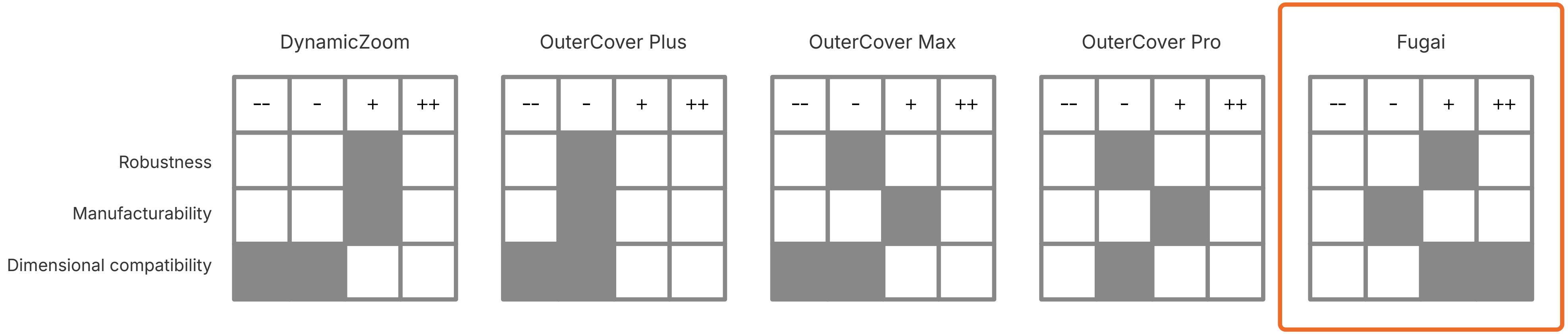


Figure 4.40 Evaluation of the concepts using the Harris profile tool.

4.3.2 Evaluation limitations

The evaluation and concept selection focused on qualitative assessment of mechanical feasibility, conceptual robustness, manufacturability logic, and dimensional compatibility. To support this process, 10:1 scale prototypes were developed. These enlarged models were primarily used to explore and compare mechanical working principles. At this scale, internal geometries and component interactions could be easily visualised and rapidly iterated, enabling early identification of conceptual strengths and weaknesses without being constrained by the extreme manufacturing limitations of miniature 1:1 components.

However, design decisions based on 10:1 scale prototypes remain inherently uncertain. At enlarged scale, friction, material stiffness, tolerances, and contact behaviour are not representative of real-world conditions, and actuation forces do not scale linearly. Mechanisms that appear smooth and reliable at 10:1 scale may therefore behave differently when miniaturised. In addition, spatial constraints are fundamentally distorted: features that appear to fit well at enlarged scale may conflict at real size, making reliable judgement of compactness and assembly feasibility difficult. Performance aspects such as sealing effectiveness, wear behaviour, durability, and realistic in-ear interaction could not be evaluated at this stage and were therefore excluded from the Harris Profile.

The use of 10:1 scale prototypes was thus appropriate for comparative concept evaluation, but not for definitive validation. The resulting design decisions should be interpreted as conceptually grounded yet provisional. Final confirmation key aspects such as sealing effectiveness, wear behaviour, mechanical reliability, usability, and integration feasibility requires subsequent development and testing at full 1:1 scale.

Takeaways 4.3

- The design must not exceed the current dimensions of the Phonak ActiveVent **(extra design requirement, R3.2)**
- The mechanism must be compatible with an internal architecture in which all components are permanently glued together **(extra design requirement, R3.3)**
- Full-scale prototyping is essential in later phases
- Critical performance aspects remain unknown, including sealing effectiveness, durability, wear behaviour, and realistic user interaction
- Spatial integration cannot be reliably judged at 10:1 scale

4.4 Optimisation of Fugai

One of the key points identified in the evaluation of concepts in Chapter 4.3.1 was improving Fugai's manufacturability. The key challenge for optimising manufacturability is ensuring that the nozzle remains securely in place within the RIC housing while still allowing controlled rotational movement around its axis. In the initial Fugai design, this was achieved using two separate retaining rings acting as rod clamps. While mechanically robust, this solution increases part count, assembly steps, and production complexity, which is undesirable for high-volume, cost-sensitive hearing aids production.

4.4.1 Press-fit connection

To address this, a press-fit solution was selected. By introducing a controlled interference between the nozzle and the rotating housing, axial retention can be achieved without the need for secondary fastening components. This not only simplifies construction, but also reduces the bill of materials and shortens assembly time. A press-fit assembly is well suited for automated production lines, which is especially advantageous in the context of hearing aid production, where efficiency and consistency are critical (personal communication Sonion employee, 2025).

When prototyped at 10:1 scale, a press-fit mechanism can appear more reliable than it would be at 1:1 scale. An enlarged scale is less sensitive to e.g. tolerances, while at product scale, small differences in dimensions have a much greater influence on rotation and retention forces. As a result, 10:1 scale prototypes are useful for conceptual feasibility of a press-fit, not to reliably represent manufacturability at real size.

From a functional perspective, a press-fit could provide sufficient frictional force to prevent unintentional axial displacement during daily use, while still allowing smooth rotational actuation of the venting mechanism. Moreover, when the interference and resulting friction are carefully balanced, a press-fit is also able to resist unintended rotational movement caused by vibration or incidental contact, which is critical for Fugai. This ensures that the venting state remains stable during wear, while still enabling smooth and controlled user interaction when adjustment is intended.

Furthermore, a press-fit approach also supports the overall dimensional constraints of Fugai. As the retention is integrated directly into the geometry, no additional space is required. This helps preserve compatibility with existing dome geometries.

Figure 4.41 shows a cross-section view of an iteration on Fugai in which the number of components has been reduced, by introducing a press-fit connection. Shown in blue, the nozzle snaps in the RIC housing, while still being able to rotate. The reduction in part count decreases manufacturing complexity, lowers production costs, and enhances overall robustness by minimising potential failure points within the RIC and its assembly.

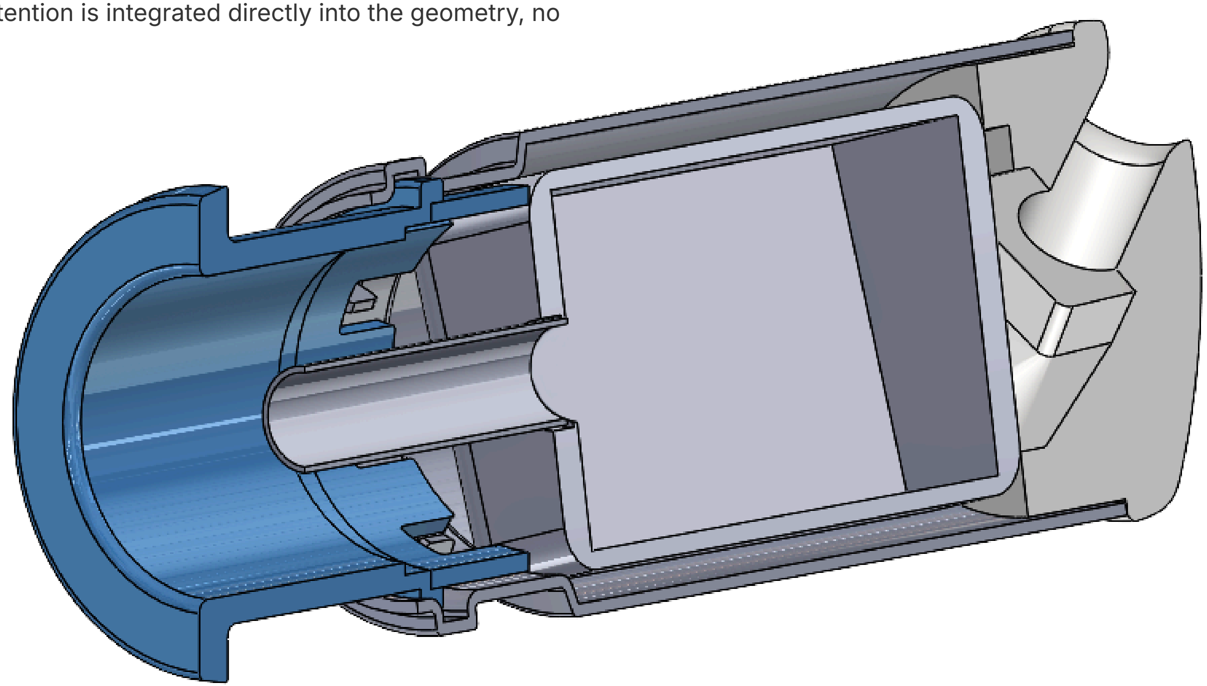


Figure 4.41 Cross-section view of an iteration of Fugai (with simplified receiver and sound outlet tube).

It is worth mentioning that, in the iteration, the nozzle geometry has also been redesigned. This adjustment was made to improve compatibility with domes, whereas earlier nozzle designs were aligned with earmoulds used for the ActiveVent. Figures 4.42 and 4.43 show how a dome (shown in orange) is integrated with Fugai in an open and closed vent position. The green arrow indicates the rotational interaction that twists the RIC housing relative to the nozzle (shown in blue) and the dome.

The nozzle was reshaped to reflect current market trends, which show an increasing preference for domes over earmoulds (personal communication Sonion employee, 2025).

4.4.2 Further development of the nozzle and RIC housing

The nozzle and RIC housing have been further optimised, aiming to improve the robustness of the vent mechanism. In the previous design, the U-shaped cut vent openings were oriented in a way that the nozzle interacted with the long sides of the stops (Figures 4.44 and 4.45). Although technically feasible, contact along the long sides increased the risk of unintended deformation, as the nozzle applied force in the same direction as the stops' folding direction. This made it easier for the stops to fold beyond their intended position.

The redesign addresses this issue by reorienting the U-shaped cuts so that the stops fold in a perpendicular direction (Figures 4.46 and 4.47). As a

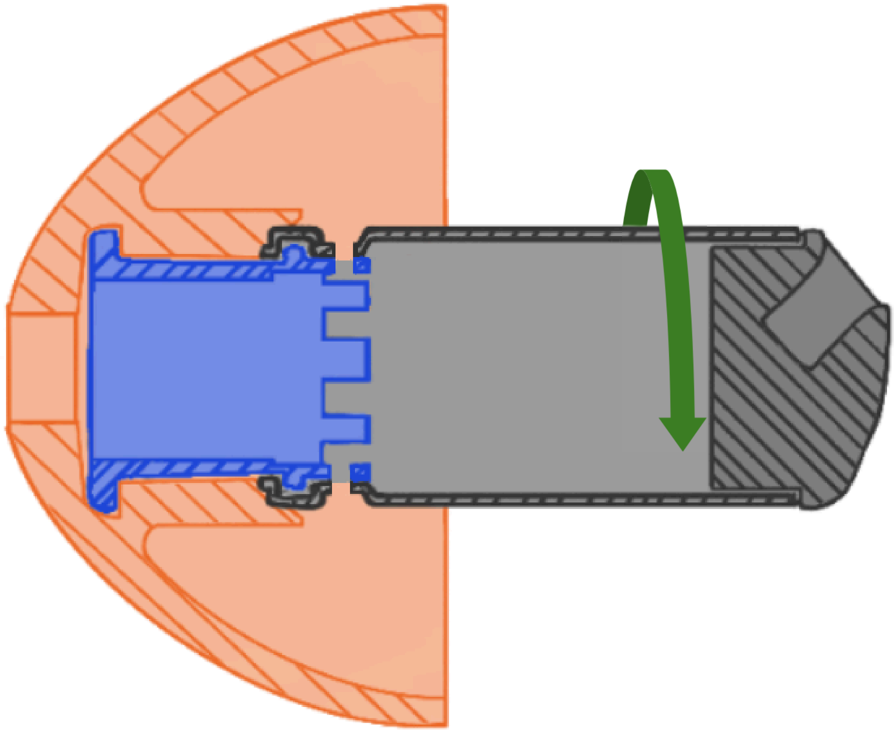


Figure 4.42 Illustration of Fugai with a soft dome in an open vent position.

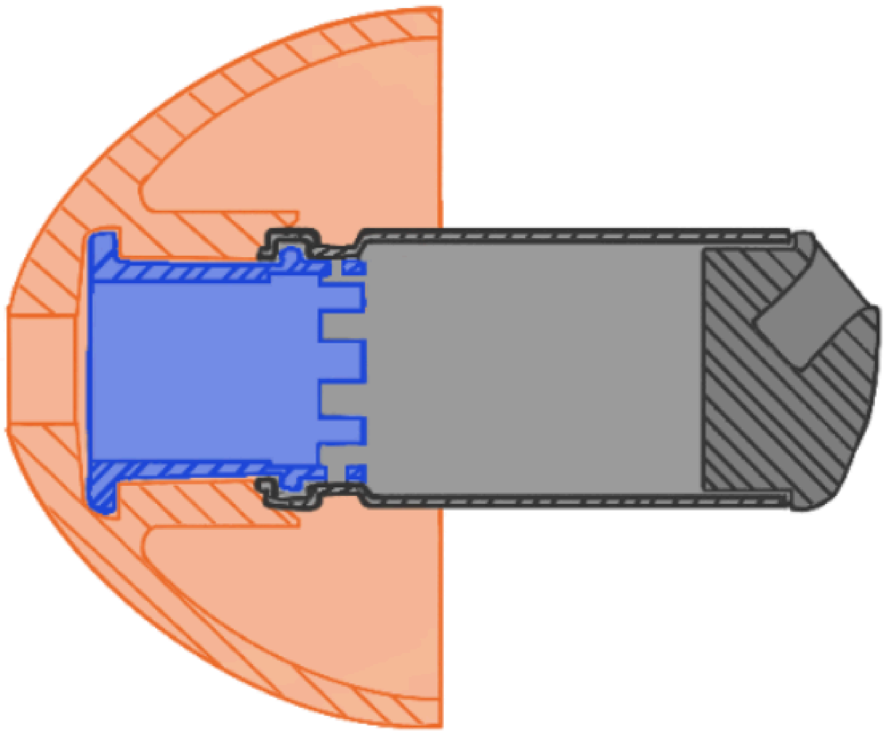


Figure 4.43 Illustration of Fugai with a soft dome in a closed vent position.

result, the nozzle now interacts with the short sides of the stops, which prevents applying force in the folding direction. The redesign increases the resistance to forced over-rotation, enhancing the overall robustness of the venting mechanism.

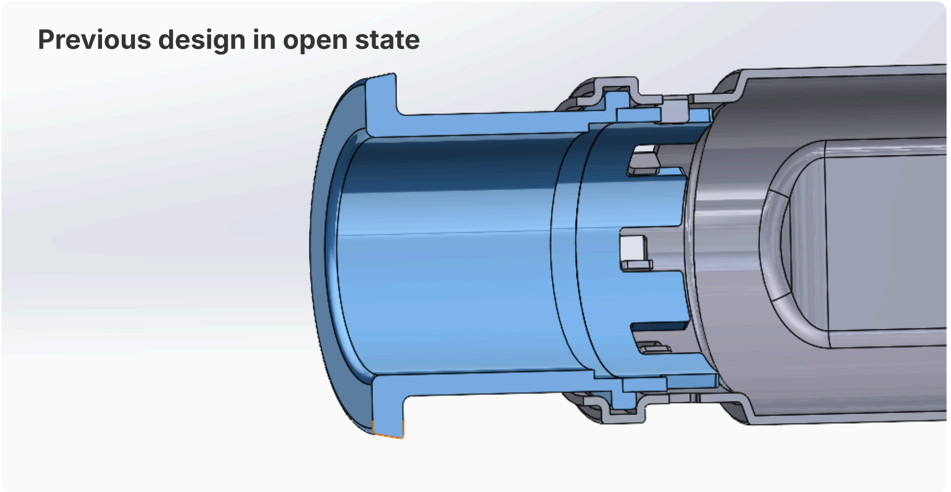


Figure 4.44 Old design of the nozzle in an open vent state.

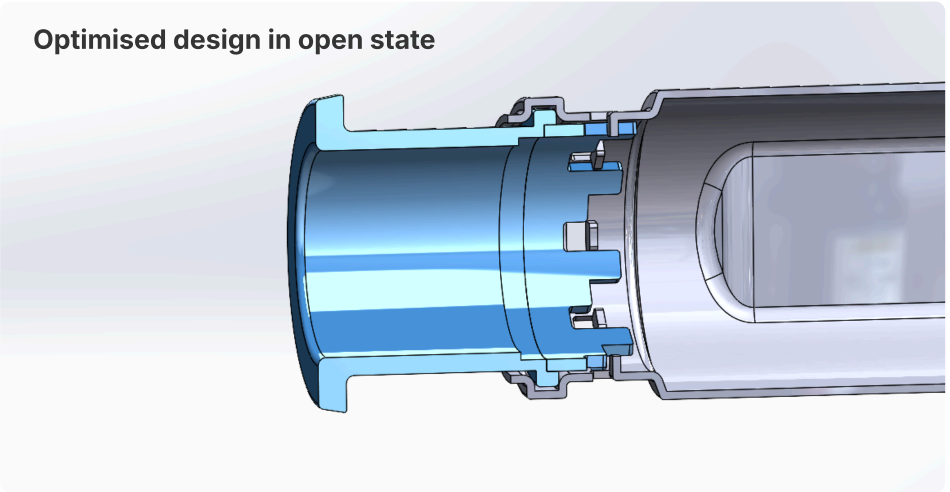


Figure 4.46 Redesign of the nozzle in an open vent state.

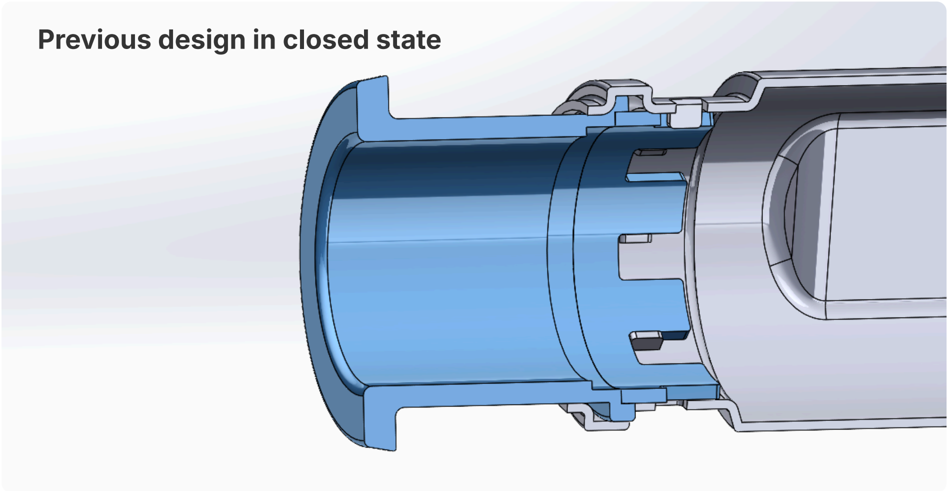


Figure 4.45 Old design of the nozzle in a closed vent state.

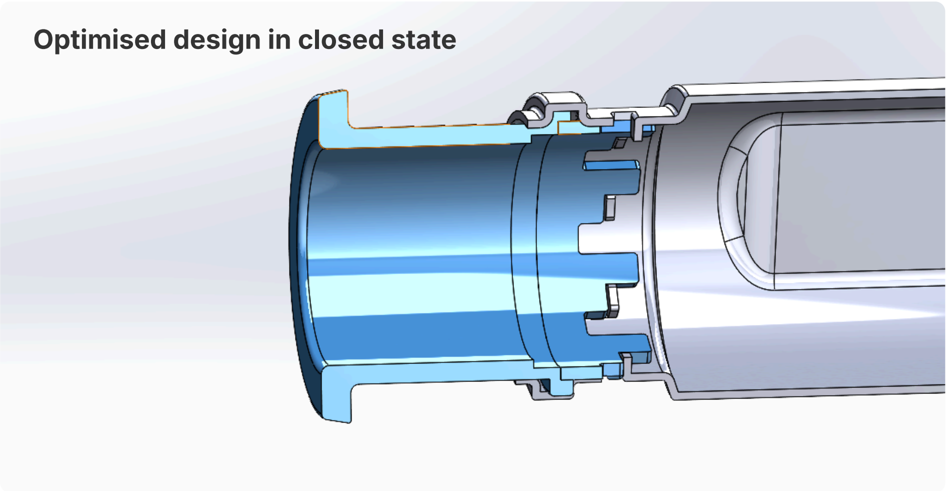


Figure 4.47 Redesign of the nozzle in a closed vent state.

4.4.3 Designing for reachability

In addition to design adaptations aimed at improving manufacturability, interaction reachability emerged as a key design challenge. As the interaction takes place in the ear, it must be intuitive and comfortable to perform, without causing discomfort due to excessive manipulation within the ear. Two design directions were created to address this interaction challenge.

External grip tool

The first direction is inspired by existing sports locks integrated into the back part of the RIC housing. These sports locks are commonly used to improve retention during movement, reducing the likelihood of the RIC coming loose from the ear canal.

From this inspiration, a small, relatively rigid element has been integrated into the back part of the RIC housing, Figure 4.48 shows a CAD model of it. This element functions as an external interaction point, allowing users to rotate the device deliberately.

New prototypes were produced at both 10:1 and 1:1 scale (Figures 4.49 and 4.50). The 1:1 scale prototype includes a BTE housing dummy, which helps to better represent the complete system and enables realistic wear testing. This allowed the prototype to be worn on and in the ear, making it possible to evaluate reachability, intuitiveness and ease of use.

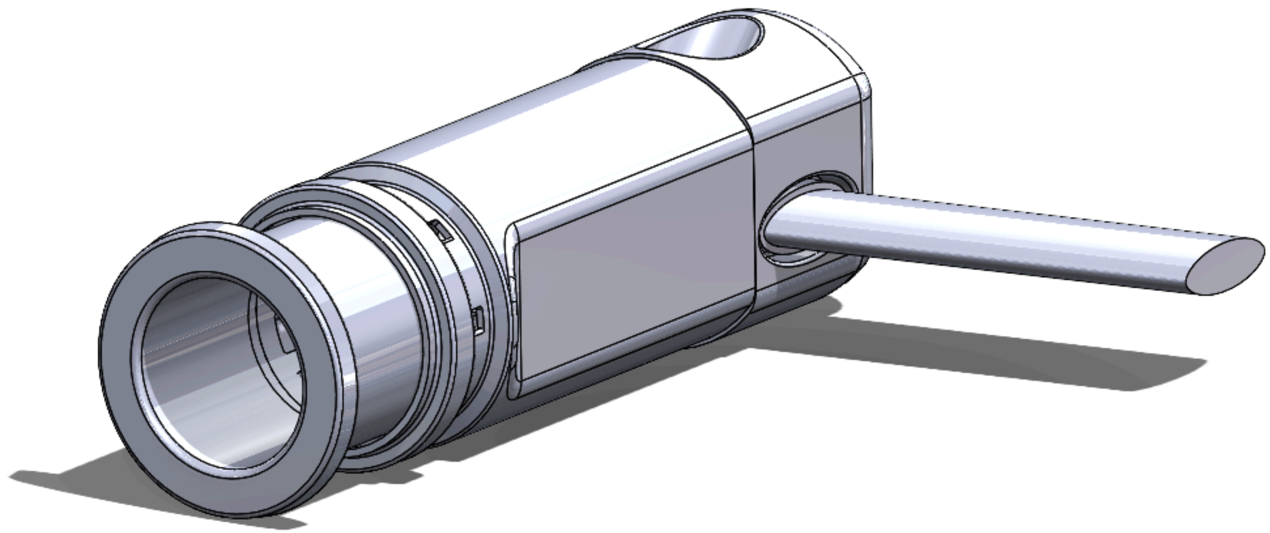


Figure 4.48 RIC body with external grip tool, aiming to improve interaction reachability.

Figure 4.49 3D-printed RIC body with external grip tool, scale 10:1 and 1:1.

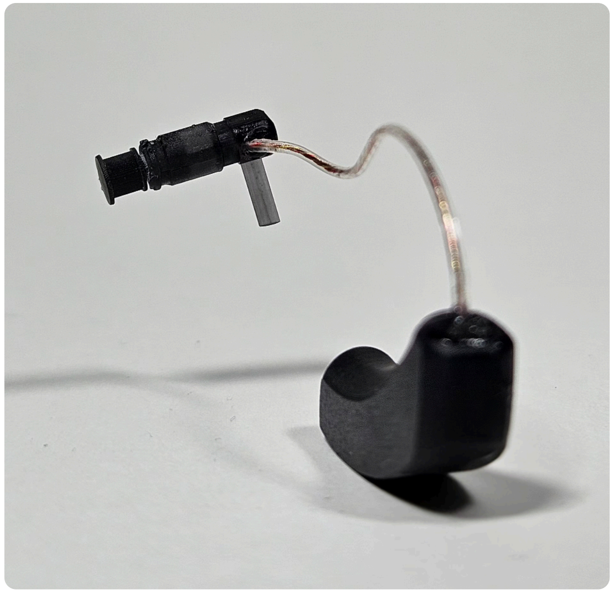
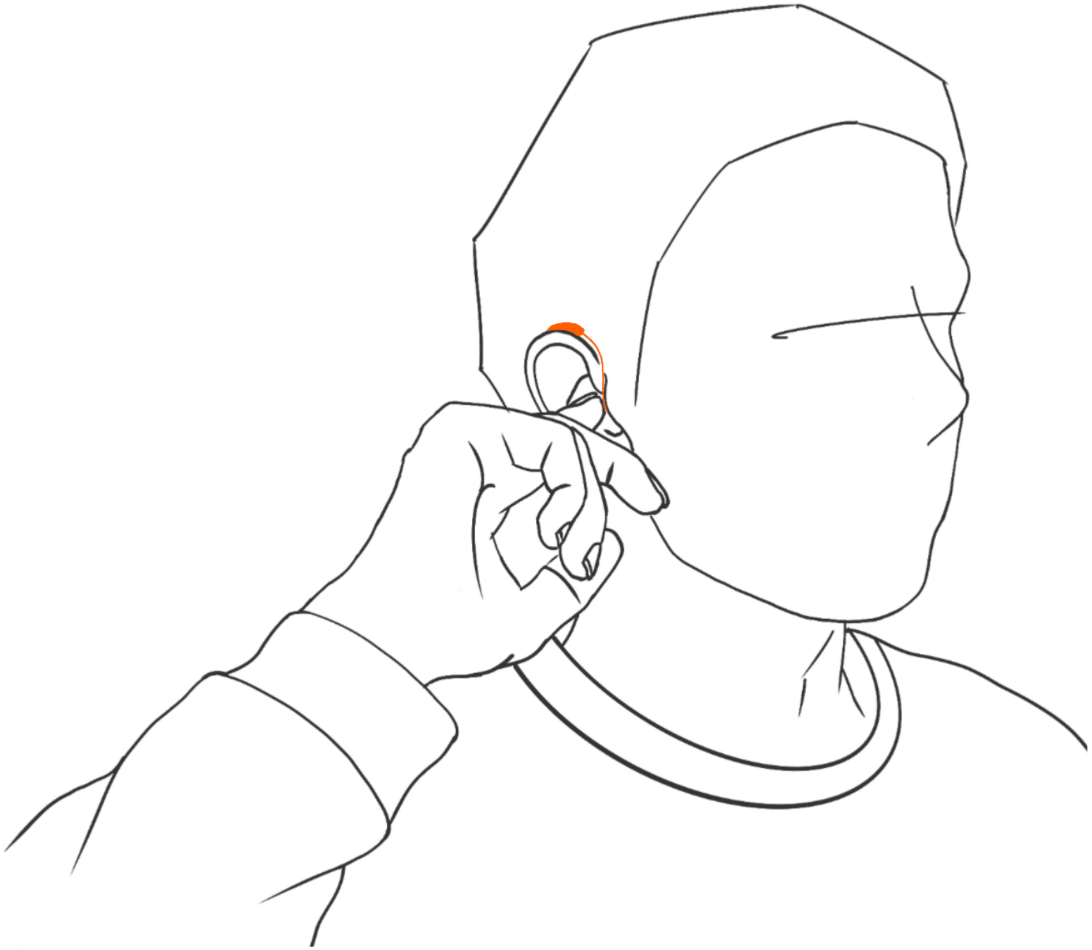


Figure 4.50 3D-printed RIC body with external grip tool, including a BTE housing dummy, scale 1:1.

The rotational movement can be initiated using a fingertip or fingernail, enabling control to be exerted largely outside the ear canal and thereby reducing the risk of discomfort (Figure 4.51). Depending on the direction, the user is able to open (up) or close (down) the venting pathway.



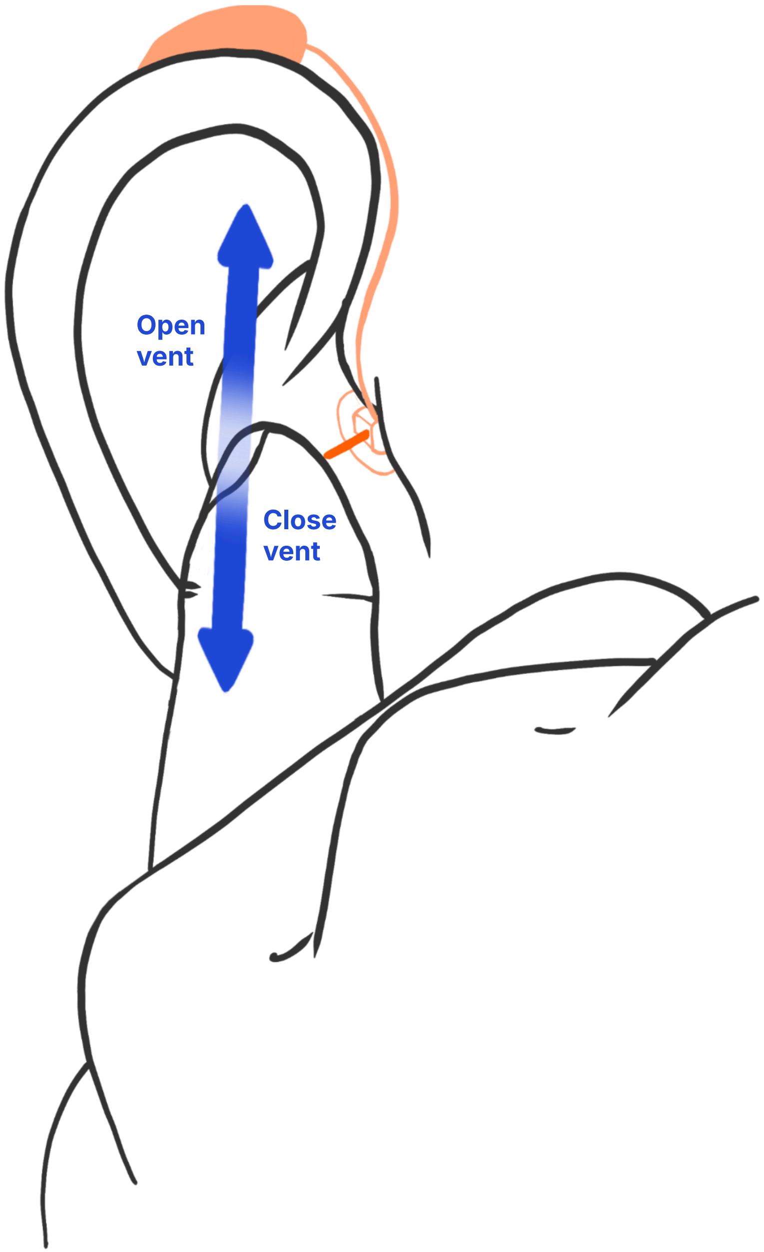


Figure 4.51 Illustrations of how a user can interact with Fugai, using an external grip tool.

Reshaping the back part

The second direction focuses on a redesign of the back part of the RIC housing, in which the geometry has been adapted to improve grip and accessibility, Figure 4.52 shows a CAD model of this direction. By reshaping the housing, the intention is to enable users to more easily grasp the end of the RIC with two fingers and apply the required rotational movement, without introducing an additional control element.

This redesigned back part aims to preserve a relatively simple, integrated, and robust RIC geometry, to avoid added components that could decrease discreteness or increase manufacturing complexity. Instead, usability improvements are sought through form optimisation alone.

To evaluate this approach, new prototypes were produced at both 10:1 and 1:1 scale (Figure 4.53). As with the previous evaluation, the 1:1 prototype includes a BTE housing dummy to enable realistic wear testing and to assess reachability, intuitiveness and ease of use (Figure 4.54).

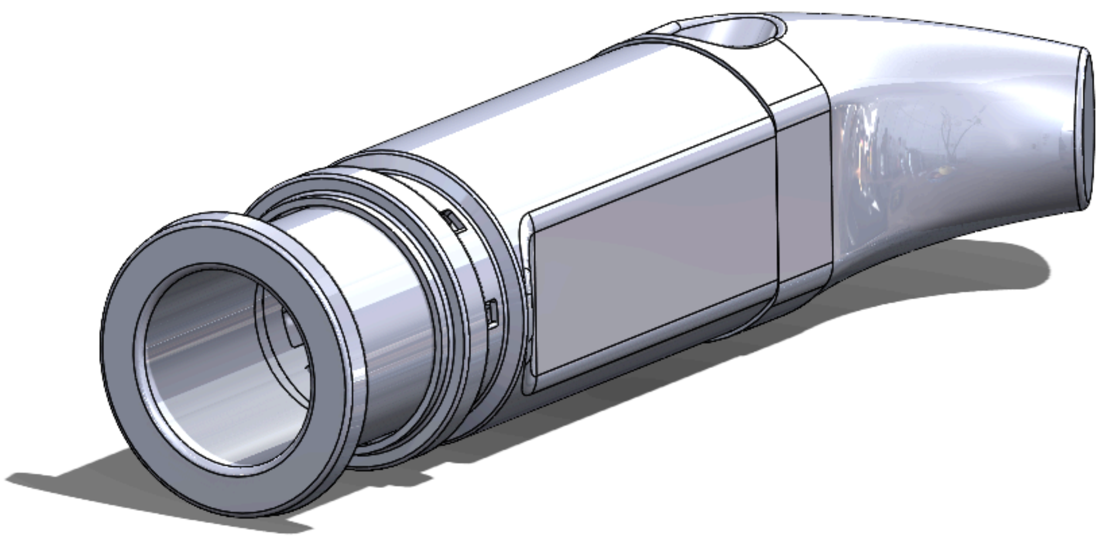


Figure 4.52 RIC body with a reshape of the back part, aiming to improve grip and accessibility.

Figure 4.53 3D-printed RIC body with reshaped back part, scale 10:1 and 1:1.

Figure 4.54 3D-printed RIC body with reshaped back part, including a BTE housing dummy, scale 1:1.

The rotational movement is initiated by lightly grasping the rear end of the RIC and applying a controlled twisting motion using two fingers, as illustrated in Figure 4.55. By rotating the housing in one direction, the venting pathway is opened, while rotation in the opposite direction closes the vent (to open; clockwise, to close; counterclockwise). This allows the user to manually adjust the acoustic openness of the hearing aid in a direct and intuitive manner.

It should be noted that the direction of operation is mirrored when the device is worn in the left ear. Consequently, the rotational direction required to open or close the vent is reversed (to open; counterclockwise, to close; clockwise), which is consistent with the symmetrical geometry of left and right RIC configurations. To verify this assumption, left-RIC testing is required with both right- and left-handed users to ensure intuitive and consistent control.

A forward rotation direction was chosen to open the vent (clockwise for the right ear and counterclockwise for the left ear), because participants associated this direction with the feeling of 'opening up' during the intuitive use test.

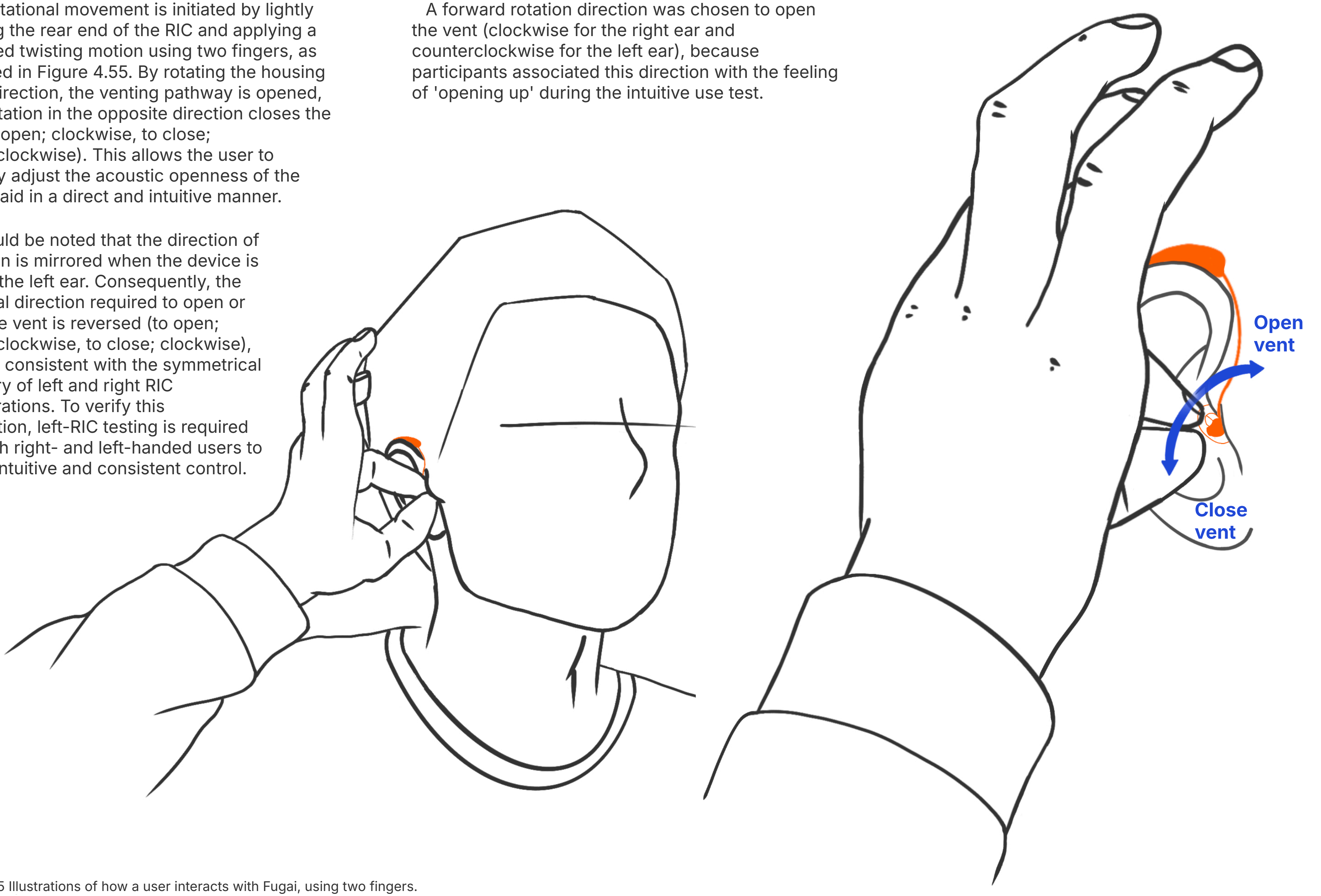


Figure 4.55 Illustrations of how a user interacts with Fugai, using two fingers.

Reachability concept selection

To make a well-informed decision about the preferred reachability solution, two 1:1 scale prototypes of the interaction concepts were developed. These prototypes were not created to validate the ventilation mechanism itself, but to assess reachability, ergonomics, and the user's perceived control during the interaction. Because realistic interaction requires a certain degree of rotational movement, the models were designed and 3D-printed to allow for limited rotation.

An exploratory, formative user evaluation was conducted using these full-scale prototypes. Three participants were asked to place each prototype in their ear canal and perform the intended interaction, using either one or two fingers, depending on the concept. The goal of the test was to assess basic usability and reachability, thereby gaining insight into how users interact with each concept.

Key findings

Key findings indicate that the external grip tool provides a significantly better user experience than the reshaped back part of the RIC housing. The external grip allowed the rotation to be performed using a single finger or fingernail, making the interaction more intuitive and reducing interference with the ear. In contrast, the reshaped back part required more effort to perform the action and offered insufficient perceptual feedback, making it difficult for users to understand whether rotation was occurring. Additionally, the ear itself remained an obstacle during the interaction, as operating this solution required the use of at least two fingers. This made access within the ear canal more difficult and suggests that interaction concepts requiring two-finger manipulation are not feasible within the spatial and ergonomic constraints of a discrete in-ear hearing aid. This also led to the insight that a short interaction is preferable when using a single finger; it is easier and more comfortable to perform a small switching movement with one finger, than performing a larger rotational action, such as a half turn.

Limitations

Despite its advantages, the external grip tool also revealed limitations. During testing, one of the prototype's grip tool broke off during testing when it was attempted to rotate the RIC housing beyond its intended rotational range, which resulted in too much stress on the grip tool. Although this occurred in a 3D-printed prototype, where material failure is more likely, it highlights a potential structural vulnerability of such solution. This indicates that the robustness of the grip tool requires further optimisation.

User testing also revealed a lack of clear tactile feedback, as users could not easily perceive when the full rotational range had been reached. Furthermore, due to the stiffness of the cable connected to the Behind-the-Ear housing, the mechanism tended to return towards its neutral position after actuation, reducing reliability.

As discreteness is considered to be a crucial factor by the market, it was unclear if an external grip tool would cause the RIC to be too visible. Figure 4.56 shows an image of the author wearing Fugai, where the grip tool is slightly visible. Although it has not been formally assessed whether this visibility is perceived as intrusive by users or the market, increasing the robustness of the grip tool, for example by increasing its thickness to improve stiffness, would further increase its visual aspect in the ear.

Future works

These findings indicate that while the external grip tool is the preferred reachability solution, further refinement is required. In the next design iteration, emphasis should be placed on improving tactile feedback and rotational stability, while balancing these improvements against the requirement for discreteness, to ensure controlled, reliable interaction without compromising wearing comfort or usability.

Figure 4.56 Author wearing a Fugai hearing aid with external grip tool which is slightly visible.

4.4.4 Tactile feedback

A mechanical solution was explored to address the lack of tactile feedback, ensuring that the mechanism remains entirely free of electronic miniature components. As Fugai is an in-ear device where discretion is desired, the goal was to generate a subtle snap sound or pressure release within the existing mechanism, while maintaining its geometry and overall functionality. An advantage of an in-ear product is the acoustic amplification provided by the ear canal. Due to its resonance characteristics, even small sounds, pressures or low friction vibrations are significantly amplified and can be perceived easily by the user. This creates an opportunity to create a clear tactile feedback using minimal mechanical intervention.

A logical position for such intervention is the place of internal movement, where the RIC housing interacts with the nozzle. Creating feedback directly within the integrated mechanism preserves the current geometry of Fugai, and allows for a purely mechanical solution.

The tactile feedback is achieved through material friction and snapping. The nozzle ring incorporates thickened 'blocks' (1, Figure 4.57). During rotation, these blocks snap into the vent openings or slide beneath the RIC housing, depending on the direction of the rotation (Figures 4.58 - 4.61).

When the vent is rotated to the open position, the blocks are pressed under the RIC housing (Figures 4.60 and 4.61). Their thickness creates friction against the housing's surface. Although the friction is low, the intention is that the acoustic amplification in the ear canal ensures that this interaction remains noticeable to the user. In addition, the friction is intended to improve the design's reliability, as it makes it more difficult for the product to return to its neutral position.

Furthermore, the thickened blocks induce a slight preload in the nozzle when the vent is open. The inward force on the nozzle places it under elastic tension. When the RIC housing rotates to the closed vent position, the blocks snap into the vent openings, releasing its elastic energy (Figures 4.58 and 4.59). This pressure release creates a snap sound, noting the user that the product's position is in the closed state.

Both new 10:1 and 1:1 scale prototypes were developed to validate this mechanical solution (Figure 4.62). Since it was not able to 3D-print the 1:1 scale prototype with the visioned mechanical working principle in-house due to its dimensions, a simplified model has been created to mimic the mechanical solution for tactile feedback. The 10:1 scale prototype was again used to evaluate the refined mechanism in a observable manner. The 1:1 scale simplified prototype focused on validating perceptibility and was used for user testing to observe whether tactile feedback was perceived. For the user tests, participants were asked to place the prototype in their ear canal, to perform the interaction and to describe how they experience the tactile feedback.

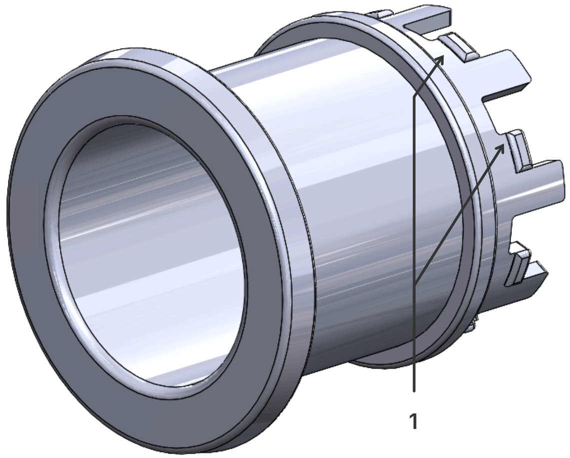


Figure 4.57 Redesign of the nozzle for tactile feedback.

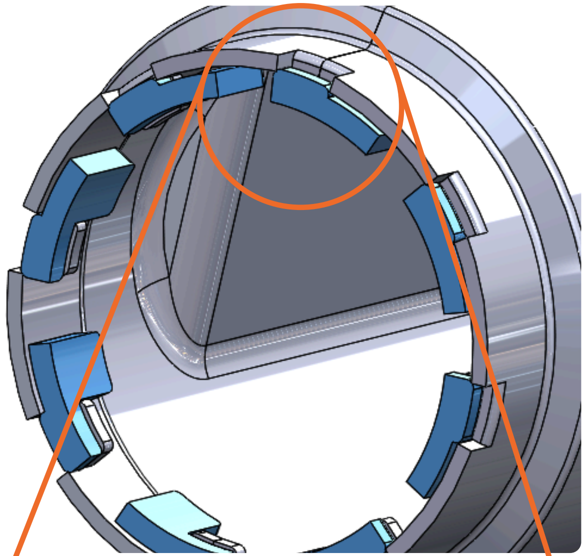


Figure 4.58 Cross section view of redesigned nozzle with thickened blocks in closed vent position.

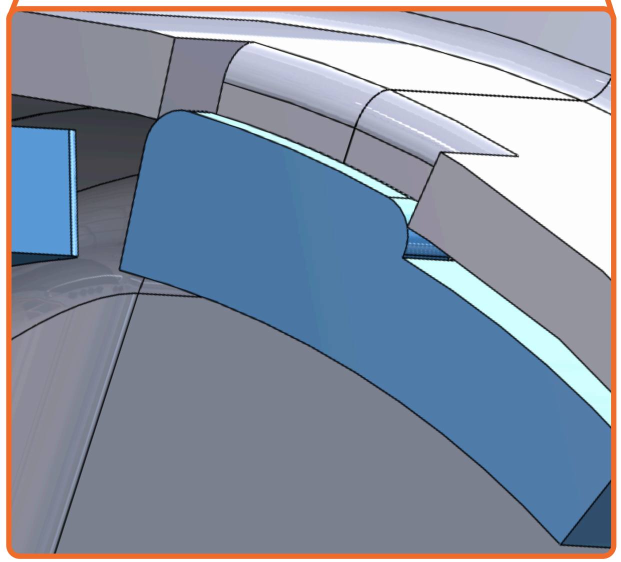


Figure 4.59 Close-up of Figure 4.58.

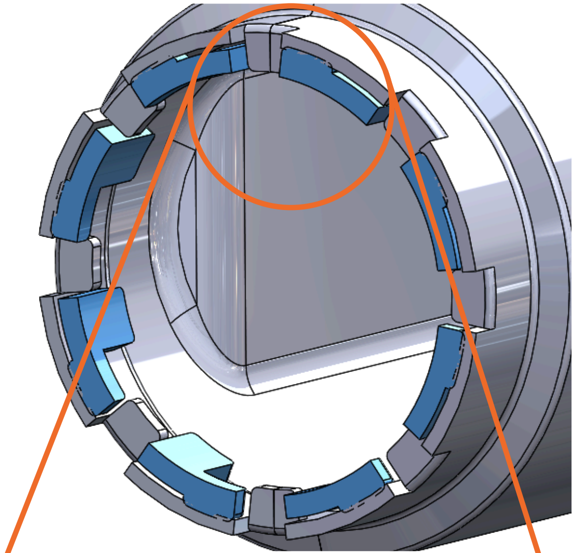


Figure 4.60 Cross section view of redesigned nozzle with thickened blocks in open vent position.

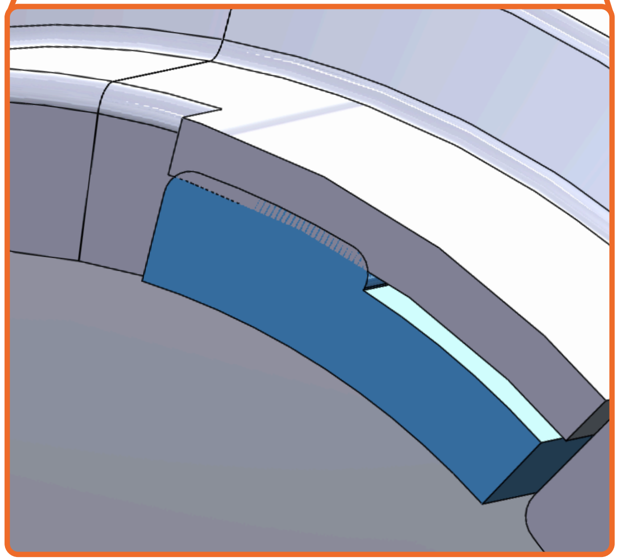


Figure 4.61 Close-up of Figure 4.60.

User tests revealed valuable insights into how the feedback was perceived. At first use, participants did not immediately recognise the clicking sound. After repeating the action several times, participants began to identify the click. This suggests that the feedback is perceptible, although a more clear differentiation is desirable.

Some users noted that the click sound was sometimes difficult to hear. The prototype is operated by inserting a finger into the ear shell. Incidental contact with the shell could have interfered with the tactile feedback, indicating that the interaction noise impacts the clarity of the tactile feedback.

Furthermore, it was difficult for users to clearly distinguish between the two different positions. An audible click was noticeable when the product was placed in the intended closed position (achieved through a slight downward twisting motion). However, due to the stiffness of the BTE cable, the prototype tended to rotate back slightly towards its neutral position, causing a secondary snapping sound. It was therefore difficult for the user to distinguish which position the prototype was in after a clicking sound.

Overall, the simplified 1:1 scale prototype demonstrated that tactile feedback can be generated without electronic components. Although the current design requires further optimisation, the concept itself has been validated. The results from user testing provide clear insights for future development.

Figure 4.62 3D-printed redesigned RIC body, scale 10:1 and 1:1.

Takeaways 4.4

- The nozzle must be designed to be compatible with soft domes **(extra design requirement, R3.4)**
- The product mechanism should be operable using only one finger or fingernail **(extra design requirement, R2.6)**
- Clear tactile or mechanical feedback is required **(extra design requirement, R2.7)**
- When using only one finger, a small interaction is preferred over a larger rotational movement
- Rotational stability must be improved in the next iteration

FUGAI: THE TUNED SOLUTION

FINAL CONCEPT PROPOSAL

5

This chapter presents Fugai as the final design concept. First, an introduction to the design is given, followed by an overview of the general working principle. Next, an exploded view of Fugai is displayed, after which the user interaction is described. Finally, a more detailed description of the mechanism is presented.

5.1 Fugai

Fugai is a Receiver-in-Canal (RIC) hearing aid concept featuring an integrated manual venting mechanism that enables users to actively control their listening experience. By allowing users to adjust the venting state according to their acoustic environment, the concept addresses the trade-off between openness and closedness in hearing aid use, while also taking individual preferences into account. This direct control increases user autonomy, improving usability by enabling users to make immediate adjustments based on their own perception rather than relying on an automated system.

By replacing the automatic venting system of the Phonak ActiveVent with a manual alternative, Fugai shifts control fully to the user. Additionally, this transition significantly reduces system complexity and cost by eliminating electronic components from the venting mechanism. At the same time, the removal of such small and fragile electronic components reduce the risk of mechanical failure. As it needs to be operated manually, the system is less sensitive to the ingress of pollution such as ear wax and debris, resulting in a more robust product with improved long-term durability.

Figure 5.1 shows how Fugai has been integrated with a silicone, closed dome and a Behind-the-Ear (BTE) housing.

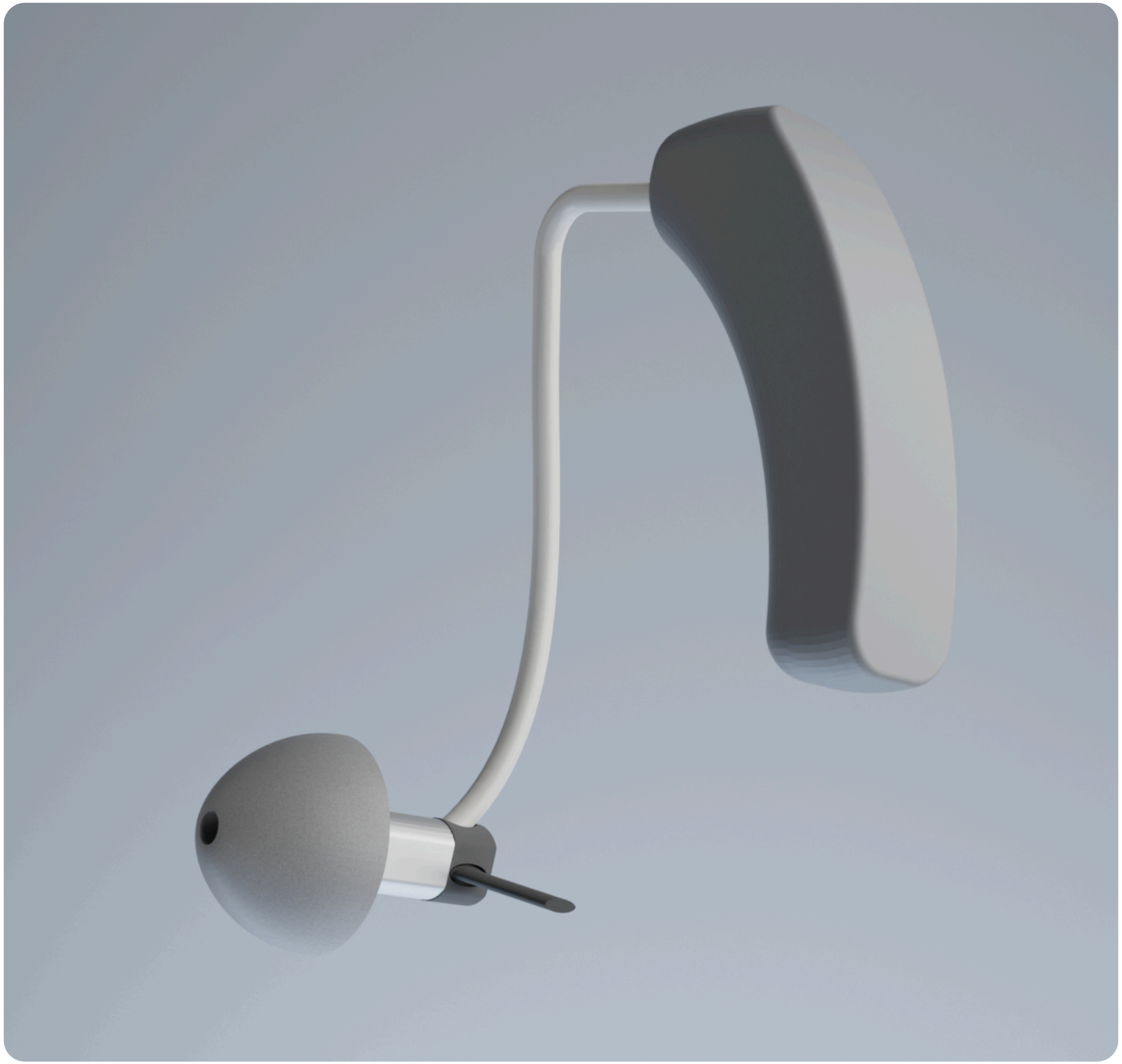


Figure 5.1 Fugai integrated with a dome and a BTE housing.

5.2 Product design explained

This chapter delves deeper into the details of Fugai. It first describes its general working working principle, followed by an overview of the system's components. It then describes how the user interacts with the device, and provides a more detailed description of Fugai's mechanical working.

5.2.1 General working principle

Fugai is based on a manually actuated, rotational venting mechanism integrated within the Receiver-in-Canal (RIC) assembly. Its working principle relies on controlled rotation to mechanically open or close the venting pathway, allowing users to adapt vent openness to their acoustic environment.

The system operates through a relative rotation between a stationary component in the ear canal, and a rotatable RIC housing operated by an external grip tool. Here, the nozzle and the dome define a fixed point in the ear canal. By rotating the RIC housing relative to the nozzle and the dome, the venting pathway is opened or closed, depending on the direction of rotation. Figure 5.2 shows the RIC's position before and after rotating the mechanism, while the nozzle and dome remain stationary.

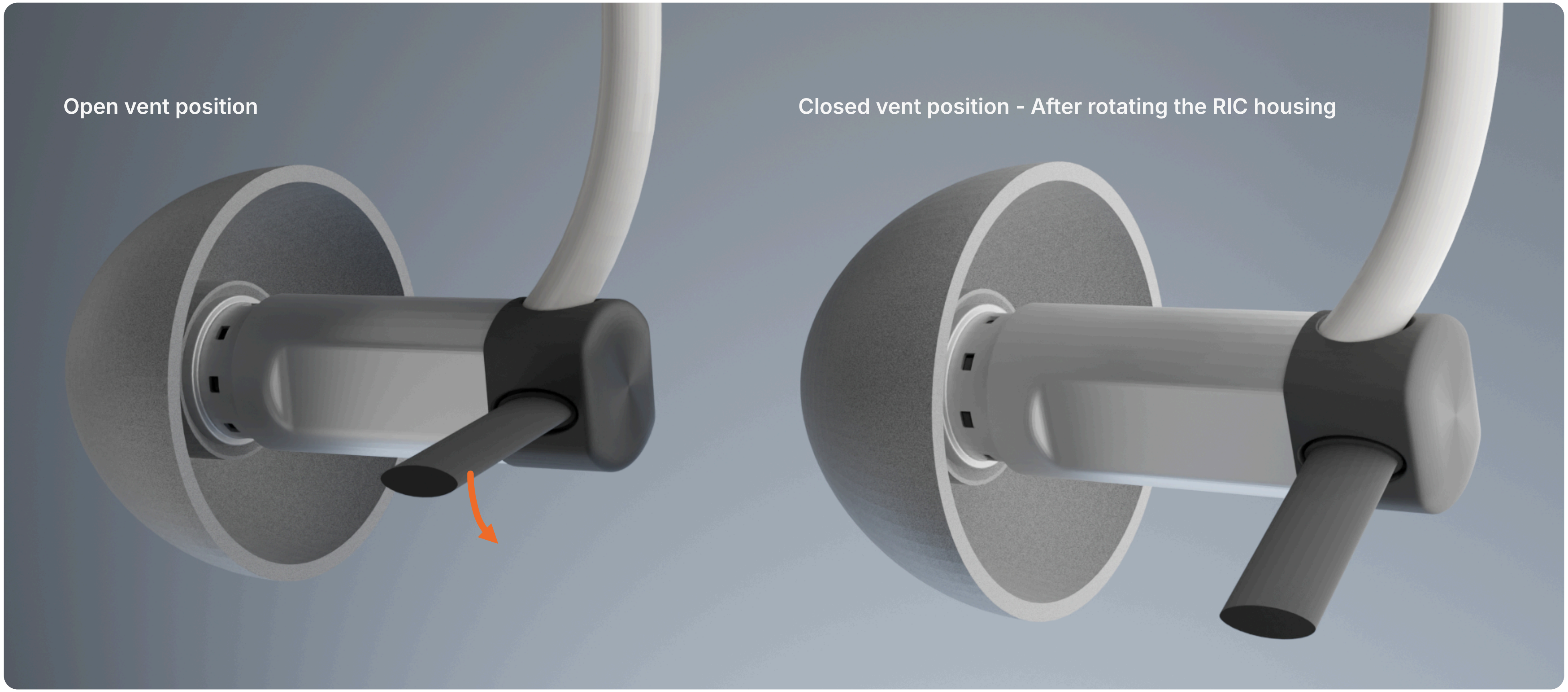


Figure 5.2 Visualisation of how Fugai's housing position changes from open into closed vent position after rotating counterclockwise.

5.2.2 Components of Fugai

A description of each component of Fugai and its function is given in Figure 5.3.

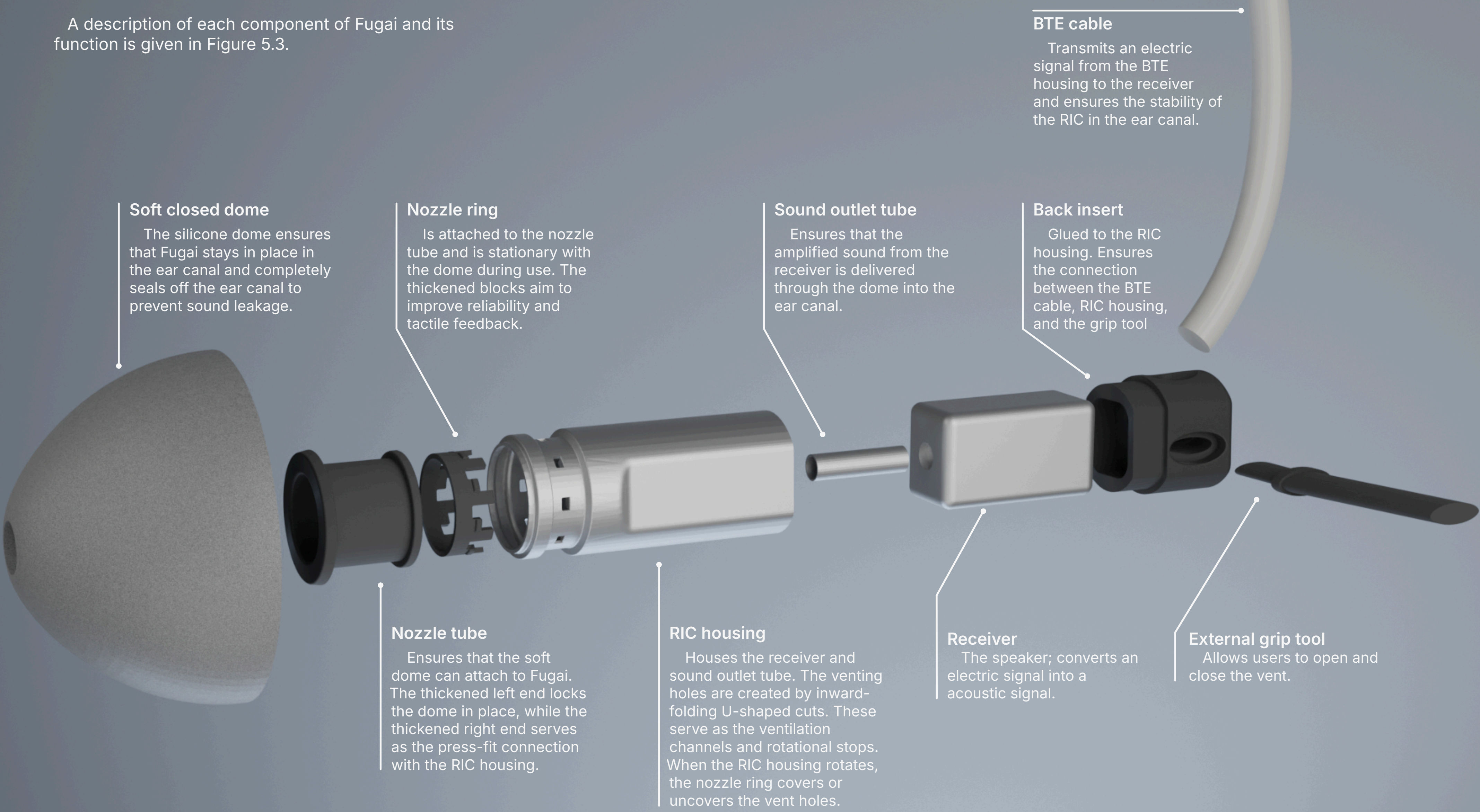


Figure 5.3 Exploded view of Fugai.

5.2.3 User Interaction

The user's interaction with Fugai is based on a simple, manual action that can be performed while wearing the device in the ear. The interaction is designed to be discrete, intuitive, and operable with one finger or fingernail. Using an interaction with one finger or fingernail avoids the need for a two-finger grip, which was found to cause discomfort due to pressure in the ear (Chapter 4.4.3). By requiring only a brief, localised action, Fugai supports user autonomy while maintaining comfort, discreteness, and suitability for everyday use.

In addition, the device's immediate response minimises disruption to the user's daily activities. Users expressed a need for a quickly accessible, easy to use interaction that enables immediate switching (Chapter 3.1.3). The mechanism therefore supports fast, direct adjustment.

Figure 5.4 shows how the user can interact with the product to manipulate its venting state. To adjust the vent state, the user applies a small movement to the RIC housing via the integrated external grip tool. As mentioned earlier, the RIC housing rotates relative to the stationary nozzle and dome, which are fixed by the ear canal. Depending on the direction of the rotation, the user is able to open (up) or close (down) the vent.

Tactile feedback is achieved through the interaction between the nozzle ring and the RIC housing. The thickened blocks on the ring induce a elastic tension in the nozzle in open vent position. When rotated to the closed vent position, the blocks snap into the vent openings, creating tactile feedback through a click sound. However, to provide sufficient tactile feedback, further development and prototyping is required.

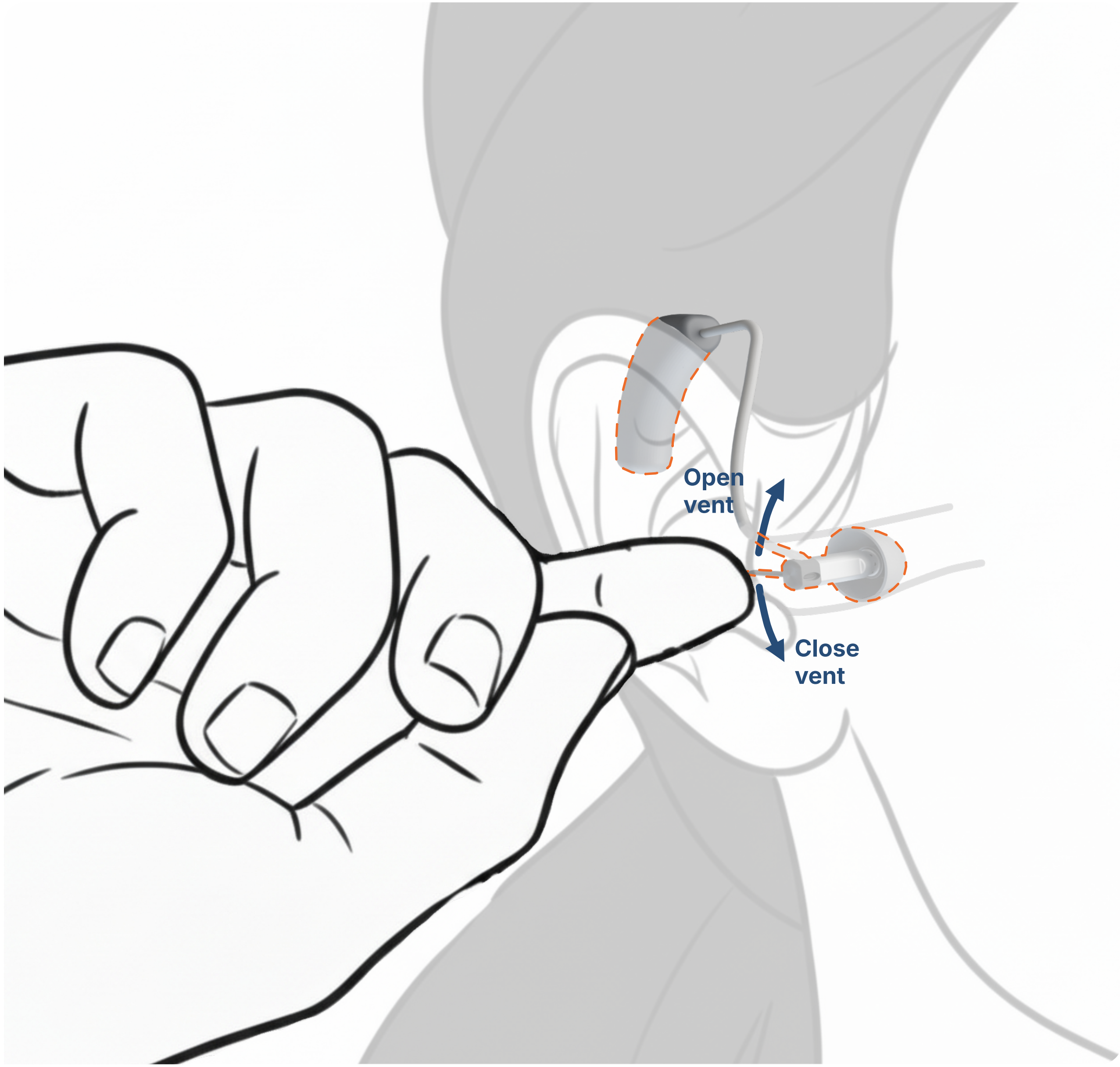


Figure 5.4 Visualisation of how a user can interact with Fugai.

5.2.4 Mechanical working

The product is able to rotate through a press-fit connection (1) between the stationary nozzle and the rotating RIC housing (Figures 5.5 and 5.6). The rotational movement is guided by inward folded, U-shaped cuts (2) in the housing, which simultaneously function as vent openings and mechanical rotation stops, defining clear open and closed vent positions and preventing over-rotation of the mechanism.

When rotated into the open position (Figure 5.5), the vent openings allow environmental sound to pass through the nozzle (Figure 5.7), increasing acoustic openness. In the closed position (Figure 5.6), airflow is restricted and acoustic sealing is increased (Figure 5.8), which is beneficial for blocking unwanted sounds in noisy environments, when speech clarity is prioritised, or for optimal sound performance during music streaming.

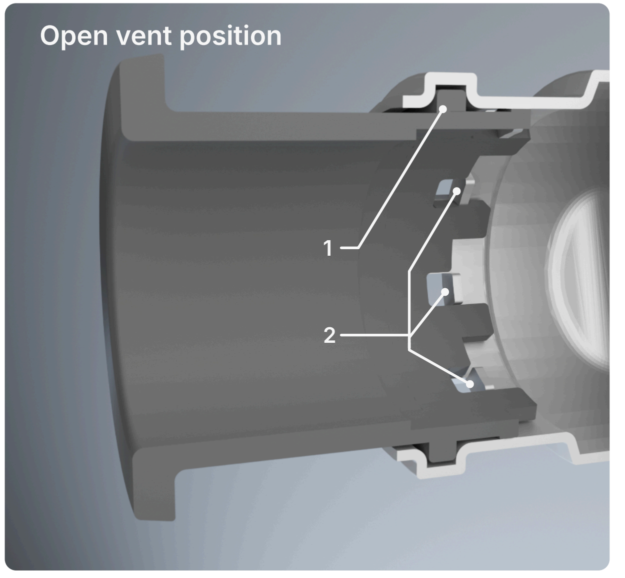


Figure 5.5 Cross-section view of the nozzle in open vent position.

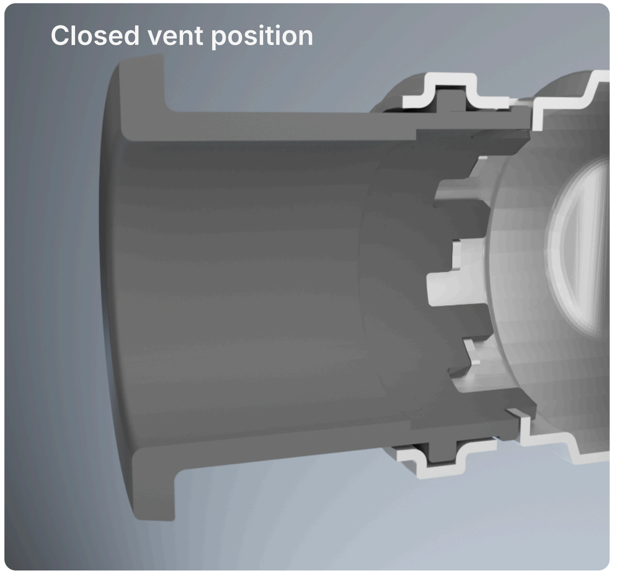


Figure 5.6 Cross-section view of nozzle in the closed vent position.

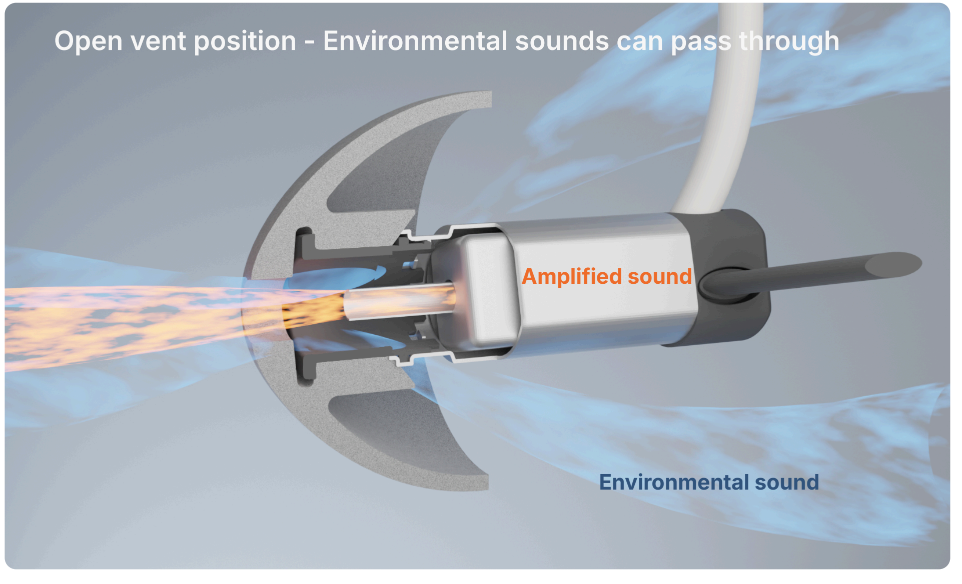


Figure 5.7 Partial cross-section view of Fugai, showing the acoustic effect with an open vent.

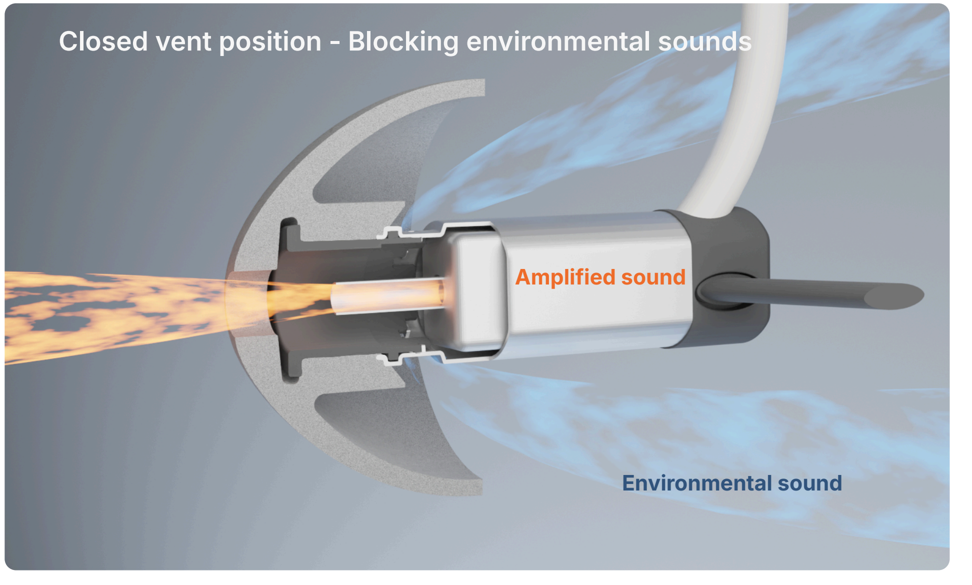


Figure 5.8 Partial cross-section view of Fugai, showing the acoustic effect with a closed vent.

FEEDBACK LOOP

REFLECTION & FUTURE DIRECTIONS

6

This chapter evaluates the results of the design process. The final design proposal is assessed against the current model, the Phonak ActiveVent, and its suitability for Sonion. The chapter reflects on the design outcomes, including the project's benefits and limitations, and discusses recommendations for future work. In addition, future opportunities for Sonion are outlined.

6.1 Design benefits

Fugai is a promising design concept proposal that could enter the market as a first of its kind solution. It is the first Receiver-in-Canal (RIC) hearing aid, with an integrated, manually operated adaptive venting mechanism.

6.1.1 Desirability

From a desirability perspective, Fugai addresses users' need for hearing aids that support autonomy, minimise disruptions, and offers the ability to quickly adapt to changing acoustic situations without requiring complex interaction. Where the Phonak ActiveVent showed unnecessary and/or disruptive switching states, Fugai avoids automated overcorrection, thus improving usability and reducing unwanted disturbances during everyday wear.

The design proposal has been developed through a user-centric approach to create a more desirable product. User tests informed the preferred interaction design, resulting in an intuitive operating mechanism that aligns closely with users' needs and preferences. In addition, the discrete in-ear design of Fugai further enhances product appeal for the hearing aid market, where discreteness is a key priority (personal communication Sonion employee, 2025).

6.1.2 Feasibility

From a feasibility perspective, Fugai has been designed in alignment with Sonion's current future vision for automated production lines. By eliminating the electronic components and reducing the amount of small and fragile components, it lowers the production complexity, making it more suitable for automated assembly processes.

Furthermore, reducing the number of components lowers the assembly steps, which therefore lowers the total tolerance stack ups. This results in lower assembly risks and errors, which in turn optimises manufacturing repeatability.

On top of that, as the design requires manual operation and does not contain sensitive electromagnetic components, the system is less susceptible to the ingress of pollution like wax and dust, improving its robustness and thus its durability.

6.1.3 Viability

The elimination of electromagnetic actuation and reduction in the amount of components also contributes to a reduced Bill of Materials and assembly time per unit. This simplification not only lowers production costs, but also limits potential failures. As a result, Fugai is cost-effective and economically viable in scale.

In addition, from a market perspective, Fugai is a first of its kind solution within the RIC segment. This differentiation provides an opportunity for strategic positioning in the hearing aid market. Fugai responds to user preferences for user control and reliability, by presenting a predictable, user-controlled vent mechanism. This value proposition creates a distinct positioning compared to hearing aids that rely primarily on automated venting or adaptive sound processing systems

Furthermore, as Fugai maintains the current dimensions of the Phonak ActiveVent, it ensures compatibility with existing components from Sonion and optimises scalability. Moreover, it preserves compatibility with existing dome designs. Together, Fugai supports a wider target group, as its unchanged dimensions allow easier fitting across a broader range of ear canal anatomies.

In summary, Fugai offers a great balance between user autonomy, ease of use, durability and cost-effectiveness. Fugai is the first of its kind in the hearing aid industry, as it presents a manual, user-controlled venting mechanism that differentiates from automated alternatives, making it a product design proposal with strong market potential.

6.2 Design limitations

Despite its potential, Fugai currently presents several limitations that need to be acknowledged.

Prototyping on a larger scale

First, as discussed before in Chapter 4.3.2, the development process relied mainly on 10:1 scale prototypes to explore and compare mechanical working principles. While it enables early concept evaluation, such scaled prototypes are not representative for 1:1 scale conditions, as mechanical behaviour differs in friction, material stiffness, tolerances, and actuation forces. Consequently, the resulting design decisions should be considered provisional, with final validation of reliability, usability, integration feasibility, and robustness requiring further development and testing at 1:1 scale.

User testing

Secondly, from a desirability perspective, the conducted intuitive use tests cannot be considered fully representative. Because the dummy prototypes differed in overall dimensions, particularly in length, the collected user feedback may not accurately reflect the actual perception of intuitiveness and comfort. Consequently, the reliability of the test results and the conclusions drawn from them are limited.

This limitation is reflected in design decisions. The RIC Twist proved to be the most intuitive concept during testing, which led to the conceptualisation phase to focus on a rotating mechanism. However, the final concept proposal does not fully integrate the interaction design of the RIC Twist.

During the development phase, it became clear that a two-finger interaction for an in-ear mechanism is suboptimal and can cause ear discomfort. Instead, the final concept proposal integrates a similar key feature of the RIC Handle, namely an external grip tool instead of a small rotating 'button' for two fingers. This suggests that the perceived intuitiveness of the RIC Twist, and thus its mechanism, may have been influenced during testing by the unrepresentative dummy prototypes.

Tactile feedback

Thirdly, although the redesigned nozzle ring was intended to generate clear tactile feedback, user tests revealed that the current mechanical principle does not provide clear tactile feedback.

While it could be argued that with a fully functional proof of concept a perceptible difference in sound can be perceived between the closed and open vent positions (as environmental sounds can pass through or are blocked), it is currently on a dummy-level unclear for users in what state the product is.

Mechanical reliability

Next, testing with a 3D-printed 1:1 scale model containing a simplified mechanism, showed that, due to the stiffness of the cable, the mechanism tends to rotate back towards its neutral position after manipulation. This negatively affects the product's mechanical reliability, impacting the usability and perceived sound quality if not resolved.

Although the redesigned nozzle ring for tactile feedback was also intended to increase Fugai's reliability, this goal has not yet been achieved. Therefore, further testing and development is required to accurately optimise reliability.

External grip tool

From a feasibility perspective, although Fugai presents increased robustness in its internal components, the external grip tool demonstrates a potential weakness. As described in Chapter 4.5.3, the 3D-printed 1:1 scale simplified model showed that the grip tool may be fragile and therefore less robust. In addition, such an external tool could complicate placing a dome or inserting the RIC in the ear, as it reduces the available gripping area of Fugai, and increases the likelihood of interference during handling.

Reachability with reduced dexterity

Lastly, reachability and ergonomics have not yet been sufficiently verified. While the interaction principle was clear, it remains uncertain whether all users are confident in operating the mechanic systems comfortably. This includes users with reduced dexterity or other limited hand mobility, for whom access within the constrained in-ear context may present challenges.

6.3 Design recommendations

Given its limitations, Fugai is far from a finished product. They indicate the development risks and needs for future work. To strengthen the overall design, several recommendations are proposed. While numerous recommendations can be made, the following are considered the most important. All recommendations should be validated using a functional 1:1 scale prototype to ensure realistic evaluation.

Full scale user testing

First, extensive user testing with a functional full-scale prototype is essential. Such testing would enable accurate evaluation of key design aspects such as ergonomics, reliability, interaction forces, robustness, and long-term wearing comfort. In addition, testing it among a larger, more diverse user group would further validate its desirability and usability.

Improved reachability

To further enhance its desirability, refinement and validation of the product's reachability is required to continue optimising the interaction between the user and the product. Currently, reachability has not been tested sufficiently. Involving users with reduced dexterity or limited hand mobility in future testing would be valuable, as it would help ensure that the interaction remains intuitive and accessible.

Robustness of external grip tool

From a feasibility perspective, the external grip tool, which supports accessibility, should be refined to improve its durability. This can be achieved by using more resilient materials, or by completely reducing the reliance on an external grip tool. Nevertheless, it should be designed so that the user can operate it with just one finger(nail), while maintaining product discreteness during wear.

Improved mechanical reliability

The mechanical reliability of the venting mechanism must be addressed to ensure a stable operation. One approach would be to reduce the cable stiffness. This would however negatively affect the retention of the Receiver-in-Canal (RIC) and the Behind-the-Ear (BTE) housing in and around the ear. An alternative solution is by introducing a passive locking feature, such as a latching ring used in the Phonak ActiveVent, could be integrated to ensure the mechanism maintains its set position. While it would improve reliability, it would also increase manufacturing complexity and production costs. A careful trade-off evaluation is therefore required.

Materials and manufacturing

Even though some components of Fugai have been designed in a way to minimise manufacturing complexity, e.g. the press-fit connection and the inward folded U-shaped cuts, materials, manufacturing and assembly processes, costs, and a durability and sustainability analysis still need to be considered.

Improved tactile feedback

Last but not least, Fugai needs further optimisation to enhance its tactile feedback. One way to achieve this is through a secondary snap fit. In this concept, the thickened blocks not only snap when rotated to the closed vent position, but would also snap into a fitting when rotated towards the open vent position, see Figures 6.1 and 6.2 for draft sketches. Although theoretically feasible, this would increase manufacturing complexity and tolerance challenges.

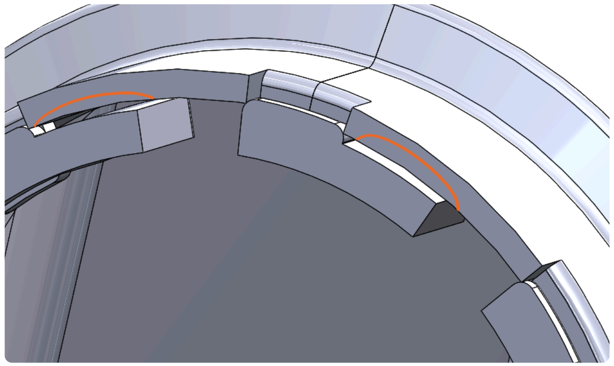


Figure 6.1 Cross-section view of the nozzle in open vent position.

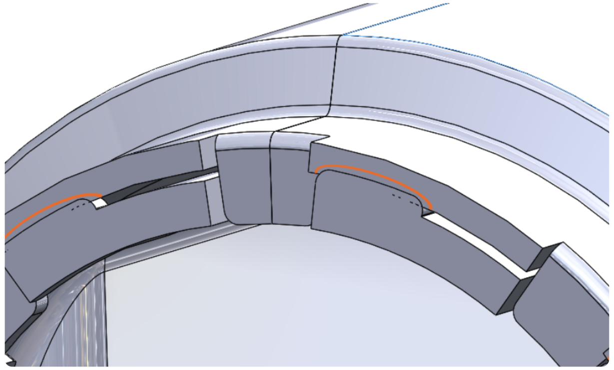


Figure 6.2 Cross-section view of the nozzle in open vent position.

One other option that came forward in discussions with colleagues from Sonion, involves incorporating a small electronic component to Fugai. For example, impedance could be measured at 20 Hz. When a change is detected, a signal from the BTE housing to the RIC can be transmitted, triggering an acoustic output to inform the user that the vent state is switched. This would convert a physical tactile feedback into an auditory feedback mechanism.

For this project, such option was excluded as adding electronic components to the design was out of scope. However, for future iterations, adding such a small electronic component might be viable to improve Fugai's tactile feedback, particularly if purely mechanical solutions prove to be too complex or costly to manufacture while still delivering sufficiently tactile feedback.

Overall, regardless of the type of future work, it must focus on resolving technical and ergonomic uncertainties through 1:1 scale prototyping, including user testing and detailed feasibility studies. These aspects are essential for turning Fugai from a conceptually validated design, to a mature, market-ready product.

6.4 Possible future opportunities for Sonion

In addition to presenting Fugai's benefits, limitations, and the recommendations for its future work, this graduation project also revealed two possible future design directions. These emerged during research and development, but were not explored further to maintain focus on the core concept development. These possibilities, however, do offer meaningful opportunities for future development.

Push/Pull mechanism

During the intuitive use test, participants indicated a clear preference against performing a push/pull interaction inside the ear. Their primary concerns were the possibility of accidentally pushing the RIC too deeply into the ear canal, or unintentionally pulling it out during the interaction.

However, Sonion still sees potential in exploring a design direction where the nozzle and dome act as a fixed point in the ear, to enable a controlled push/pull mechanism. However, a key challenge remains: ensuring the system can be reliably operated with a single finger(nail). While a push action can be performed relatively easily, a pulling action is challenging. Using two fingers is impractical, as it is difficult to operate the mechanism in the ear canal with two fingers in such a confined space, without any discomfort.

Hearing aids as personal identity

While the hearing aid market suggests users seek discrete designs to avoid stigma (personal communication Sonion employee, 2025), interviews with hearing aid users revealed otherwise. They reported no negative experiences or feelings of shame when wearing their hearing aids. Instead, hearing aids have become an important part of their identity, and participants often compared it to wearing glasses for having eye sight impairment. The key difference, however, is that glasses are socially acceptable.

Today, glasses are available in countless styles, colours, sizes, and shapes, to suit different preferences and an individual's personality. Over time, glasses have evolved from purely functional medical devices to fashion items. Some people even wear glasses without visual impairment, purely to express their personal style and identity. Despite this shift, glasses remain, at their core, medical products, designed to correct low vision.

On the contrary, interviews show that hearing aids are still considered medical devices and are strongly associated with older people. For younger users, including those with congenital hearing loss, wearing hearing aids can be socially awkward and is still considered unusual. This age-related stigma is reinforced by current marketing campaigns.

Designing hearing aids that are more visible offers an opportunity to challenge this perception. By allowing hearing aid users to express their identity, hearing aids could evolve from something people need to something they actively choose. Some early designs already exist, such as jewellery accessories from Deafmetal and fashion concepts presented by Vogue, to integrate fashion statements into medical devices (Figures 6.1 - 6.3). While this market is still niche, it is showing a growing interest in the hearing aid industry.

In addition, increased visibility also offers functional advantages. By making the device visible, interaction with a component of the hearing aid, such as a vent mechanism, can increase the ease of use, further improving usability. This offers Sonion the opportunity to address this small but emerging market by developing a vent mechanism specifically designed for visible, identity-driven hearing aids. In this way, technical innovations can align with new, emerging societal perceptions.

Figure 6.1 Male jewellery attached to a Behind-the-Ear housing (*Deafmetal Hearing Jewelry*, n.d.).

Figure 6.2 Male jewellery in context use (*Deafmetal Hearing Jewelry*, n.d.).

Figure 6.3 Model wearing a hearing aid with attached jewellery Photo from Courtesy of Private Policy (Allaire, 2021).

6.5 Personal reflection

As mentioned before in the Preface of this report, this graduation project was exactly what I was looking for, as it combined two areas I like working in; niche product development and user-centred design. The clear frame and specificity of the project, together with the focus on a challenging context of use, made me motivated from the start of the project.

However, at times, designing for such a confined design space proved to be quite challenging. The technical and contextual design constrains sometimes limited my ability to think outside the box during the ideation and development phases. Consequently, I became stuck in the design process more than I had experienced in previous design projects. For me, this led to moments of uncertainty regarding design decisions I was making, or developing ideas of which I was not sure they were feasible.

From these moments, I now recognise that it could have been helpful to be more proactive towards my colleagues at Sonion. There is a huge amount of knowledge within Sonion regarding technical development insights or giving tips and tricks. Their expertise might have pushed the project to a higher level of detail and validation. On the other hand, taking a more independent approach also strengthened my self-resilience. I learned to trust my own judgement and to make design decisions with greater confidence. Although not all of them turned out to be the optimal one, but each of them contributed to my learning process. These lessons are definitely insights that I will take with me to future projects.

One aspect I am proud of is my time management and consistency throughout the graduation project. Even though the design process was at times a bit unstructured or uncertain, I maintained a steady workflow. I continuously had a feeling of being in control and having a clear overview of the entire process. This was partly because I had a well-defined vision at the beginning, which I translated into a structured planning. For me, this planning provided clarity on what to expect in each phase, which also made it easier to anticipate when certain activities were not progressing as imagined.

Moreover, breaking the planning down into smaller, weekly targets was helpful. By restructuring, I created a sense of control and calm for myself. This brought me into a rhythm of stability throughout the project.

One other aspect that I learned this semester, is collaborating within a company across various departments. Working closely with the Prototyping, Measurements and Tests department, the department that 3D-printed my prototypes, taught me how to communicate in a clear, effective way. In addition, it also allowed me to consider (prototyping) perspectives and learn from colleagues' expertise.

Lastly, this graduation project made me look differently towards hearing aids. I realised that, before the start of this project, I subconsciously viewed them as medical products that are primarily designed for elderly people with hearing loss. However, I now am convinced that hearing aids represent a complex and evolving field of technical innovation, not only designed for elderly people. On top of that, I now understand that young hearing aid users see their devices as part of their identity and I believe it should be widely socially accepted, no less normal than glasses.

TRACING THE SIGNALS

REFERENCES

7

Allaire, C. (2021, March 15). *Private Policy's Jewelry Collaboration Celebrates the Deaf and Hard of Hearing Communities.* Vogue. Retrieved February 5, 2026, from https://www.vogue.com/article/private-policy-chella-man-jewelry-collab-deaf-community

Alshuaib, W. B., Al-Kandari, J. M., & Hasan, S. M. (2015). Classification of hearing loss. In *InTech eBooks*. https://doi.org/10.5772/61835

Apple. (2025, November 19). Apple introduces AirPods 4 and the world's first all-in-one hearing health experience with AirPods Pro 2. *Apple Newsroom*. https://www.apple.com/newsroom/2024/09/apple-introduces-airpods-4-and-a-hearing-health-experience-with-airpods-pro-2/

ASH Audiology. (n.d.). *Phonak ActiveVent MAV Receiver (Speaker Wire) — ASH Audiology*. https://www.ashaud.com/shop/p/phonak-activevent-receiver-speaker-wire

Audio Service Hearing Aids. (2022, May 3). *How to insert a Audio Service RIC hearing aid in the ear* [Video]. YouTube. https://www.youtube.com/watch?v=GfXESFQqw9c

AudioCardio. (2020, November 16). *The Anatomy of the Middle Ear*. https://audiocardio.com/hearing-loss/the-anatomy-of-the-middle-ear/

Bed Bath & Beyond. (n.d.). *Ceretone Beacon OTC Self-Fitting Hearing Aids*. Retrieved December 25, 2025, from https://www.bedbathandbeyond.com/Electronics/Ceretone-Beacon-OTC-Self-Fitting-Hearing-Aids/42787065/product.html?option=89507622

Bissmeyer, S. R. S., & Goldsworthy, R. L. (2017). Adaptive spatial filtering improves speech reception in noise while preserving binaural cues. *The Journal of the Acoustical Society of America, 142*(3), 1441–1453. https://doi.org/10.1121/1.5002691

Burns, J. C., & Corwin, J. T. (2013). A historical to present-day account of efforts to answer the question: "What puts the brakes on mammalian hair cell regeneration?" *Hearing Research, 297*, 52–67. https://doi.org/10.1016/j.heares.2013.01.005

Carillo, K., Doutres, O., & Sgard, F. (2021). On the removal of the open earcanal high-pass filter effect due to its occlusion: A bone-conduction occlusion effect theory. *Acta Acustica, 5*, 36. https://doi.org/10.1051/aacus/2021029

Celikgun, B., Serbetcioglu, B., & Park, M. K. (2024). Selection and application principles of hearing aids in pediatric and adult population. In *Comprehensive ENT* (pp. 203–256). https://doi.org/10.1007/978-3-031-76173-7_11

Chung, K., & Zeng, F. (2024). Over-the-counter hearing aids: implementations and opportunities. *Frontiers in Audiology and Otology, 2*. https://doi.org/10.3389/fauot.2024.1347437

Cochlear Australia. (n.d.). *Bone conduction implants*. Cochlear. Retrieved December 28, 2025, from https://www.cochlear.com/au/en/home/diagnosis-and-treatment/how-cochlear-solutions-work/bone-conduction-solutions/bone-conduction-implants

Cooling, G. (2020, October 2). *Phonak ActiveVent, what can you expect?* Hearing Aid Know. https://www.hearingaidknow.com/phonak-activevent-what-you-can-expect

Cubick, J., Caporali, S., Lelic, D., Catic, J., Damsgaard, A. V., Rose, S., Ives, T., & Schmidt, E. (2022). The acoustics of Instant Ear Tips and their Implications for Hearing-Aid Fitting. *Ear And Hearing, 43*(6), 1771–1782. https://doi.org/10.1097/aud.0000000000001239

Davidson Hearing Aid Centres. (2015, July 10). *Ear Anatomy Labeled*. Retrieved November 15, 2025, from https://davidsonhearingaids.com/fr/ear-anatomy-labeled-2/

Davis, A., McMahon, C. M., Pichora-Fuller, K. M., Russ, S., Lin, F., Olusanya, B. O., Chadha, S., & Tremblay, K. L. (2016). Aging and Hearing Health: the Life-course approach. *The Gerontologist, 56*(Suppl 2), S256–S267. https://doi.org/10.1093/geront/gnw033

De Siati, R. D., Rosenzweig, F., Gersdorff, G., Gregoire, A., Rombaux, P., & Deggouj, N. (2020). Auditory Neuropathy Spectrum Disorders: From diagnosis to Treatment: Literature review and case reports. *Journal of Clinical Medicine, 9*(4), 1074. https://doi.org/10.3390/jcm9041074

Deafmetal Hearing jewelry. (n.d.). Retrieved February 5, 2026, from https://www.deafmetal.store/product/281/double-gold

Dickinson, W. W. (2010). Audiology and baha: good. . . good. . . good vibrations! *The Hearing Journal, 63*(5), 10. https://doi.org/10.1097/01.hj.0000373445.68203.7f

Estes, S. (2020, October 19). *Learn About the Different Styles of Hearing Aids*. Empire Hearing & Audiology. https://empirehearing.alpacaaudiology.com/blog/understanding-different-hearing-aid-styles/

Gomez, R., Habib, A., Maidment, D. W., & Ferguson, M. A. (2021). Smartphone-Connected Hearing Aids Enable and Empower Self-Management of Hearing Loss: a qualitative interview study underpinned by the Behavior Change Wheel. *Ear And Hearing, 43*(3), 921–932. https://doi.org/10.1097/aud.0000000000001143

Hermes, D. J. (2023). The ear. In *Current research in systematic musicology* (pp. 89–140). https://doi.org/10.1007/978-3-031-25566-3_2

Hidden Hearing. (n.d.). *Finding the right type of hearing aid.* Retrieved December 30, 2025, from https://www.hiddenhearing.co.uk/hearing-aids/types

Jiang, C., Han, K., Yang, F., Yin, S., Zhang, L., Liang, B., Wang, T., Jiang, T., Chen, Y., Shi, T., Liu, Y., Chen, S., Tong, B., Liu, Y., Pan, H., & Han, Y. (2023). Global, regional, and national prevalence of hearing loss from 1990 to 2019: A trend and health inequality analyses based on the Global Burden of Disease Study 2019. *Ageing Research Reviews, 92*, 102124. https://doi.org/10.1016/j.arr.2023.102124

Kerckhoff, J., Listenberger, J., & Valente, M. (2008). Advances in hearing aid technology. *Contemporary Issues in Communication Science and Disorders, 35*(Fall), 102–112. https://doi.org/10.1044/cicsd_35_f_102

Kuk, F., & Baekgaard, L. (2008, March 2). *Hearing Aid Selection and BTEs: Choosing Among Various "Open-ear" and "Receiver-in-Canal" Options*. The Hearing Review. https://hearingreview.com/practice-building/practice-management/hearing-aid-selection-and-btes-choosing-among-various-open-ear-and-receiver-in-canal-options

Liebich, S., & Vary, P. (2021). Occlusion Effect Cancellation in Headphones and Hearing Devices—The sister of Active Noise cancellation. *IEEE/ACM Transactions on Audio Speech and Language Processing, 30*, 35–48. https://doi.org/10.1109/taslp.2021.3130966

Lieu, J. E. C., Kenna, M., Anne, S., & Davidson, L. (2020). Hearing loss in children. *JAMA, 324*(21), 2195. https://doi.org/10.1001/jama.2020.17647

Livingston, G., Sommerlad, A., Orgeta, V., Costafreda, S. G., Huntley, J., Ames, D., Ballard, C., Banerjee, S., Burns, A., Cohen-Mansfield, J., Cooper, C., Fox, N., Gitlin, L. N., Howard, R., Kales, H. C., Larson, E. B., Ritchie, K., Rockwood, K., Sampson, E. L., . . . Mukadam, N. (2017). Dementia prevention, intervention, and care. *The Lancet, 390*(10113), 2673–2734. https://doi.org/10.1016/s0140-6736(17)31363-6

Manchaiah, V., Picou, E. M., Bailey, A., & Rodrigo, H. (2021). Consumer ratings of the most desirable hearing aid attributes. *Journal of the American Academy of Audiology, 32*(8), 537–546. https://doi.org/10.1055/s-0041-1732442

Mecklenburger, J., & Groth, T. (2016). Wireless technologies and hearing aid connectivity. In *Springer handbook of auditory research* (pp. 131–149). https://doi.org/10.1007/978-3-319-33036-5_5

Moore B. C., Glasberg B. R., Baer T. (1997). *A model for the prediction of thresholds, loudness, and partial loudness*. J Audio Eng Soc 45(4):224–240. http://www.aes.org/e-lib/browse.cfm?elib=10272

Natalizia, A., Casale, M., Guglielmelli, E., Rinaldi, V., Bressi, F., & Salvinelli, F. (2010). An Overview of Hearing Impairment in Older Adults: Perspectives for Rehabilitation with Hearing Aids. In *European Review for Medical and Pharmacological Sciences* (Vols. 14–14, pp. 223–229). https://www.europeanreview.org/wp/wp-content/uploads/728.pdf

NIDCD. (2018, January 26). *Auditory Neuropathy*. National Institute on Deafness and Other Communication Disorders. https://www.nidcd.nih.gov/health/auditory-neuropathy

NIDCD. (2024, June 13). *Cochlear Implants*. National Institute on Deafness and Other Communication Disorders. https://www.nidcd.nih.gov/health/cochlear-implants

Olson, C. R. [Doctor Cliff, AuD]. (2019, January 18). *Why Ear Mold Vent SIZE is Critical for Hearing Aid Performance* [Video]. YouTube. https://www.youtube.com/watch?v=eR7AI75CI_c

Olson, C. R. [Doctor Cliff, AuD]. (2021, August 18). *Worlds FIRST Intelligent Receiver for Paradise Hearing Aids | Phonak ActiveVent Review* [Video]. YouTube. https://www.youtube.com/watch?v=uOcG8zd8gIY

Ostrowski, E. (2025, May 21). *Millennials and Gen Z are at increased risk for hearing loss*. Healthy Hearing. https://www.healthyhearing.com/report/53644-Hearing-loss-in-millennials-and-gen-z#:~:text=Kurth%2C%20AuD%2C%20director%20of%20audiology,half%20saying%20they%20play%20daily

Oticon Canada. (2013, May 28). *Oticon Inium Custom Program* [Video]. YouTube. https://www.youtube.com/watch?v=WSuV1o18DjE

Phonak. (2021, August 18). *Phonak announces ActiveVent, the world's first intelligent hearing aid receiver, and CROS Paradise. Sonova*. https://www.sonova.com/en/media/phonak-announces-activevent-worlds-first-intelligent-hearing-aid-receiver-and-cros-paradise

Prabhu, P., & Barman, A. (2016). Effectiveness of Low Cut Modified Amplification using Receiver in the Canal Hearing Aid in Individuals with Auditory Neuropathy Spectrum Disorder. *International Archives of Otorhinolaryngology, 21*(03), 243–249. https://doi.org/10.1055/s-0036-1593471

Phonak Audeo Fit. (n.d.). Phonak. Retrieved December 25, 2025, from https://www.phonak.com/en-ca/hearing-devices/hearing-aids/audeo-fit

Ryan, J., Coenen, I., & Brennan, R. (2025). The Evolution of System on Chip Integrated Circuits for Hearing-Aid Signal Processing. *IEEE Xplore*, 1–5. https://doi.org/10.1109/icassp49660.2025.10888470

Sanga, T. M. (2018, December 9). *Let's get to know the BA or Balanced Armature drivers.* https://www.allabout.in.th/knowledge-ba-balanced-armature/

Sonova. (2021a). *Phonak ActiveVentTM Receiver*. https://www.phonakpro.com/content/dam/phonakpro/gc_hq/en/products_solutions/hearing_aid/active_vent/PH_Candidacy_editable_form_ActiveVent_Receiver_EN_V1.00_027-0642_02.pdf

Sonova. (2021b, August 18). *Phonak announces ActiveVent, the world's first intelligent hearing aid receiver, and CROS Paradise.* https://www.sonova.com/en/media/phonak-announces-activevent-worlds-first-intelligent-hearing-aid-receiver-and-cros-paradise

Speech & Hearing Associates. (2021, December 29). *Types of Hearing Loss & Degrees of Hearing Loss*. Retrieved November 18, 2025, from https://speechandhearingassoc.com/types-hearing-loss/

Sterkens, J. [TEDx Talks]. (2024, March 2). *What you don't know about hearing aids | Juliëtte Sterkens | TEDxOshkosh* [Video]. YouTube. https://www.youtube.com/watch?v=0vf1q_HgLpw

Svantek. (n.d.). *What is Sound?* SVANTEK. https://svantek.com/academy/what-is-sound/

Sygrove, C. (2025, July 30). *Hearing Aids with Artificial Intelligence (AI): Review of Features, Capabilities and Models that Use AI and Machine Learning (2025).* Hearing Tracker. https://www.hearingtracker.com/resources/ai-in-hearing-aids-a-review-of-brands-and-models

van Boeijen, A., Daalhuizen, J., & Zijlstra, J. (2020). *Delft Design Guide: Perspectives, models, approaches, methods* (2nd edition). BIS Publishers. https://www.bispublishers.com/delft-design-guide-revised.html.

Verhaert, N., Desloovere, C., & Wouters, J. (2013). Acoustic hearing implants for mixed hearing loss. *Otology & Neurotology, 34*(7), 1201–1209. https://doi.org/10.1097/mao.0b013e31829ce7d2

Walker, J., Cleveland, L.M., Davis, J.L., & Seales, J.S. (2013). Audiometry screening and interpretation. *American family physician, 87 1*, 41-7 .

Wani, G., & Faizullabhoy, M. (2025). Hearing Aids Market Size - By Product, By Patient, By Distribution Channel, Growth Forecast, 2025-2034. In *Global Market Insights Inc.* https://www.gminsights.com/industry-analysis/hearing-aids-market

Wardenga, N., Snik, A. F., Kludt, E., Waldmann, B., Lenarz, T., & Maier, H. (2020). Hearing Aid Treatment for Patients with Mixed Hearing Loss. Part II: Speech Recognition in Comparison to Direct Acoustic Cochlear Stimulation. *Audiology and Neurotology, 25*(3), 133–142. https://doi.org/10.1159/000504285

Wilson, B. S., & Tucci, D. L. (2021). Addressing the global burden of hearing loss. *The Lancet, 397*(10278), 945–947. https://doi.org/10.1016/s0140-6736(21)00522-5

World Health Organization. (2013). MULTI-COUNTRY ASSESSMENT OF NATIONAL CAPACITY TO PROVIDE HEARING CARE. In *Institutional Repository for Information Sharing* (ISBN 978 92 4 150657 1). https://iris.who.int/server/api/core/bitstreams/fc5c04c5-d566-4f46-8fd9-f8647ad2142f/content

World Health Organization. (2017). Global costs of unaddressed hearing loss and cost-effectiveness of interventions: A WHO report. In *Institutional Repository for Information Sharing* (ISBN 978-92-4-151204-6). https://iris.who.int/server/api/core/bitstreams/73bf2a87-4c87-4ca9-b9d9-3b852277e105/content

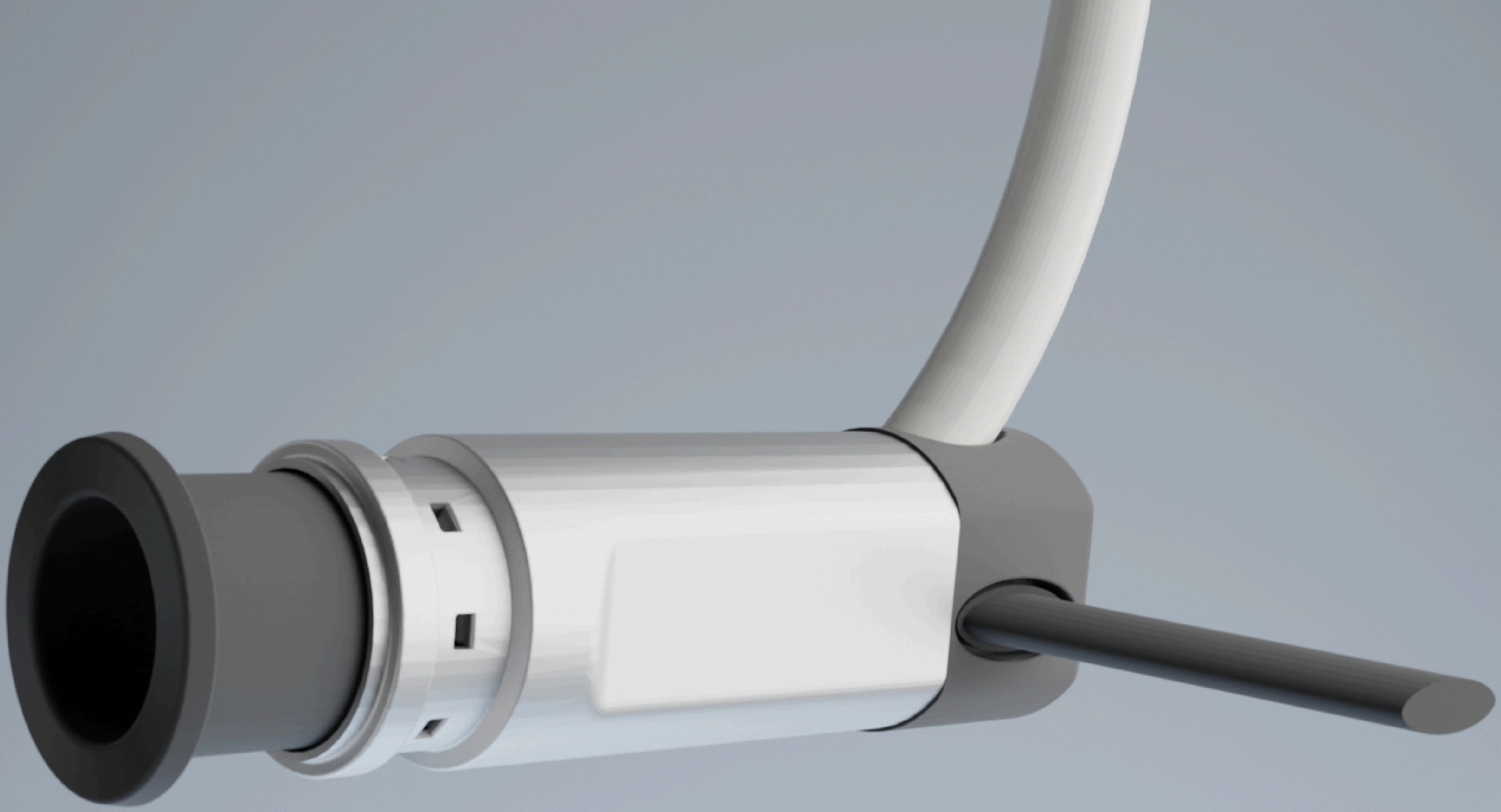
World Health Organization. (2021, March 2). WHO: 1 in 4 people projected to have hearing problems by 2050. *World Health Organization*. https://www.who.int/news/item/02-03-2021-who-1-in-4-people-projected-to-have-hearing-problems-by-2050

World Health Organization. (2025, February 26). *Deafness and hearing loss.* https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss

Xu, D., Lu, H., Jiang, Y., Kim, H., Kwon, J., & Hwang, S. (2017). Analysis of sound pressure level of a balanced armature receiver considering coupling effects. *IEEE Access, 5*, 8930–8939. https://doi.org/10.1109/access.2017.2696565

Zahnert, T. (2011). The differential diagnosis of hearing loss. *Deutsches Ärzteblatt International, 108*(25), 433–443; quiz 444. https://doi.org/10.3238/arztebl.2011.0433

Zedalis, J., & Eggebrecht, J. (2018, March 8). *27.4 Hearing and vestibular Sensation*. Retrieved December 30, 2025, from https://openstax.org/books/biology-ap-courses/pages/27-4-hearing-and-vestibular-sensation



Job Nuijen
MSc. Graduation Thesis
March 2026

Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology