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Thesis

CRESCENDO: DEVELOPING A SMARTPHONE BASED HEARING SYSTEM

UNDERGRADUATE THESIS

B.S.c Computer Science

Zoe Tagboto

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UNDERGRADUATE THESIS

Undergraduate Thesis submitted to the Department of Computer Science, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Computer Science

Zoe Tagboto

2020

DECLARATION

I hereby declare that this Undergraduate Thesis is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: ....

Candidates Name: ....

Date: ....

I hereby declare that preparation and presentation of this Undergraduate Thesis were supervised in accordance with the guidelines on supervision of thesis laid down by Ashesi University.

Supervisor's Signature: ....

Supervisor's Name: ....

Date: ....

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This thesis was completed with the help, support and contributions of many people whom I appreciate greatly. Unfortunately, as a result, I cannot individually name all those who assisted me. However, I would like to recognize, with utmost gratitude, some specific individuals for their contributions to the success of this thesis.

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Furthermore, I would like to thank my little sister, Emefa Tagboto. She inspired me to take on this challenge. Her willingness to answer questions and share insights into the difficulties faced by the hard of hearing community motivated me to stay on task even in the hardest times.

Abstract

The ability to hear is an integral part of being a human being. It plays a vital role in various facets of the human experience, communication, listening to music and even being aware of one's environment. Unfortunately, not everyone is born with this gift, and the hard of hearing or deaf are thus isolated from society; simply because they cannot communicate and build social connection in the same way as the hearing population. The development of hearing aids was the attempt to bridge that gap; however, the considerable expense and lack of production mean that these assistive technologies are not accessible to those that really need it. Although this has continuously been an issue, the adoption of smartphones across the globe means that technology is more accessible to people no matter what part of the world they live in. Discoveries in digital signal processing algorithms also suggest that sound can be manipulated to augment users hearing. The combination of these accessible devices and improvements in technology means that there should be a way to provide low cost, accessible hearing devices to all individuals, even those from low-income countries. This research will explore how a functional application may be created both to test a users hearing and function as a hearing aid. **Keywords:** *Digital Signal Processing; low income; audiologists; smartphones; hearing loss*

Contents

1 Introduction and Background

Approximately 466 million people worldwide suffer from disabling hearing loss, which is defined as hearing loss higher than 40 decibels (dB) in the better hearing ear for adults and hearing loss greater than 30 dB in the better hearing ear for children [15]. Globally this costs 750 billion dollars annually, and most of these costs are incurred by low to middle-income countries[15]. These figures are in part due to the limited resources in such countries which prevent the provision of adequate ear and hearing care services to these under-served populations. The high costs and lack of resources have led to hearing loss being more common in low to middle-income countries, and over 10% of those with disabling hearing loss are located in sub-Saharan Africa [15].

Although the figures are alarming, initiatives by the World Health Organization (WHO) and various other social enterprises have been put into place to combat hearing loss and the rising costs associated with it. There are numerous ways in which this issue has been addressed including early identification of hearing loss, provision of hearing devices, and raising awareness of as well as empowering individuals who suffer from hearing loss [15]. However, the most practical approach to tackle this issue is the provision of hearing devices which have been said to be the most cost-effective primarily when supported with rehabilitation services making it the dominant strategy recommended by the WHO [15].

Although hearing aids are the primary devices focused on solving this issue, the production of hearing aids is not enough to meet the rapidly growing need, meeting only 10% of the needs globally. In developing countries, this figure is much worse with, less than 3% of individuals who need hearing aids having one [7]. This is in part due to the expense of owning these devices since they can range from $1800 to $10,000 [7]. Apart from their initial cost, hearing aids mostly use non-rechargeable batteries that need to be replaced once a week, thus proving unaffordable for people with low incomes [7]. In numerous countries, including Ghana, these costs are excluded from the national health insurance policies meaning those with hearing loss have to fund these purchases themselves or wait for possible donations by Non-Governmental Organizations (NGO's) [14] [2, 11]. Even when these devices can be purchased, in many mid to low income countries, there are not enough trained personnel to correctly fit the hearing aids to the people who need them [15]. In Ghana, for example, it is estimated that there only 20 audiologists in the entire country, approximately one audiologist per every 1,126,000 individuals [7, 12]. The limited resources result in long wait times meaning many people who suffer from hearing loss and may thrive from the use of hearing aids are undiagnosed and unable to get fitted contributing to the high costs associated with hearing loss.

The goal of this research is to improve access to hearing devices, particularly in middle to low-income countries, which can be done by converting devices owned by a large percentage of the population into hearing devices. Smartphones and their adoption across sub-Saharan Africa have quadrupled across the last decade [1, 21, 19, 22]. Ghanaians are estimated to be among the top smartphone users in the continent with over 1/3 of the population using smartphones [19, 21, 22]. This number is slated to grow dramatically with governmental initiatives to provide smartphones and other specialized software to students with disabilities [13]. For this reason, this paper will aim to investigate the possibility of harnessing the computational power of smartphones combined with the users' earphones to create hearing devices that would not be affected by the limitations of the current healthcare system for those with a hearing impediment. This will be answered by investigating whether the use of digital signal processing algorithms can be used to convert a smartphone to a hearing device.

1.1 Research Questions

How to developing low cost hearing devices for those in low income countries has increasingly become more important. However, there is very little work being done on how to do this without the use of traditional hearing aids. Despite this demands for better earbuds, and earphones that are noise cancelling mean that researchers are consistently improving hardware, and digital signal processing algorithms to better augment users hearing experiences.

This research is predominantly centred on the development of an application that can provide low-cost, accessible hearing devices specifically to people living in low-income countries. The research questions that would be explored and answered in this work are:

1. How far can we go with building a hearing aid system using a smart phone and digital signal processing algorithms?
2. Can a pure tone audiometry test be built using data to create a comprehensive hearing application ?
3. Can the hearing application work in real time?

2 Related Work

2.1 Low Cost Hearing Solutions in the Developing World

The profound lack of hearing aids to fulfil global needs is not a new problem, and it has motivated numerous innovative low-cost projects aimed at bettering the poor living conditions faced by hearing-impaired individuals in developing countries. Some of these projects focus on the continuous cost of the batteries needed to maintain the aids thus utilizing solar energy to improve these costs and improve access to these populations [1, 18, 3, 4].

Solar Ear, is a social business based in Brazil focused on creating low cost, solar rechargeable hearing aids that allow those from underprivileged backgrounds to hear again [18]. It focuses predominantly on children by supplying them with affordable hearing devices that improve their ability to develop language skills that will enable them to go to regular schools. This is important because, due to the lack of audiologists and cost of hearing devices, most children in low-income societies are unable to communicate early, which significantly impacts their education and prospects. It was the first rechargeable hearing aid, utilizing solar technology to charge the hearing aid batteries, thus drastically reducing the cost that buying batteries imposes on those who use hearing aids. Although this hearing aid works effectively for individuals with mild to severe hearing loss at a fraction of the cost, starting from around $100 [18], it does require an audiologist to program the device, which is not a free service.

Many other projects aiming to create low-cost alternatives focus on the use of Personal Sound Amplification Devices (PSAPs). These can be used as supplementary hearing aids to address the needs of people with low to mild forms of hearing loss [17, 23, 3]. PSAPs, offer a similar effect as hearing aids however, they do not meet the detailed standards for hearing aids and are most effective for those with mild hearing loss.[23]

However, this research focuses on developing an solution that is accessible to numerous people around the world. For this reason it focuses on the use smartphones, a device that these patients are likely to already have. Then developing an application on this multifaceted device to access a wider range of people. In addition, unlike a traditional hearing aid, this project should not require fittings by an audiologist.

2.2 Over the Counter Hearing Devices

Accessibility of hearing aids is one of the biggest reasons those that need hearing devices are unable to get them. Hearing aids have to be ordered from manufacturers and then specially fitted making their acquisition them a time consuming processes. However, the technological shift toward Bluetooth and the Internet of Things (IoT) may change this narrative. Earbuds are now transforming in becoming hearables “wearable devices that live in your ears [and] enable the customization of environmental sound” [9]. These devices are available over the counter which makes them easily accessible to all. Though they can not be marketed as hearing aids some of these have transformed as they are fitted with technology allowing users to have more control of how they hear based on their environment [20, 6, 9, 8] . The ability to calibrate and take charge of your hearing is something that most traditional hearing aids do not allow without the assistance of an audiologist, prompting people with mild hearing loss to make the transition in order to have more control of what they hear. Although, these devices are seeming to be effective, especially for those with low to mild hearing loss, their price tag is still quite steep and these earphones cost an average of $500, meaning they are still inaccessible for those in underprivileged communities.

Nuheara, is an Australian based company focused on developing audio wearables with hearing technology that allows their users to be able to “seamlessly listen, communicate, and connect to their physical and digital world” (CITE). They created the IQ buds boost, Bluetooth earphones that function as hearing buds for people with low to moderate hearing loss. This is done with their EarID technology which first tests a users hearing ability and then uses this data to automatically calibrate their earbuds to the users personal hearing profile. Although this device is seen to be very useful, especially for individuals with mild hearing loss, the price tag is still quite steep at $500, meaning they are still inaccessible for those in underprivileged communities.

Another example of Bluetooth earbuds that are designed as "conversation-enhancing headphones" are Bose Hearphones [5]. These work by using noise-cancelling and directional microphones to filter out background noise and focus on the sound the user wants to hear. In addition, it also contains real-world settings like group conversation, focused conversation and television to allow users to have control of what they hear based on their specific situations. The Bose Hearphones aren't explicitly marketed to those with hearing impairments; however, they are have been found to have some benefit for those with mild hearing loss [5]. Unfortunately, these earbuds are also quite expensive at around $500; however, unlike Nuheara IQ buds, they do not contain a hearing test.

Although these over the counter devices both have their benefits, this project aims on providing a lower-cost alternative, while capitalizing on the ability of a smartphone to allow users control over their own hearing data.

2.3 Smart Phone Based Research

Combining smartphone technology and hearing aids is not a novel idea and borrowing the computational power of the smartphone has repeatedly been investigated in research. However, most of the research done has focused on the research done on using a smartphone to augment or improve the capabilities of a traditional hearing aid [17, 20]. This approach still relies on using expensive hearing aids that require an audiologist to fit. A luxury that is not available in less-developed countries. Other work done utilizing smart phones and hearing devices have been to test an individuals hearing, thus providing insight into the process audiologist use to fit hearing devices to the hearing impaired [1].

2.4 Hearing Prescriptive Fitting Strategies

In order to create a hearing device, it is first important to test the users level of hearing in order to amplify the frequencies they can't hear. Hearing prescriptive fitting strategies are a way of doing this. In this prescriptive fitting strategy the audiologist is focused on finding "amplification settings that are appropriate for a patient based on his or her audiometric characteristics" [16]. There are a wide variety of hearing prescription strategies being used worldwide which means that there is no specific fitting model that is scientifically more sound than another.

However, when identifying the prescriptive procedures most used by audiologists there are two main verified prescriptive procedures that are most used [10]:

a. National Acoustics Laboratory Non Linear Version 2 (NAL – NL2) This is the hearing loss prescription was developed by the National Acoustics Laboratory in Australia as the updated version of the NAL-NL1 for non linear hearing aids. These devices prescribe different amounts of amplification for Soft, Average, and Loud sounds.

b. Desired Sensation Level Version 5 (DS5) – This hearing loss prescription was developed predominantly for children because they tend to require more amplification than adults as this sound can be critical for speech development. The formula results in different frequency response curves, insertion gain, and compression parameters than the NAL formulas.

2.5 Pure Tone Audiometry

Pure Tone Audiometry, is the most commonly used test worldwide to diagnose and manage hearing loss. It is done to calculate a users hearing threshold which can be defined as "the minimum effective sound pressure level of an acoustic signal producing an auditory sensation.

This test is commonly carried out by an audiologist who checks sounds from 250Hz - 8000Hz for conventional hearing loss and 8000Hz to 12,500 Hz for high frequency hearing loss. These specific frequencies are tested because they are the frequencies at which human speech is heard.

In these testing centers both right, and left ear are tested by playing these tones at different intensities or magnitudes. The hearing level of each individual is recorded at the lowest dB at a specific frequency at which a response can be obtained 3 times by the patient. The results are then mapped by an audiologist to inform a patient as to the type of hearing loss they have.

The sections of Hearing Loss are defined follows:

- Normal hearing up to 25dB
- Mild 25-40dB
- Moderate - 40-55dB
- Moderately Severe 55-70DB
- Severe - 70-90dB
- Profound >90DB

In addition, the audiogram can tell an indivdual not only the level of hearing loss but the type of audiotory disorder they have, and whether hearing aids would be useful for them.

Some of these types are listed below:

- Prebycusis - age-related hearing loss
- Otitis media - fluid in the meddle ear space
- Noise induced hearing loss -due to exposure of high intensity noise
- Otosclerosis - slow progressive conductive or mixed hearing loss
- Menieres disease - attacks that affect the cochlear and vesitubular system
- Sensorineural hearing loss - damage in the inner ear

3 Approach and Methodology

The central hypothesis of this thesis was that a smartphone application could be used as a hearing aid device by amplifying the frequencies the user of the application could not hear via their earphones. In order to evaluate this hypothesis, a proof of concept, Crescendo was built. This application was separated into two key areas

1. Hearing Test

2. Digital Signal Processing

For the hearing test, pure tone auditory data was collected online and then used to build the hearing test portion of crescendo, specific to pure tone guidelines. After which, the users hearing levels were stored in a database. Then, using the data that had been collected, a hearing aid equalizer was built that used various digital signal processing algorithms and filters to adjust the sound the users were hearing.

An overview of the system architecture is shown in Figure 3.1 below

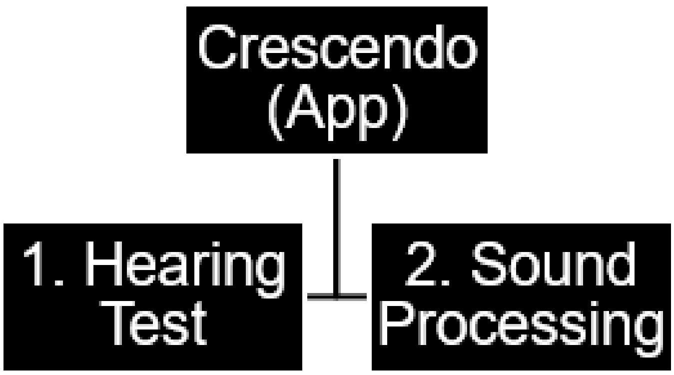

Figure 3.1 - Crescendo

This section will discuss the steps that were taken to evaluate this proposition.

3.1 Collecting Pure Tone Audiometry Data

In order to build the hearing aid system, pure tone audiometry sounds had to be collected. This is because pure tone audiometry is the primary method used by audiologists to diagnose and manage individuals hearing loss. Tones between 250 hertz (Hz) and 8000 Hz were required as that is the international standard for most conventional audiometry tests. This range is recognized because it represents the speech spectrum for human beings.

Six tones were collected from Tone Generator, a sound frequency generator. Only six tones were required because conventional pure tone audiometry calculates hearing in 6 different frequencies(250Hz,500Hz,1000Hz,2000Hz, 4000Hz,8000Hz) Each tone was 2 seconds long, meaning the total duration of all the collection frequencies were 12 seconds. These frequencies were individually created in Tone generator as stored in a .wav format, and each file name was dependant on the frequency (e.g. 250.wav). The tones were tested in PyAudio to ensure the system recognized them as being at the same frequencies as the tone generator. This was because PyAudio was the framework of choice for manipulating frequencies in the digital signal processing part of this project, and consistency was required for the best results.

3.2 Building the Application

A smartphone application was proposed as the approach to building an accessible hearing test. The main reason for this, was that it would make the solution easily accessible to anyone in the deaf community who possessed a smartphone. In addition, there have been proposals by the Ghanaian government and phone companies in Ghana to provide smartphones to students in deaf school meaning the deaf individuals would not need to bear any extra costs [13] . These considerations would ensure that the system being built would be low-cost as the user would only be required to purchase earphones. In addition, the processing power of smartphones and the presence of powerful digital processing chips illustrate the potential of these devices to work as a hearing aid system.

The application itself carries out the following activities:

1. Takes in user data, in order to personalize the experience for each user.

2. Executes a hearing prescription test to collect data about what sounds the user can

hear

3. Publishes user hearing data to a database and provides the user with a graphical representation of such data

After this, the data is then fed to the digital signal processing system to process the sound and sent to the user through the users' earphones. These activities had to be carried out in real-time in order to work as efficiently as traditional hearing aids.

A flow chart of the application is shown in Figure 3.2 below.

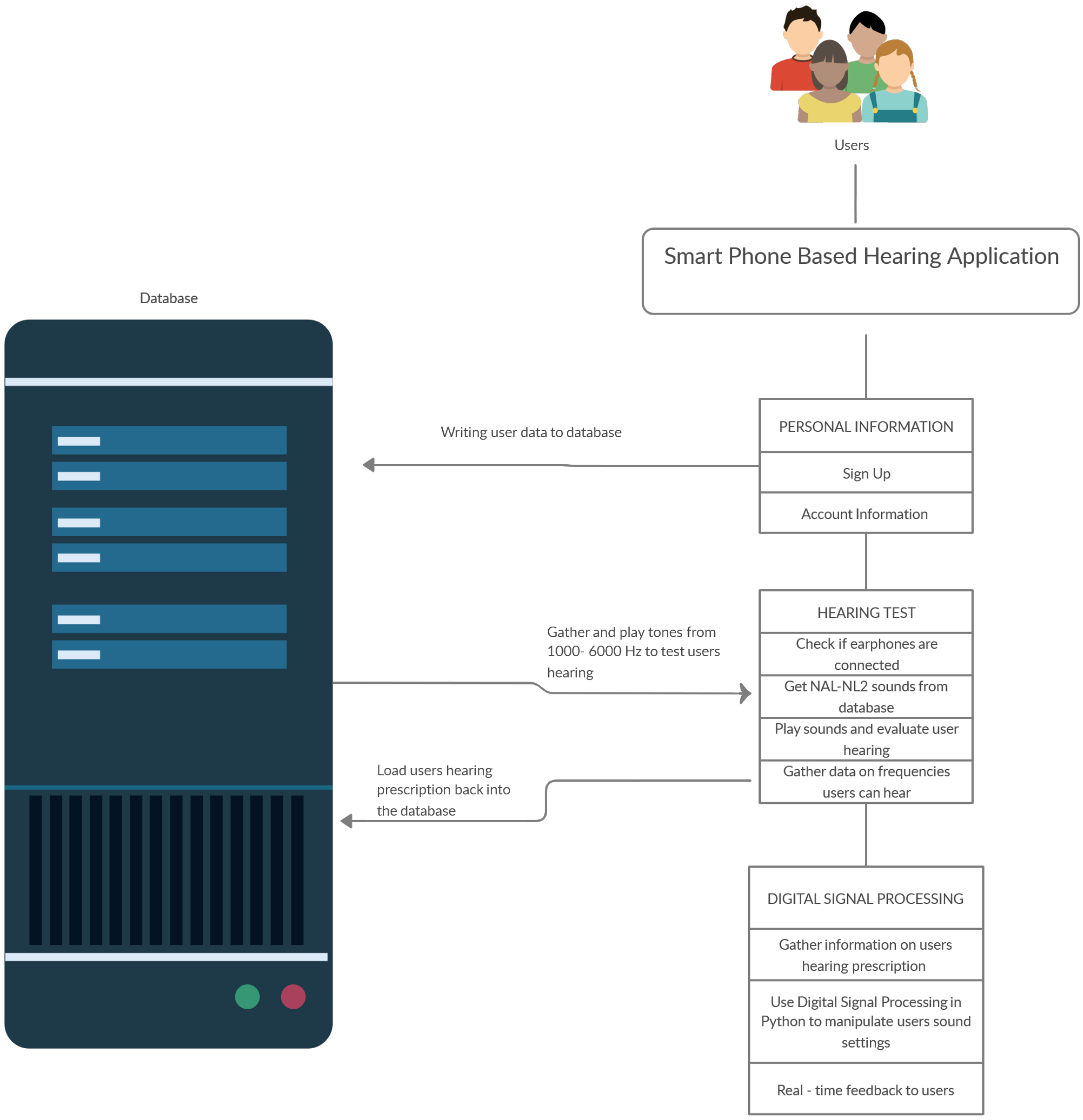

Figure 3.2 - Design Structure

3.2.1 Languages used to develop Crescendo

The application used to implement the proof of concept, Crescendo, for this research was Kotlin. Kotlin was chosen mainly because of its simplicity, the reduction of boilerplate code and its compatibility with Java. It is one of the fastest-growing languages for developing native android mobile applications. This research focuses predominantly on android applications as android have the largest market share globally, meaning an android application would reach more people. In addition, Apple devices tend to be more expensive meaning that they are not as accessible as android devices, especially for those with a low income.

3.3 The Hearing Test

The hearing test is an integral part of the application. This is because, in order to build a hearing aid, it is essential to gather data on what the user can or can not hear. This will give insight into which sounds need to be manipulated to augment each users hearing. Given the lack of audiologists in the country to get this data from, it was essential to collect this data in the application. Although, there are applications currently in circulation that check hearing, these applications do not use certified hearing prescription tests which makes them unreliable and using them could have impacted the results of this study

The pure tone hearing test was chosen for this application for two main reasons. The first being that it is the most commonly used diagnostic test worldwide for hearing loss. This test would be administered to the user by playing tones from 250 Hz to 8000 Hz and using a descending and ascending technique. This technique, involves playing frequencies at different levels of sound intensity. The frequency and the sound intensity level is decreased if there is a response from the user and increased if there is no response from the user allowing the system to identify the range of each users hearing at different frequencies and sound intensities.

In order to do this in the application, the user would be asked to tap on a button every time they heard a tone. This hearing data collected by the hearing test would then be stored in a database and processed by the NAL-NL2 Prescriptive hearing algorithm. This would then be used to inform the digital signal processing stage on the frequencies that needed to be adapted. It would also be presented to the user in an easy graphical format as shown below:

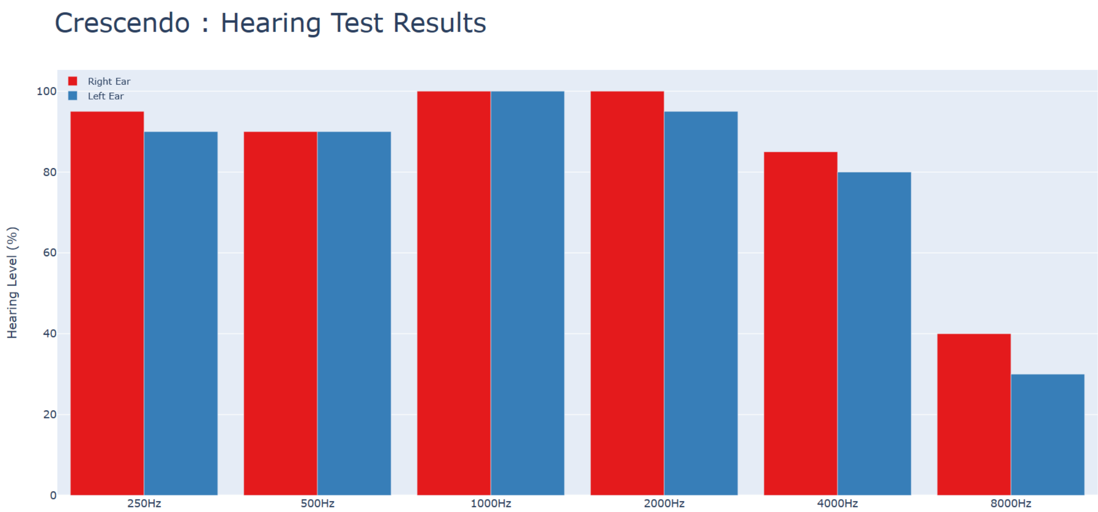

Figure 3.3 -Hearing Test Results

3.4 Digital Signal Processing

The first commercial digital hearing aid was produced in 1996, and the benefits of this have caused digital signal processing (DSP) to be increasingly exploited in hearing aids with digital hearing aids being the most popular hearing aids to date. One of the main reasons for the change from analog to digital systems is the versatility of DSP. Digital signal processing can manipulate signals in an unlimited number of ways which means that it is possible to manipulate the signal to better match the acoustic needs of the patient. The acoustic needs of the patient can depend on the type of hearing loss they have, and the environment they find themselves in. Different environments may require more signal noise reduction (SNR) whilst others may require higher levels of amplification. DSPs adaptability means that these environmental factors can be considered in the algorithms to be executed at the signal processing stage. Below is a diagram explaining how DSP will work with the current architecture to meet these acoustic needs for this research project

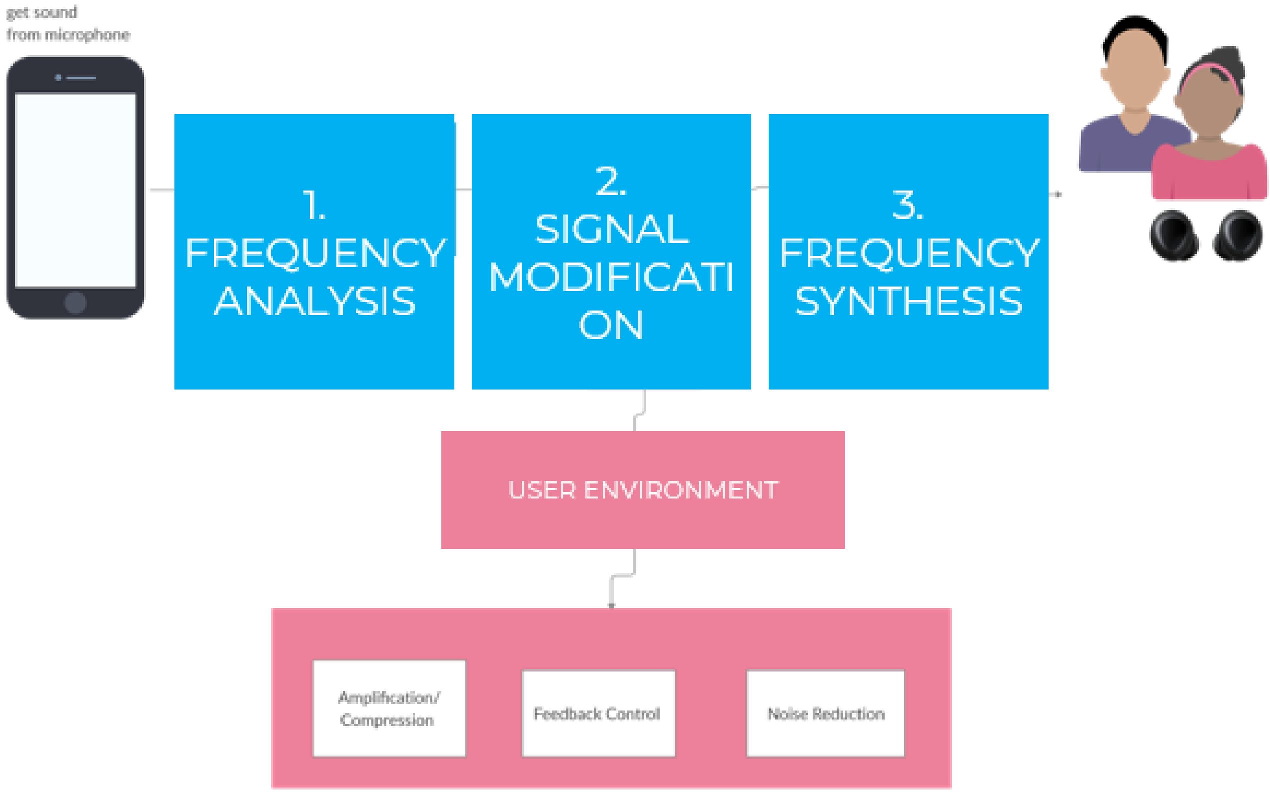

Figure 3.4 - DSP Design Structure

Figure 3.4 depicts the design structure of the hearing equalizer portion of crescendo. It is explained in further detail below:

1. Get Sound from Microphone: The sound would be collected via the smartphones microphone

2. Frequency Analysis: This sound would then be analysed to identify which frequencies are present

3. Signal Modification: This is the processing stage which includes several processing blocks (e.g. amplification and compression, feedback control, noise reduction schemes), which are controlled by automatic environment classification (e.g., activating noise reduction depending on estimated noise condition).

4. Frequency Synthesis

5. Give Sound: The processed data is sent back to the user's earphones or earbuds

3.5 Libraries and Technologies Used

3.5.1 Application Building Tools

In order to build the Crescendo Application the following tools were used for the application development.

- Android Studio – this is the official integrated development environment for Google's Android operating system.

- Kotlin - is the programming language I chose to build my application. This is because it is 100% interoperable with Java and because it is a functional programming language this allows us to reduce code complexity and write more elegant code

3.5.2 Digital Signal Processing Tools

The process of signal analysis in this project included the use of various tools. Which are listed and explained below.

- SciPy – An open source python library for scientific computing and technical computing. It contains signal a module specifically for signal processing algorithms

- Numpy – Library in python for large multi dimensional arrays and matricies. SciPy is heavily reliant on this library to run its algorithms

- Liborosa – Library in python for music and audio analysis

- Pyaudio – PyAudio is a python library that provides bindings for PortAudio a cross-platform audio I/O library
- PyQt5 - PyQt5 is a python module used to build GUI applications in Python.

4 Methodology 2: Implementation

4.1 Implementation of Hearing Test Data

The tones that were collected for the hearing test were chosen because : (1) they are at frequencies that determine human speech and (2) they are the tones used in conventional audiometry tests.

In addition, the sound intensities of these sounds were chosen to be between 5 and 25 decibels (dB). This data was obtained using the NCH Tone Generator, a program allowing sound frequency generation, and therefore research participants were not needed. The recordings were, designed, collected, stored and subsequently used to develop and test the system. After the process of data collection, the recorded audio was tested using PyAudio a python framework for audio analysis in order to ensure consistency across the system.

4.2 Implementation of Hearing Test Program used to collect hearing data

In the implementation of Crescendo, the hearing test application, Kotlin was used to design the application. The MediaPlayer API was used to play specific frequencies at different decibel levels.

First, Crescendo made sure the user was in a quiet environment before the user was able to proceed to the hearing test. This is because any external sound could affect the data collected by the hearing test thus adversely affecting the results of the research

Then the MediaPlayer API was used to play the audio files for each ear. In each ear, the hearing test started playing the sound at the lowest frequency (250 Hz). Each frequency was played initially at an intensity of 30dB. If the user heard this value the intensity would be lowered by 10 dB (to a minimum of 5dB and if not the intensity was increased by 10 dB (to a maximum of 70dB). The minimum and maximum values were enforced because this application was meant for people with mild to moderate hearing loss which ranges from 25-70dB. The application then kept track of which frequencies at which intensities were detected by the user and the number of times. If the user detected a sound at a specific frequency and sound intensity three times, it was recorded in the system as their hearing level. This process was repeated for both ears.

After this was completed, the hearing level of each user for the six different frequencies (200Hz,500Hz,1000Hz,2000Hz,6000Hz,8000Hz) were recorded in a database and presented to the user in a graphical format. This data was then presented to the user in a graphical format and with information about the type of hearing loss they have. To educate the user about hearing loss, given that they were unable to get the education provided if they were able to go to an audiologist. The decision was made not to replicate traditional audiologist results as shown in Figure 4.1 but to present this data in more user friendly manner as shown in Figure 4.2:

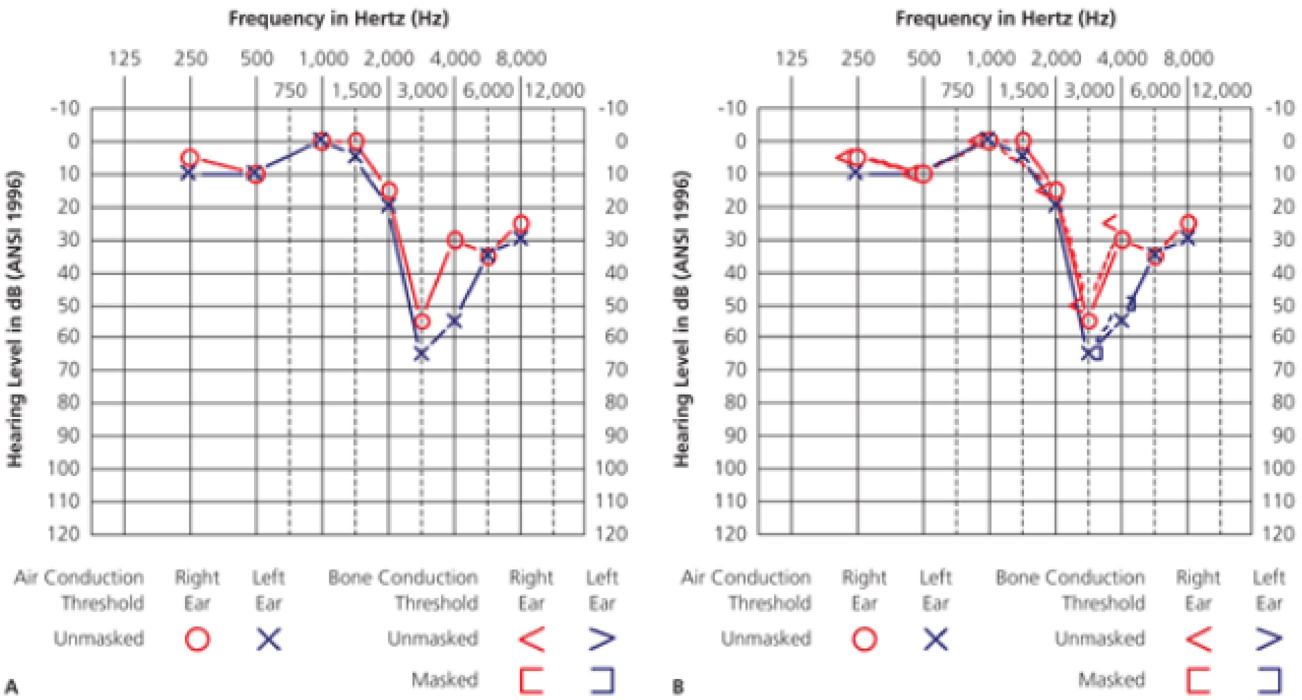

Figure 4.1 - Traditional Audiometry Results

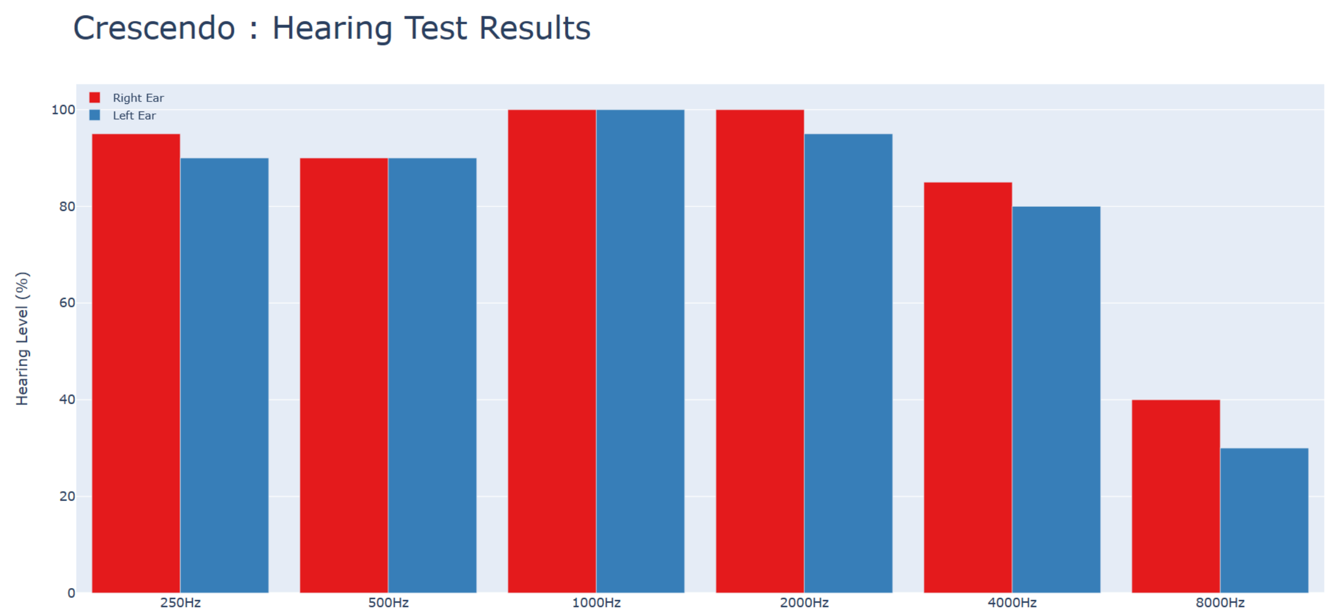

Figure 4.2 - Crescendo : Audiometry Results

Traditional results from a hearing test are displayed on an audiogram, as seen in Figure 4.1. An audiogram illustrates the softest sounds an individual can hear at the different frequencies tested. However, these can be difficult to read without the explanation of a licensed audiologist. Given that Crescendo's users are expected to use this test at home, and without an audiologist, it was vital for them to understand their results. Some conventional parts of the audiogram were kept, for example, red being used to show the hearing level for the right ear and blue being used to show the level for the left ear. However, Crescendo employed the use of a Bar Chart, as shown in Figure 4.2. The x-axis of this bar chart showed the frequencies that were tested, and the y-axis showed the users hearing level in a percentage format. The higher the bar, the more complete their hearing was at that frequency. Then the user was given the following breakdown to help them interpret and understand their results in the graph.

- 85-100% is considered to be normal hearing
- 75-84% is considered to be slight hearing loss
- 60-74% is considered to be mild hearing loss
- 45-59% is considered to be moderate hearing loss

- 30-44% is considered to moderate-severe hearing loss
- 10-29% is considered to be severe hearing loss
- <10% is considered as profound hearing loss

4.3 Implementing the Digital Processing System

The Digital Processing System that was used in this research was built using PyAudio, and PyQt5. PyAudio is a python library that provides bindings for PortAudio a cross-platform audio I/O library. In this research, PyAudio was used to implement the processes of frequency analysis, signal modification and frequency synthesis. PyQt5 is a python module used to build GUI applications in Python.

This system was implemented both in real time and not in real time. This was in order to help with testing. Therefore before frequency analysis, signal modification and frequency synthesis were executed, some data preparation tasks were performed. In this stage, all the testing data was collected and files containing an image representation of frequencies and sound intensity of the testing files were collected. This helped to understand if the features in the initial audio file were the same as the features in the manipulated audio file.

4.3.1 Implementing Frequency Analysis

The process of frequency analysis was done using PyAudio and plotted in matplotlib. The algorithm used to do this was the Fast Form Fourier Transform (FFT). This was done to decompose the audio signals received into the constituent frequencies as well as detecting the magnitude or intensity of each frequency present in the signal. This was important to do because it allowed real-time analysis of the frequencies present in an audio file, providing necessary data for the signal modification stage of the process.

An image representation of this process is presented in Figure 4.3

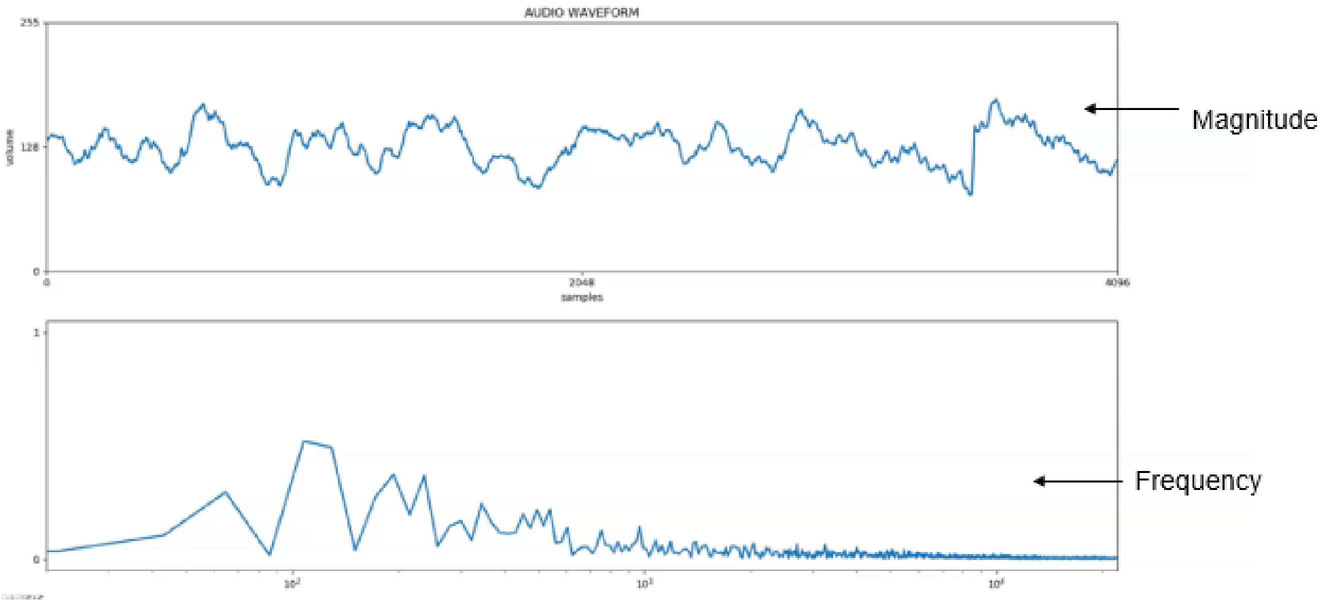

Figure 4.3 - Frequency Analysis

4.3.2 Implementing Signal Modification

The signal modification stage was by far the most complicated stage as it involved various different algorithms and filters that needed to be used in order to properly manipulate the audio. It was done using these python libraries (1)scipy, (2)PyAudio, and (3)numpy

The various stages of the signal modification were:

- Amplification/Compression - This was done in real time using a dynamic transfer function that analyzes the frequencies of the audio present in the wav file, identifies the frequencies that needed to be manipulated and uses filters to amplify the specific signals them then maps them to an output version

- Feedback Control - In order to address the issues with feedback it was needed to adjust the buffer rate. However, the feedback control was less of a problem if earphones were used.

- Noise Reduction - this was done by applying masks to the audio file in order to smooth the signal and reduce unnecessary background noise

4.4 Implementing Frequency Synthesis

PyAudio and scipy were also used for the frequency synthesis part of the digital signal processing stage. These libraries were used to implement the inverse Fast Fourier Transform, which takes the frequency representation that was modified in the signal modification step and synthesises it back into the time domain. To form a signal that can be played back to the user.

5 Experiments and Results

This chapter discusses the experiments which were conducted to assess the performance of Crescendo. In this chapter, both the hearing test and the equalizer, that was developed for the sound processing stage, were tested. This chapter also reveals and discusses the results that were obtained from the experiments that were performed in order to prove or disprove the hypothesis suggested in chapter one.

5.1 Experiments

In this research, various experiments were performed to measure the quality of the hearing test and the digital signal processing model.

5.1.1 Experiment 1 - Assessing Test Precision

This experiment was done to test the efficiency of the hearing aid, portion of the program. The research used an online pure tone audiometry test found on hearingtest.online and aimed to compare that to Crescendo's hearing test. This was to ensure the program was working as precisely as possible. For this experiment, wired earphones were used based on the assumption that the users of Crescendo would only have access to these type of earphones.

HearingTest.online presented its information in a traditional audiogram, whereas Crescendo used a more novel approach to represent its data. Therefore to help with interpreting the results. The following key has been developed.

Hearing Level	**Crescendo**	**HearingTest.online**
Normal Hearing	80-100%	0-20 dB
Mild Hearing Loss	60-79%	21-40 dB
Moderate Hearing Loss	30-59%	41 - 70 dB
Severe Hearing Loss	0-29%	71 -100 dB

The results of this experiment were thus obtained by using the key presented above and comparing the results of the Crescendo audiometry test as shown in Figure 5.1 with the results of an online audiogram test found on hearingtest.online as shown in Figure 5.2.

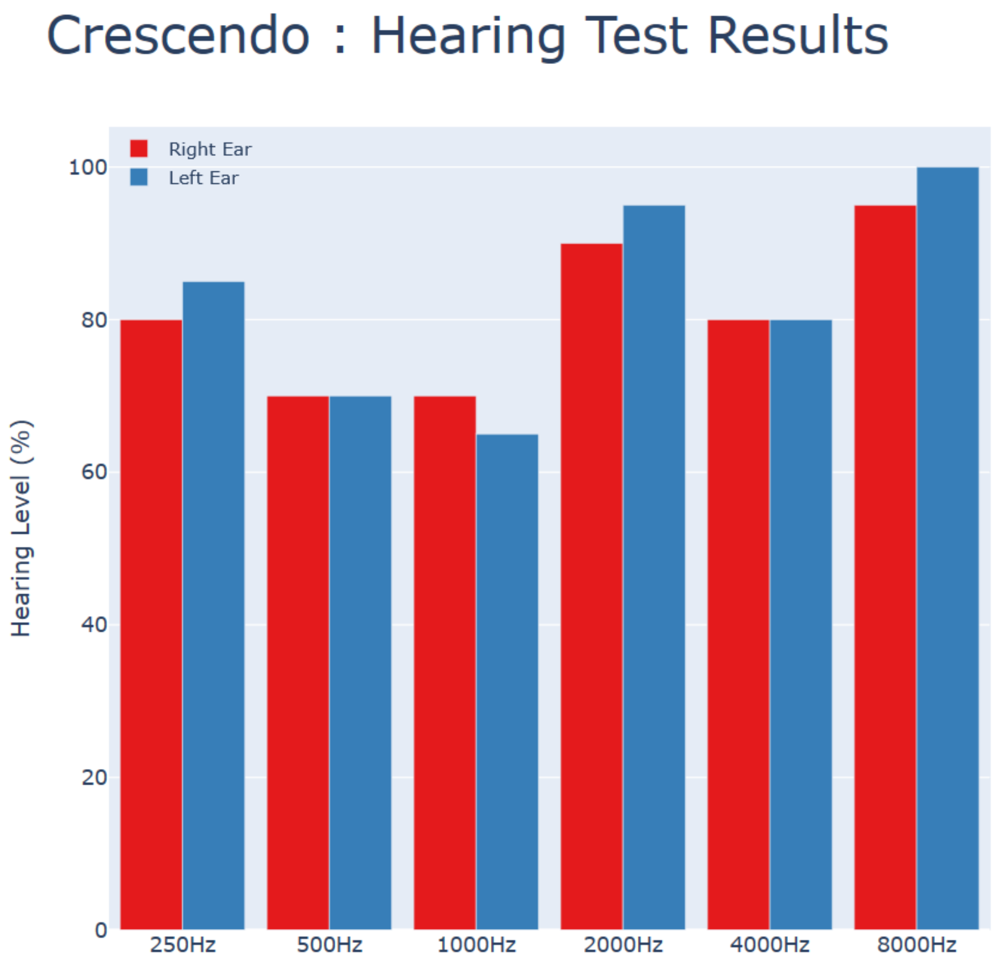

Figure 5.1 - Crescendo Hearing Test

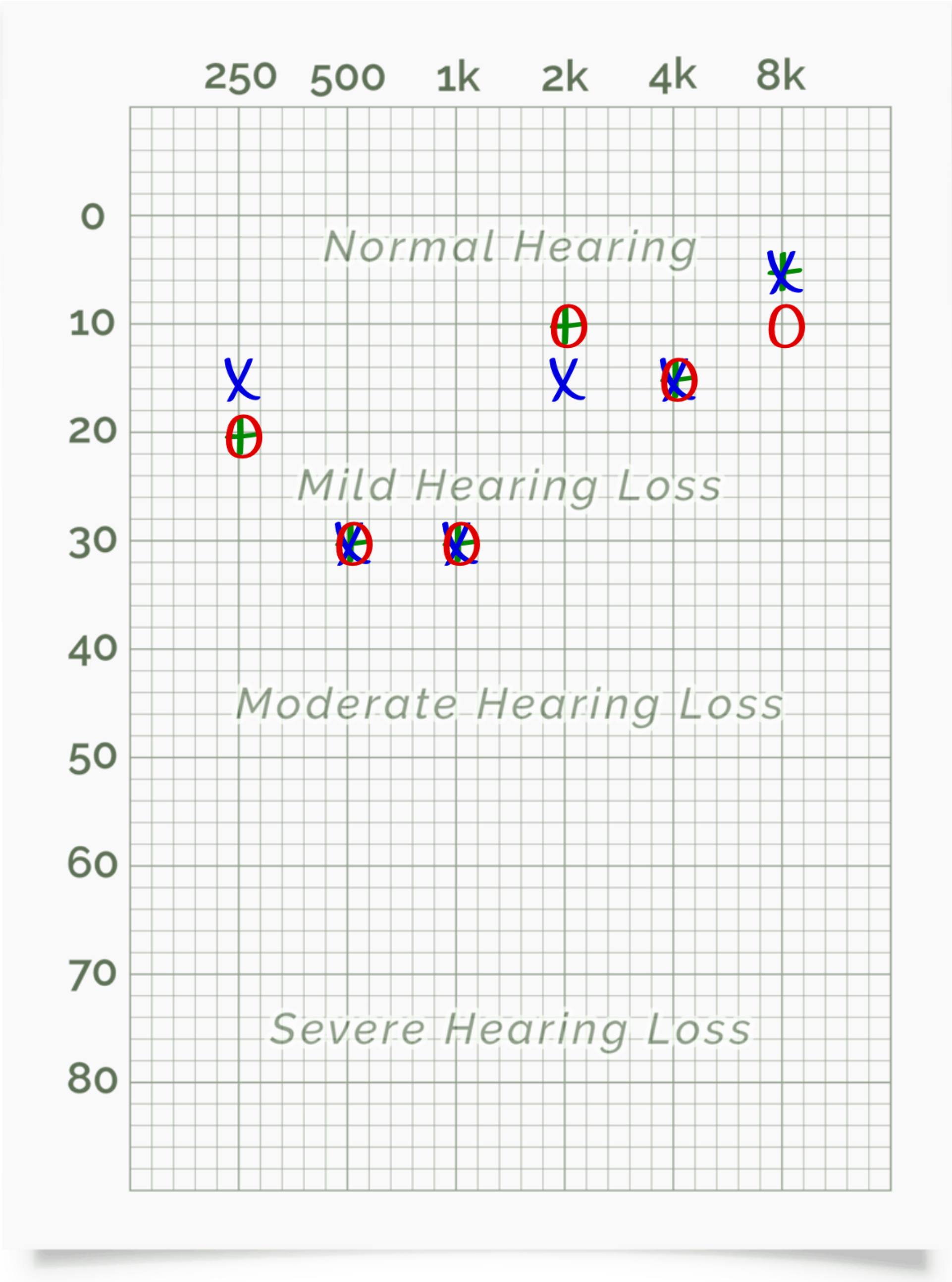

Figure 5.2 -Online Hearing Test

When comparing the results, both the online hearing test (Figure 5.2) and the Crescendo application (Figure 5.1)had very similar results. In both applications, the user had the highest hearing level at 8000Hz, and mild hearing loss at 500 Hz and 1000 Hz. Additionally, it was apparent the users hearing was better in their left ear than their right for most frequencies.

Although the results at the various frequencies were not completely the same, this may have been for multiple reasons. Firstly the tones used from this online system were different from the tones used in Crescendo. Crescendo used one continuous tone for 2 seconds, whereas this test used four tones at the same frequency for 2 seconds. Both these ways of testing are used in pure tone audiometry, but the variations could have led to the slight differentiation in the results of both tests.

Unfortunately, this experiment may lack validity because the online test is not a licensed audiology test. This means that it is impossible to compare Crescendo to the results an individual would have if they went to a licensed audiologist. As the hearing test portion of the Crescendo application was intended to be comparable to a licensed audiology test, the inability to compare with a licensed audiology test means it is hasn't been adequately validated.

However, despite these variations, the similarity in both sets of results meant that if the online test was valid, then this system worked well.

5.1.2 Experiment 2 - Manipulating Single Frequencies

In the second experiment, sound files at specific frequencies were fed into the system. Then the system manipulated the frequencies (amplifying or compressing the frequency represented in the audio file). This was to see whether the system was able to manipulate an individual frequency.

The experiment illustrated in Figure 5.3 and Figure 5.4 aimed to amplify the sound at 1000Hz.

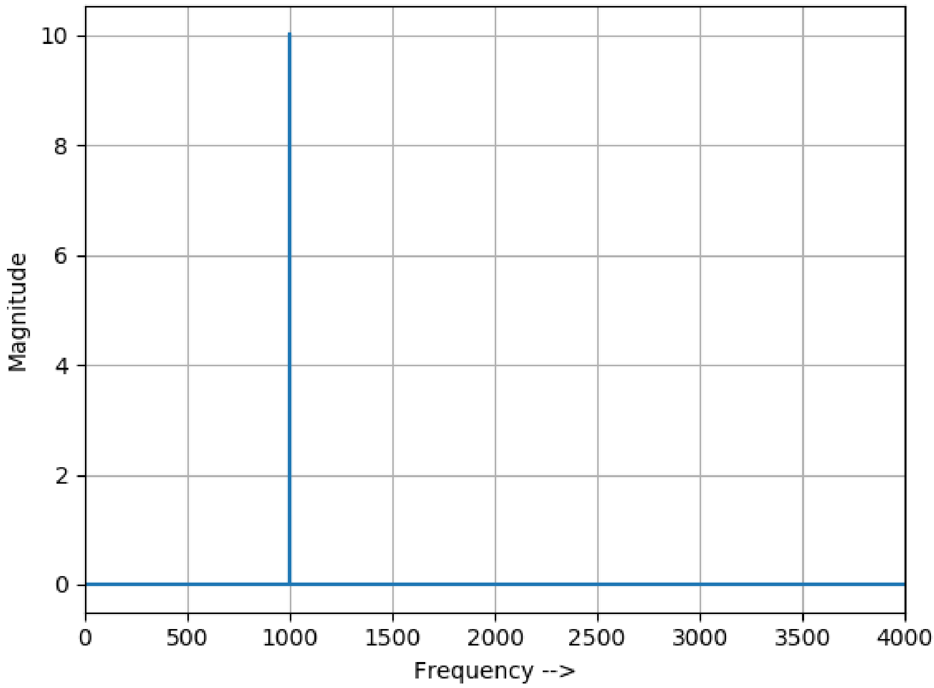

Figure 5.3 - 1000 Hz before amplification

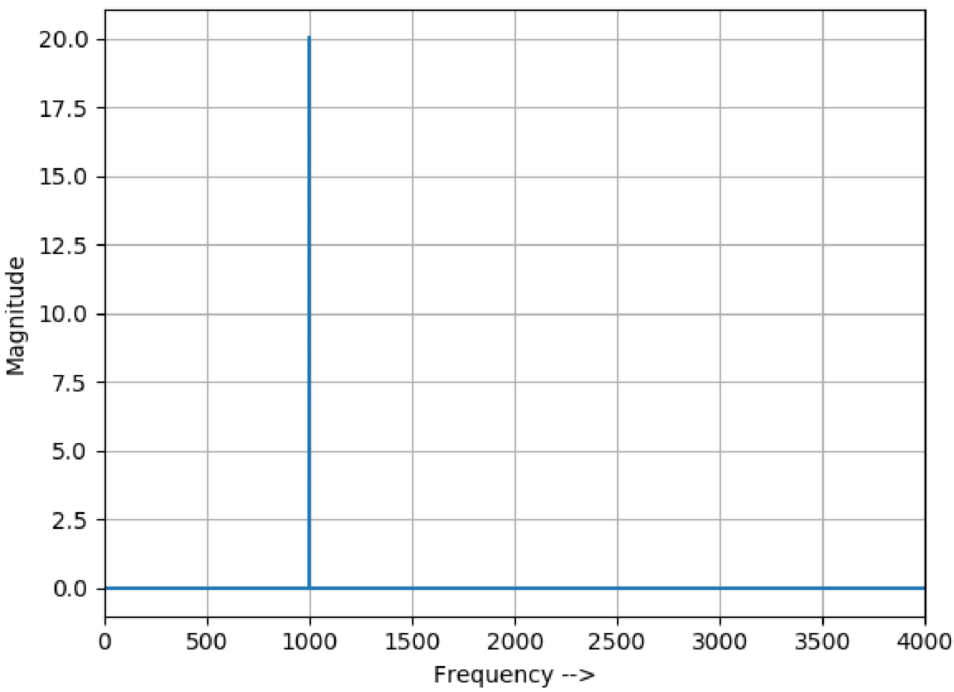

Figure 5.4 - 1000 Hz after amplification

When comparing the results, it was evident that there was a change in the amplitude. This meant that when there was only one tone present Crescendo was able to compress or amplify the sound accurately. In Figure 5.3 the 1000Hz sound was played at 10dB, and when the sound processing step was applied that sound was amplified to play at an amplitude of 20dB shown in Figure 5.4

5.1.3 Experiment 3: Manipulating a Single Frequency

In the third experiment, short audio clips of the tones tested were fed into the non-real-time system. Unlike the first experiment, these audio files were made up of multiple frequencies (from 250Hz - 8000 Hz). In this experiment, only one frequency was manipulated per audio file. This was to identify whether the system was able to manipulate a specific tone even in environments with multiple tones and frequencies.

The experiment illustrated in Figure 5.5 and Figure 5.6 shows that this experiment was able to compress the sound at 500Hz without affecting the other frequencies.

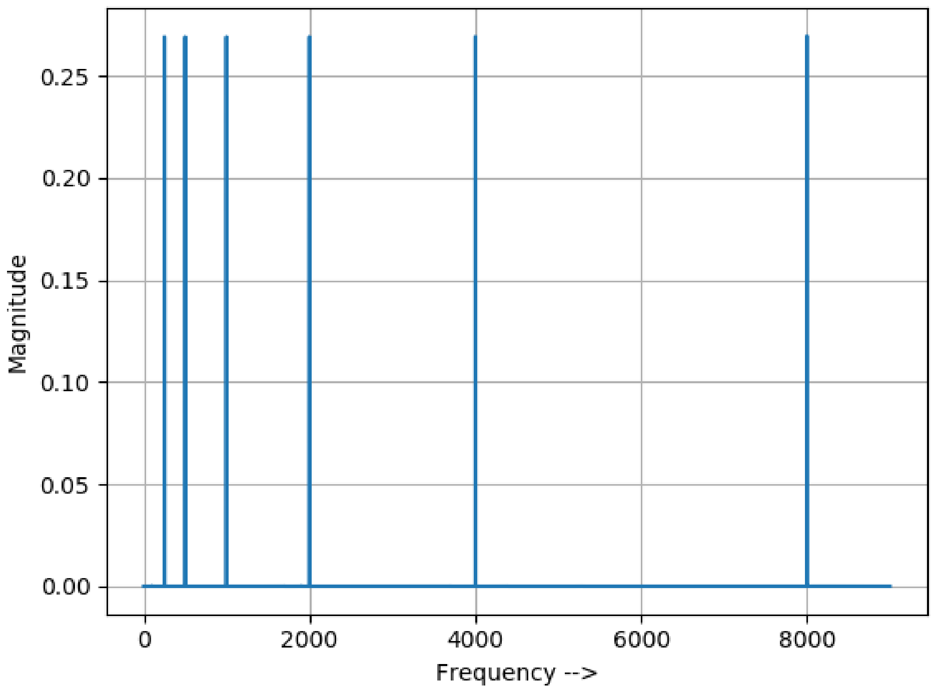

Figure 5.5 - 500 Hz before compression

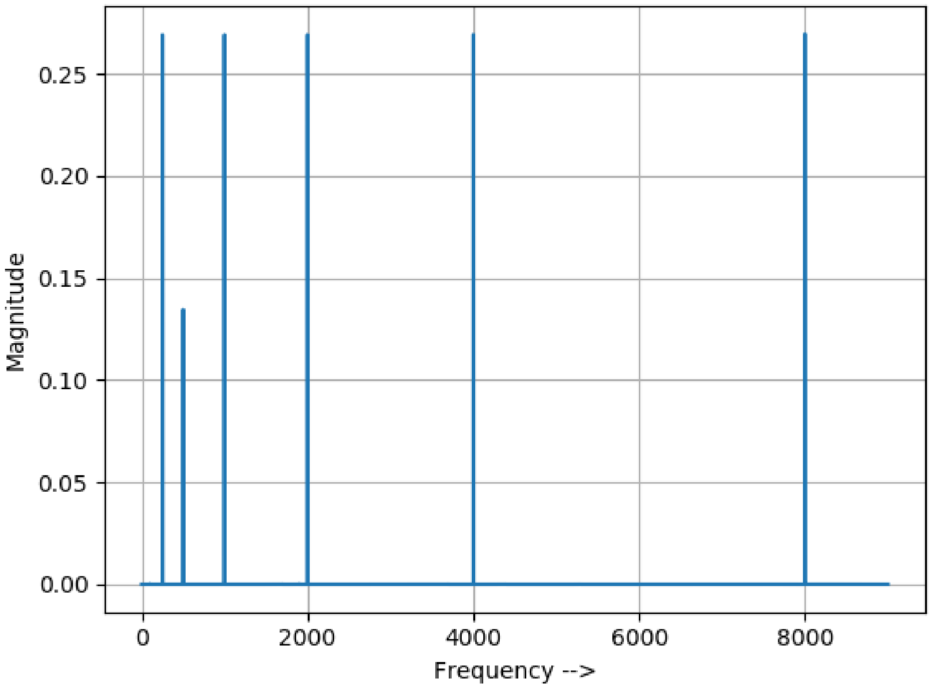

Figure 5.6 - 500 Hz after compression

When comparing the results, it is evident that there was a change on 500 Hz frequency when signal modification was applied. This meant that when there were multiple tones present Crescendo was able to accurately compress a sound at one frequency without affecting the other frequencies. In Figure 5.5 the 500Hz sound was initially played at a magnitude of 0.28dB, and when the filter was applied that sound was compressed by 50% to play at a frequency of 0.14dB, while the other frequencies stayed at 0.28dB shown in Figure 5.6

5.1.4 Experiment 4: Multiple Frequency Manipulation

In the third experiment, short audio clips of the tones tested were fed into the non-real-time system. Like the second experiment, these audio files were made up of multiple frequencies. In this experiment, multiple frequencies were manipulated per audio file. This was to identify whether the system was able to manipulate tones at different frequencies without affecting the tones at other frequencies

The experiment illustrated in Figure 5.7 and Figure 5.8 for this experiment were amplifying the sounds at 250 Hz, 1000Hz and 8000Hz without affecting the other frequencies.

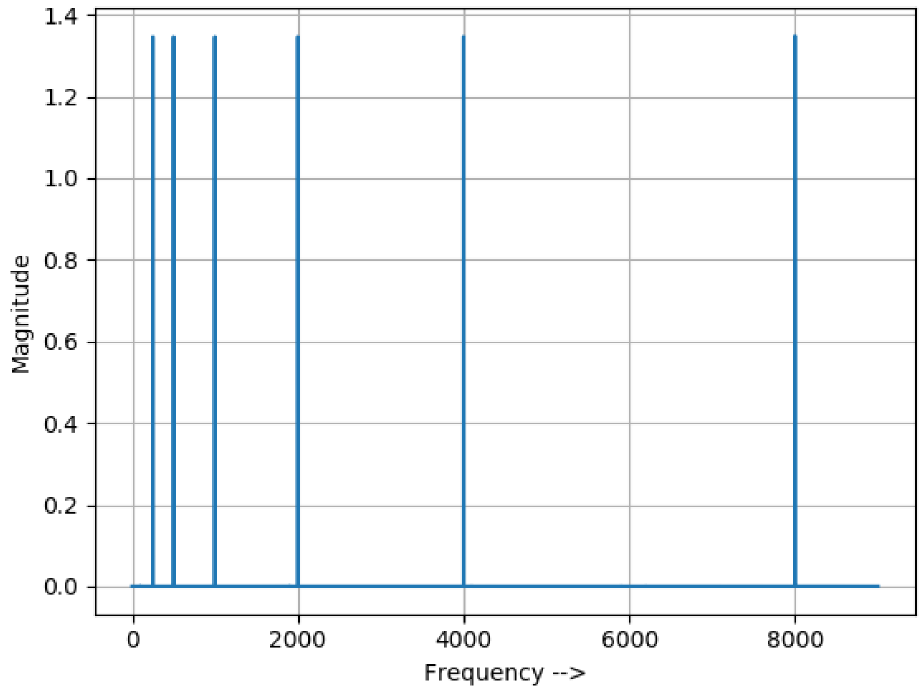

Figure 5.7 - Original Tones before amplification

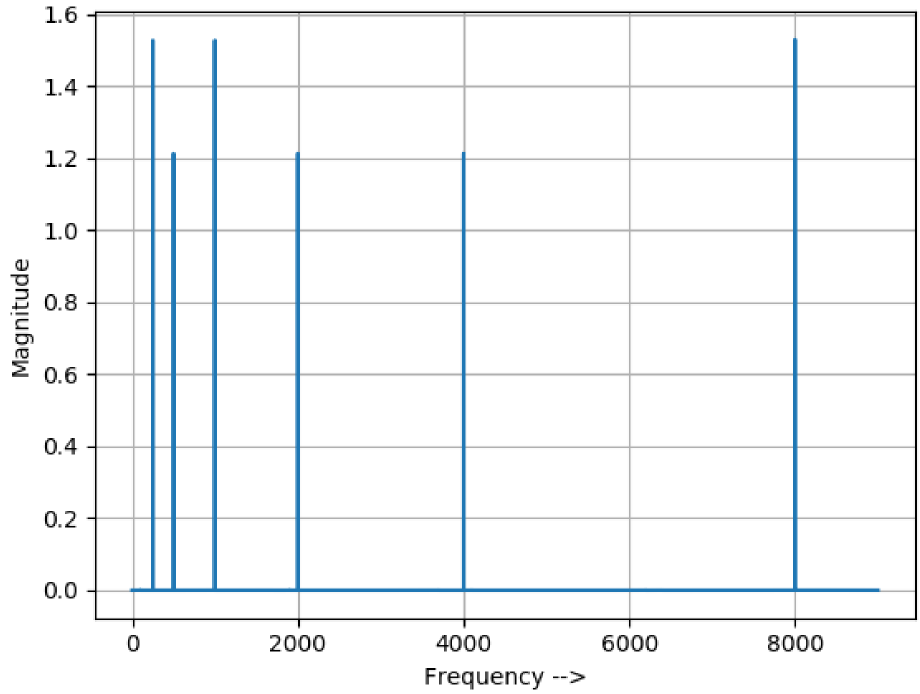

Figure 5.8 - 250 Hz, 1000Hz and 8000Hz after amplification

When comparing the results, it was evident that the 250Hz, 1000Hz and 8000Hz frequencies were successfully amplified. They were initially at 1.36dB and then they were amplified to 1.58dB. Unfortunately, this time the other tones were mildly affected as, they appear to have been compressed from 1.35 dB to 1.25 dB. This may have occurred because of the mercurial nature of sound.

5.1.5 Experiment 5: Full Frequency Manipulation

In the fifth experiment, short audio clips were fed into the non-real-time system. This experiment was also tested the audio files with made up of multiple frequencies and sound intensities. Like in experiment four, multiple frequencies were manipulated as they would have been in actual hearing aid systems. However, these audio files were noisier as they were not made up purely of tones but were youtube files made up of human speech and other noise. This was to identify whether the system was able to manipulate various frequencies even in environments with multiple tones at various intensities, and frequencies.

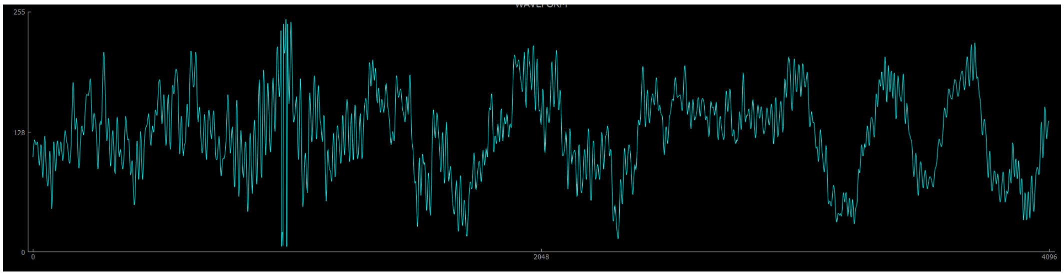

Figure 5.9 - Noisy Youtube File

Unfortunately, it was hard to determine if this experiment worked or not because of the vast array of sounds present in the audio file, as shown in Figure 5.5. However, when listening to the audio, it was evident that some of the background noise present in the original audio recording was reduced. This unexpected effect is favourable for those with hearing loss, as one of the chief complaints of hearing aid users is the inability to distinguish background noise from human speech.

All these experiments were done to ensure the system worked effectively; however, they focused on testing different parts of the system's functionality. The first test was performed specifically to detect how effective the hearing test was. The second, third and fourth and fifth experiments were conducted to test whether the signal processing stage was able to manipulate sounds at specific frequencies.

6 Conclusion and Future Work

6.1 Summary

This research focused on exploring whether digital signal processing algorithms could be used to build a hearing aid application, Crescendo. Crescendo was a comprehensive system that was split into two main components which were: (1) the hearing test component and (2) the digital signal processing component.

The hearing test component was build using Kotlin and the MediaPlayer API. The data obtained to build this part of the application was sourced from and was made up of 6 tones ranging from 250Hz to 8000Hz. The digital signal processing component was split into a further three parts; (1) feature extraction, (2) signal modification and (3) frequency synthesis. All of these parts were built using the PyAudio, Numpy Scipy, Liborosa and the PyQt5 Python library. The digital signal processing component of the system was build using various digital signal processing algorithms and techniques like the FFT used for frequency analysis, Butterworth filters and second-order resonant filters (bandpass filters) for signal modification. Additional data was collected to test the digital signal processing capabilities of this system, and these were sourced from recording sourced from youtube. Each audio clip had a duration of 2 minutes.

The results from the experiments performed on both the hearing test and digital signal processing elements have demonstrated generally favourable outcomes. Since the system was able to amplify and compress various frequencies, we can conclude that a hearing device can be developed with digital signal processing algorithms.

6.2 Limitations

This section discusses the constraints faced that may have negatively affected the performance of the system.

The first constraint was the inability to test the hearing test portion of the test against a licensed audiometry test. This was a crucial part of making sure the system worked effectively. However, the varying factors made this difficult

The second constraint was the lack of current open-source real-time audio processing libraries in Kotlin or Java. Although there were a few libraries that allowed the inclusion of the audio processing section inside the application, these libraries were outdated, which would not allow the digital signal processing to be done in real-time. Given that real-time analysis is necessary for hearing aids, the project was thus split into two parts—the hearing test, done in Kotlin and the digital signal processing section done in Python.

6.3 Suggestions for Future Work

This section presents suggestion extensions that can be done to improve this research. Implementing the suggestions presented in this section work will ensure that this study can be expanded on to create a full and workable solution to solve the issue of underproduction of hearing aids to people in the developing world.

6.3.1 Application

The first step would be to combine the hearing test and digital signal processing component into one application. This would make things more accessible to users as they would only require their smart phones. It was difficult to do this for this research because of the difficulty finding a real time signal processing library that could be used for Java Applications.

6.3.2 Signal Modification

Due to limitations, with the audio processing libraries used, although Crescendo works as a hearing augmenting system it does not make all of the modifications made by digital hearing aids.

Some areas that were not fully developed were:

- Background Noise
- Dynamic Feedback Control

,

Given the difficulty of this research, many assumptions were made, including the assumption the user would not go to areas like restaurants or gyms using their hearing aids, where there is a lot of background noise. In situations like this, the system needs to be able to distinguish between noise and speech and work on compressing the noise while amplifying the proper tones. And it needs to do this in real-time. The current application is mildly successful with the use of high and low pass filters; it can filter out a limited amount of background noise. However, this needs improvement to be comparable to a hearing aid

Dynamic Feedback control may have resulted if any sounds leaked from the speaker may be amplified to the point it could not be amplified anymore, leading to painful squeaks. Thankfully some phones do handle this; however, it is still important to add.

Binaural synchronisation this is the communication of hearing aids to synchronise adjustments and create a perfectly balanced sound. Unfortunately, given the type of earphones used, this was not possible.

6.3.3 Different Earphones

Although smartphones have high computational power and are used for all the processing tasks in this project, earphones were a very necessary part of the system design. This is because, the processed sound needs to be fed directly into the users' ears in order to offer the best possible benefit.

Given the objective of producing a low-cost hearing aid system, this project intended to test on two types of earphones: 1. Wired Stereo earphones 2. Bluetooth based Earbuds (specifically Samsung Galaxy Buds)

However, unfortunately, due to time constraints. Only wired stereo headphones were tested on, given that they were the most accessible for users and they do not require charging. However, they restrict user movement, and do not work in the same way as hearing aids

For this reason, Bluetooth connected earbuds should be considered and also tested in the application. Although the Bluetooth based connection could result in some interference, they would provide the user with a hands-free experience like traditional hearing aids. In addition, the earbuds are touch controlled and this touch functionality can be mapped which is beneficial for our application as users can adjust settings by tapping on their earbuds. Samsung Galaxy Buds are some of the cheaper, quality earbuds on the market (GHC 450 +) meaning that although they are more expensive than most wired earphones, they offer the benefit of superior sound quality and changeable, tips which contribute to noise isolation.

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