oTo

Adaptive headphones that can compensate for hearing losses and sensitivities, designed for a variety of soundscapes

Pepa Chesworth Russell / Final Year Project MEng / 10 Page Summary

The increase in the number of employees working from home means that meetings are now often held online, with Zoom alone hosting 300 million meeting participants per month.

However, this means that many deaf people are confronted with online experiences not designed for hearing losses. Deaf listeners struggle to hear digital audio due to compression, and cannot understand the radio, television or lyrics of music. Many of the solutions out there are targeted towards the elderly, which make up for approximately 70% of the deaf population within the UK.

Currently, not many options exist for improving music quality for those with hearing losses for the younger generation.

User experiences

As a hard of hearing person, previous interactions with headphones and hearing losses helped to clarify the existing user experiences. For this project, it was important to approach with an unbiased view - therefore experiences of both hearing and hard of hearing individuals had to be researched. It was found in a general survey that, despite being relatively content with the audio quality of their headphones, 91% of respondents (all full hearing) have a lot of interest in bespoke audio. Interestingly, the majority of respondents did not change the EQ of their headphones, or did not know what it was.

To gain further insights within the deaf community, interviews were conducted with individuals with a wide range of hearing abilities.

“I have to turn the phone output and Spotify EQ settings to max, which ruins the music playback”
- Uses hearing aids with severe losses

“Honestly, I’m not satisfied with headphones, simply because they don’t work for me when I’m not using my hearing aids”
- Uses both cochlear implants and hearing aids

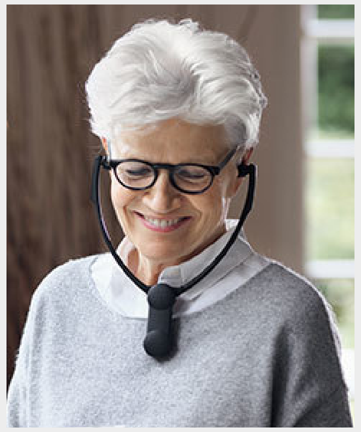
Existing products

Current products on the market can be split into two categories: high quality headphones with no consideration of deaf users, or medical devices that have one singular purpose.

Consumer headphones focus on excellent noise cancellation, high quality audio, and luxury materials, but have no consideration of deaf listeners.

On the other hand, hearing solutions are aimed at the elderly deaf population (approximately 70% of all hard of hearing people), and as a result are typically aesthetically unappealing, single-function, and simplistic.

Therefore, there is a gap in the market for a product aimed at the younger deaf population.



Focus group

A focus group of six individuals with a range of hearing abiliites and different experiences relating to the problem was created. They were contacted frequently throughout the project, and provided feedback on current concepts and suggested ideas that could help further development.

- Severe hearing loss, high freqs.
- Wears hearing aids in both ears
- Works in the tech industry, attends many videocalls

- No medical hearing losses
- Designs amplifiers
- Degree in Music Technology and Electronics

- No medical hearing losses
- Full time under-grad student
- Has worked from home as a customer service advisor

- No medical hearing losses
- Youth Worker for Deaf Action
- In the process of learning British Sign Language (BSL)

- No medical hearing losses
- Full time post-grad student
- Works from home, spends a lot of time on videocalls

- Mod. hearing loss, high freqs.
- Does not wear hearing aids
- Works in the music industry as a musician and producer

Brief

Design a product that improves the digital audio experiences of people with and without hearing losses, by adapting the audio to fit the user's hearing sensitivities.

Concept generation

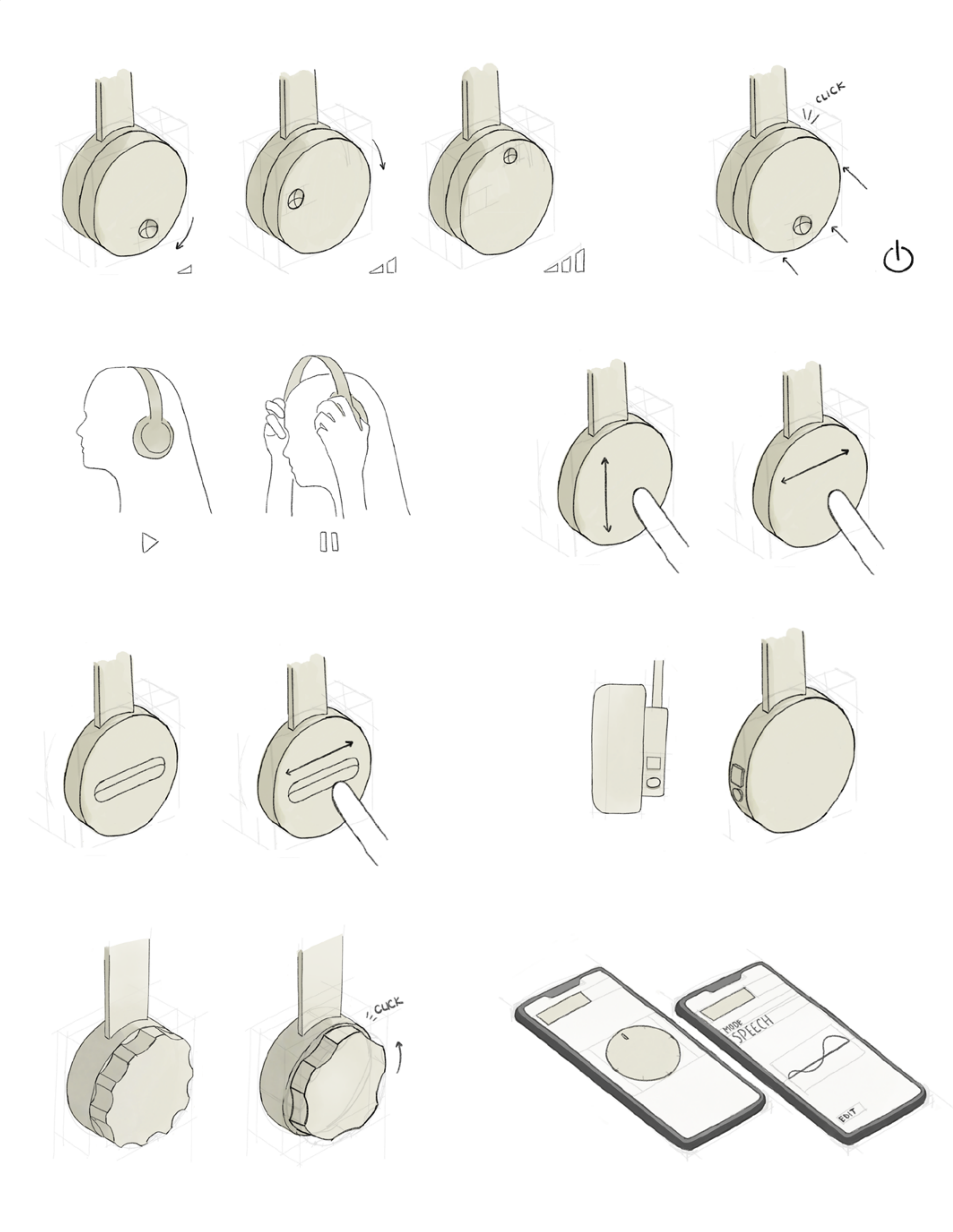
Initially, I looked at different methods of communicating sound, but decided that only headphones offered the individualisation necessary to meet the brief, whilst also remaining inclusive.

Following this decision, I looked at different mechanisms and forms. Performing a basic product design specification led me to the first 3D realisation, with key dimensions such as the earcup size determined from anthropometric data.

However, the design wasn't satisfactory as it didn't consider the user interactions. Furthermore, the overall form was bulky, disproportionate and unappealing.

2D concept generation

Initial 3D realisation



Interaction design

Taking inspiration from existing products such as amplifiers and smart thermostats, I generated some more quick concepts based on how the user interacts with the product. From user feedback I had previously gained and the observation of the use of existing products, it was clear that more complex controls should be left to a supporting app, which is standard for most modern consumer headphones. It was also discovered that many people enjoy the use of a physical mechanism to adjust a variable, as it provided a more concrete communication of state.

The concept taken forward utilised two dials on the outside of each earcup to control two variables: the volume of the audio playback, and the style of listening. These dials should have tactile feedback to distinguish between the two controls - the volume dial is a smooth turn, whereas the mode dial turns incrementally. A simple sliding power button displays state through both colour and position, and an LED located below signifies bluetooth connectivity, battery life and charging status. A USB-C port is located at the bottom for charging.

Concept taken forward

OTO are a pair of headphones that can compensate for hearing losses and sensitivities by adjusting the audio playback to the listener’s hearing profile

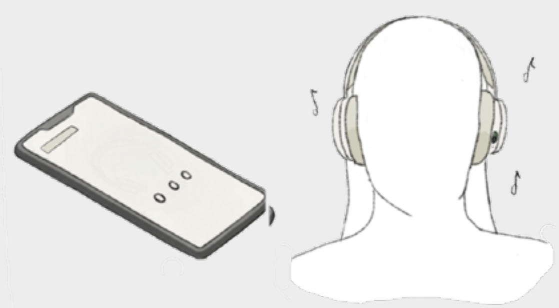
How it works

Upon set-up, the listener undergoes a hearing test. The supporting app maps out their hearing spectrum and creates an personalised hearing profile - all audio playback is then adjusted according to that individual profile.

Audio playback is further optimised depending on the type of listening through two modes. Immersive Mode is designed for maximum engagement with the audio, whereas Speech Mode looks at amplifying voices for easier clarification of spoken word during videocalls and podcasts.

There are two rotary dials on the outside of each earcup - the left toggles the mode of listening, and the right adjusts the volume. These are distinguished by tactile feedback - the mode dial has an incremental movement.

Other functions are also applied, including a hybrid noise cancellation system that utilises both feedforward and feedback active noise cancellation. An automatic play/pause function pauses music when the listener takes the headphones off for brief periods of time, and is useful for public areas and commuting.



Summary

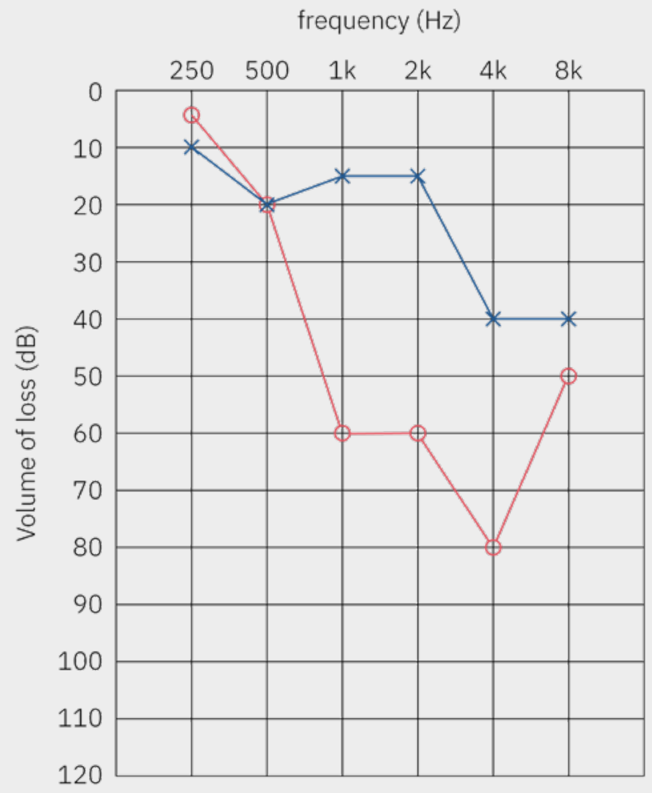
Development of the audio technologies was carried on throughout the project, prioritising the theory of how the headphones could adapt to potential hearing losses. The solution was to include personalised hearing profiles that the listener could change themselves, either automatically or manually if they already knew their details.

Hearing profiles

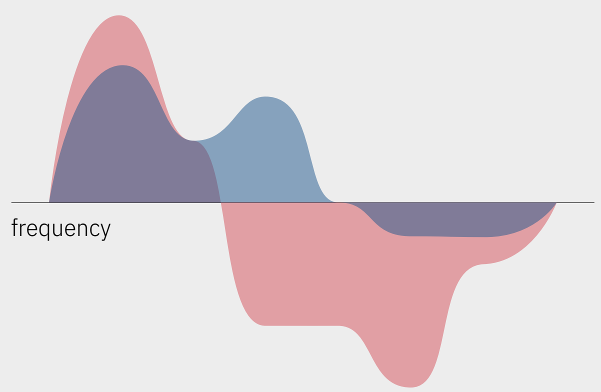
In order to compensate for hearing losses, the headphones must account for the frequency spectrum that can be heard by the listener.

Some experiments were performed using Adobe Audition's EQ adjuster and two participants, one with hearing losses and one without. It was found that an exact correction to the hearing loss results in an unpleasant and painful sound for those with more severe losses, but a minor correction makes the sound more clear. For people with minor hearing losses, there might not be so much impact - but further experimentation may prove beneficial, as products like Nuraphone have been very successful. It was decided that the hearing profile should therefore take the listener's hearing spectrum, and apply the inverse at a lower amplitude to the EQ of audio playback.

Whilst the audiogram is a useful method for understanding the hearing loss, it can be difficult to read. A graphic visualisation was created for easier viewing.



Audiogram of hard of hearing person, with severe losses in right ear and mild losses in left



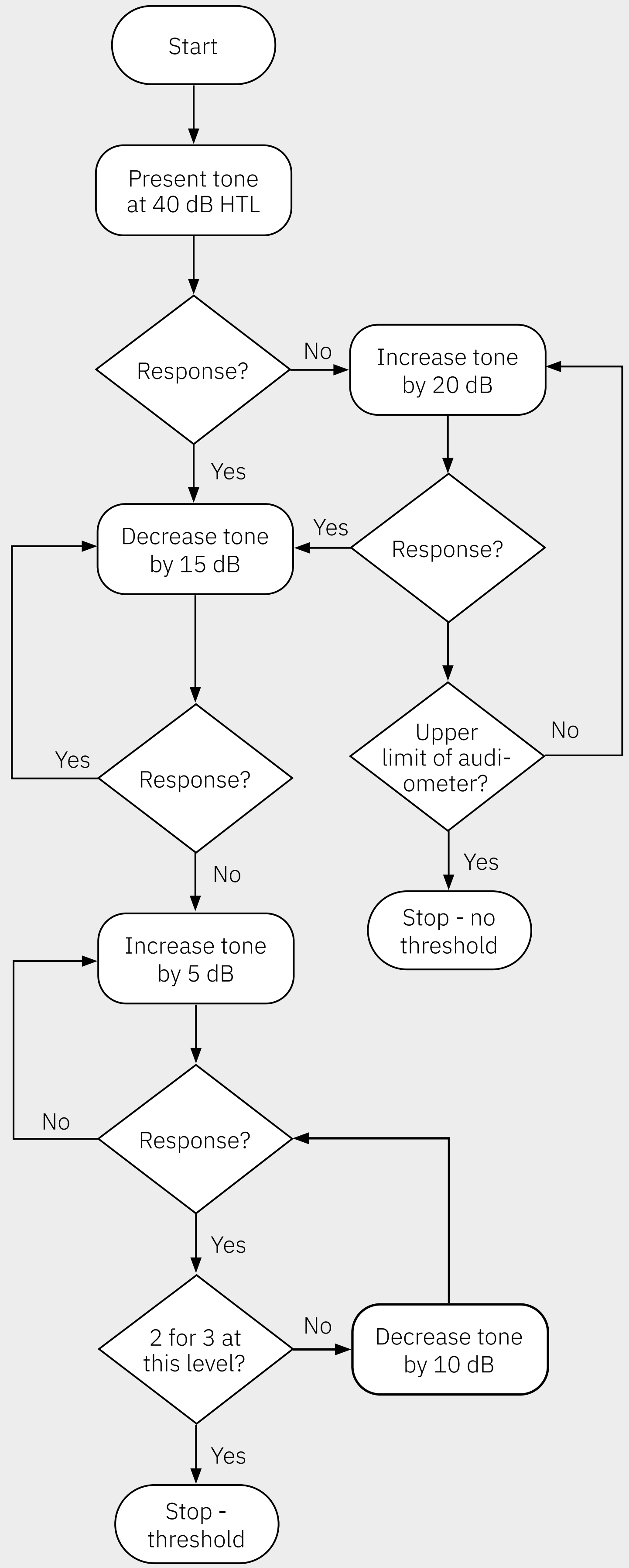
Graphic visualisation of the same hearing loss

Calibrating for hearing losses

Both otoacoustic emissions and preference tests were investigated to see whether they would be suitable for calibrating to the user's hearing loss, by looking at existing products that utilise each technique. Both methods have proved unsuitable, due to their inaccuracy when it came to moderate to severe losses.

The method of measuring hearing losses medically is to perform a manual audiometry test, where the signal is controlled by an audiologist. The typical method used is the 'method of limits', which offers a fair balance between accuracy and time taken to perform the test. Within this method, the listener responds to a variety of signal intensities, and the listener's hearing threshold is recorded at the intensity at which a response is made at least 50% of the time. The modified Hughson-Westlake flow chart, shown on the left, is used in industry.

I chose to use an automated version of this process, where a response is recorded on the app. The benefits of including a test similar to the one used in industry is that it may provide a warning for the user that they should get their ears checked professionally.

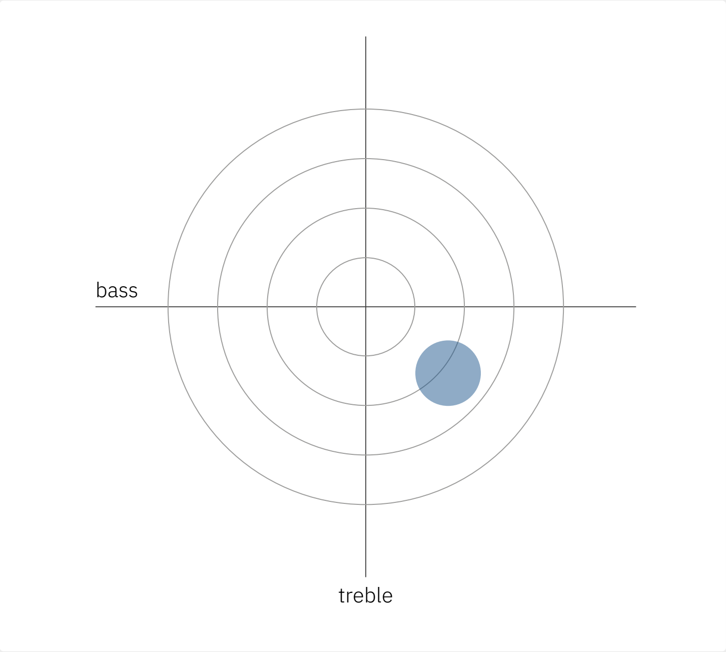


Immersive Mode

I looked at methods of increasing the immersion of listeners when they want to fully engage with audio playback. From market research of existing products, it was clear that effects like noise cancellation were imperative to improving the immersion of listening.

Many existing products also included a way to personalise audio playback by including a simple EQ system. Reflecting on the general survey conducted, the introduction of a fully adjustable eight node EQ system would not be intuitive for most users. The end result included a simple interactive visualisation of bass against treble, which can be seen below.

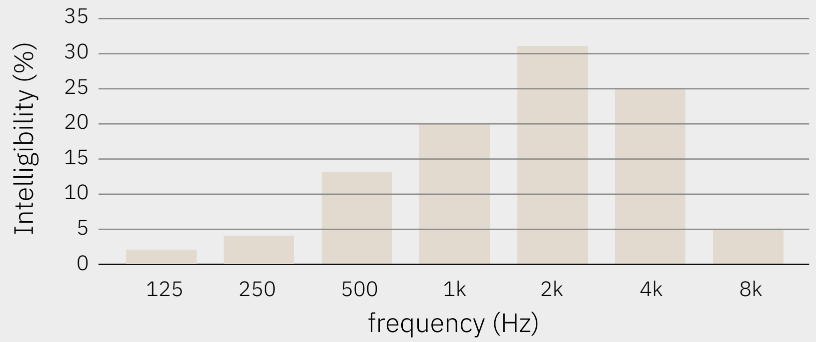
The difference between frequency spectrums in different genres of music was also researched, which could factor into future development. A feature could be automatic switching between frequency spectrums for different genres.



Polar grid of EQ

Speech Mode

Speech Mode is built on two techniques: spectral noise gating and increase in amplitude of higher frequencies.



Importance of frequencies on the intelligibility of speech

It was found that in non-tonal languages such as English, consonants are of the greatest importance when distinguishing words. These occur in the 2k - 4k Hz range, and unvoiced consonants (such as f, s and t) are in the range of 2k - 8k Hz. This can be seen in the graph above.

I tested this with an audio clip of a flight attendant speaking over an engine. Adjusting the EQ to match the shape shown in the graph resulted in audio that was much clearer to understand, but with a greater volume of background noise.

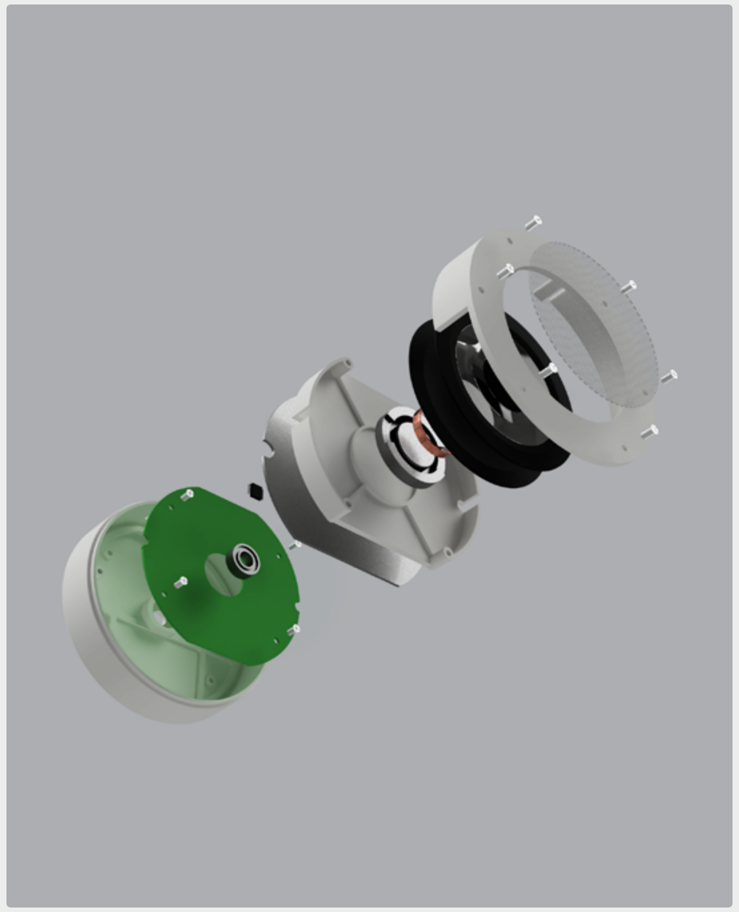
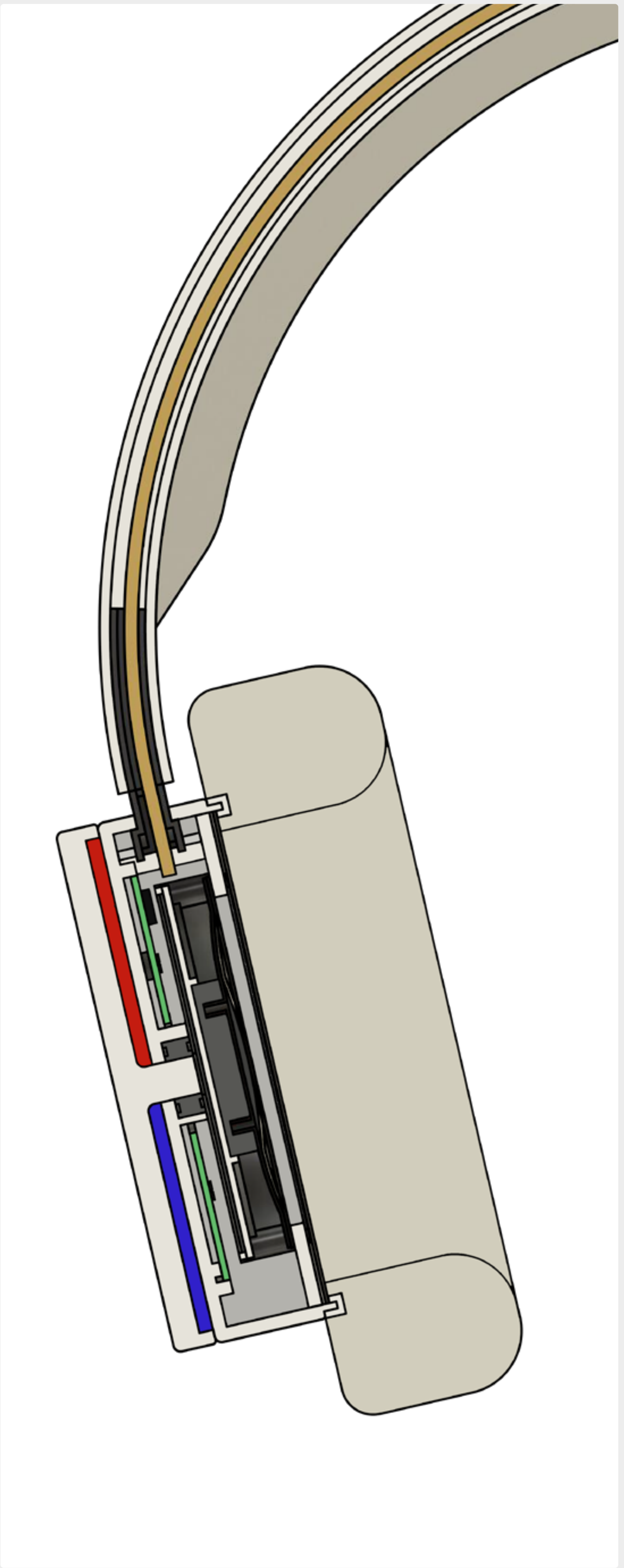
To reduce the noise in the audio clip, I used Audacity's noise reduction tool, known to be one of the best commericially available. It uses fourier analysis to create a 'noise fingerprint' of the background noise, by breaking it down into a series of pure tones (sine waves) called a frequency spectrum. The Audacity algorithm then finds the frequency spectrum of the rest of the audio, splits it into small sections, and reduces the volume of any pure tones that aren't sufficiently louder than that of the noise fingerprint. This technique is called 'spectral noise gating'. Running the same audio clip into Audacity's noise reduction software greatly reduced the engine noise.

Immersive Mode

Speech Mode

A direct comparison of audio with and without Speech Mode can be heard here (headphones advised).



Initially, potentiometers and rotary position switches were considered for use within the dials, as they are easily accessible and inexpensive. However, feedback from both the focus group and tutorials warned that both components could be subject to wear, due to the fact that both components employed contact methods to detect rotary position.

Research was performed into both components, and whilst potentiometers had a life cycle of 100,000 full rotations (lasting over 13 years at 20 rotations per day), rotary position switches would only last just over a year.

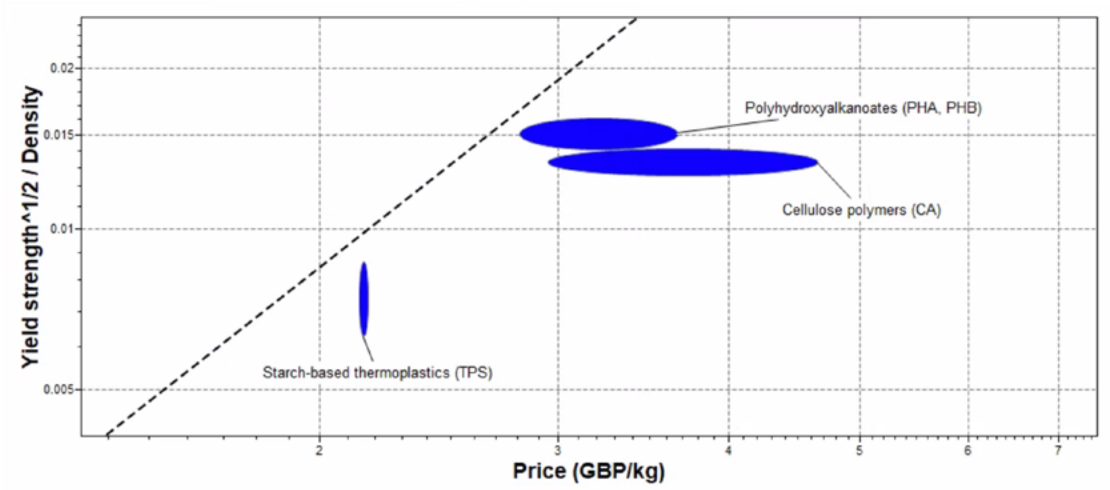
Therefore, other solutions for the dial mechanism were sought and compared, including inductive position sensors, anisotropic magneto-resistive (AMR) sensors, optical rotary encoders and capacitive sensing.

Inductive position sensors were intially chosen to take forward due to their non-contact method and non-magnetism, which was a concern with the proximity of the dials to the speakers. Inductive position sensors use principles of induction with coils printed onto a PCB to determine the rotary position. Standard components from Cambridge IC were used to build the CAD prototype.

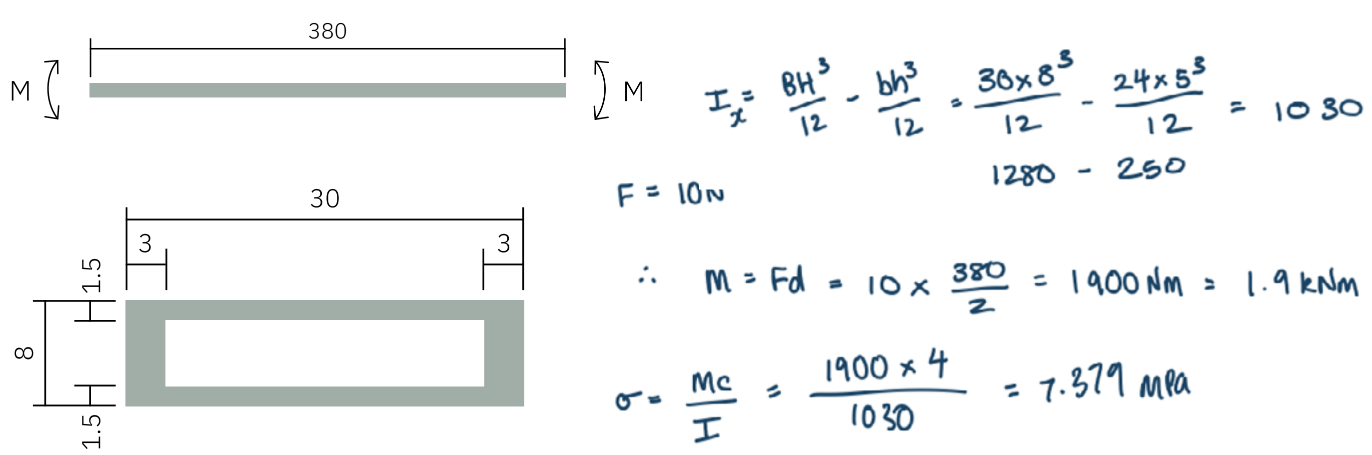
However, once the prototype had been fully assembled, I was unhappy with how disproportionate the main housings were to the rest of the parts due to the size of the sensor. Unfortunately there was no way to rearrange the components to reduce the size, and therefore the component had to be reconsidered. Another disadvantage of using inductive position sensors is that they would have bumped up the cost quite dramatically - two sensors would have cost just under £26.

The only other viable option were AMR sensors, which were initially avoided due to their reliance on magnetism - they detect rotational position through the disturbance of a magnetic field. On the other hand, their overall volume was very small - a micro sensor as part of a PCB, and a magnetic target. Not only did this reduce the volume of the main housing, but the dial housing as well.

In order to reduce the distortive effect of the speaker's electromagnet on the sensor, research was performed into magnetic shielding. MuMetal is a commercially available material that helps to 'insulate' against magnetism - this was built into an inner barrier that separates the speaker from the rest of the electronic components. A second iteration moved the ball bearing from inside the dial to inside the main component, which reduced the overall dimensions of the part further.



Biodegradable materials only



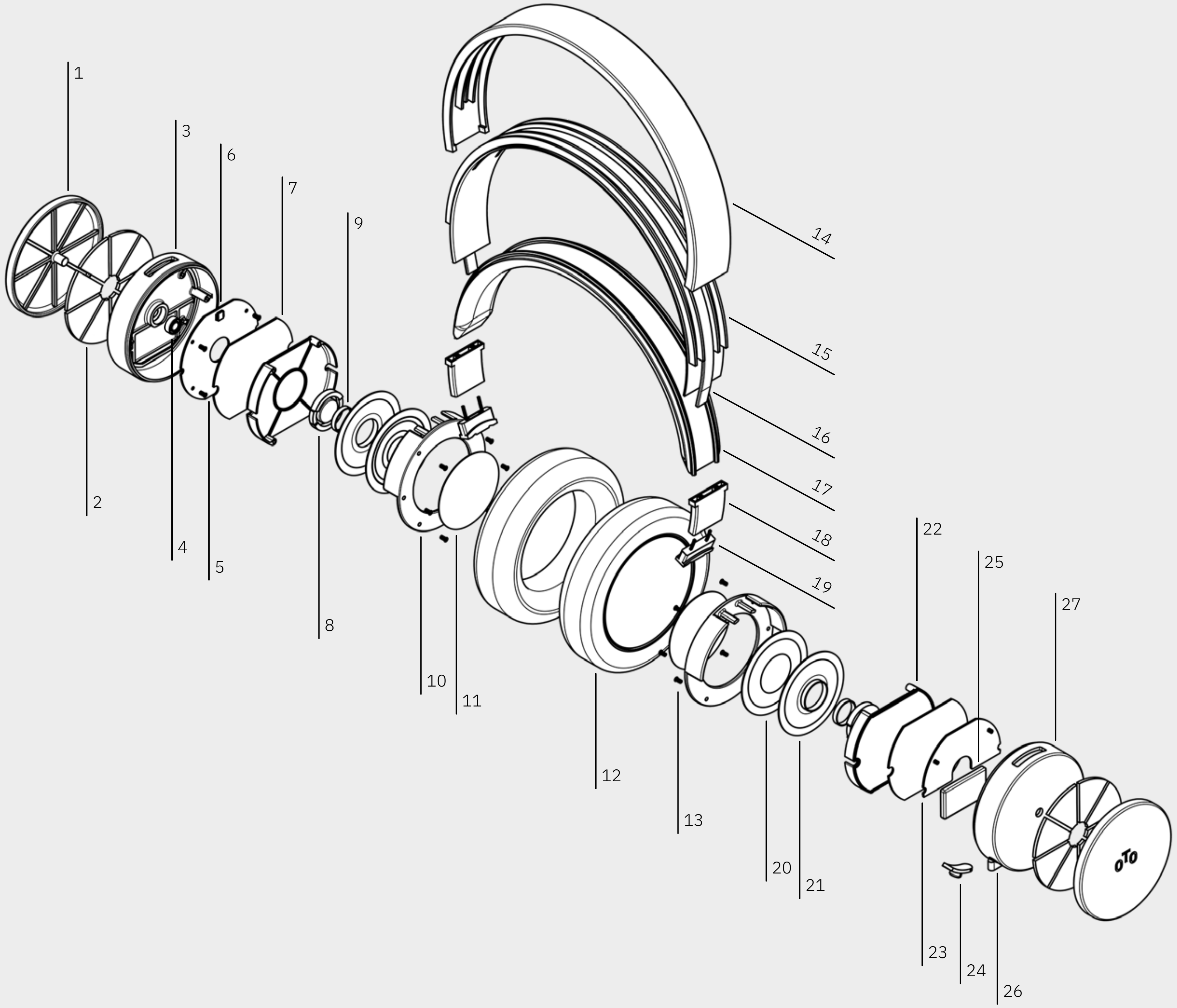
A set of requirements were established for the main structural material - the key functions were to house electronic components safely and withstand a flexural stress when the headband is getting pulled to fit on the head.

Material selection graphs were created in Granta Edupack for both biodegradeable and recyclable materials - the top three of each was then researched in more depth, weighted and compared. It was found that less than a third of recyclable plastics are recycled, leading to a large focus on environmentally friendly materials. Therefore, cellulose polymer (CA) was chosen as the final material for the main housings.

Some simplified calculations were then performed to determine whether it would meet the flexural strength requirement - the resulting 7.4 MPa is less than a fourth of the flexural strength of CA, at 31 - 41 MPa.

To match the environmentally friendly qualities of CA, research was done into vegan-friendly leathers. Often, they are often worse for the environment - but Zoa's solution offers a high performance with an estimated 80% reduction of greenhouse gas emissions than traditional leathers. It is also water and abrasion resistant, suitable for long periods of wear on the head whilst minimising damage from perspiration.

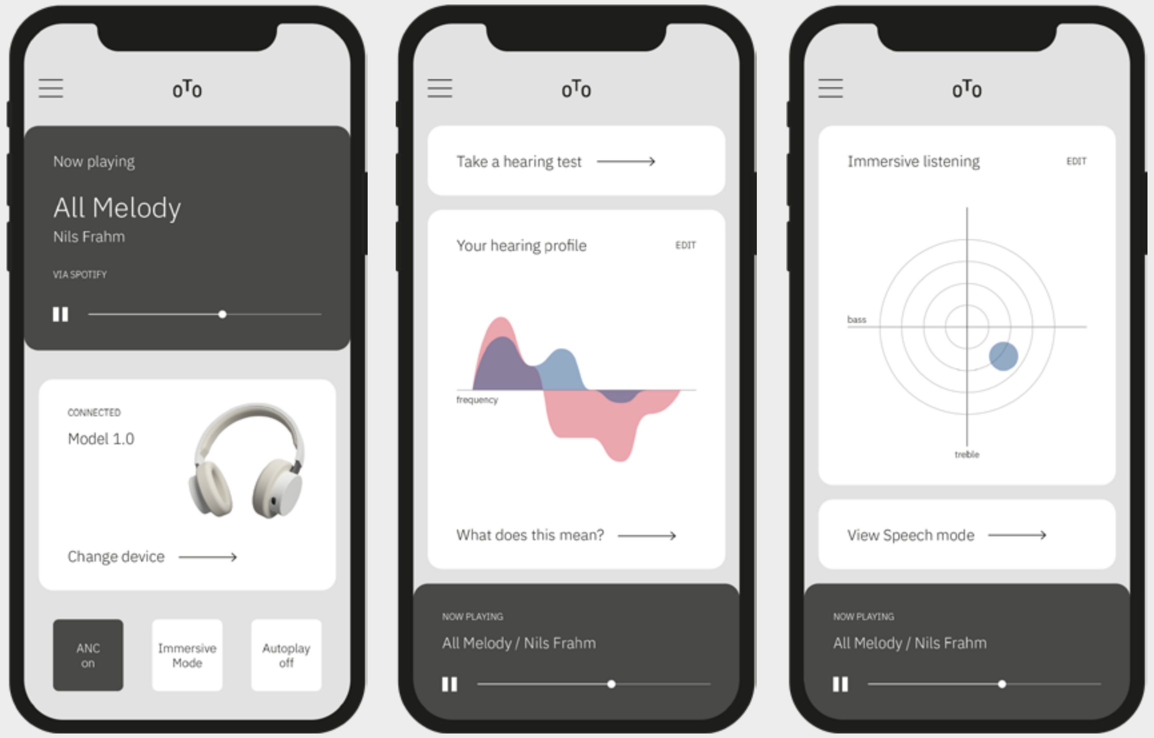
Part	Qty	Description	Material
1	2	Dial housing	Cellulose acetate
2	16	Target magnets	Iron
3	1	Main housing, left	Cellulose acetate
4	2	Plain bearing	Steel, multiple
5	1	PCB (1)	Composite, multiple
6	2	AMR sensor	Multiple
7	2	Magnetic shield	MuMetal
8	2	Electromagnet	Iron
9	2	Coil	Copper
10	2	Inner housing	Cellulose acetate
11	2	Mesh covering	Fabric
12	2	Earcup	CA, foam, vegan leather
13	20	M2 x 4mm flathead screw	Steel
14	1	Outer headband housing	Cellulose acetate
15	1	Inner headband housing	Cellulose acetate
16	1	Headband wire	Multiple
17	1	Headband padding	CA, foam, vegan leather
18	2	Adjuster (1)	Cellulose acetate
19	2	Adjuster (2)	Cellulose acetate
20	2	Diaphragm	Polypropylene, multiple
21	2	Diaphragm support	Polypropylene, multiple
22	2	Internal barrier	Cellulose acetate
23	1	PCB (2)	Composite, multiple
24	1	Switch	Cellulose acetate
25	1	Lithium-ion battery	Multiple
26	1	USB-C port, LED	Multiple
27	1	Main housing, right	Cellulose acetate



The above shows all of the components included in the headphones, with the exception of smaller, secondary components such as microphones. Cellulose acetate and high performance vegan leather were chosen with biodegradeability and performance requirements in mind, meaning that the headphones can be easily disposed of once they have reached the end of their life.

The components have been designed so that they can be taken apart easily by the user. This means that the user can replace broken components themselves if they do not wish to get the headphones serviced, or apply upgrades which would normally require buying a new product. It also allows for further personalisation and individualisation.

Each custom component made from CA has been designed for manufacture, with features such as screw bosses, drafts, ribs, consistent wall thicknesses and radii on each edge. Injection moulding tolerances have been accounted for, not only on each component itself but in how each component fits together. Each visible surface will be finished to B-1, a semi-gloss finish.



The supporting app was designed to match the aesthetic provided by the headphones themselves, with an intuitive user interface.

On the app's homepage, key buttons controlling the noise cancellation, toggled mode and the autoplay function are easily accessible. The homepage also displays the linked streaming provider and audio controls.

The hearing profile can be viewed in app, as both a graphic visualisation for easier comprehension, and as a standard audiogram for more in-depth editing.
The pages on Immersive Mode and Speech Mode allow for full control over features, including the option to toggle louder high frequencies in Speech Mode, which might be beneficial for hearing users.

The headphones are named 'OTO', after the Japanese word 音 (kanji) or おと (hiragana) meaning 'sound' or 'note'.
The logo was designed to look visually similar to a pair of headphones.

OTO will be available in six colours: white, black, dark green, navy, sage and sand. These colours were selected as they kept the timeless aesthetic of the overall design, and from focus group approval.

Each colour is also reflected within the packaging, which is made from moulded paper to provide a stiff and strong yet environmentally friendly padding. The packaging also features a debossed silhouette of the headphones on the front, with a foiled logo in the centre.