Development of a custom, 3D-printed, multi-microphone, noise-cancelling, hearing protection device with a magnetically attached printed ear canal for sound localization preservation

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DEVELOPMENT OF A CUSTOM, 3D PRINTED, MULTI-MICROPHONE, NOISE-CANCELLING, HEARING PROTECTION DEVICE WITH A MAGNETICALLY ATTACHED PRINTED EAR CANAL FOR SOUND LOCALIZATION PRESERVATION

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Dean of the Graduate School
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Brenda Leticia Valadez Mesta

2022
Dedication

Quisiera dedicar este trabajo a mi familia, principalmente a mi abuelo, Roberto Mesta, por apoyar mi decisión de seguir un camino diferente. A mi padre y a mi hermana por contribuir a mi desarrollo diario, y a mi mamá por haberme dejado la constancia que me llevó a completar este logro.
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MAGNETICALLY ATTACHED PRINTED EAR CANAL
FOR SOUND LOCALIZATION PRESERVATION

by

BRENDA LETICIA VALADEZ MESTA, B.S. MECHATRONICS ENGINEERING

THESIS

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The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Metallurgy, Materials and Biomedical Engineering
THE UNIVERSITY OF TEXAS AT EL PASO
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Abstract

Hearing loss is a prominent health issue that affects a significant fraction of the global population. One of the main causes behind hearing loss is exposure to harmful noise levels in the workplace. There have been multiple efforts to prevent hearing loss from excessive noise in occupational settings, such as hearing conservation programs and use of hearing protection devices (HPDs), however, these are often ineffective. Although HPDs are frequently available in the workspace, they are not used as intended since they usually generate discomfort and hindered sound localization. The loss of sound localization can be hazardous in occupational settings, since it restricts the user from detecting the originating source of useful noises such as auditory warning signals. Anatomically, the outermost part of the ear, denominated the pinna, is responsible for sound localization since it filters sounds to determine its originating direction. With the expertise of GN Resound, prior work was developed to prove the hypothesis that embedding an artificial ear pinna could preserve the auditory localization properties on HPDs. Since the pinna is an intricate structure, conventional manufacturing is not convenient in its reproduction. Thus, additive manufacturing (AM), which can create complex geometries, was used to replicate the human pinna.

Initial iterations of a noise-cancelling, sound-preserving headset were manufactured and tested, demonstrating that the embedded pinna aided sound localization. A new version of the device was designed focusing on the improvement of user experience, convenience, and comfort. The latest device design, denominated V14, included features not found in its predecessors, such as multiple microphones and a magnetic coupling. The magnetic coupling was designed to replace the fixed attachment that existed between the muffs of the device and the printed ear canal (PEC) that inserts the device’s speaker into the anatomical ear canal. This magnetic attachment consists
of two main parts, a membrane PEC and earpiece PEC, that house magnets to achieve a clasp, and contact surface plates, which transmit signals from the digital sound processor (DSP) in the muff to the speaker in the user’s ear canal. A test was conducted to verify if the magnets would interfere with the acoustic performance of the speaker, and the results showed that there was only an average difference of 1.56 dB between the setup with and without the presence of the magnetic coupling, which is approximately 50% below the SPL changes barely perceivable by humans. The cavities for two additional microphones were added to the computer aided design (CAD) model of the headset to improve the sound localization quality of the device by increasing the sound capturing capacity of the same. Of the three microphones incorporated in the design, only two were connected to the DSP according to its capacity.

The noise-cancelling, sound-preserving headset has hearing aid electronic components integrated in it for its advanced functionality. A standard 312-battery pill has been used as a power source since such batteries are often used for hearing aids. To increase the battery life of the headset, the prototype for a rechargeable battery circuit was constructed and tested. A voltage within the working range of the DSP was achieved, and the battery life was measured to last a minimum of 40 hours. Embedment of the circuit into the headset CAD models was not possible at this stage due to its dimensions. The square surface of the printed circuit board (PCB) used for the prototype did not fit into the available area in the muff, therefore, the PCB was trimmed to adequately fit within the muff. The rearrangement of the circuit in the CAD models of the headset was recommended for future work and to fully implement the rechargeable battery.

Results for the acoustic testing of the previous version of the device, V13, were analyzed and compared against an anthropometric manikin designed for acoustic testing without any device donned (Unaided KEMAR manikin). Favorable results on the preservation of sound localization
in V13, such as an average difference in directivity index of 2.18 dB in relation to an Unaided KEMAR manikin, were obtained. The results of the acoustic testing for signal amplitude were also examined. The average difference from Unaided KEMAR was calculated for four principal azimuths, yielding results lower than the 5 dB in sound pressure level (SPL) changes that are noticeable for human beings. Sound attenuation results demonstrated that the device requires an increase in its noise reduction capabilities, since it reached an attenuation of 18 dB in contrast to the 25 dB required to match the performance of HPDs in the market.

Finally, a design requirements list was introduced to standardize the specifications that the device should fulfill by determining quantifiable objectives. The design requirements were established by researching other HPDs and the changes in SPL audible to human beings. Overall, the differences in amplitude and directivity index of V13 from Unaided KEMAR were below the values set in the design requirements list presented in this thesis. The battery capacity for V14 is also within the specifications described in said list. However, the attenuation levels were 7 dB below the indicated goal in the design requirements list, demonstrating a need for further development in the noise-cancelling properties of the device.
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Chapter 1: Introduction

1.1 Research motivation

According to the World Health Organization, more than 1.5 billion people in the globe suffer from hearing loss. Apart from impacting the quality of life of those affected, unaddressed hearing loss can cause more than 980 billion dollars in costs related to healthcare and productivity losses. Of the many factors that can contribute to the development of hearing loss, exposure to excessive noise in occupational settings accounts for 16% of hearing loss in adults (World Health Organization, 2021). In the United States alone, 22 million people were recently reported to be subjected to hazardous noise levels in their occupational environment (Themann & Masterson, 2019).

To prevent hearing loss, the reduction of daily exposure to noise in the workplace is essential. Noise-level monitoring, hearing surveillance, and the use of hearing protection equipment are all measures implemented in programs designed to preserve hearing (World Health Organization, 2021). Hearing protection devices (HPDs), such as earmuffs and earplugs, are frequently used as a tool to diminish exposure to loud noises. However, inconsistent use reduces their effectiveness to avert hearing loss (Le et al., 2017). Some of the reasons behind the limited compliance of HPDs use includes discomfort, interference in communication with others, and the loss of the ability to hear certain sounds and determine their originating direction.

The ability for one’s brain to determine where a sound is coming from, also referred to as sound localization, is possible, in part, due to cues provided by the pinna. The pinna plays a crucial role in sound localization since its shape is responsible for processing sound and delivering the necessary cues for the hearer to determine its originating direction. Nevertheless, sound
localization is compromised when using HPDs, specifically earmuffs, since the pinna is blocked and no longer as efficient in its functions (Themann & Masterson, 2019). Although occupations such as the military, construction, and transportation require HPDs to protect personnel against the high noise levels inherent to the environment, they also rely on situational awareness to lessen safety risks in the workplace (Smalt et al., 2020). For the military the ability to hear and localize selected sounds is crucial to their operations. However, much of the equipment, such as weaponry, aircraft, or other vehicles used in missions or training, exceeds the U.S. Army’s and U.S. Air Force’s permissible noise exposure level of 85 decibels (dB). Although HPDs are required and available, the same phenomenon as in other occupations occurs, in which military personnel choose not to wear the devices because of the loss of situational awareness previously described (Melzer et al., 2018).

Therefore, HPDs that preserve the ability to identify and determine the direction of certain sounds would be beneficial to several workers across different industries. The primary motivation of the research presented in this thesis is to refine the design of a previously conceptualized headset that reduces incoming noise levels while preserving sound localization. Additionally, the new HPD design developed here will also incorporate comfort-focused features, addressing another deterrent of HPD use.

1.2 Background

For sound localization, the outermost part of the ear, called the pinna (Fig. 1.1), plays a crucial role since it provides the spatial cues required to determine the direction of a sound (Gelfand, 2018). The use of earmuffs disables the pinna shape from performing its function, thus rendering the user incapable of localizing sounds. In prior work done by Acosta (2019), it was
hypothesized that embedding an additive manufactured ear pinna would preserve auditory localization of an HPD.

![3D model of a human pinna](image)

**Figure 1.1.** 3D model of a human pinna

Contrary to traditional manufacturing, where material is removed to obtain the desired object, additive manufacturing (AM) is the manufacturing technology that selectively adds material to build parts. AM, previously also referred to as rapid prototyping and 3D printing, can be used in many applications due to its advantages, such as design freedom and the reduction of the need for tooling. These benefits lead to the opportunity of creating complex geometries that would not be possible otherwise (Reeves et al., 2011). Consequently, by facilitating the creation of physical models from complex digital 3D models, AM provides a solution to applications in several fields, including biomedical engineering and medicine, where anatomical parts are often studied (Javaid & Haleem, 2018). Therefore, AM is ideal to reproduce the intricate structure of the pinna.
1.2.1 Previous developments

The project presented in this thesis is a continuation of previous work done by Acosta (2019) and Belmont (2020), as well as by graduate student Angel Vega. To create an HPD that would preserve the localization of sounds, additive manufacturing (AM) was applied to replicate the pinna shape. AM comprises seven process categories, including material extrusion, vat photopolymerization, material jetting, binder jetting, powder bed fusion, directed energy deposition, and sheet lamination. For the project at hand, the first three processes were used, and their high resolution led to successful reproduction of the details of the complex geometry of a KEMAR (Knowles Electronics Manikin for Acoustic Research) ear. After 3D scanning the right-small pinna of KEMAR, a model was created and adjusted for 3D printing. The obtained model was then manufactured using material extrusion, vat photopolymerization, and material jetting. The resultant parts of each process were tested for dimensional and acoustic accuracy and compared against the original KEMAR ear, with favorable results, demonstrating that replicating a pinna through AM was possible. Based on the results obtained, a preliminary design for a pinna-embedded headset was developed (Acosta, 2019). The following steps in the research focused on developing a headset that delivered sound directly to the anatomical ear canal. Before the creation of the headset design iterations described in the upcoming chapters of this thesis, two additional versions were acoustically tested and analyzed. Versions 7 and 10 of the device, referred to as V07 and V10, were created with different defining characteristics that contributed to the objective of the device, preservation of sound localization.

The first prototype of the headset to be fully manufactured and tested was composed only of one muff for each ear, similarly to the HPDs available in the market. However, the results from said initial version showed that the sound was being reflected in the inner blank space of the muff
before entering the anatomical ear canal. Therefore, a printed ear canal (PEC) was implemented in version 7 (V07) of the device (Belmont, 2020). Described in the work of Belmont (2020), the main purpose of the PEC introduced in V07 was to connect the reproduced pinna to the user by creating a pathway that transported signals received by the artificial ear canal directly to the anatomical ear canal. Additionally, the PEC also housed the electronic components from an in-the-ear (ITE) hearing aid required for acoustic testing and analysis. In V07, the PEC had a straight shape, which prevented the correct alignment of the part with KEMARs ear canal. Furthermore, the area surrounding the pinna was flattened, a feature that underwent modifications in the successive version of the headset. As its predecessor, V10 had a PEC that encased all electronic components present across the different versions of the device. However, in V10, graduate students Angel Vega and Emerson Armendariz introduced an angle at the proximal end of the PEC that enters the anatomical ear canal, facilitating its insertion into KEMARs ear. Furthermore, V10 also added KEMARs circumaural profile to the headset, meaning that the area surrounding the artificial pinna was no longer flat. Results from acoustic testing were promising, proving again that the embedded pinna performed similarly to KEMAR pinna in regards to sound localization (Belmont, 2020).

In Version 13 of the device (V13) comfort and user convenience became subjects of focus, with new features included to increase said aspects of the device. Some of the elements incorporated by graduate student Angel Vega into V13 of the headset were: an adjustable mechanism formed by a flexible membrane within a sliding ring, an interchangeable pinna for user customization, and the relocation of electronics from the PEC to the earmuff. The adjustable mechanism provided adaptability to the potential needs of the user. By introducing a silicone membrane into the PEC-to-muff attachment, freedom of movement was also added to the
connection of both elements. The previously rigid joint was replaced by a ring capable of limited
displacement within the transverse plane of the head, which also encased a membrane that enabled
the PEC to move within the sagittal plane of the head.

Another characteristic introduced in V13 was the interchangeable pinna plate. Although
KEMAR small ears have been used throughout the development of the device, pinnae are unique
to each individual. Therefore, the noise-cancelling, sound-preserving headset presented in this
work should be custom for every user. In contrast to preceding versions, V13 included a pinna
plate that could be removed and reinstalled in the headset. The ultimate goal is to facilitate the
customization of the product by having the possibility to adapt it to any user.

1.3. Thesis Objectives

The objectives for this thesis are listed as follows:

1. Design and manufacture a new version of the headset with added features
   (multiple microphones and a magnetic attachment)

2. Develop a rechargeable battery circuit for the device

3. Introduce a design requirements list for the product

4. Analyze the acoustic test results for the previous version of the headset

1.4 Thesis Outline

The next chapters are divided as follows. Chapter 2 is a literature review comprising of
subjects relevant to the purposes, including, but not limited to, ear anatomy and sound localization,
multiple microphones hearing aids, comfort of hearing protection devices, and additive
manufacturing. Chapter 3 describes the incorporation of the added features of the new headset
design version, along with manufacturing techniques utilized. Additionally, the experimental setup for the acoustic tests on noise reduction and sound localization are contained in Chapter 3. Chapter 4 consists of the results and discussion for the noise reduction and acoustic tests. Finally, Chapter 5 presents the conclusions for the thesis, as well as recommendations for future work.
2.1. Ear anatomy and sound localization

2.1.1. Ear anatomy

The human ear, one of the main elements of the auditory system, is divided and studied into three parts classified relative to their position within the head: the inner ear, the middle ear, and the outer ear (Figure 2.1). These three parts are in charge of fulfilling different roles in sound conduction and processing (McFarland & Netter, 2015).

![Anatomy of the ear: inner, middle, and outer ear.](image_url)

**Figure 2.1.** Anatomy of the ear: inner, middle, and outer ear.

The outer ear is formed by the pinna and the external auditory meatus, and it is responsible for capturing sounds and guiding them to the middle ear. The pinna is a fibrocartilaginous appendage that plays a key role in sound reception and localization (McFarland & Netter, 2015).
Its complex shape has several landmarks (Figure 2.2), and it directs sound to the ear canal, or auditory external meatus. The ear canal is an S-shaped conduit in charge of leading sounds from the pinna to the eardrum, which vibrates in response to soundwaves. Like the pinna, part of its structure is cartilaginous, however, most of it is osseous (Gelfand, 2018).

![Image of ear with landmarks](image)

**Figure 2.2.** Landmarks of the pinna

The middle ear, which starts at the end of the ear canal, consists of the tympanic membrane, three ossicles (malleus, incus, and stapes), and two muscles (tympani and stapedius). Its function involves matching the impedance of the inner ear’s cochlear fluid to the impedance of air, thus assisting in the transformation of sound to vibrations of said fluid (Møller, 2013). Finally, the
inner ear comprises the cochlea and vestibular system, which convert vibrations coming from the middle ear into neural activity (McFarland & Netter, 2015).

2.1.2. Sound localization and pinna relationship

Amongst the complex processes that are part of hearing, sound localization is one that human anatomy performs with accuracy. Sound localization refers to the ability to determine the direction from which a sound originates (Lopez-Poveda, 2014). Although it provides a three-dimensional sense of direction, sound localization is commonly studied as the combination of a horizontal and a vertical angle. Angles of azimuth are used to characterize the horizontal direction around the head. An azimuth of 0° is directly in front of the hearer, while sounds behind have an angle of 180°. The remaining values of azimuth are defined according to their position from the center. On the other hand, vertical directions are referred to as elevation angles, and much like for horizontal directions, an elevation angle of 0° is straight ahead. An elevation value of 90° means that the sound comes from directly above the head, while an elevation value of 180°, means the sound is generated directly behind the head. Figure 2.3 shows the diagram for different azimuth and elevation values.
Sound localization involves externalization, which is defined as the capacity to perceive that sounds originate from a source outside the head. Externalization has been linked to sound localization since their execution relies on the same cues (Best et al., 2020). Previous studies have demonstrated that there are three types of acoustic cues linked to sound localization: the interaural time differences (ITDs), interaural level differences (ILDs), and spectral cues provide information useful to define the sound source’s position (Jin et al., 1999).

The duplex theory of localization defines that ITDs and ILDs complement each other since they correspond to the localization of separate frequency ranges. Said theory explains that since lower frequencies have longer wavelengths than the distance of the path between left and right ear, ITDs offer information regarding the time it takes for a sound to reach both ears, thus providing clues as to where the sound originates from. On the other hand, ILDs deliver the data required for localization of high frequencies. Opposite to their low counterparts, high frequencies have short
wavelengths that do not exceed the path from one ear to the other, which leads to an obstruction of said path. This phenomenon, denominated head shadow, produces a variation in sound level intensity that provides the required cues for sound localization.

![Cone of confusion in hearing](image)

**Figure 2.4.** Cone of confusion in hearing

However, it has been shown that ITDs and ILDs are insufficient to locate sound within a “cone of confusion” (Figure 2.4). The pinnae fill the gap by providing the cues required to accurately localize sound within and outside of the “cone of confusion”. Spectral cues, also known as pinna cues, are a product of the filtering produced by the folds of the pinnae, and they contribute to front-back distinctions and the perception of elevation. Studies measuring the head-related transfer function (HRTF) have been performed to analyze the role of spectral cues (Langendijk & Bronkhorst, 2002). The HRTF is a representation of how the amplitude of a sound varies according to the path from the source to the ear. In a study by Wenzel et al., it was shown that the use of non-personalized HRTFs hinders sound localization, demonstrating that pinnae cues play a crucial part, particularly when defining elevation angles and front-back directions (Wenzel et al., 1993). HRTFs are particular to each listener, and they vary for different azimuth and elevation values.
2.2. Hearing devices with multiple microphones

2.2.1. Directional and Omnidirectional microphones

In hearing devices, microphones execute the task of transducing acoustic signals into electric signals. Their capacity and adequate function are crucial to the performance of devices such as hearing aids. One of the ways in which microphones are classified is according to the spatial scope from which they can capture sounds. Omnidirectional and directional microphones are often used simultaneously in hearing aids since their differing directional sensitivity is beneficial for distinct purposes.

The directional sensitivity of the two types of microphones mentioned previously is usually mapped in a polar sensitivity pattern (Figure 2.5) to study the distinctions between the two types of microphones. Omnidirectional microphones are characterized by a circular polar pattern, shown in Figure 2.2.1, which reflects their ability to capture sounds from all directions (Butterfield & Szymanski, 2018). Directional microphones, however, are sensitive to sounds coming from a defined direction but conceal sounds from others. This behavior produces heart-shaped or cardioid patterns that reflect the polar region from where sounds are suppressed (Figure 2.5).
2.2.2. Location of multiple microphones in hearing devices

Hearing aids are the most prominent devices in which the position of multiple microphones has been studied, since one of the principal challenges in the design of hearing aids is providing the capacity to capture sound coming from behind the user. A common approach to solve this issue is the incorporation of multiple microphones, often executed in one of two ways: first, by combining omnidirectional and directional microphones, or second, by applying the dual-microphone technique, which consists of using two omnidirectional microphones. Multi-microphone products offering enhanced hearing, such as the ReSound Multi Mic, by ReSound GN, are available in the market.

Various studies analyzing different microphone locations have been conducted, as stated before. Feigin et al. (1990) researched the effects of the position of a reference microphone in respect to the microphone of a hearing aid. Using a 25-point grid around the pinna (Figure 2.6)
created by Madaffari (1974), Feigin et al. examined the response of hearing aids by placing two microphones in different coordinates of the grid system. The research demonstrated that the sound pressure levels were affected, particularly in the results from the reference microphone further from the hearing aid microphone (Feigin et al., 1990).

![25-point pinna grid](image)

**Figure 2.6.** 25-point pinna grid

Denk et al. performed a study focusing on the effects of microphone placement in spatial cues. Six configurations, five similar to those present in hearing aids and one in the concha, were used to obtain HRTFs that provided information on their respective impact on spatial cues. The results demonstrated that complete spatial data is only available when microphones are placed at the entrance or inside the ear canal. Furthermore, behind the ear (BTE) microphones showed they could not capture spatial cues compared to the other configurations (Denk et al., 2018).
2.3. Magnetic attachments in biomedical devices

2.3.1. Magnetic attachments in dental prostheses

Magnetic attachments have been used and proposed for various biomedical devices. However, their application is most prominent in dental prostheses, of which there are over one million applied globally (Gonda et al., 2013). Their development has been studied since the 1950s, which has led to modern prostheses that dentists can fit without difficulty. Over time, these prostheses have undergone modifications to overcome the challenges inherent to the application and environment in which they are used. Magnetic attachments must have the capacity to perform in terms of magnetic forces and anti-corrosion properties while maintaining a size that suits their implantation site.

A crucial factor in the progress of magnetic attachment for dental prosthetics has been the material of which the magnets are composed. According to Riley et al. (2001) Alnico V magnets were the first implemented for dental prostheses. However, their large size and lack of magnetic force led to misalignments and poor retention. Developments moved towards Co-Pt magnets, which achieved a higher magnetic force while decreasing the size from their predecessors. Still, they were costly and represented a health risk since the material could travel into bone and tissue within its surroundings. Finally, rare-earth magnets, made of alloys such as Nd-Fe-B, which are currently in use, provide the required force while maintaining a size fitting for dental applications.

Nevertheless, two issues remain with the use of rare-earth magnets: corrosion and magnetic leakage flux. Since they corrode fast when exposed to oral fluids, rare-earth magnets undergo a coating or encapsulation of corrosion-resistant materials, such as titanium, stainless steel, or polymers that separate them from saliva (Riley et al., 2001). The process involves enclosing the
magnet in a housing, denominated yoke (Figure 2.7), and welding it shut using a laser energy source. This technique also eliminates the magnetic flux leak by creating a closed magnetic circuit (Gonda & Maeda, 2011).

![Figure 2.7. Layout of a yoke-type magnetic dental prosthesis](image)

As mentioned before, other attempts at incorporating magnetic attachments into biomedical devices have been made. Reissman et al. (2018) developed an upper-limb gel liner with built-in electrodes which collected electromyography signals to control the prosthesis. They proposed a magnetic attachment interfacing between the liner designed and the upper-limb prosthesis. Three magnets with alternating polarities were used to prevent electrical or mechanical misalignments and guarantee adequate information transmission from the sensors to the prosthesis. The results showed that the magnetic connector facilitated the donning process for the test subjects, who reported that they could audibly confirm a successful adjustment and feel a guiding pulling force while donning the device (Reissman et al., 2018).

Another study by Fox et al. proposed a magnetic attachment for an epiretinal prosthesis. The researchers developed the complete design of a prosthesis that was stably attached to the retina. They noted that the environment in which the prosthesis was implanted determined many
factors in the design. Much like for dental prostheses, corrosion from fluids and magnetic flux had to be considered. In this case, a variety of anti-corrosion coatings were tested to determine if they could protect the magnets and diminish magnetic flux leakage. Additionally, a demagnetization technique was developed, which reduced the magnetic flux density (Fox et al., 2016).

2.3.2. Magnetic flux exposure recommendations

According to the World Health Organization (2007), electric and magnetic fields can present a health hazard due to their potential short and long-term effects. To avoid the risk that electromagnetic and static magnetic fields pose, various organizations have determined recommended threshold levels for occupational exposures of a maximum of eight hours weighted average time (World Health Organization, 2007). Table 2.1 shows the suggested limits according to three organizations: The International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2009), the American Conference of Governmental Industrial Hygienists (ACGIH, 2003), and the U.S. Department of Defense (U.S. Department of Defense, 2009), for which Zone 0 corresponds to unrestricted areas, and Zone 1 refers to areas where training regarding electromagnetic and static magnetic fields is required. Additionally, as stated by the Food and Drug Administration (FDA), electromagnetic and static magnetic fields can also interfere with medical procedures such as magnetic resonance imaging (MRI) scans or with the functioning of pacemakers. Therefore, these limits serve as a guide when designing devices meant for continuous use (Food and Drug Administration, 2021).
Table 2.1 Recommended threshold limit values for exposure to static magnetic fields by organization

<table>
<thead>
<tr>
<th>Organization</th>
<th>Magnetic field (G)</th>
<th>Zone 0</th>
<th>Zone 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Commission on Non-Ionizing Radiation Protection (ICNIRP)</td>
<td>4000 G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>American Conference of Governmental Industrial Hygienists (ACGIH)</td>
<td>600 G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DoD Instruction 6055.11</td>
<td>1180 G</td>
<td>3530 G</td>
<td></td>
</tr>
</tbody>
</table>

2.4. Hearing protection devices and sound localization

Hearing loss is a prominent healthcare issue that affects more than 18% of the global population, according to the World Health Organization. One of the principal factors that cause hearing loss is the exposure to hazardous noise levels. Noise-induced hearing loss is a common condition across different industries, due to the noise levels that workers are subjected to on a day to day basis (Mirza et al., 2018). Hearing protection devices (HPDs) are an effective protection measure against occupational noise-induced hearing loss, however, they often reduce the user’s ability to determine where sounds originate from (Berger & American Industrial Hygiene Association, 2003). Different studies have demonstrated that the two principal types of HPDs, earplug and earmuffs, interfere with sound localization.

Brown et al. (2015) tested the sound localization accuracy of four earplug-type HPDs using a head turning method. The experiment consisted of emitting an acoustic signal from one of the 12 loudspeakers located at a 0° elevation every 30° in azimuth. The subjects were asked to determine were the sound source was perceived to be by turning and pointing to said location. The root-mean-square (RMS) error for the azimuth degrees was calculated to quantify the performance
of the four devices being tested and the control group, which corresponded to no device. As reported by the researchers, all devices had a less favorable performance than the control group, with RMS errors between 20 and 30 degrees. Another study by Abel et al. (2007) describes a similar approach in which the subjects were asked to identify the source out of eight speakers set up at different azimuths. In said research, two earplugs and three earmuffs were examined against unoccluded listening. The control group, unoccluded listening, had a 94.1% of correct sound localization. In contrast, the three earmuffs had results of 69.2%, 46.1%, and 36.1%, while the two earplugs also had lower accuracies at 71.1% and 51.7% (Abel et al., 2007). These studies showed that HPDs can hinder sound localization, further increasing the reasons behind the lack of compliance and the risk of occupational accidents (Simpson et al., 2005).

2.5. Comfort of hearing protection devices

2.5.1. Attributes of comfort of hearing protection devices

HPDs are a common solution to harmful levels of noise exposure. However, their effectiveness decreases with the lack of consistent use, which is known to be the result of factors such as discomfort and inconvenience of use (Groenewold et al., 2014). Several studies have analyzed the attributes that influence the comfort of HPDs in an attempt to formulate methods that improve the use of HPDs. Some of the concepts that repeat themselves throughout several of these studies are mechanical pressure, temperature, weight, attenuation, and texture (Arezes et al., 2008; Doutres et al., 2019; S. N. Y. Gerges, 2012). Each of these defines the four dimensions of comfort established by Doutres et al. (2019): physical, acoustical, functional, and psychological. The following sections will discuss the most prominent dimensions, to which the concepts previously listed belong, physical and acoustic.
2.5.1.1 Physical dimension of comfort

According to Doutres et al., physical comfort refers to the biomechanical and thermal interactions between user and device. In earplugs, these attributes mainly include the pressure applied to the ear canal and the texture or heat absorption of the device, associated with pain and skin irritation, respectively. The principal determinant of mechanical discomfort, or pressure, is the fit of the earplug. Shape and size largely influence the comfort of the user; in a study by Fu and Luximon (2020), it was found that the prototypes that did not insert further than the first bend of the ear canal were more comfortable due to the high sensitivity of the ear canal. Furthermore, mechanical discomfort can also come from jaw movement, which leads to rigid earplugs being less convenient than flexible ones (Doutres et al., 2019). In another study by Sviech et al. (2013), the same concepts contributing to earplug comfort are echoed. A questionnaire was developed and distributed to create a Comfort Index, which determined the statistical significance of sixteen attributes according to the answers received from the test subjects. It was discovered that earplug comfort is primarily defined by pressure, weight, and softness (Sviech et al., 2013).

In the case of earmuffs, in addition to temperature and mechanical pressure, weight also affects physical comfort. Arezes et al. (2008) found that weight seemed to be the most influential feature for user comfort. Additionally, Hsu et al. (2004) determined that earmuffs weighing less than 245 grams were not perceived as heavy for the majority of the study’s participants. Since weight can be proportional to sound attenuation, balancing both is often a challenge for earmuff design. The same study by Arezes et al. (2008) noted that heat dissipation is another crucial issue with earmuffs since they provide insulation, which leads to increased temperature, particularly for workers in hot environments (Arezes et al., 2008). Furthermore, Gerges (2012) developed indices for the attributes mentioned, including the force exerted by the headband. The research explained
that a higher headband force increases comfort as long as the pressure is well-distributed in the circumaural area in contact with the device (S. N. Y. Gerges, 2012). Although in the study by Gerges (2012) the headband perceived as “most comfortable” had a force of 16.7 N. lower force pressures can be recommended, for example, standard EN352-1 establishes that the headband force should not exceed 14 N, which is 2.7 N below the results presented by Gerges (2012) (Hsu et al., 2004).

2.5.1.2 Acoustic dimension of comfort

Doutre et al. (2019) define the acoustic dimension of comfort as the alteration that the user’s perception of external and internal noises undergoes when wearing HPDs. The purpose of HPDs is to reduce noise exposure or to attenuate sounds. When selecting HPDs for the workplace, attenuation is the deciding feature since it specifies the protection capacity of the device (Arezes et al., 2008). However, it is crucial to select only the required amount of attenuation, such as not to cause counter-productive effects.

One of the physical factors that impact attenuation is sealing, which directly correlates to the pressure that HPDs exert on the user. In the case of earplugs, the device must seal the ear canal to avoid sound leakage (Doutres et al., 2019). Samelli et al. (2018) found that the pressure applied in the ear canal is heavily affected by the ear anatomy. Additionally, none of the models used in the study were suitable for small-diameter ear canals, for instance, those of women (Samelli et al., 2018). On the other hand, different measures have been taken to analyze the sealing of earmuffs (S. N. Y. Gerges, 2012; Russell & May, 1976). One of the methods implemented has been to obtain the distribution of the force on the circumaural area of the user and interpret the data as a determinant for earmuff sealing. Gerges (2012) used an index relating the contact area to the cushion area of an earmuff to analyze sealing, determining that the cushion material is crucial to
distribute forces, reduce sound leakage, and increase comfort. The percentage of the contact area was calculated by dividing the non-contact area over the total area of the cushions. The non-contact area was measured using an arrange of over one-thousand pressure sensors that had a lower limit of 2 kPa, thus the areas where there could be a lack of sealing had a pressure lower than said value.

Attenuation has also been used as a measure of the sealing capacity of earmuffs. Gerges (2012) and Russell & May (1976) applied sound attenuation levels in dB to determine the sealing qualities of earmuffs. In both studies, the reduced leakage due to non-contact areas caused drops in attenuation levels of up to 5 dB. These non-contact areas can be caused by seemingly inoffensive factors, such as wearing safety glasses and the presence of hair. Thus, their elimination when fitting earmuffs is essential. Ideally, HPDs should achieve a 100% sealing since this correlates to the attenuation marked in the specifications for the device, which are crucial to determine the appropriate HPD for the noise levels at the workplace. As an example, if a HPD has a denoted attenuation of 25 dB, it can be suited for environments in which noise levels are up to 110 dB, to fulfill OSHA standards and maintain exposure below 85 dB (Themann & Masterson, 2019).

As mentioned above, sound attenuation is an intrinsic feature of HPDs. However, reduced noise exposure can lead to comfort from the protection of harmful sounds or discomfort from overprotection that inhibits the perception of valuable sounds (Doutres et al., 2019). Multiple studies state that HPD-caused discomfort or lack of use is due to the effects of excessive attenuation. Overall, the terms that repeat throughout the literature point to the interference with communication and hearing of useful sounds, such as alarms and warning signals, that users report to feel with HPDs (Arezes et al., 2008; Doutres et al., 2019; S. N. Y. Gerges, 2012; Hsu et al.,
Hsu et al. (2004) reported that 53.4% of the participants in their study had difficulties in conversation. Sviech et al. (2013) identified that barriers for HPDs use included the need to communicate and hearing loss, as indicated by 20% and 10% of the participants, respectively. Overall, both the physical and acoustic dimensions of discomfort can interfere with the sound attenuation of the device since they directly impact the appropriate use of the device. Therefore, HPDs must be chosen to provide a sufficient level of attenuation according to the environment in which they will be used, without hindering the hearing capabilities of the users.

2.6. Additive manufacturing

Contrary to traditional formative or subtractive manufacturing, additive manufacturing (AM) refers to the process in which parts are created by adding material in layers. Seven different process categories belong to AM: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (ASTM Standard 52900, 2015). AM has the potential to reduce production processes along with production time. Additionally, AM can deliver highly customized, complex, and true-to-design parts. These benefits have established AM in applications such as the automotive, aerospace, and medical industries. Each of the seven process categories has intrinsic advantages useful for different purposes (Tofail et al., 2018).

2.6.1. Vat photopolymerization

Vat photopolymerization is the process of selectively curing liquid photopolymer in a vat. Photopolymers are resins that can be cured using radiation since they go from the liquid to the solid state after being irradiated. A diagram of the usual configuration of vat photopolymerization equipment is shown in Figure 2.8. Their use in AM began in the 1980s after stereolithography
(SL) was developed by 3D Systems as a rapid prototyping process. The most common photopolymers currently on the market are hybrid resins which combine epoxides with acrylate content since they produce stronger, more accurate, and less brittle parts (Gibson et al., 2010).

Figure 2.8. Vat photopolymerization system typical components

Vat photopolymerization is available in three configurations, vector scan, mask projection, and two-photon approach. Vector scanning is predominant in the market, with companies such as 3D Systems and Formlabs offering vat photopolymerization machines with this configuration. It consists of a laser focusing on one point at a time, conforming to the part’s shape. On the other hand, mask projection involves irradiating one layer at a time, leading to a faster process. Finally, two-photon approaches are similar to vector scanning in that they focus on one point of the layer at a time, however, the point cured is at the intersection of two radiation sources. (Gibson et al., 2010).
The benefits of vat photopolymerization include high part accuracy, resolution, and surface finish quality, which are product of the micron-sized features achieved by laser sources in vector scanning and two-photon approaches (Gibson et al., 2010). Additionally, although mask projection sacrifices resolution, it has the ability to produce parts at speeds of up to two orders of magnitude greater than the other vat photopolymerization configurations, making it a fast AM process (Zhang et al., 2021). However, the main drawback of vat photopolymerization is that the process is limited to photopolymers of which there are few. They can also lack heat resistance found in other polymers or metals and can age at a more rapid rate than other materials since they continue to absorb radiation over time (Gibson et al., 2010).

The work of Belmont (2020) compared the accuracy of material extrusion and vat photopolymerization processes when replication a pinna. GRAS KB0060 Small Right KEMAR Pinna and GRAS KB0061 Small Left KEMAR Pinna (GRAS Sound & Vibration, Denmark) were reverse engineered to reproduce their geometry. The silicone pinnae were scanned using Computed Tomography (CT) technology, the data obtained was used to create CAD models and Standard Tessellation Language (STL) files that were then printed using the technologies mentioned. Four sets of printed pinnae were generated with two material extrusion and two vat photopolymerization systems. All manufactured components were acoustically tested and evaluated against the original silicone pinnae from the KEMAR manikin. The experiment results showed that the 3D Systems’ Viper SL printer (3D Systems Inc., Rockhill, SC) performed the closest to KEMAR’s pinnae, with differences as low as 0.5 dB (Belmont, 2020). Therefore, the Viper printer was selected for the accurate development of the device.
2.6.2. Additive manufacturing for custom medical devices

The benefits of AM make it possible to produce custom parts with complex geometries without the lengthy processes that traditional manufacturing could require. In recent years AM has been used in the medical field to create models of anatomical parts. Particularly in orthopedics, AM has been useful to develop implants by replicating structures such as the spine and knee. Medical imaging techniques, such as CT scans, and Magnetic Resonance Imaging (MRI), are used to obtain high-quality images, which are then translated into 3D models that can be fabricated via AM (Javaid & Haleem, 2018).

Similarly, orthotics and prosthetics are other fields that benefit from AM. Traditional methods to produce orthoses are highly manual, which results in lengthy processes that require expertise. As is the case for orthopedics, the manufacture of custom orthoses and prostheses consists of acquiring the geometry, designing the device to compensate for the condition under treatment, and fabricating said device. Using AM, a 3D scanner software captures the desired geometry, which is then edited in computer-aided design programs and produced (Chen et al., 2016). The company Align Technologies has also applied AM for the mass production of custom products. Their Invisalign brace molds are manufactured with SL printers that deliver the required resolution to reproduce the dental anatomy (Pereira et al., 2019).

2.6.3. Hybrid AM manufacturing

Hybrid AM manufacturing refers to the setups in which additive and other manufacturing processes are combined in order to obtain the advantages of both. The creation of complex shapes, as well as the reduction of material waste, can be preserved and supplemented by stronger parts with improved surface finishes. Both metal and polymers AM have been implemented in hybrid
AM. For metal AM, hot isostatic pressing (HIP) is used to increase the strength of printed parts, while shot peening improves their surface finish. On the other hand, resin infiltration and electroplating, respectively, are the processes applied in polymer AM for the same purposes (Dilberoglu et al., 2021; Sealy et al., 2018).

Amongst the potential applications for hybrid AM, embedding electronic systems to create fully functional structures has been explored. Electronic components and conductive materials are introduced between layers of the AM process to achieve 3D parts with embedded electronic systems. Li et al. (2016), for example, used vat photopolymerization to manufacture a 3D electronic system. The part was first printed via vat photopolymerization to a desired layer, in which silver electrically conductive adhesive was deposited to then add surface mount (SM) integrated circuits. Finally, the part would be completed employing vat photopolymerization and post-processed by UV curing it. Parts that had three layers with light-emitting diodes (LEDs) incorporated were successfully produced, with the inner circuitry functioning as designed by the researchers (Li et al., 2016). The use of hybrid manufacturing to embed electronics could prove useful in devices such as the one described in this thesis, where small electronic components need to be incorporated and the process to do so is complex. However, hybrid AM is affected by limitations that should be taken into consideration before planning to use it. The challenges stem from the inherent drawbacks of AM, and include limited materials, support removal, and process variability (Dilberoglu et al., 2021).
Chapter 3 : Experimental setup and procedures (Materials and methods)

3.1. Introduction

As stated in the first chapter of this thesis, the objective of this research is to continue developing the design of a previously conceptualized headset meant to decrease incoming noise levels while preserving sound localization. Therefore, this chapter will detail the modifications made to the device during the development of this thesis. The new version of the headset also seeks to preserve the sound localization quality that preceding iterations of the device achieved. Furthermore, version 14 (V14) of the headset also focuses on user convenience and comfort. The following sections center on the added features previously mentioned, along with the acoustic test methodology applied.

During the development of the most recent version of the device, V14, a design requirements list was created to define the constraints the device should fulfill. Apart from defining values for physical properties of the device, such as dimensions and weight, the design inputs for acoustic performance were also determined. These acoustic requirements refer to the two main objectives of the device, which are sound preservation and noise attenuation. Furthermore, comfort was also addressed in reference to previous research (S. N. Gerges, 2010). Other conditions regarding power source and battery life were also established according to the current circuit being used in the device, as well as the possible needs of workers to wear the device continuously for five 8-hour working days. Finally, user needs regarding aesthetic attributes and configuration were included. Table 3.1 shows the requirements and their corresponding design inputs.
Table 3.1. First design requirements list of the sound-preserving hearing protection device

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Design Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuate loud noises</td>
<td>Must have a NRR of at least 25dB</td>
</tr>
<tr>
<td>Lightweight</td>
<td>Must weigh less than 300 grams</td>
</tr>
<tr>
<td>Comfortable to wear</td>
<td>8 N &lt; Headband force &lt; 12 N</td>
</tr>
<tr>
<td>Durable battery life</td>
<td>Desired operating time between charges of 40 hours</td>
</tr>
<tr>
<td>Preserve sound localization</td>
<td>Must have a customized artificial pinna</td>
</tr>
<tr>
<td></td>
<td>Directivity Index average difference from natural hearing &lt; 5 dB</td>
</tr>
<tr>
<td>Configurable by user</td>
<td>Must have a power off/on button</td>
</tr>
<tr>
<td></td>
<td>Must have settings button</td>
</tr>
<tr>
<td>Include current DSP</td>
<td>Power source of 1 to 1.2 V</td>
</tr>
<tr>
<td>Preserve acoustic similarities to natural hearing</td>
<td>Amplitude difference from natural hearing &lt; 5 dB</td>
</tr>
<tr>
<td></td>
<td>Impulse response delay &lt; 10 ms</td>
</tr>
</tbody>
</table>
| Muff must fit commercially available cushions            | Muff plate inner dimensions:  
|                                                         | Height = 99 ± 0.100 mm  
|                                                         | Width = 71 ± 0.100 mm                                                       |
| Customized pinna should be interchangeable for testing  | Clearances between pinna and muff plate = 120 microns                        |
| purposes                                                | Muff thickness ≈ 60 mm                                                       |
|                                                         | Include shell covering                                                       |
| Aesthetically pleasing                                  |                                                                              |
| Rechargeable battery                                    | Standard battery charging port (Micro USB/USB Type C)                        |
| Fast recharging cycle                                   | Battery charging time < 6 hours                                              |

V14 was manufactured and assembled in its entirety, with the process for the iteration of the device reaching the experimental stage, in which the headset was transported to the testing facilities in the Beltone headquarters (GN Resound, Glenview, IL). However, due to complications originating in the design of the device, V14 could not be tested and thus data was not obtained. The identified areas of opportunity were addressed in Version 15 (V15) of the noise-cancelling, sound-preserving headset. V15 was developed incorporating the improved elements of the headset.
and a final prototype of V15 was fabricated. The modifications made, as well as the justification behind them, will be detailed in this section.

3.2. Incorporation and placement of three microphones in custom hearing protection device

One of the objectives for the V14 of the headset was to incorporate two additional microphones into the existing setup of the prior version. The main challenge in achieving this goal was a lack of literature regarding the location of multiple microphones in similar devices, such as earmuffs. Therefore, the references used originate from the available literature on hearing aids, particularly the work of Feigin et al. (1990) and Madaffari (1974). The researchers used and created a 25-point grid to map the pinna and analyze the acoustic influence of microphone location, respectively (Feigin et al., 1990; Madaffari, 1974). The 25-point grid served as a guide when determining the placement of the two new microphones within the device.

![Diagram of added microphones positions and features](image)

**Figure 3.1** Added microphones positions and features
Figure 3.1 shows the two points selected for the microphones, labeled A and B. The chosen positions do not match the exact coordinates of the grid created by Madaffari (1974) since two considerations were crucial when placing the microphones within the headset. Reduced manufacturing complexity and the microphones' position relative to the ear canal entrance were the defining factors of the final A and B points. The aim was to place the newly implemented microphones at the front and back of the pinna. Therefore, both microphones were aligned in the horizontal axis to the existing microphone, which resided at the artificial ear canal. Additionally, the cavity for the microphones was to remain in the non-custom part of the headset assembly (Figure 3.2) to prevent inconsistencies in production.

The inclusion of the two microphones involved further modifications that could adequately accommodate to the electronic components. The microphones require a connection to the digital signal processor (DSP) to fulfill their function of capturing sound and delivering it to the speaker. Consequently, the multi-microphone design contains pathways for the wiring of both microphones. These embedded conduits travel from points "A" and "B" to the location of the DSP within the muff plate. A defining characteristic in the creation of said conduits was the dimensions of the wire used. GN Resound provided the specialty wire used for the circuitry in the faceplates utilized in the headset. Preferred due to its properties, litz wire is useful to the purpose in question since it is able to distribute the electrical current in applications where the operating frequency is crucial, such as hearing aids. According to vendor recommendations, 30 AWG litz wire fits the frequency range in which the DSP operates, which is between 1 and 10 kHz (MWS Wire Industries, 2022). All conduits have a fixed width of 1.200 mm, providing sufficient space for the 0.254 mm diameter of the wires described. However, only two of the three microphones were connected to the DSP, since the latter does not have the processing capacity for more than two receivers.
An additional focus when incorporating the two additional microphones was their protection from potential damage. Unlike the rest of the electronic components, the new microphones were directly at risk due to being directly exposed to the outer surface of the muff plate. Therefore, to preserve their integrity, the design includes a net-shaped safeguard (Figure 3.1) for the microphones, which limits the possibilities of any harm that could affect the overall performance of the device.

![Diagram showing the headset assembly with a custom pinna part and added microphone position](image)

**Figure 3.2.** Custom pinna part and added microphone position in headset assembly

3.3. Headset magnetic attachment design and manufacture process

3.3.1. Initial conceptualization and design of magnetic attachment for V14

A printed ear canal (PEC) has been part of the headset design from the initial versions of the device. The purpose of the PEC is to enter the anatomical ear canal while housing the speaker
that transmits the sounds captured by the microphone and filtered by the DSP. In previous versions, the connection between the PEC and the headset was possible due to design features in the parts that produced a fitting assembly. In V13, the attachment underwent modifications that increased flexibility and comfort by allowing the user to adjust the headset's circumaural position and pressure on the head. However, putting on the device was a complicated process since, in the final assembly, the PEC was permanently fixed to the device, and thus it could not be adjusted within the ear canal once donned.

V14 includes a magnetic attachment able to connect the PEC to the headset after donning and adjusting the latter. As seen in Figure 3.3, for V14 of the headset, the PEC from V13 (Figure 3.4) was divided into two separate parts. The membrane PEC, as its name suggests, attaches to the headset by fastening to a flexible membrane created for V13. On the other hand, the earpiece PEC has a geometry similar to commercially available earphones and enters the outer ear canal, delivering sound. Both PECs have a set of magnets that form the desired attachment.
Figure 3.3. V14 PEC divided into two parts, a) membrane PEC which attaches to the muff and

b) the earpiece PEC which goes into the ear canal
Since the earpiece PEC houses the speaker and the headset contains the DSP, the connection between both electronic components must be maintained. Therefore, copper contact surfaces were used to preserve continuity and transmit the electric signals that produce outgoing sound from the speaker. Flathead copper rivets (Model C0093F00187, Jay-Cee Sales and Rivet, Inc., Farmington, MI) were utilized as the contact surfaces that transmit the electronic signals.
Figure 3.5 shows the connection diagram between the components. Noting that there are two conductors with different polarities, the two copper plates that connect DSP and speaker, and correspond to each of the wires, must remain aligned while the device is in use. Thus, the magnets should be arranged asymmetrically such that the attachment is achieved only when correctly positioning the headset, preventing the misalignment of the speaker wires (Figure 3.3).

Figure 3.5. Connection diagram of the circuit in V14 incorporating the magnetic coupling between DSP and speaker

In addition to the requirements described, the development of the magnetic attachment involved challenges due to the dimensional constraints of the device. The final iteration of the design was created after the initial concept led to a series of complications in manufacturing and assembly. Both versions of the design, referred to as versions 1 and 2, are depicted in Figure 3.6. Dimensions of commercially available magnets were taken in order to accurately design the cavities in both parts of the PEC. All magnets were purchased from the K&J Magnetics, Inc.,
which offers STEP files for their products (K&J Magnetics, Inc., Pipersville, PA). Said STEP files were used to have a dimensionally correct model in Fusion 360, where all parts were modeled.

Figure 3.6. V14 magnetic coupling versions. a) Countersunk magnet design. b) Cylindrical magnet design.

The membrane PEC, which attaches to the muff, had spherical magnets (Model S2, K&J Magnetics, Inc., Pipersville, PA) incorporated for both versions of the magnetic coupling, while the earpiece PEC featured different magnet geometries in versions 1 and 2. Initially, countersunk magnets (Model R422CS-P, K&J Magnetics, Inc., Pipersville, PA) were selected since their shape had an incorporated cavity in which the spherical magnets from the membrane PEC fit. However,
the dimensions of the countersunk magnets led to complications. After placing the copper rivets within the CAD design, the remaining area was not sufficient to accommodate three countersunk magnets, which resulted in adapting the design to only two magnets per PEC. Therefore, the asymmetry quality that promoted proper alignment of the contact plates was not achieved optimally. Furthermore, the spherical magnets in the membrane PEC aligned with the rim of the countersunk magnets instead of the concave section.

Considering the issues described, the design shifted to a second iteration, which incorporated different magnets for the membrane PEC. As seen in Figure 3.6, the countersunk magnets from version 1 were replaced by cylindrical magnets (Model D101-N52, K&J Magnetics, Inc., Pipersville, PA) that were significantly smaller and allowed the implementation of three attachment points in an asymmetrical distribution. The neodymium magnets used for the prototype of version 14 were chosen primarily due to their availability in sizes fitting for the application. Additionally, the same type of magnets is successfully used in other biomedical applications such as dental prostheses (Gonda & Maeda, 2011; Riley et al., 2001). However, since the device is intended for use in contact with the head, more specifically the area around the ear, safety considered when selecting the magnets. Due to the risk that static magnetic fields pose on human health; the magnetic flux of the magnets used was researched in the supplier’s website. According to K&J Magnetics, at 10 mm, which is approximately the separation between the magnetic coupling and the user’s head, the magnetic field of both magnets is of less than 500 Gauss (G). Therefore, the magnetic fluxes are below the thresholds recommended by the International Commission on Non-Ionizing Radiation Protection and the U.S. Department of Defense (Table 2.1).
The manufactured prototype for the magnetic coupling can be seen in Figure 3.7, which shows its two main conforming parts, the membrane PEC and earpiece PEC (Fig. 3.7a and 3.7b, respectively), as well as the union of both (Fig. 3.7c). The embedded speaker in the earpiece PEC, which enters the ear canal, is also shown. Additionally, the prototype depicted contains the components (magnets and copper rivets) previously described. The magnets were secured using adhesive (Super Glue Liquid, 3M, St. Paul, MN), while the copper rivets were inserted for a tight fit.

**Figure 3.7.** V14 magnetic coupling. a) Membrane PEC. b) Earpiece PEC with embedded speaker and wiring. c) Union of both PECs that conform magnetic coupling.
The assembly of the magnetic coupling was successful in terms of its attachment to the muff. However, the components that made up the magnetic coupling interfered with the sealing of the headset at the circumaural area. Furthermore, donning the complete device on the KEMAR manikin without disrupting the magnetic attachment proved complicated. When setting up the V14 of the headset to test at the Beltone headquarters (GN Resound, Glenview, IL), the connection between the DSP and the computer in which the data is measured and analyzed could not be completed. Additionally, the magnetic coupling was frequently interrupted since the wiring connected to the copper rivets and to the electronic components would be easily detached. Therefore, a redesign of the magnetic coupling was completed to improve the sealing of the cushions of the headset and facilitate the donning and measuring process when testing.

3.3.2. Magnetic attachment rework for V15 of the headset

Amongst the first modifications done to the magnetic coupling from V14 was the reduction from three magnets to two magnets on each of the conforming parts of the PEC. Due to the asymmetric arrangement of the magnet trio, an imbalance in forces was caused by the two closest magnets, which separated the section with only one magnet and led to the disconnection of the copper rivets. By decreasing the number of magnets, a more uniform contact was achieved between the copper terminals, achieving a more stable connection. Furthermore, the assembly process was simplified. In addition, the alternating polarities were preserved to prevent the misalignment of both PECs, allowing the user to join both parts only when the magnets are properly paired. Figure 3.8 shows the contact plates of both membrane and earpiece PECs from V15, which house only two magnets in comparison to those of V14, depicted in Figure 3.7.
The thickness of both the membrane and earpiece PECs were also modified to decrease the distance between the cushion of the headset and KEMAR’s ear canal. In the magnetic coupling for V14, the membrane PEC maintained its original dimensions, which did not take into account the added thickness from the earpiece PEC. Additionally, the sections housing the magnets and copper rivets contributed to the separation between the cushion and KEMAR’s head. Therefore, both components underwent a reduction in their dimensions. As seen in Figures 3.9 and 3.10, the membrane and earpiece PECs underwent a thickness reduction of approximately 17% and 12%, respectively. With said adjustments, the headset was able to be positioned closer to the manikin’s circumaural zone.
3.4. Electronics placement within headset

The components that constitute the circuitry needed for the headset to adequately function are supplied by GN Resound (Figure 3.11). In iterations before V13, the electronic components were placed within the PEC, as shown in Figure 3.12. Although the concept was executed and included in a complete prototype of an earlier device version, incorporating the electronic
components into the PEC was complex and challenging. Since the electronics used are small, the soldered wiring was prone to disconnect. In addition, their size also makes the components vulnerable to rapid accumulation of heat when exposed to the soldering iron used. Furthermore, the housing space available was limited since it was specifically designed to accommodate the components, which prompted difficulties when arranging them within their designated location. The issues described often resulted in the waste of electronic parts that were rendered useless while assembling them inside the PEC.

**Figure 3.11.** Electronic components that constitute the circuits in the device
In V13, the electronic components were transferred from the PEC to the headset to avoid the complications described (Figure 3.13). However, the button to configure the DSP settings, and the battery port, remained on the inner portion of the headset, as seen in Figure 3.14. Therefore, in order for the user to select one of the three DSP settings or replace batteries, the device could not be donned. Feedback provided by the GN Resound personnel after testing V13 was that both interfaces were complicated to access, motivating the design changes to relocate the components.

**Figure 3.12.** V13 PEC with all electronics embedded

**Figure 3.13.** Electronic components relocation to muff in V13
3.4.1. Button relocation

Considering that user convenience is one of the main focuses of V14, the configuration button for the DSP was relocated to the outermost portion of the headset (Figure 3.13). This modification intends to enable the user to choose between settings without the need to remove the headset once donned. The updated position of the button in the new design was determined by defining an intuitively reachable site within the rim of the muff. As seen in Figure 3.14, the button is located where it can be comfortably accessed by the user's thumb when the device is worn.

A crucial element when developing the design for the button housing in V14 was that said component was simple to assemble. In the final stages of manufacturing the V13 device, the principal delaying factor in finishing the prototype was that many of the parts were difficult to assemble into the muff due to their reduced size. Thus, before determining the final form of the button housing, proof-of-concept prototypes were printed to test for ease of assembly. Figure 3.15 shows the produced parts, which were manufactured using a MakerBot ABS filament (MakerBot Industries, LLC, Brooklyn, NY) in a MakerBot Method X-1 3D printer (MakerBot Industries, LLC, Brooklyn, NY). The results showed that the housing dimensions needed to be increased to facilitate handling the part. With the obtained feedback, the button housing underwent the modifications that led to the final form, which was effortlessly assembled and did not interfere with the wires from the button to the DSP. Finally, wire conduits from the button to the DSP location were implemented to provide an embedded space within the muff plate.
Figure 3.14. Fusion 360 model of the button relocation for V14

Figure 3.15. Initial prototype of the button relocation design
3.4.2. Rechargeable battery

3.4.2.1 Rechargeable battery circuit design for V14

To provide the power required for the circuit, a standard size 312 battery, commonly used for GN Resound's hearing aids, has been used in previous versions of the device. Although their dimensions make them a convenient power source for hearing aids, incorporating them into a marketable version of the headset described in this thesis might result ineffective due to their characteristics. The batteries in question have limitations that originate from batteries' intrinsic characteristics: chemistry, voltage, and capacity. Size 312 batteries provide the hearing aids DSP with the required 1.2 V; however, the chemistry most commonly offered in the market is zinc-air. Once the seal to the air inlet is removed, zinc-air batteries should be used immediately since the chemical reaction begins once exposed to air and could lead to battery aging. Furthermore, these batteries are often found only in disposable format (Harting et al., 2012). Therefore, the incorporation of a rechargeable battery was explored for V14 to extend the wear time of the headset to a duration similar to those of electronic earmuffs available in the market, such as the Worktunes Connect (3M, Saint Paul, MI) and the Razor Slim Low Profile (Walker’s, Irving, TX), which have a battery life of approximately 30 and 40 hours, respectively.

The rechargeable batteries most frequently used for portable devices are lithium-ion (Li-ion), however, they are often commercially available in voltages above 2.0 V, which is outside the maximum voltage that the DSP can receive. Therefore, the primary focus of the rechargeable battery circuit was to implement a voltage regulator that provided a voltage between 1.0 and 1.2 V, which is the range in which the DSP adequately functions. A LM3674 step-down DC-DC
converter (Texas Instruments Incorporated, Dallas, TX) was incorporated to achieve the desired voltage. The integrated circuit is often used in conjunction with Li-ion batteries to provide power to devices such as mobile phones and digital cameras, and the output voltage that it provides can be adjusted to the required value. The LM3674 characteristics made it ideal for the application at hand, and the circuit in Figure 3.16 was created including it.

![V14 rechargeable battery circuit diagram](image)

**Figure 3.16. V14 rechargeable battery circuit diagram**

The first prototype of the circuit was constructed with a protoboard, and the provider’s recommended input and output capacitors, of 4.7 µF and 10 µF respectively, were used. However, the regulated voltage obtained with said capacitor values was 1.5 V, higher than the required by the DSP. Therefore, a series of surface mount (SM) and through-hole (TH) capacitors were tested to reach a voltage within the acceptable range (Table 3.2). Ultimately the combination of two ceramic 10 µF capacitors was utilized, the input capacitor being SM and the output capacitor TH. After the protoboard prototype was successful in achieving a voltage within the working range of the DSP, the circuit was transferred and soldered to a pre-made printed circuit board (PCB), with the intentions of embedding it into the design of V14 (Figure 3.17).
Table 3.2. Input and output capacitors combinations tested for rechargeable battery circuit

<table>
<thead>
<tr>
<th>Type in</th>
<th>C in (pF)</th>
<th>Type out</th>
<th>C out (pF)</th>
<th>Voltage output (V)</th>
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<td>SM</td>
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<td>TH</td>
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<td>0.201</td>
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<td>4.7</td>
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</table>
3.4.2.2 Rechargeable battery circuit redesign for V15

Along with the adjustments made to the magnetic coupling for V15 of the device, the rechargeable battery circuit was also modified to fit within the space of the muff. To downscale the initial circuit, the battery charging circuit was separated from the main PCB and connected via wires. This allowed for the voltage regulating section for the circuit to be installed in a smaller, micro-scale PCB (MBSS Products, Fall City, WA) of 25.4 mm by 20.32 mm. As seen in Figure 3.18, the new design was assembled into the muff.
Figure 3.18. Rechargeable battery circuit redesign and downscale for V15

The three main components of V15’s rechargeable battery circuit were the battery charging circuit, the voltage regulator circuit, and the rechargeable battery. A cavity was embedded into both muffs to accommodate the micro-USB connector to recharge the battery. However, the three parts previously mentioned still required a stable attachment to the muffs. Therefore, industrial grade double sided adhesive tape (Scotch-Mount™ Extreme Double-Sided Mounting Tape, 3M, St. Paul, MN) was used as a temporary, prototype-only, solution to fix the components onto the muff. A robust adhesion was achieved, and the micro-USB port could be used without disturbing the layout of the components.
3.4.3 Battery port relocation for V15

To capture the data from testing, the connection between the DSP and the computational equipment is achieved via contacts situated at the battery port of the faceplate that is incorporated into the headset. For V13 and V14, said battery port was situated in the inner section of the muffs, as seen in Figures 3.3 and 3.4. However, said localization made it difficult to correctly reach the contacts and attain the connection between the DSP and the computational equipment. For V14, the connection could not be completed due to the issue mentioned, which in turn made it impossible to record data from the device. Therefore, to facilitate the connection process, the battery port from the faceplate was relocated to the outer rim of the muff, as seen in Figure 3.19.

![Figure 3.19. CAD of relocated battery port for V15](image)

The CAD design of the muffs were modified to include a cavity in which the battery port from the faceplate could fit. To assemble the battery port, the faceplate had to be trimmed to the
dimensions of the cavity. Initially, the size to which the faceplate had to be reduced led to fracture of the same, which rendered it unusable. Then, the cavity was enlarged from its original dimensions of 8 mm by 15 mm to 12 mm by 20 mm, to decrease the complexity of the trimming and assembly procedures. Additionally, a fillet was added in all the borders of the opening to prevent stress concentrators. The connection between V15 and computational equipment was verified via software provided by GN, which showed that both left and right muffs were successfully linked. The final assembly of the battery port can be seen in Figure 3.20.

Figure 3.20. Battery port relocation assembly in final prototype of V15, shown without mesh cover
3.5. Design and manufacture of a sound-transparent headset covering

The iterations of the device before V13 did not include a covering for the printed pinna. Instead, the pinna remained visible from the outside, which raised concerns regarding the aesthetic appeal of the headset. Furthermore, the microphone remained exposed as it is located directly at the entrance for the artificial ear canal (Figure 3.21). Therefore, V13 incorporated an outer shell that concealed the artificial pinna and protected the microphone, also called the transmitter, without interfering with the quality of the sound reaching the microphone. The acoustic transparency of the shell, or covering, is crucial for the electronic element of the device to adequately perform since it means that the sounds can get to the microphone with minimal distortion (Winer, 2012). Thus, although the shell primarily serves an aesthetical purpose, its design should remain open enough to not interfere with the sounds processed by the circuitry.

![Microphone position at the artificial ear canal](image)

**Figure 3.21.** Microphone position at the artificial ear canal

Considering the requirements that the covering should fulfill, the shell depicted in Figure 3.22 was created for V13 of the headset. The design contains cavities alongside its entire surface
to remain unrestricted to sounds originating from any possible direction. However, its overall structure is fragile and complex to manufacture (Figure 3.22). The prototype parts of the V13 of the device were fabricated using the AM process of vat photopolymerization. Like other AM processes, vat photopolymerization requires removing supports in the post-processing step of production. Due to its thin net-like shape, manipulation of the shell of V13 while eliminating supports often led to the part sustaining damage. The covering was also prone to breakage when handling it for assembly. For V14, the shell shown in Figure 3.23 maintains the openness of its predecessor while also featuring a more robust construction. Said improvement facilitates the fabrication of the part and protects the microphone and the artificial pinna from potential damage. Additionally, it increases user convenience by reducing the probability of accidental damage.

![V13 shell with damaged parts highlighted](image)

**Figure 3.22.** V13 shell with damaged parts highlighted
3.6. Part manufacturing using vat photopolymerization

The defining feature of the headset developed in this research is the artificial pinna, which is essential to fulfill the device’s purpose but also has a complex geometry with various intricacies. Therefore, the process selected to be used when fabricating the prototype parts must be highly accurate. Amongst the seven process categories of additive manufacturing (AM), vat photopolymerization is distinguished by its high precision, surface quality, and part resolution. The characteristics of vat photopolymerization make it an efficient method to produce the parts that form the headset, which require the benefits inherent of the process.

A 3D Systems’ Viper SL printer was used in V10 of the device, as well as for V13 and V14. All parts were sliced using the software 3D Lightyear 1.5.2, and printed with a layer thickness of 102 microns and a diameter of the laser beam at the curing point of 254 microns, which aided in the creation of the fine feature of all components, including the artificial pinna and
the smaller parts that compose the PEC’s of both V13 and V14. Clearances on the XY and XZ planes were determined based on the printer capabilities and the print orientation of the components. Parts of an assembly that were printed in such a manner that the fit between parts occurred in the z-axis (Figure 3.24a) were designed with the highest clearances (130 microns) to compensate for the overhangs within the attachment between components. On the other hand, parts with cavities in the XY plane (Figure 3.24b) were created with lower clearances (100 microns), since their print orientation did not interfere with the assembly joints.
Figure 3.24. Print orientations for assembled parts in V14. a) Crucial clearances for parts with attachments in the z-axis. b) Crucial clearances for parts with attachments in the x-y plane.

Somos® Watershed XC 11122 (Stratasys, Eden Prairie, MN) clear resin was used for all parts manufactured, which resulted in translucent parts. The semi-transparency of the components allowed for an easier embedding of the electronics since they could be distinguished from the outside and aligned in their designed spaces. An example of such can be seen in Figures 3.12, where the embedded electronics are seen in the PEC for V13.
3.7. Acoustic test setup

The acoustic testing for previous versions of the device, as well as for V13, was performed at an anechoic chamber in the Beltone headquarters (GN Resound, Glenview, IL). Anechoic chambers provide an environment in which sounds are not reflected from the walls, which eliminates echoing. Such conditions are achieved by insulating the room walls, ceiling, and floor with sound-absorbing materials, like rock-wool and foam panels. Since acoustic signals are not reflected in said chambers, the background noise can be close to 0 dB, making them ideal to test devices such as hearing aids and the headset described in this work (Zuckerwar, 2003). All acoustic experiments for the V13 headset took place in the anechoic chamber depicted in the drawing provided by GN Resound (Figure 3.25).

![Anechoic Chamber Used for Acoustic Testing of V13](image)

**Figure 3.25.** Anechoic Chamber Used for Acoustic Testing of V13. Figure provided by GN Resound.

In addition to the anechoic chamber, a KEMAR (Knowles Electronics Manikin for Acoustic Research, GRAS Sound & Vibration, Denmark) manikin was used for all acoustic testing. The KEMAR manikin is an anthropometric head and torso built after the anatomical characteristics of a grown adult. Its design contains facial features that provide the manikin with
the acoustic properties of a human. KEMAR can also include different sets of anthropometric pinnae that are easily interchangeable. For V13, testing was performed using GRAS KB0060 Small Right KEMAR Pinna and GRAS KB0061 Small Left KEMAR Pinna, since said pinnae are incorporated in V13 of the headset. The characteristics described make KEMAR an ideal tool to obtain realistic results in anthropomorphic acoustic testing of devices such as hearing aids and headphones. The software used to measure the audio components in KEMAR was SoundCheck Version 18 (Listen Inc., Boston, MA), used in research and development, along with production settings, since it has test sequences available and allows for data import and export.

Table 3.3. Acoustic testing setup parameters for V13

<table>
<thead>
<tr>
<th>Measurement parameters</th>
<th>V13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (Source Speaker - DUT):</td>
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</tr>
<tr>
<td>KEMAR Rotation</td>
<td>Clockwise</td>
</tr>
<tr>
<td>Measurement System:</td>
<td>SC18</td>
</tr>
<tr>
<td>Source Speaker:</td>
<td>Tannoy VX6 (1 driver)</td>
</tr>
<tr>
<td>Anechoic Room:</td>
<td>GN ReSound, Glenview, IL</td>
</tr>
<tr>
<td>Anechoic Room Dimensions:</td>
<td>280&quot; (L) x 184&quot; (W) x 129&quot; (H)</td>
</tr>
<tr>
<td>Temperature (deg C):</td>
<td>23</td>
</tr>
<tr>
<td>Humidity (%):</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3.3 lists further measurement parameters as provided by GN Resound, of which all, except for the test signal used, were the same for the acoustic tests performed. The setup for the acoustic tests consists of placing KEMAR in front of a sound source and on a rotating base, which allows for the manikin to be turned towards all azimuths tested. From 0° to 360°, and in a clockwise direction, KEMAR was repositioned 36 times with 10° steps between each azimuth. On the other hand, the elevation for the data obtained corresponds to 90°, at which angle KEMAR faces directly to the sound source. An illustration of the azimuth angles in relation to the clockwise
rotation of KEMAR is depicted in Figure 3.26. The sound source was positioned at 1.4 meters from KEMAR, a distance at which sound reflection between both objects is avoided.

![Figure 3.26. Azimuth configuration for acoustic testing of V13](image)

As mentioned previously, the test signals used for each of the experiments varied. To analyze the impulse response and directivity index of the V13 headset, two different noise signals were utilized, which allows for KEMAR to be exposed to multiple frequencies at once. In contrast, the amplitude test was performed with a frequency sweep from 100 Hz to 20 kHz. The latter was chosen to capture the amplitude since the test aimed at comparing the absolute amplitudes of the devices under testing (DUT), for which multiple simultaneous frequencies were not required. Said devices consist of the following: an unaided KEMAR which serves as reference since it does not include any additional equipment, the V13 headset placed on KEMAR, and a receiver-in-ear (RIE)
hearing aid from GN Resound. The third DUT was only tested for directivity index, as an extra comparison point for the performance of V13.

3.8. Speaker performance with magnetic coupling

Electromagnetic interference has been proven to disturb the adequate functioning of hearing aids (Skopec, 1998), which generated concerns when the idea of a magnetic coupling was initially proposed as a new feature of V14. Additionally, the magnets are the mechanism by which the connection from the DSP to the speaker is achieved. Therefore, in order to verify that the magnetic coupling did not interfere with the acoustic performance of the electronic components, or the signal transmitted from the DSP to the speaker, the circuit used in V14 was tested with and without the inclusion of the magnetic coupling. The setup shown in Figure 3.27 was created to emulate the magnetic coupling and its main parts, the membrane PEC and the earpiece PEC. Fusion 360 was used to design the two fixtures that contain the magnets and accommodate the microphone and speaker of the circuit for the device. The parts were manufactured via material extrusion with a Makerbot Method X-1 3D printer with ABS filament. On the other hand, the reference or control group consisted of the same configuration except for the fixtures that replace the magnetic coupling, and the speaker was soldered onto the DSP as supplied by GN Resound.

The acoustic setup to evaluate the speaker’s response consisted of three components, a microphone, a sound source, and software for acoustic measurement. Due to the size of the microphone in the circuit, a Jabra Elite 65t earbud was used since it allowed for the sound to be focused. Additionally, a UMIK-1 USB microphone (miniDSP Ltd., Hong Kong) was used in conjunction with the REW Room Acoustics Software (REW) (Version 5.20.7; John Mulcahy, 2005). The REW Software was selected since it is a free measurement system that can generate
sweep signals and analyze the response of a microphone in real time. This function was beneficial for the experiment in question since a frequency sweep corresponding to the working range of the DSP (1 to 10 kHz) at a level of 75 dB was used to perform the test. As for the microphone selection, the UMIK-1 is recommended by REW’s supplier for a simple configuration since it can be connected via USB and calibrated using the REW software. Furthermore, it is capable of capturing signals from 20 Hz to 20 kHz, covering the range in which the DSP adequately functions. The experiment process can be seen in Figure 3.28 which shows the data flow for the entire setup.

Figure 3.27. Setup for the test on the speaker performance with the magnetic coupling
Figure 3.28. Speaker performance with magnetic coupling process
Chapter 4 : Results

4.1. Introduction

The results presented in this chapter mainly encompass the acoustic tests performed for V13. Although the design work for V13 is not covered within the scope of this thesis, the production and assembly of the final prototype (Fig. 4.1) was completed within the timeframe of the research presented. Therefore, the analysis of the results for V13 will be discussed in the upcoming sections. Due to the nature and the objectives of the device, it is crucial to analyze its acoustic performance in an appropriate setup, such as an anechoic chamber. To obtain reliable results, all acoustic testing was performed at the Beltone Headquarters (GN ReSound, Glenview, IL) with the expertise from GN Resound personnel. All raw data mentioned throughout the upcoming sections was provided by GN Resound. Upon fitting the finished V13 on the KEMAR manikin at the Beltone Headquarters, a misalignment between the right PEC and the manikin’s right ear was discovered. The defective fitting caused the right PEC to be obstructed, which interfered with the data capture for KEMAR’s right side. Therefore, all the results discussed correspond exclusively to the left side of KEMAR, in which an adequate PEC to ear configuration was achieved.

The testing procedures and setup implemented for V13 has been used in previous versions of the device and yielded the necessary metrics to determine if the objectives of the headset, which are noise attenuation and sound localization preservation, are being met. The same conditions were prepared for the tests corresponding to V14, which reached the ready-to-test stage; yet, said device version could not produce data due to the issues described in the previous chapter. Since the acoustic testing performed requires resources, time, and represents a significant cost, the
experimentation on V15 could not be performed. Therefore, although the acoustic testing for V15 was not completed due to its complexity, expense, and time constraints, the same testing methods will be used for said version and presented in a subsequent publication. Maintaining a constant methodology in the experimentation for V15 will provide the data needed to compare its performance to that of its preceding versions.

Additionally, the results for the tests performed on two of the features of V14 and V15 are also presented. These experiments were performed to verify if the concepts developed for V14 and V15 could be feasible before manufacturing a final prototype that can be acoustically tested. They also served as a tool to determine the modifications that the two iterations required. The results described belong to the analysis of the speaker performance with the magnetic coupling and the rechargeable battery circuit.

Figure 4.1. V13 Final Prototype
On the development of the device, the advancements made from the starting point for the work on this thesis to the final versions manufactured can also be referred to as levels from the Technology Readiness Level (TRL) scale that the National Aeronautics and Space Administration (NASA) uses to measure the progress of their projects. In versions preceding V13, the headset could be located at the third level of the TRL scale, with a device that served as a proof-of-concept for the hypothesis that an artificial pinna embedded into a headset could preserve sound localization. The progress from said prototype versions to V13, V14, and V15 can be measured in the number of levels that were completed. It could be affirmed that the latest three versions reached the seventh level of the scale by providing a completed prototype tested in a relevant environment, such as the anechoic chamber (Tzinis, 2021). The current state of the headset, which stands in a transitional stage to a marketable product, also signifies a unique development in the field of hearing health and biomedical engineering. Although efforts have been performed to improve HPDs, the headset developed in this thesis is the first of its kind, and the results show that its sound localization capacities could represent a meaningful innovation in the biomedical engineering field.

4.2. Noise reduction results

As the name of the device presented in this work suggests, one of its main objectives is to block out noises that can be detrimental to human hearing. A sound-attenuation test is crucial to determine if said goal is being accomplished in a similar manner to earmuffs available in the market. The performance of V13 as a noise-cancelling device was obtained by using a pink noise signal, which emulates sounds commonly found in nature and is often used for acoustic testing,
since it covers all frequencies within the human audible range (Keele, 1973; Kyon et al., 2013). The sound attenuation was measured as the difference between the output in decibels of V13 and an unaided KEMAR, which had no additional equipment other than the required for data collection. After obtaining the noise reduction values for V13, the results were compared against the Bilsom UF-1 headset model. The data for the latter was extracted from a study by Berger and Royster (1996) in which the attenuation measures of the Bilsom UF-1 model, which has a labeled NRR of 25 dB and is qualified for military use, were obtained from the average of four different laboratory studies testing a fit protocol for earmuff-type HPD. Figure 4.2 shows the noise attenuation capabilities of both devices.

![Attenuation of KEMAR Unaided vs V13](image)

**Figure 4.2.** Attenuation levels for the Bilsom UF-1 and V13 headsets

As seen in Figure 4.2 both attenuation values were graphed across a range of frequencies between 125 and 8000 Hz. A notable contrast between the attenuation of both the Bilsom UF-1
earmuffs and V13 of the headset is shown in the graph. To quantify the difference between both datasets, the absolute average attenuation of both devices was obtained at three frequency ranges, as presented in Table 4.1. After that, the absolute averages from the Bilsom UF-1 device were subtracted from those of V13; meaning that a positive difference indicates that V13 achieved a greater attenuation, and vice versa.

For the frequencies above 2000 Hz the difference is positive, and as described before, favorable, since it denotes that V13 outperformed the Bilsom UF-1 device (Table 4.1). However, for the lower frequencies the opposite happens, since V13 reaches smaller average attenuation levels. As Table 4.1 shows, the Bilsom UF-1 earmuff has an overall absolute average attenuation of 24.14 dB, while V13 only reaches 18.04 dB.

**Table 4.1. V13 and Bilsom UF-1 Average Attenuation from 125 to 8000 Hz**

<table>
<thead>
<tr>
<th>Frequency Range (Hz)</th>
<th>125 - 8000</th>
<th>125 - 1000</th>
<th>2000 - 8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>V13</td>
<td>18.04</td>
<td>1.94</td>
<td>40.61</td>
</tr>
<tr>
<td>Bilsom UF-1</td>
<td>24.14</td>
<td>14.00</td>
<td>33.00</td>
</tr>
<tr>
<td>Difference</td>
<td>-6.10</td>
<td>-12.06</td>
<td>7.61</td>
</tr>
</tbody>
</table>

The obtained results suggest that, although V13 reached a high attenuation level of 40.61 dB in the frequency range of 2 to 8 kHz, it does not perform as effectively for all frequencies. With an average attenuation of 18.04 dB, V13 is below the 25 dB value specified in the design requirement list (Table 3.1). Furthermore, when compared to earmuffs that were available in the market and presented as HPDs, V13 presents inferior capabilities to reduce noise levels. Therefore, the noise-reduction objective of the device is not being accomplished for the complete spectrum of tested frequencies. In order to declare that the device designed functions as an HPD,
the difference between V13 and the Bilsom UF-1 earmuffs should remain on the positive spectrum, indicating that a larger attenuation value is being achieved.

4.3. Impulse response results

Since V13 has a DSP amongst its electronic components, it is expected to observe a delay in the impulse response of the headset in comparison to the impulse response of Unaided KEMAR. Analyzing the delay is relevant since the results obtained can indicate whether the signal has a perceivable set back. The delay between the response of Unaided KEMAR and V13 was measured to analyze if it would be unnoticeable to the device’s user. For the delay to be within an acceptable limit is crucial regarding user comfort, since a delay of more than 10 ms can lead to undesirable effects such as mismatch in speech intelligibility and audio signal and echo (Launer et al., 2016). Therefore, the impulse response of Unaided KEMAR and V13 were both captured to compare the difference in time between one and the other.
Figure 4.3. Impulse response plots for Unaided KEMAR and V13

Figure 4.3 shows the results obtained by GN Resound, in which both responses are depicted. The plot displays the sound pressure levels (SPLs) generated by V13 and Unaided KEMAR at different time points, with a preset delay of 5.940 ms. The graphic representation of the data can lead to the presumption that there is a delay of 4 ms between the signal generated by Unaided KEMAR and V13. To confirm the exact delay in V13, the raw data of the impulse response was analyzed as follows: the starting point of the signal was determined to be when the SPLs first reached a value of 0.100 Pa, while the finishing point for the sound wave was selected as the instant that the SPLs had a value of 0.050 Pa and decreased further. These considerations led to the values shown in Table 4.2, which contains the beginning and ending times of the acoustic signal. The delay between the start point for V13 and Unaided KEMAR is of 4.400 ms, which is
close to the estimated value and within the time limits for an acceptable delay. The analysis demonstrates that the delay of V13 would not cause a perceivable effect on the user, preventing possible discomfort. A spectrogram provided by GN Resound depicting the results for both V13 and Unaided KEMAR can be seen in Appendix Figures 4.1 and 4.2.

**Table 4.2. Impulse response delay and acoustic wave duration of Unaided KEMAR and V13**

<table>
<thead>
<tr>
<th>Start Point</th>
<th>Unaided KEMAR</th>
<th>V13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (ms)</td>
<td>-0.25</td>
<td>4.15</td>
</tr>
<tr>
<td>SPL (Pa)</td>
<td>0.14</td>
<td>0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>End Point</th>
<th>Unaided KEMAR</th>
<th>V13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (ms)</td>
<td>1.29</td>
<td>6.80</td>
</tr>
<tr>
<td>SPL (Pa)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal Length (ms)</th>
<th>Unaided KEMAR</th>
<th>V13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.54</td>
<td>2.65</td>
</tr>
</tbody>
</table>

On the other hand, the duration of the acoustic signals was also examined for the two devices. As highlighted in Figure 4.3, the extent of the signals for the two groups exhibits a difference. For the identification of the starting and ending points to determine the delay of V13, the raw data was used to calculate the duration of both acoustic signals. The values obtained illustrated that the lengths between V13 and Unaided KEMAR are not identical (Table 4.2). The acoustic wave of V13 extends 1.110 ms further in comparison to the length of Unaided KEMAR. However, the longer interval of the captured signal in V13 is generated by a ringing inherent to the DSP. Nevertheless, this does not increase the delay and does not represent a possible inconvenience to the user.
4.4. Acoustic results for V13

4.4.1. Magnitude sound pressure levels over frequencies and azimuths

Amongst the multiple indicators used throughout the literature for the intensity of acoustic waves, sound pressure level (SPL) is one of the most common. It is directly correlated to the strength of sound waves, and it could be associated to the human perception of sound volume (Bies & Hansen, 2003; Long, 2014). According to Bies and Hansen (2003), for humans to distinctly notice variations in loudness, the change in SPL should be of 5 dB, since changes of 3 dB or lower tend to be barely perceivable to the hearer. The magnitude of the SPLs was measured to compare the response between V13 and KEMAR, to verify that the design of V13 was not interfering with the SPL reaching the device’s user. Figures 4.4 and 4.5 shows the SPLs corresponding to the amplitude measured in Unaided KEMAR and V13 in relation to four azimuths. Additional 3D plots and spectrograms for the amplitude of V13 and Unaided KEMAR can be found within Appendix Figures 4.3 and 4.4. Although the test which yielded the results in this section was performed for all azimuths between 0° and 360°, in increments of 10°, the azimuths selected correspond to the direction in front (Fig. 4.4a), behind (Fig. 4.4b), and at both sides of KEMAR (Fig. 4.5). The variation between the two datasets was quantified by subtracting the values of Unaided KEMAR from those of V13 for the frequency ranges in Table 4.3., which displays all calculated differences.

Table 4.3. Average amplitude absolute differences between V13 and Unaided KEMAR

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>0°</th>
<th>90°</th>
<th>180°</th>
<th>270°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000 - 10,000</td>
<td>3.25</td>
<td>4.97</td>
<td>3.02</td>
<td>4.11</td>
</tr>
<tr>
<td>100 - 20,000</td>
<td>12.01</td>
<td>13.01</td>
<td>10.82</td>
<td>10.71</td>
</tr>
</tbody>
</table>
Figure 4.4. Amplitude for Unaided KEMAR and V13 a) in front and b) behind of the KEMAR manikin.
The most notable differences in responses between both plots are within the frequency ranges below 1 kHz and above 10 kHz. As seen in Fig. 4.4b, the SPL results for V13 are significantly below those for Unaided KEMAR. The plots corresponding to V13 donned on KEMAR are lower in the y-axis than those for Unaided KEMAR. The calculated absolute average difference for all frequency values reflect this behavior, particularly in contrast to the values for the frequency range between 1 kHz and 10 kHz. These variations in response are attributed to the frequency range in which the digital sound processor (DSP) used for the device adequately functions. Since the DSP incorporated within the headset operates in the frequencies between 1 kHz to 10 kHz, all SPL for frequencies outside this scope are not accurate, meaning that there is no sound being emitted by the speaker connected to the DSP.

Another remarkable contrast between the responses for V13 and Unaided KEMAR is found at the frequency range between 3.15 and 4.75 kHz, where the data shows a dip in amplitude (dB), highlighted in Figure 4.4a. Although the frequencies are within the working range of the DSP, the variation between V13 and Unaided KEMAR is significant in comparison to the rest of the frequency values within 1 and 8 kHz. The data reflecting the dip described is shown in Table 4.4, where the differences between V13 and Unaided KEMAR for the four azimuths in Figures 4.4 and 4.5 can be seen to gradually increase from and decrease to values of less than 1 dB. The wavelengths corresponding to these frequencies are between 109.52 and 72.63 mm, which are close to the dimensions of muff as shown in Figure 4.6. Said amplitude drop and increased difference to Unaided KEMAR might be attributed to the muff dimensions, since the wavelengths are similar in size and could start reflecting off from the device (Talbot-Smith, 2002).

Apart from the noticeable contrasts described, the data obtained within the working frequency range of the DSP exhibits that both groups have a similar behavior across all azimuth
values. The absolute average differences for the working frequency spectrum of the DSP are near one third than the ones for the complete frequency range. The absolute amplitude of the sweep signal used for the experiments is mainly influenced by the DSP configuration, however, an inefficient mechanical design could lead to unfavorable results. Overall, the average difference in SPL for the four azimuths within 1 kHz and 10kHz is approximately 3 dB. Meaning that the data shown in Figures 4.4 and 4.5 demonstrates that the mechanical design does not affect the amplitude of the acoustic signal.
Figure 4.5. Amplitude for Unaided KEMAR and V13 at the a) left ear and b) right ear of the KEMAR manikin
Table 4.4. Average amplitude absolute differences between V13 and Unaided KEMAR for the frequencies between 3,350 and 4,750 Hz

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Average Differences (V13 - Unaided KEMAR) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,350</td>
<td>0°    1.68</td>
</tr>
<tr>
<td>3,550</td>
<td>0°    4.07</td>
</tr>
<tr>
<td>3,750</td>
<td>0°    5.94</td>
</tr>
<tr>
<td>4,000</td>
<td>0°    7.87</td>
</tr>
<tr>
<td>4,250</td>
<td>0°    7.17</td>
</tr>
<tr>
<td>4,500</td>
<td>0°    3.90</td>
</tr>
<tr>
<td>4,750</td>
<td>0°    1.01</td>
</tr>
</tbody>
</table>

Figure 4.6. V14 Outer muff dimensions
4.4.2. Directivity index

As stated throughout this thesis, one of the principal goals of the designed headset is to preserve sound localization while attenuating noise. Therefore, amongst the results obtained by GN Resound, the directivity index (DI) was calculated to establish if the device fulfils the objective previously mentioned. The DI indicates the difference between sounds coming from an azimuth of 0° to sounds originating from different directions around a device (Long, 2014). In the case of V13, its DI was determined and compared to the reference of Unaided KEMAR to verify if the directionality of sound was maintained even when V13 was donned on the manikin. Additionally, the DI for two previous versions of the device, as well as a GN Resound in-the-ear (ITE) hearing aid, were included in the comparison.

Table 4.5. DI average differences comparison

<table>
<thead>
<tr>
<th>Frequencies (Hz)</th>
<th>Absolute Average Differences DUT - Unaided KEMAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V07 - Unaided</td>
</tr>
<tr>
<td>All</td>
<td>2.42</td>
</tr>
<tr>
<td>&lt;1000</td>
<td>0.70</td>
</tr>
<tr>
<td>1000 - 2000</td>
<td>1.87</td>
</tr>
<tr>
<td>2000 - 3000</td>
<td>2.52</td>
</tr>
<tr>
<td>3000 - 4000</td>
<td>2.13</td>
</tr>
<tr>
<td>4000 - 5000</td>
<td>4.97</td>
</tr>
<tr>
<td>5000 - 6000</td>
<td>6.37</td>
</tr>
<tr>
<td>6000 - 7000</td>
<td>8.12</td>
</tr>
<tr>
<td>7000 - 8000</td>
<td>2.87</td>
</tr>
<tr>
<td>8000 - 9000</td>
<td>5.23</td>
</tr>
<tr>
<td>9000 - 10000</td>
<td>5.28</td>
</tr>
<tr>
<td>&gt;10000</td>
<td>3.00</td>
</tr>
<tr>
<td>1000 - 8000</td>
<td>3.52</td>
</tr>
</tbody>
</table>
The DI raw data for all devices analyzed, listed in Table 4.5, was gathered for 75 frequency values within a range of 205 Hz to 14.5 kHz. To quantify and compare the difference of each device under testing (DUT) in relation to Unaided KEMAR, the data was organized into the frequency intervals shown in Table 4.5. The method to compute the absolute average difference was similar to the one used in the analysis of the amplitude, which involved subtracting the data points for Unaided KEMAR from those of the devices tested. This allows an organized visualization of how V13 performed in contrast to the previous two versions of the device, versions 07 and 10 (V07 and V10), and the GN Resound ITE hearing aid.
Figure 4.7. Directivity Index differences between V07, V10, V13 and an ITE Hearing aid for frequency ranges of 1 kHz. a) Graph of discrete data points joined by a line for better visualization. b) Graph only portraying each discrete point for the different frequency ranges.
Figure 4.7 shows the absolute average differences for all frequencies and for each of the frequency groups shown in the x-axis of the graphs. The obtained values were graphed in two formats, one featuring a line that joins the discrete points of each of the devices tested for better visualization (4.7.a), and an additional format portraying only the discrete values for each of the frequencies (4.7.b). The results demonstrate that V13 had less significant differences for over half of the frequency groups, as well as for the overall frequency range. Although V13 had a higher difference than its predecessors for the remaining frequency groups, the highest difference value for V13 was of 3.48 dB which is around 30% less than the 5 dB threshold for it to be noticeable, meaning that it is close to Unaided KEMAR; furthermore, as stated before, it obtained the lowest overall absolute average difference with 2.18 dB, as highlighted in Table 4.5. In comparison, the second lowest difference, which corresponds to V10, is 6% higher than that of V13. It can be affirmed that V13 had the best performance in terms of directivity, being the closest DUT to Unaided KEMAR; and thus, conserving sound localization.

4.4.3 Polar plots of V13 and unaided KEMAR

A separate test was performed to evaluate the sound localization preservation capacity of the headset. As for the Directivity Index results, V13 and the ITE Hearing Aid were compared against Unaided KEMAR. The polar patterns for the Unaided KEMAR, V13 and the ITE Hearing Aid are shown in Figures 4.8 to 4.10, respectively, and they display the acoustic intensity captured by the KEMAR manikin for a variety of frequencies within the working range of the DSP at 37 different azimuths ranging from 0° to 360°, which provides a visual representation across the horizontal plane at a 0° elevation. Since the objective of the headset is to preserve sound localization, the plots were created to verify that the polar patterns for V13 where similar to those of Unaided KEMAR. Like for the Directivity Index, a lower difference represents a higher
conservation of sound localization. The ITE Hearing Aid was also measured to have and additional reference of the polar patterns for another device. Additional polar patterns for frequencies above 8 kHz, and outside the working range of the DSP, can be found in Appendix Figures 4.5, 4.6, and 4.7. Furthermore, 3D plots and spectrograms of the normalized gain response used by GN Resound to obtain the directivity index are shown in Appendix Figures 4.8 through 4.11. All polar patterns, along with the data from where they were generated, were provided by GN Resound.

**Figure 4.8.** Polar plots for Unaided KEMAR from 103 to 7290 Hz
Figure 4.9. Polar plots for V13 from 103 to 7290 Hz
To confirm the visual similarities between V13 and Unaided KEMAR in contrast to the ITE Hearing Aid, the raw data for the polar plots of the frequencies in Figures 4.8 to 4.10 was studied. The comparison was quantified with a similar method as for the Directivity Index, by obtaining the average absolute differences between the DUT and Unaided KEMAR. As shown in Table 4.6, said variations were calculated for the 12 frequency values under 8 kHz plotted in Figures 4.8 through 4.10. The results show that V13 had lower differences for 75% of the
frequencies analyzed, and while for the remaining frequencies the opposite occurred, these were outside or near the threshold of the working frequency range for the DSP. Furthermore, the highest difference for V13 reached only 4.50 dB, while the maximum for the ITE Hearing Aid was 7.84 dB, demonstrating that V13 had a less significant discrepancy to Unaided KEMAR. A notable observation for the values in Table 4.6 is that the highest difference for V13 is at 4.34 kHz, which falls within the frequency range at which the dip in the amplitude graphs in Figures 4.4 and 4.5 was located. It could be hypothesized that this is caused by the same phenomenon discussed in Section 4.4.1, where the muff dimensions start matching the wavelengths generated and interfering with the sound pressure levels.

**Table 4.6.** Polar plot differences between DUT and Unaided KEMAR for frequencies below 8 kHz

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>103</th>
<th>259</th>
<th>516</th>
<th>103</th>
<th>1540</th>
<th>2590</th>
<th>3650</th>
<th>4340</th>
<th>4870</th>
<th>5460</th>
<th>6490</th>
<th>7290</th>
</tr>
</thead>
<tbody>
<tr>
<td>V13 - Unaided KEMAR (dB)</td>
<td>0.80</td>
<td>0.87</td>
<td>1.81</td>
<td>1.85</td>
<td>1.93</td>
<td>2.58</td>
<td>1.69</td>
<td>4.50</td>
<td>1.68</td>
<td>2.21</td>
<td>1.62</td>
<td>3.51</td>
</tr>
<tr>
<td>Hearing Aid - Unaided KEMAR (dB)</td>
<td>0.37</td>
<td>0.69</td>
<td>2.03</td>
<td>1.35</td>
<td>2.23</td>
<td>3.96</td>
<td>4.29</td>
<td>5.90</td>
<td>7.84</td>
<td>6.62</td>
<td>4.73</td>
<td>5.36</td>
</tr>
</tbody>
</table>

4.5. Speaker performance with magnetic coupling

Electromagnetic interference has been proven to disturb the adequate functioning of hearing aids (Skocz, 1998), which generated concerns when the idea of a magnetic coupling was initially proposed as a new feature of V14. Additionally, the magnets are the mechanism by which
the connection from the DSP to the speaker is achieved. Therefore, in order to verify that the magnetic coupling did not interfere with the acoustic performance of the electronic components, or the signal transmitted from the DSP to the speaker, the circuit used in V14 and V15 was tested with and without the inclusion of the magnetic coupling. The results are shown in figure 4.11, where the SPLs for both groups are presented across a frequency range of 1 to 10 kHz. To compare the variation between the circuit with the magnetic coupling and the control setup, the raw data produced by the REW Software was examined. The average difference of the V14/V15 circuit from the control group was quantified, yielding a 1.56 dB result, confirming the closeness between the plots in Figure 4.11. Furthermore, the standard deviation of the data for both experimental setups was calculated as it appears in Table 4.7, both datasets produced values below 1 dB, indicating that the testing process is reliable.

![Speaker Performance With Magnetic Coupling](image)

**Figure 4.11.** Speaker acoustic performance with and without the presence of the magnetic coupling
Table 4.7. Standard deviation values for the acoustic performance data of the control and experimental group

<table>
<thead>
<tr>
<th>Group</th>
<th>Standard Deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.84</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.95</td>
</tr>
</tbody>
</table>

4.6. Voltage regulation for rechargeable battery

The voltage regulated for the rechargeable battery circuit was registered to be 1.181 V, which is within the bounds of the working voltage range of the DSP. The LiPo rechargeable battery reached a maximum charge of 4.2 V and could sustain the load of the electronic components for more than 40 hours. Figure 4.12 shows the completed circuit, with the electronic components that support the device connected. Although the desired voltage was achieved, and the DSP was energized, the initial circuit could not be embedded into the muff due to its dimensions. Figure 4.12 indicates the size of the V14 circuit prototype used in relation to the space that it would occupy within the muff. Therefore, as previously stated, the circuit was redesigned for V15, and successfully embedded into the headset (Figure 4.13). The regulated voltage resulted in 1.194 V due to the change in the PCB used, but the battery time remained the same as for the V14 circuit.
Figure 4.12. Approximate space that the PCB would occupy in the muff for V14

Figure 4.13. V15 rechargeable battery circuit assembled with rest of headset components
Chapter 5 : Conclusions and recommendations for future research

5.1. Conclusions

A new version of the design for a noise-cancelling, sound-preserving hearing protection device was created. This headset iteration, denominated V14, underwent modifications that separate it from its predecessors. These defining features consisted of a magnetic coupling and multiple microphones. A magnetic attachment between the muff and the PEC was generated to promote user convenience and replace the mechanical connection in preceding versions of the headset. The main restriction in the development of this coupling was the preservation of the connection between the DSP of the device and the speaker, as well as the acoustic performance of the latter. Before producing the final version of the magnetic coupling, the speaker functioning was tested by creating a setup in which a prototype of the magnetic attachment was incorporated into the original circuit used for the device. The average difference between the circuit with and without the magnetic connection was less than 2 dB, demonstrating that the acoustic performance of the speaker was maintained in the presence of the magnets. Therefore, the parts that constitute the magnetic coupling were redesigned for fabrication. The PEC from prior iterations of the device was divided into a membrane PEC and an earpiece PEC, which housed the wires that connect the DSP to the speaker. The magnetic coupling was achieved using contact surfaces that transmit the signal between DSP and speaker.

The space for the additional microphones was added into the muff for V14. The new microphones were placed in accordance with a spatial grid that divided the pinna and aligned horizontally to the artificial ear canal. Only two of the three microphones in the device were successfully connected to the DSP provided by GN Resound, since the available DSP lacks the
capacity to sustain more than two microphones. Protections for the microphone cavities at the outermost part of the muff were included to prevent possible damage to the components. Furthermore, the covering shell for the preceding version of the headset was modified to increase its strength and the shielding it provides to the muff. Additional modifications made to the headset involved the relocation of the settings button from the circuit for the device. The button was placed at the outermost surface of the muff to facilitate its use and configuration. All the parts that conform the headset were generated using Fusion 360 and printed using vat photopolymerization. A prototype of a rechargeable battery circuit was designed and built. The main challenge was to obtain a voltage within 1 to 1.2 V, which is the range in which the DSP adequately functions. A 3.7 V Li-ion battery was used and regulated with the LM3674 by Texas Instruments, which delivered a voltage of 1.181 V. After constructing an initial draft in a protoboard, the circuit was soldered onto a PCB.

The final prototype for V14 was constructed, however, design flaws prevented the obtainment of results from the version. To address the possible improvements identified, V15 was designed maintaining the principal features of V14: multiple microphones, a magnetic coupling, and a rechargeable battery circuit. However, the latter two underwent significant alterations to produce an upgraded device. The components of the magnetic coupling were reduced over 10% in thickness, to promote the sealing between the cushion of the headset and KEMAR’s circumaural area by decreasing their distance in respect to the other. Furthermore, the number of magnets per part were changed from three to two, to balance the pull forces and obtain a more uniform union. Finally, the rechargeable battery circuit was redesigned for its embedding. The voltage regulating section of the circuit was transferred to a smaller, micro-PCB that allowed for a better distribution in the available muff space, leading to the successful incorporation of the circuit.
The results for the acoustic tests of the previous iteration, V13, were analyzed. After finalizing the manufacturing process for V13, the prototype was sent to Beltone headquarters for acoustic testing. In comparison to a commercially available HPD, the attenuation levels for V13 were lower, achieving only 18.04 dB in contrast to the 24.14 of the reference earmuffs. Furthermore, the amplitude for V13 and Unaided KEMAR was compared, and the average difference obtained for four azimuths. The values for the amplitude average difference were between 3.02 and 4.97 dB, demonstrating that the mechanical design of the device maintained SPL differences below 5 dB, which is the level perceivable to humans, and thus it can be affirmed that its configuration does not interfere with the intensity of the sound waves. However, higher differences were observed in the frequency range between 3.15 and 4.75 kHz. It is believed that this could be due to sound reflecting from the headset, since the wavelength corresponding to said frequencies match the outer dimensions of the muff. Finally, V13 had favorable results regarding sound localization. The absolute average difference of the DI between Unaided KEMAR and V13 was determined to be 2.18 dB, which is not perceivable to the human ear. Additionally, the polar plots of V13 showed similar patterns to those of Unaided KEMAR, and the highest average difference between both devices was 4.50 dB. Overall, the headset shows that the AM pinna preserves sound localization and can continue to be developed with features that focus on user convenience and comfort.

5.2. Recommendations for future work

Future work should include upgrading the rechargeable battery circuit by incorporating a power button that can allow the user to turn the device on or off, since currently there is no such option available. To further contribute to user convenience, the micro-USB port required for charging the device should be singular, which would implicate using one rechargeable circuit for
the overall device instead of one per muff. Upcoming efforts should also focus on incorporating visual markers that allow the user to easily identify the state of the battery in terms of charge, letting the user know if recharging is needed.

The magnetic coupling developed in this work can also be improved for a version closer to a commercial product. Enhancing the robustness of the magnetic coupling to prevent accidental disconnection can be achieved by using a higher grade of neodymium magnets, which would allow for the needed dimensions to be preserved while increasing the pull force. Furthermore, rotation between the contact plates can also be prevented by adding geometric features that maintain the two parts of the magnetic coupling aligned.

The results of the acoustic tests performed on the V13 prototype indicate a favorable trend regarding sound localization preservation. However, all results were obtained only for KEMAR’s left ear since there was a misalignment on the right side that prevented the personnel at GN Resound from taking accurate measurements of the right muff. Therefore, the performance described in the results section of this paper remain to be corroborated for the right side of the muff. It is believed that the issue with the right muff was generated by mishandling the CAD model of said side of the headset, since it was created by reflecting all components in the left side of the device. In the next version of the device, currently under work, this step in the design of the right side of the headset was corrected to improve its fit with KEMAR’s right ear. However, the developments remain to be verified by testing and analyzing the results from V15, which will further provide information regarding its features.

Additionally, the dip in amplitude described in the Magnitude Sound Pressure Levels Over Frequencies and Azimuths section of the paper has been assumed to be generated by the
dimensions of the muff. However, this hypothesis remains to be tested. A proposed experiment for the upcoming developments of the noise-cancelling, sound-preserving headset is to modify the dimensions of the muff and submit the altered design to the same testing conditions as V13. Analyzing these results could lead to the clarification of the reason behind the dip in SPL described previously.

Finally, the attenuation results for the device demonstrate that future efforts should focus on increasing the noise reduction attribute of the headset. Future work should investigate the leakage that the device might present between the cushion and the ear. Improving the sealing of the device will directly affect its attenuation properties, therefore gaps between the cushions and the circumaural area must be avoided. On the other hand, additional material, such as the foam that commercial earmuffs have integrated, could be integrated to promote noise reduction.
References


Appendix

**Appendix Figure 4.1.** Impulse response spectrogram of Unaided KEMAR

This plot shows impulse responses over time and azimuths. Measured with fixed delay of 5.94ms. Colors represent levels and vertical offset represents time of arrival relative to 5.94ms for GLV BioLab setup.

Multiplyer M = 600. When comparing plots, be sure to set same multiplyers in all files.
Appendix Figure 4.2. Impulse response spectrogram of V13
Appendix Figure 4.3. 3D graphs of the amplitude levels for a) Unaided KEMAR and b) V13 over frequency and azimuth
Appendix Figure 4.4. Spectrograms of the amplitude levels for a) Unaided KEMAR and b) V13 over frequency and azimuth.
Appendix Figure 4.5. Polar plots for Unaided KEMAR for frequencies above 8 kHz
Appendix Figure 4.6. Polar plots for V13 for frequencies above 8 kHz
Appendix Figure 4.7. Polar plots for ITE Hearing Aid for frequencies above 8 kHz
Appendix Figure 4.8. 3D graphs of the normalized responses of a) Unaided KEMAR and b) V13 over frequency and azimuth.
Appendix Figure 4.9. 3D graphs of the normalized response of an ITE hearing aid over frequency and azimuth.
**Appendix Figure 4.10.** Spectrograms of the normalized responses of a) Unaided KEMAR and b) V13 over frequency and azimuth
Appendix Figure 4.11. Spectrogram of the normalized response of an ITE hearing aid over frequency and azimuth.
Vita

Brenda Valadez was born in Durango, Mexico, where she completed her first years of education. For her academic performance, she was awarded the first-place grant for high school studies, and a second-place grant for undergraduate studies. Both degrees were obtained at Instituto Tecnológico y de Estudios Superiores de Monterrey in Ciudad Juárez, Mexico, where she graduated with a B.S. in Mechatronics Engineering with excellence honors in 2019. Her projects as an undergrad centered on applying her knowledge to create biomedical engineering projects. As a graduate student, she continued to focus on the development of biomedical devices. Her involvement in the W.M. Keck Center for 3D Innovation centered on learning to merge biomedical engineering and additive manufacturing.