2013

Analysing a new mobile bilateral audiology test for children

Luke J. Brook
Edith Cowan University

2013

Analysing a new mobile bilateral audiology test for children

Luke J. Brook
Edith Cowan University

Analysing a New

Mobile Bilateral Audiology

Test for Children

A thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of Computer Science Honours

By: Luke James Brook

Student ID: 10147571

Faculty of Health, Engineering and Science

Edith Cowan University

Supervisor(s): Associate Professor, Dr Trish Williams

Date of submission: 11th October, 2013 (Extension granted)

Table of Contents

List of Tables and Figures

Acknowledgements

I would like to thank the many people who have helped, and guided, me through the completion of this thesis.

The first is my supervisor and mentor, Dr Trish Williams, who has supported me throughout. You are kind, honest, knowledgeable, and extremely patient and your calmative phone calls have been my saviour.

Thank you to Shane Henderson who, during the final year of my undergraduate degree, provided me with the encouragement to jump in, feet first, and continue with my studies and helped to kick-start my academic career. I am extremely grateful for your support over the years; you are a one of the most genuine people I have ever met, and a true friend.

I also wish to thank everyone from Telethon Speech and Hearing, with a special mention to Yuriko, for your time and access to services.

To my parents, Carol and David; step parent, Ian; and in-laws, Gayle and Terry. You have been a constant source of emotional support. Thank you for your invaluable advice and for keeping me focused.

I am also extremely thankful for, and would like to acknowledge, my amazing wife and best friend, Jaye. Your unconditional emotional and moral support and late night coffees have maintained my sanity during the long periods of social isolation. Without you, I would not be the person I am today.

Thank you to my four wonderful children, my boys Riley, Ashton, Cooper and my little ‘princess’ Isabelle, for being understanding and having sacrificed far too much time while I have been doing my “work on the computer”. You are, by far, the best bug testers ever. If anyone can break it, it’s you.

Finally, I would like to dedicate this thesis to my son Cooper. You came into the world far too soon, have endured so many hardships, and still wake up every morning with a smile on your face. It is my hope that, one day, you will hear the world as I do and experience it in all its beauty. You are my inspiration, and I love you with all my heart. This is for you, ‘Pork chop’.

Abstract

Hearing loss in Australian children, primarily Aboriginal and Torres Strait Islanders, is a growing concern for the Australian public health sector. In certain rural communities up to 90 per cent of children have been found to experience some form of hearing loss. Although hearing loss can be the result of a number of different causes, including congenital influences, the most common cause of hearing loss in Australian children is attributed to a common middle ear infection, otitis media.

To address the issue, numerous solutions have been proposed, tested and implemented, although the problem persists due to geographic, environmental and cultural limitations. However, the availability of new technology, including smart phones and extended mobile telecommunications networks, has provided new opportunities to overcome these limitations.

This research project comprised of the development of an application for Apple iOS devices and initial testing of this for accuracy and proof of concept. The application is designed to emulate a professional gold standard hearing test, which is traditionally conducted in a calibrated and controlled environment. While similar applications currently exist, many utilise non-standard testing methods and there is no data or published documentation to support claims for their accuracy.

This thesis discusses the pilot study conducted to determine whether this specially developed mobile application can be utilised for self-administered hearing tests for children; to reduce the strain on current telehealth services; and complement similar solutions to achieve a holistic approach for diagnosing hearing loss and ear infection.

The results of the study outline a number of unforeseen circumstances encountered, which resulted in minimal obtained quantitative data. However, findings during the testing, that impacted on the testing procedures of the application, were derived from surveys, interview and observations and

provide evidence to support the claim that a mobile application, used for mobile phone and tablet devices, can be used to supplement audiology testing of children and would be accepted by both parents and audiologists.

Chapter 1. Introduction

1.1 Background of the Study & Statement of the Research Problem

Hearing loss in Australian indigenous children is becoming an increasing concern for the health sector, with the percentage of affected children comparable to that of third world countries (Weber, 2012). In metropolitan areas, this percentage is believed to be as high as 75 per cent while, in regional communities, up to 94 per cent of Aboriginal children suffer from some form of hearing loss (O'Keefe, 2012).

There is unanimous agreement that increasing frequency of hearing loss is a result of a middle ear disease, otitis media (OM), where fluid solidifies and impedes conduction of sound through the middle ear (Burrow & Thomson, 2006; Weber, 2012; Yiengprugsawan, Hogan, & Strazdins, 2013). Left untreated OM can result in hearing loss or, in severe cases, lead to Chronic Suppuratives Otitis Media (CSOM), where fluid can rupture the ear drum, further limiting the conduction of sound, or result in permanent hearing loss (Burrow & Thomson, 2006).

To address the issue there have been numerous solutions developed, over the past few years, primarily in the area of mobile telehealth services. An example of these studies includes *The Feasibility of a community-based mobile telehealth screening service for Aboriginal and Torres Strait Islander children in Australia* (Bensink et al., 2010). While the cause of OM is frequently disputed, and some believe it to be an unavoidable and common occurrence in all children (Weber, 2012; Yiengprugsawan et al., 2013), the study discovered an alarming number of children who were unaware that they suffered from hearing loss, and had not been diagnosed due to lack of immediate and regular access to health care and professionals to seek diagnosis and treatment of their ear health (Bensink et al., 2010).

Additionally, although the results of existing telehealth services, provided by mobile clinics, are promising, Australian geography is vast and traversal by land vehicles is time consuming (O'Keefe, 2012). According to Carol Jacobs, Assistant District Director for the Department of Child Protection, in Cannington Western Australia, services such as these are impeded by numerous issues. Some of these include access to certain remote Aboriginal communities being restricted to time frames outlined by Aboriginal customary lore, and other barriers such as seasonal flooding (personal communication, 17 April, 2013). To overcome these issues, additional solutions need to be developed to bridge the geographical gap between metropolitan health services and rural communities.

A proposed solution to the ongoing problem, of undiagnosed hearing loss, is a self-administered audiology testing application for Apple iOS smart phone and tablet devices, emulating an audiogram traditionally conducted in an audiometric sound booth, with results electronically transmitted to health professionals for review. Furthermore, with cellular network carriers, such as Australian telecommunications provider Telstra, rolling out new infrastructure to increase network coverage, and significant developments in mobile technology (M. Thompson, personal communication, March 12, 2013), this solution is a very real possibility.

1.2 Significance of the research

The issue of hearing loss, and causative ear infection, has been a persistent issue in Australian health for many years. According to Paul Higginbotham, former CEO of Telethon Speech and Hearing, part of the reason the problem persists is “that there has been no systematic strategic approach to it” (Weber, 2012). And, despite the fact several solutions to the problem have been proposed, trialled and implemented, the issue of hearing loss as a result of ear infection in Australian children remains unresolved, and early detection poor.

The persistence of the issue is not due to the failure of prior solutions. For instance, the Telethon Speech & Hearing Earbus and Mobile Telehealth Screening Service are prime examples of successful approaches yet they are limited by a lack of systematic application and limited resources.

Limitations such as these have created issues all over the world for health care (He, Wei, & Zhang, 2008; Karunanithi, 2007); however the advancement of technology is making the ability to overcome them more attainable via telehealth solutions.

Telehealth methods of diagnosis and treatment have become a significant trend in healthcare, and have also proven to be highly cost effective (Fabry, 2010). Some of the more recent implementations include elderly monitoring and outpatient homecare services (He et al., 2008; Karunanithi, 2007), remote stroke diagnosis and even speech-language pathology treatment (Brennan & Barker, 2004; McCarthy, Muñoz, & White, 2010).

In direct relation to this study, a clinical trial is currently being conducted in the United States for a custom otoscope, which attaches to an iPhone, capturing images of the middle ear for diagnosis of middle ear infections (Korschun, 2012). Although the device does not diagnose hearing loss, the use of a device combined with the self-administered audiology testing application would aid in developing a holistic approach to the diagnosis of middle ear disease and hearing loss.

While similar solutions to this research have been developed, including unverified and untested mobile applications for hearing tests of mobile devices (Shargorodsky & Fligor, 2011) and web based hearing test applications for personal computers (Masalski & Kręcicki, 2013), there has been no research conducted into the accuracy and feasibility, or consumer and clinical specialist impressions, of a self-administered mobile audiology testing application for children.

Additionally, the methods utilised by many existing applications are based upon pure-tone, static, pitch and speech discrimination, while the application used for this research utilised third octave band warble tones, developed by Dr Stephane Pigeon, PhD engineer and professional sound engineer. According to Dr Pigeon, the tones are based upon the international standard ISO389-7:2005, which is recommended by the British Society of Audiology

(Pigeon, 2013). These tones differ from other test methods, as they do not require specific hardware, and minimise room and headphone resonance.

Without the application, or additional solutions to aid in the diagnosis of hearing loss in children, the impact in the long term is potentially dire. A child's growth and development occurs rapidly throughout early childhood, and thought to be heavily influenced by their environment and experiences (Stevens, 2013). Issues such as undiagnosed hearing loss can have an ongoing impact throughout life, and the inability to hear, or hear well, is proven to cause delay in receptive and expressive communication skills, can cause social isolation and poor self-concept, and result in poor performance in classrooms, resulting in the inability to learn (O'Keefe, 2012; Timms, Grauaug, & Williams, 2012)

1.3 Statement of Research Questions

The study was designed to answer a primary research question based on the previously discussed gaps and limitations and supporting hypothesis (1.1):

1) "Can an application, developed for smart phone and tablet devices, be used to supplement audiology testing for children?"
    1.1. It is hypothesised that an audiogram emulation application, previously developed for smart phone and tablet devices, may be used to assist in the diagnosis of hearing loss in children.

In addition, to evaluate the accuracy and validity of the application, an additional subsidiary question was defined:

2) "What level of accuracy can applications, developed for smart phone and tablet devices, utilising third octave band warble tones, deliver in comparison to traditional audiograms conducted in a controlled environment?"

1.4 Definition of Terms

The following terms are defined as they apply to this thesis.

Term	Description
App	A software application developed for Apple iOS devices, running the iOS operating system.
Audiogram	A graphed chart of hearing test results, showing a subset of tested frequencies, at different sound levels, within the human hearing range.
Audiometric Sound Booth	A soundproof booth, specifically designed for audiometric testing in industrial and diagnostic test environments. They are also referred to as sound chambers, screening booths, testing suites or testing rooms.
Frequency	Refers to the pitch of a sound, measurable in hertz.
Hertz	The number of wave lengths that fit into a unit of time, used to measure the pitch/ frequency of a sound.
Player	A participant in the application testing.
Tone	A sound that repeats itself at a particular frequency, but may differ in loudness/volume.
Volume	The loudness of a tone, played at a particular frequency.

Table 1 Definition of terms

1.5 Summary

This thesis discusses the history of hearing loss, and causative effects, in Australian indigenous children, including a review of previous solutions developed and tested, and their results. Additionally, the application development and structure is introduced, followed by the methodology and structure for the pilot study.

Finally, an analysis of the results from the research is presented, with a discussion to determine whether this specially developed mobile application can be utilised for self-administered hearing tests for children; to reduce the strain on current telehealth services; and complement similar solutions to achieve a holistic approach for diagnosing hearing loss and ear infection.

Chapter 2. Literature Review

2.1 Introduction

Hearing loss in Australian indigenous children is thought to be attributed to frequent and ongoing middle ear disease, with the percentage of affected children comparable to that of third world countries (Weber, 2012). According to the World Health Organisation, the number of children affected in Australia brings about “a massive public health problem requiring urgent attention” (Burrow & Thomson, 2006).

As this is clearly a growing concern and, with the health and well-being of Australian children at stake, there have been numerous studies and articles published to develop awareness, attempt to identify the causes, and provide potential solutions to the problem. The principle areas for the following literature review were sought from those same categories, refined into the topical headings of: *Causes, breadth and severity of hearing loss in Australian children*; *Solutions for the diagnosis of hearing loss in rural communities*; and *Solutions similar to the study*.

2.2 Causes, Breadth and Severity of Hearing Loss in Australian Children

Otitis media, or inflammation of the middle ear, is a general terminology given to commonly occurring viral and bacterial middle ear infections. It is also cited as the primary cause of various symptoms including fever, ear pain and, in direct relation to this study, temporary and permanent hearing loss (Hendley, 2002).

The extent of the disease is so vast that, in 2002, it was reported more than five million cases of otitis media were diagnosed each year in the United States, and the most common reason for prescription of antibiotics in children (Hendley, 2002). In Australia, otitis media is considered a common occurrence in all children, with statistics from the National Centre for Epidemiology and Population Health, at the Australian National University, showing more than half of Australian children experience at least one episode of otitis media by the age of 3 years (Yiengprugsawan, Hogan & Strazdins, 2013). Recent longitudinal studies have also shown that otitis media occurs more frequently, and with higher severity, in Australian indigenous children (O'Keefe, 2012).

To provide further evidence, for the severity of the disease in Australia, are claims made by Professor Harvey Coats, a paediatric ENT surgeon, who has spent 35 years travelling to remote areas of Australia, treating over 100,000 people diagnosed with otitis media. During an interview with ABC Premium News in 2012, Professor Coats stated that Australia has the worst middle ear disease of any first world country, with a majority of the people treated being children of Aboriginal descent (O'Keefe, 2012).

With such concerning statistics, it raises the question as to why the cause of the issue hasn't been addressed. Unfortunately, although many experts agree about the current state of ear infection in public health, the same experts have voiced conflicting opinions on the cause, making it difficult to establish effective preventative measures.

In 2006, an article published in the Aboriginal and Islander Health Journal, titled *Summary of Indigenous Heath: Ear Disease and Hearing Loss,* noted that the poor condition of indigenous children's ear health, especially in remote communities, was due to environmental and living conditions such as overcrowding, poor hygiene and housing (Burrow & Thomson, 2006).

In contrast, more recent studies and reports have defined middle ear infection as a common occurrence in both indigenous and non-indigenous Australian children (Weber, 2012; Yiengprugsawan et al., 2013) typically following an infection. An example of this is the influenza virus, where bacteria and/or virus spread via fluid to the middle ear, resulting in build-up of fluid and inflammation of the middle ear. Unfortunately, trials conducted to prevent otitis media with vaccines targeted towards the initial infection, such as influenza, were ineffective (Hendley, 2002).

While a preventative measure has not yet been found, the general consensus of all reviewed literature is that although otitis media is easily diagnosed and treatable, early intervention is crucial. The primary issue that needs to be addressed is in regards to poor access to health services in remote communities, which often results in undiagnosed and repeated infection (Burrow & Thomson, 2006; O'Keefe, 2012; Weber, 2012; Yiengprugsawan et al., 2013).

If left undiagnosed and untreated, otitis media can or lead to temporary hearing loss, or more painful and serious middle ear infections, such as Chronic Suppuratives Otitis Media (CSOM). CSOM is a recurrent or persistent infection of the middle ear, where fluid becomes trapped and thickens, commonly called 'glue ear', that needs to be treated with surgery and can result in permanent hearing loss (Burrow & Thomson, 2006). In a recent interview with Dr Janet May Wollard and Paul Higginbotham, former CEO of Telethon Speech and Hearing, it was claimed that symptomatic hearing loss from middle ear infection is as common as the disease itself, with more than 90% of children in some rural Aboriginal communities suffering from some form of hearing loss as a result of middle ear infection (O'Keefe, 2012).

In order to address the issue, additional solutions need to be developed to reduce the number of undiagnosed children, and improve their quality of life. To reiterate the importance, while OM is easily diagnosed and treatable, and early intervention a key solution, poor access to services results in undiagnosed and repeated infection and may lead to permanent hearing loss (Burrow & Thomson, 2006; O'Keefe, 2012; Weber, 2012; Yiengprugsawan et al., 2013).

2.3 Solutions for Diagnosis of Hearing Loss in Rural Communities

Given that there has been little research conducted into the use of mobile applications for the diagnosis of hearing loss in children, the proposed solution, and focus of this research, was to implement a mobile hearing loss application for Apple iOS devices and determine the feasibility. The following literature identifies alternate solutions that have been implemented, which primarily consist of methods of physical transportation, taking diagnosis and treatment facilities to rural communities, with accompanying review and analysis.

The Earbus program, run by the not-for-profit organisation Telethon Speech and Hearing, utilises mobile ear clinics, which travel around Western Australia, visiting rural communities to conduct free hearing screenings for Aboriginal children. The service was created after “an interim report from the standing Senate Committee for Health Education which revealed the appalling hearing loss figures” (O'Keefe, 2012).

Since the initial implementation, the results of the service have been promising. An example given describes the results from a school in Northam, 100 kilometres north-east of metropolitan Perth, in Western Australia. On initial scheduled visitations to the school, 75 per cent of children who were tested failed to pass the screening. Within two years, the results returned a 75 per cent pass rate (O'Keefe, 2012).

Similarly, a study was conducted in 2009 in Queensland, Australia, to determine the feasibility of a telemedicine enabled van. The van was outfitted with detection, monitoring and treatment equipment for health, run by local indigenous health workers, with test results sent via the internet to specialists for review. The service was made available solely for Aboriginal and Torres Strait Islander children, aged 0-16 years of age, and provided hearing and visual screening (Bensink et al., 2010).

The study showed great potential, backed by promising results. These results included 75 per cent of children receiving parent/guardian consent for screening, which indicated strong support by the community. The screening service revealed approximately 230 children (35 per cent of those tested) with potential hearing problems, who were referred to local health professionals for additional testing and treatment (Bensink et al., 2010).

Review of these services indicates the need for telehealth solutions in order to reach rural communities in Australia. Unfortunately, some of the limitations of these solutions include significant costs, long travel times, and certain communities being inaccessible as they are located too far rurally to travel (Bensink et al., 2010; O'Keefe, 2012). In a recent interview with Carol Jacobs, Assistant District Director for the Department of Child Protection in Cannington Western Australia, these issues were reaffirmed; with limiting factors identified, such as environmental issues, including seasonal flooding, and Aboriginal customary lore, which forbids outsiders from passing through their lands during certain times of the year (C. Jacobs, personal communication, 17 April 2013). Issues such as these make diagnosis and treatment more difficult, and the impact of undiagnosed ear health problems is potentially magnified.

Another example of telehealth solutions for hearing loss, which has been implemented in Australia, is the Outreach Program offered by the not-for-profit organisation ‘The Hear and Say Centre’. The Outreach program differs from previously discussed solutions, as the service is used to provide support for children who have already been diagnosed with a hearing loss, and are located in rural locations, but require access to auditory-verbal therapists (Healy, 2008).

The service provides real-time internet-based conferencing, allowing children with hearing disabilities to access specialist lessons, and taught to listen and speak in normal range for their age by the time they are ready to start school. At present the Outreach Program utilises Voice over Internet Protocol (VOIP), or video conferencing using a web-camera and the software application Skype (Healy, 2008).

Although the technology is not being used to diagnose hearing loss, the program provides evidence to support how new technology can be used to reach people in remote communities, and is currently in use in Queensland and the Northern Territory in Australia.

2.4 Solutions Similar to the Study

When initially conducting the literature review a gap was discovered, with little published data to directly support the use of mobile applications for the diagnosis of hearing loss. Exceptions to this include a specially developed device, called a Remotoscope, which attaches to an iPhone to aid in diagnosing middle ear infections, and literature to analyse existing applications available on the Apple iOS App Store, which claim to offer a similar solution to the Mobile Bilateral Audiology Test app used for the research.

Remotoscope iOS Device

The Remotoscope is a tool that has been developed as part of a clinical trial conducted by Georgia Tech and Emory University. The Remotoscope is a specially developed paediatric medical device designed to emulate an audiology otoscope, and attaches to an Apple iPhone, utilising the iPhone's flash light and camera. Using a custom software application, developed for iOS, images and video of the child's ear drum are captured and magnified, before being digitally sent to local medical specialists for review (Korschun, 2012).

The initial purpose of the study was to determine the accuracy of the device's ability to diagnose middle ear infections. The clinical trial commenced in September 2012 and is part of a multi-stage study, with the next phase to analyse a "watchful waiting plan", where physicians wait to prescribe antibiotics and receive regular updates on the child's condition via images sent from the Remotoscope application (Korschun, 2012).

Additionally, part of the clinical trial involved surveying parents to determine general opinions of the device. Results of the survey showed that parents were willing to use home diagnostic tools for testing hearing in their homes, with Kathryn Rappaport, a member of the research team who conducted the survey, stating "many parents were enthusiastic about using the device at home, asking me where they can get it" (Korschun, 2012).

Although the device and application are not aimed at diagnosing hearing loss, the development and study of the device alone provide support for the need for new solutions based on mobile devices for the testing and diagnosis of ear health. Ideally, the final Remotoscope product could be used in conjunction with the self-administered hearing test application, to provide a holistic approach to the diagnosis of ear disease and hearing loss.

Review of Similar Applications

During the initial development of the research process, an in-depth analysis of existing applications available on the Apple iOS Store was taken, to ensure the research had not previously been attempted. While several iOS applications exist, and many claim to provide accurate testing, there is no supporting documentation to provide evidence to the claims. Many are also only available outside of Australia, and none are specifically designed for children.

A similar analysis has also been conducted, titled *Apps for Better Hearing* by the Deafness Research Foundation. The study identifies several popular applications, which are specifically developed for self-administered hearing tests, providing a thorough review of the applications, noting features, limitations and concerns, and methods of implementation (Shargorodsky & Fligor, 2011).

The article confirms initial findings, with the accuracy of the apps unknown. The most concerning factor, as stated by Shargorodsky and Fligor, is that although some of the apps claim to be scientifically verified, there is no published documentation, data or academic evidence to support the claims or “draw a comparison to a gold standard hearing test”. Several of the applications also use non-standard methods of testing, using spoken word in background noise and word recognition (Shargorodsky & Fligor, 2011).

2.5 Summary of Literature

From the reviewed literature, it is evident that hearing loss in Australian children, particularly indigenous children, is becoming an increasing concern.

While there is some disagreement on the cause of middle ear disease, and lack of preventative measures currently in place, there are strategies to reduce the number of cases of ongoing and recurring otitis media, and the symptomatic hearing loss as a result.

Early intervention, through testing and diagnosis, has been identified as a key solution, and several studies have been conducted into the use of telehealth services which deliver promising results. Unfortunately, certain limitations restrict these services from reaching all children in remote areas of Australia, and additional solutions need to be developed to build upon and support existing services.

The proposed solution, for the implementation of a specially designed hearing test application for Apple iOS devices, is possible with the advancement of technology, and similar solutions have been discussed to support this proposal. And, while similar applications have been developed, there is no supporting documentation to support or verify claims on their accuracy, with many applications have been found to implement non-traditional methods of testing.

Chapter 3. Methodology

3.1 Theoretical Framework

The following theoretical framework (Figure 1) describes the assessment of hearing loss definition, which includes dependent and independent factors. It is defined by the dependent variable of (E) CSOM, ongoing temporary or permanent hearing loss, for children in remote areas of Australia, and influenced by two independent variables- (A) bacterial and/or viral middle ear infections, commonly referred to by the general term of Otitis Media, and (B) restricted access to immediate health services. The two independent variables are interrelated and, according to Yiengprugsawan et al. (2013) and Weber (2012), middle ear infection is a common occurrence in all children, but limited access to health services in remote areas of Australia is believed to be a primary contributor to undiagnosed ear infections.

Additionally, the intervening variable (D) shows that the (lack of) diagnosis of hearing loss and ear infection surfacing at time (t2), as a result of the relationship between middle ear infections and restricted access to immediate health services (t1), can lead to CSOM, ongoing temporary or permanent hearing loss (t3).

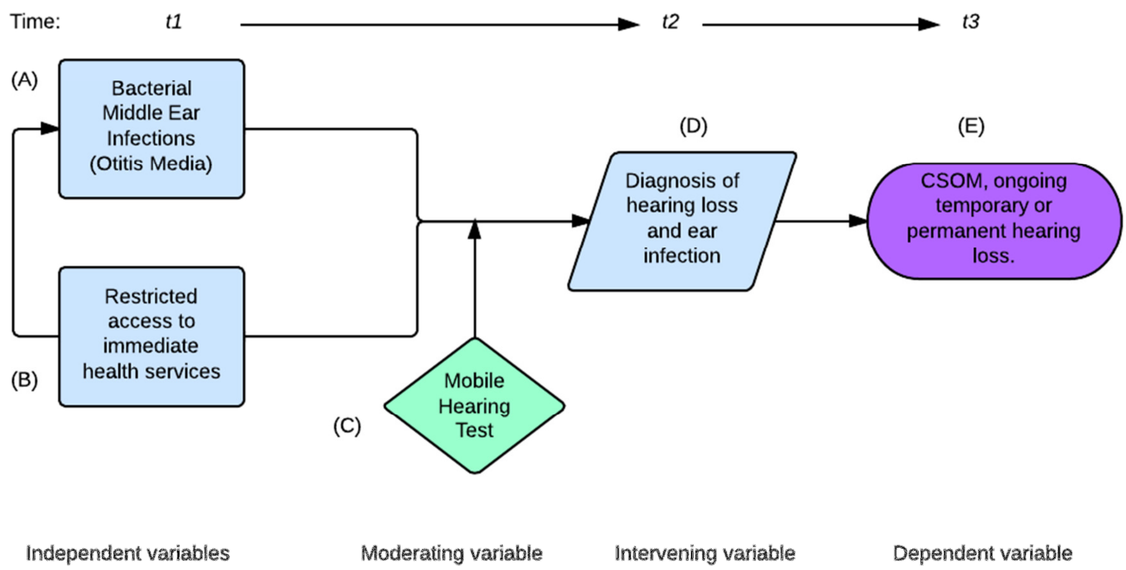

Figure 1: Schematic diagram for theoretical framework

The above diagram (Fig. 1) depicts how introducing the moderating variable of a (C) mobile hearing test, the basis for this research may alter the relationships between variables, potentially increasing the (D) diagnosis of hearing loss and ear infection, negating the end result of (E) CSOM, ongoing temporary or permanent hearing loss.

For this research, the time frame for the study has restricted the implementation of certain methodologies, such as a longitudinal study to determine the effectiveness of the moderating variable (C). A longitudinal study may be suitable in future research, for determining the impact of the hearing test application within a school in a remote community. By determining the percentage of children with an undiagnosed hearing loss in a school at initial implementation of the application, and the percentage of children with an undiagnosed hearing loss at regular intervals over the period of a year, the effectiveness of the application could be determined.

However, before such a design can be considered, it is important to first ensure the hearing test application (C) functions in a controlled environment and to verify the accuracy. Additionally, we need to determine whether parents/guardians would be comfortable with their children utilising the application in their schools or their homes.

To ensure the application meets these requirements, sequential mixed methods research was selected, as it provides “multiple ways of seeing and hearing” (Greene, 2007, p. 20) by utilising both quantitative and quantitative methods, and is reflective of how we conduct research in everyday life making it “a natural outlet for research” (Creswell & Plano-Clark, 2011). The mixed methods research consists of quantitative research, qualitative surveys and observations. The answers to the research questions are determined by comparing both qualitative and quantitative data and results.

Sequential mixed methods research refers to research design with philosophical assumptions as well as methods of inquiry. As a methodology, it involves philosophical assumptions that guide the direction of collecting, analysing and mixing qualitative and quantitative approaches throughout the research process.

These assumptions include:

1. The researcher chooses which method to use to answer a specific research question.

2. The researcher conducts the study, anticipating the results based on own values and explanations.

As a method it focuses on collecting, analysing and mixing both quantitative and qualitative data in a single study or series of studies (Creswell & Plano-Clark, 2011). The model for this research can be summarised as follows:

1. Determine a purpose- which is to answer the given research questions.

2. Collect and analyse one type, or strand, of data, as a basis for another type of data.

3. Collect and analyse a second type of data to confirm or disconfirm the first strand

4. Draw conclusions (if warranted) and write a final report. (Johnson & Onwuegbuzie, 2004).

The first strand of data for the research was collected and analysed as part of the quantitative research process. Once this data was collected, and an answer to the subsidiary research question determined, the second strand of data, the surveys and observational records, were used to confirm or disconfirm the first strand.

The selection of mixed methods research was decided on based on a pragmatic mixed-method single paradigm stance. While it has long been argued mixed methods are not possible due to an incompatibility with the paradigms underlying them (Johnson & Onwuegbuzie, 2004, pp. 15-16), and a “choice of an appropriate paradigm [...] a necessary step to justify the use of mixed methods" (Hall, 2012, p. 2), there have been significant developments in recent years.

These developments include three alternate approaches which have been established including a-pragmatic stance, where the choice of a paradigm or world view is not made explicit; multiple paradigm stance, where multiple world views are used to define the research; and single paradigm stance, supporting either pragmatic or transformative world views (Creswell & Plano-Clark, 2011; Tashakkori & Teddlie, 2003). The choice of a pragmatic single paradigmatic position has been advocated by a number of mixed methods researchers, including Johnson and Onwuegbuzie, Maxcy, and Morgan (cited in Hall, 2012, p. 4), and was adopted for this research.

3.2 Materials and Methods

As the research examines a relatively new field, which has previously not been explored extensively, it was important to note the constraints of the research and recognise what could be achieved within the allocated time-frame. In order to lay the foundation for this and future research, the primary concern was first answering the subsidiary question of "What level of accuracy can applications, developed for smart phone and tablet devices, utilising third octave band warble tones, deliver in comparison to traditional audiograms conducted in a controlled environment?"

The results are aimed at providing proof of concept within a controlled environment, with the potential for future research to determine how the approach would fare in an uncontrolled environment, and verify the previously stated hypothesis. In order to answer the research questions, a mixed methods approach was selected (see section 3.3 Theoretical Framework).

The data collection was undertaken in two stages. Initially, feedback from Telethon Speech and Hearing (TSH) experts was sought to clarify the concept and revised the mobile application with additional parameters as required. This feedback was provided at meetings with the relevant expert prior to the permission for the second stage to occur at TSH.

The second stage was the comparison testing of the application by recruiting children, aged 3-4 years, who attend Telethon Speech and Hearing for hearing tests. Each child participated with parent consent, and parents were provided with extensive information on the pilot study, in the form of an information letter and discussion prior to commencement of the testing. This testing incorporated two methods. The first method takes the form of a quantitative research approach, requiring the gathering of data from the application and, during the same session, from a professional audiogram conducted by an audiologist in a calibrated audiometric sound booth. The audiogram output from the Mobile Bilateral Audiology Test application was then compared against the professional audiogram to determine the overall accuracy of the application. Once the testing phase of the application had been completed, the results were collated and used to answer the subsidiary question.

In addition, a qualitative research method was implemented during the testing phase, with audiologists and parents/guardians of child participants asked to complete surveys to provide general feedback and opinion regarding the application's effectiveness. To address the subsidiary question, the results from the qualitative data is used to answer the primary research question (Figure 2).

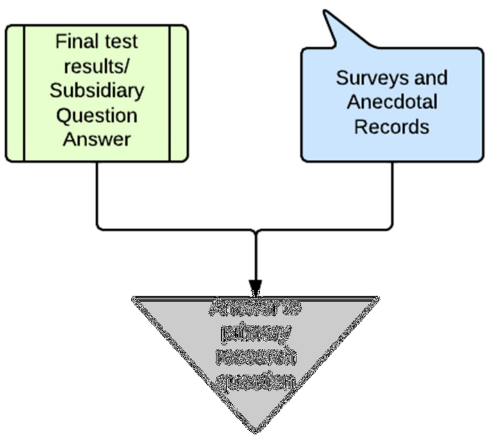

Figure 2: Combination of Qualitative and Quantitative Data

The qualitative survey used open ended questions, to avoid limitation of the breadth of information the respondent could provide. Observations were also recorded by the researcher for each test. The observations were used to provide further evidence and documentation of each participant's actions.

3.3 Data Collection Procedures

The procedure for the testing phase, and collection of data, was as follows:

1. Deploy Mobile Bilateral Audiology Test application on iOS devices, using iTunes to synchronise the device.

2. Perform a calibration test of the iOS device, by connecting audio cable to microphone port on Windows/Apple computer. Using Audacity, complete a comparison of the iOS device output, and the original test tones. Record the results, to accompany the test results.

3. Setup the controlled testing environment, in an Audiometric sound booth, using the iOS device and circum-aural, passive, overhead, noise cancelling headphones.

4. Remove any sources of background noise, including talking or distant noise (sound booths are self-contained, with doors to seal off outside noise).

5. Perform noise assessment, using the included Background Noise Analysis tool feature of the Mobile Bilateral Audiology Test iOS App.

6. Fit the participant with the headphones, with parents and Audiologist present, guiding them through the application, explaining the testing process. Perform an initial test run of the first few frequencies, to ensure the participant is aware of what is required.

7. Commence the test, entering the participant's name, and advising them to press the button to start.

8. While the child is participating in the test, continue to ensure no distractions are present, and complete the observations using the template provided.

9. Once the test has been completed, the resulting Audiogram is saved to the camera roll on the device's storage. The audiogram is then sent through to the tester's email account and stored for data analysis.

10. Once the test has completed, request for the parent/guardian and Audiologist to complete their respective surveys on the test.

11. Repeat from step 3 for each participant.

3.4 Data Analysis

Once the data has been collected, the professional audiogram, provided by the audiologist, and the audiogram output from the iOS application, will be directly compared. A comparison for all test results collected will be made for each frequency, noting the lowest heard decibel level, combined and averaged to determine how accurate the iOS application is in comparison to a professional audiogram. An example of this is provided in Table 1. This data analysis will be manually performed by the researcher, and no additional software or materials will be required.

Any disparity between the output of the application's audiogram and the traditional audiogram provided by the audiologist will be documented and analysed. For example, an error of 10 dB is considered highly inaccurate, so if an average error level of 14dB for a 250Hz frequency was discovered, the application's level of accuracy would be classed insufficient. Any recommendations for improvement will then be made to accompany the results.

	Traditional Audiogram	Application Audiogram
Child #1	250hz- Lowest level heard 10dB	250hz- Lowest level heard -5dB
Child #2	250hz- Lowest level heard 0dB	250hz- Lowest level heard 10dB
Child #3	250hz- Lowest level heard 15dB	250hz- Lowest level heard 0dB
Child #4	250hz- Lowest level heard 5dB	250hz- Lowest level heard 25dB
Child #5	250hz- Lowest level heard 20dB	250hz- Lowest level heard 10dB
Average (15 + 10 + 15 + 20 + 10) /5 tests = Average 14dB error level for 250Hz		

Table 2 Example of an analysis of frequencies

In the event that any test result collection is hindered by the inability for tests to be completed or unexpected errors, given the participants will be children, these will be omitted from the averaged results, and records of these will be accompanied by the observational records to provide evidence. Examples of potential issues may include children not being able to detect a rhythm or failing to understand how to interact with the test correctly.

The final results of the data analysis will be used to answer the subsidiary research question: “What level of accuracy can applications, developed for smart phone and tablet devices, utilising third octave band warble tones, deliver in comparison to traditional audiograms conducted in a controlled environment?”

Once the response to the above research question has been determined, the primary research question can be answered. An analysis of the surveys provided by the parent/guardian of the participants and the audiologist will be conducted, and a summary will be compiled. Observational records will also be analysed to determine what, if any, factors impeded the accuracy of the testing process.

Finally, as part of the mixed methods procedure, the feedback from the surveys, observational records and the response to the subsidiary question will be compared, and a response derived for the primary question, which is:

“Can an application, developed for smart phone and tablet devices, be used to supplement audiology testing for children?”

3.5 Limitations of the Study

Certain limitations and confounding factors for the research were identified during the research development, and every attempt had been made to overcome these. It is important to note some of the limitations identified were unavoidable, and these are noted below.

- Participants of the testing phase are selected by the parents and therefore are a targeted limited group and not randomly selected. This is unavoidable, due to the availability of resources, time and budget.

- The size of the sample group is relatively small, which is a result of available participants, time, those willing to participate, and organisations willing to provide facilities for testing.

- The participant’s willingness to participate (given the age of the participants) may be impeded by a number of unforeseen factors such as their mood, behaviour and general attitude. An example of this may include a child becoming bored and refusing to complete the test. To ensure these factors do not affect the overall results, observations have been introduced. The records will allow incomplete test results, or results impeded by external factors, to be omitted with accompanying observational records to provide evidence for their removal.

- A slight learning curve for the application may require the child’s initial attempt at the application to result in an inaccurate or incomplete test. This is not unusual, as audiologists generally practice with children over a prolonged period of time to perfect their testing process. Unfortunately, due to time limitations, this is not a viable option. Instead, children will be given a short demonstration of the application, prior to commencement, with the option for another attempt if required.

- The results of the test may be impacted by background noise, resulting in inaccurate results. In this case, it would be difficult to determine whether the audiogram was capable of performing accurate testing. To combat this, limits have been set, and the testing is being completed in a controlled environment.

- Potential to alienate audiologists, who may interpret the application as a replacement for their profession. This issue has been addressed, as surveys and information sheets for audiologists clearly state the tool is for supporting clinical diagnosis, not to replace it, referring children with potential hearing loss to audiologists for follow-up testing and diagnosis.

Chapter 4. Application Design

Prior to the commencement of the pilot study testing phase, a development project was undertaken to produce an application that was capable of emulating an audiometric sound booth, utilising either passive noise cancelling headphones for testing conductive hearing mechanisms. This application is a foundational aspect of the entire research study. This section serves to assist the reader to understand the testing, data collection and results interpretation.

4.1 Specific Concepts

The application consists of four components:

- Main Menu, with preceding menu to enter name of participant;
- Background noise assessment tool;

  The background noise assessment tool is used to sample background audio over a period of time, providing the user with a final reading of the average background noise. These results are then used to advise the user whether their environment is suitable to perform the test.

- Posting-box hearing assessment tool;

  The posting box component flows in a manner that procedurally advances the player through several frequencies, with up to twelve levels of volume for each. Each sound played at a different volume for the same frequency is referred to as a tone. While there are 18 tones per frequency, the number of tones played-per-frequency is dependent on the child's hearing ability, determined by a specially developed search algorithm.

- A final audiogram graph of results.

  Results of the test are then collated, and presented in an audiogram at the end of the test, which displays the date, time, user's name and summary of the background noise analysis, with the option to save the audiogram to the device's local storage. A comparison of an audiogram from an Audiologist and the Audiogram output from the application are as follows (Fig. 3, Fig. 4).

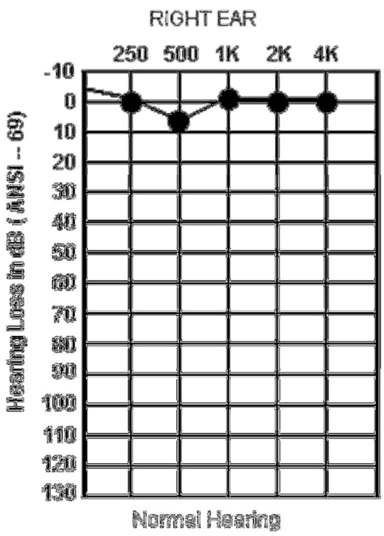

Figure 3: Audiologist Audiogram

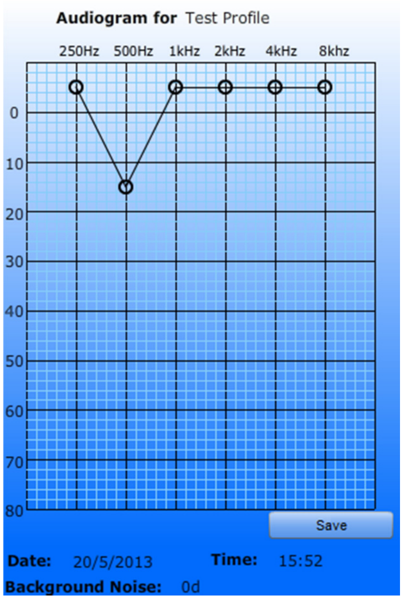

Figure 4: Application Audiogram

4.1.1 Global Display and Interaction

The application has been designed for both iPhone/iPod and iPad devices. The display orientation is dependent on the device, with a fixed portrait orientation for iPhone and iPod devices, and fixed landscape orientation for iPad devices. All elements of the application have been developed using scalable components and vector graphics to allow for scaling on larger devices.

As the application takes the form of an interactive posting-box game, the primary form of interaction is through touch, where users are required to drag a token into a container when they hear a tone (Fig. 2).

These methods of interaction between the user and the application are native to Apple iOS devices, which includes the touch input methods available. This includes touch-down, touch-release and touch-drag methods of interaction through finger pointers and swipe actions. Other user input, such as the soft keyboard, are implemented through the Apple iOS's existing features, which also rely on touch input.

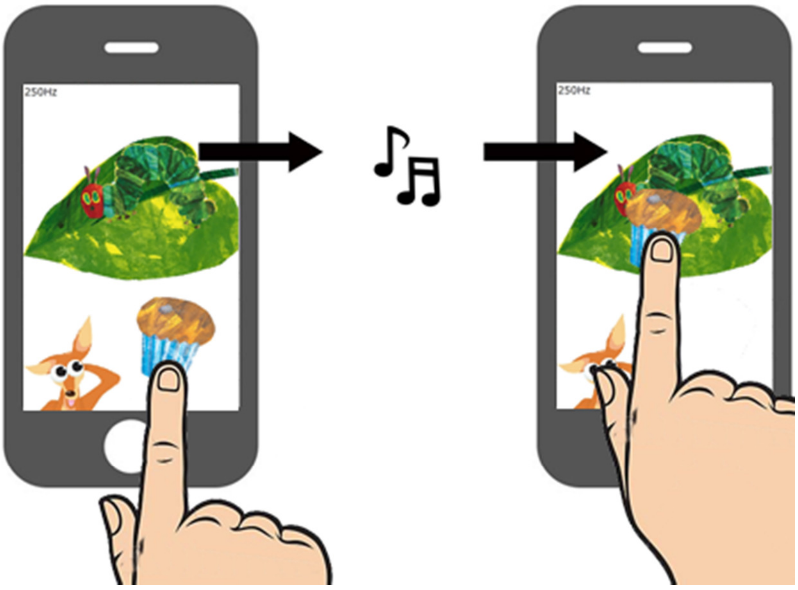

Figure 4: Drag-and-drop of tokens in response to tones

4.1.2 Logic Structures

Timers

To perform accurate measurement, two timers have been implemented specifying the amount of time the user has to 'drag-and-drop' a token into a container displayed on screen once a tone has commenced playing, and the amount of time between tones played (or amount of silence).

These values are set to a 6000ms response time, and between 5500ms-12500ms for the amount of time to wait between tones played. This random timer resets after each tone is played, resulting in a random gap time for each tone, potentially preventing users from detecting a recurring pattern in the testing process.

Search algorithm

The original testing process, as outlined in the design documentation for the application, was based on a linear progression, with tones ranging between -

5dB and 80dB for six frequencies, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz. The process for this was as follows:

1.0 Initialise the application and set the frequency to 250Hz and dB to -5.

2.0 IF the current frequency is less than or equal to 8 kHz, play the frequency.

2.1 IF the player responds to the sound AND the response if correct

2.1.1 Store data, increase frequency, and return;

2.2 IF the player does not respond to the sound OR response is incorrect

2.2.1 IF 80dBHL has not been reached

2.2.1.1 Increment dB and return;

2.2.2 Else

2.2.2.1 Store data, increase frequency, and return;

3.0 ELSE Display the audiogram of results

While this may be a thorough means of testing the participant, each frequency in an audiometric hearing test consists of 18 tones of differing loudness, from -5db to 80db, over 6 frequencies, for a total of 108 test tones.

Using Big O notation, this can be represented with worse case O*(n)* time complexity. In a real-time calculation, with 3 seconds per tone, a 6 second response time, and median value of 8.75 second gap time between each tone, the worst case running time approximately 31 minutes and 3 seconds.

$$((12-((12-5.5)/2) \ = \ 8.75 \ + \ 3 \ + \ 6) \ * \ 108 \ = \ 1917)/60 \ = \ 31 \ minutes \ 57 \ seconds.$$

The primary concern was the impact this may have on the accuracy of test results, with the potential for inaccuracy if the user became uninterested or disengaged. In order to reduce the testing time, and potentially increase accuracy, a different strategy was devised.

Typically, audiologists will not play all 108 sounds to a participant. An audiologist may commence by playing a median volume tone, wait for a response and, using their own judgement, observation and professional experience, determine whether the participant can hear a sound. If necessary, the audiologist will play a louder or quieter sound, or even replay a tone multiple times to confirm whether the participant has heard the tone.

Unfortunately, without the implementation of a complex intelligent system to learn and adapt for testing of every child, the ability to create an application to emulate an Audiologist is not possible and outside of the project scope.

However, using solutions developed for similar applications, an algorithm was devised based upon commonly used divide-and-conquer method, based heavily on the binary search algorithm. The implementation for the algorithm is as follows:

1. *Create a sorted array of tones of the same frequency, in ascending volume order.*
2. *Get the middle element of the array.*
3. *Test the user. Two cases are possible:*
    3.1. *If the user responds, than the result is less than the middle element. In this case, go to step 1 for the part of the array before the middle element*
        3.1.1. *If the current element can no longer be divided, return current element.*
    3.2. *If the user does not respond, test again. If the user fails to respond a second time, the result is greater than the middle element. In this case, go to step 1 for the part of the array after the middle element.*

The time taken to execute the test for each frequency is dependent on the number of tones, but runs logarithmically as it constantly divides the possible number of results, resulting in a time complexity of O(log *n*).

Using a similar calculation to the example given above, we can determine that the worst case running time for the test at approximately 8 minutes 52 seconds:

$$((12 - ((12 - 5.5)/2) = 8.75 + 3 + 6) * 30 = 532.5)/60$$
$$= 8\ mins\ 52\ seconds$$

4.1.3 Application Structure Map

The following diagram (fig. 1) depicts the structure of the application, commencing at *Enter User Details*. The main menu and background noise assessment tool, which precede *Enter User Details,* have been omitted.

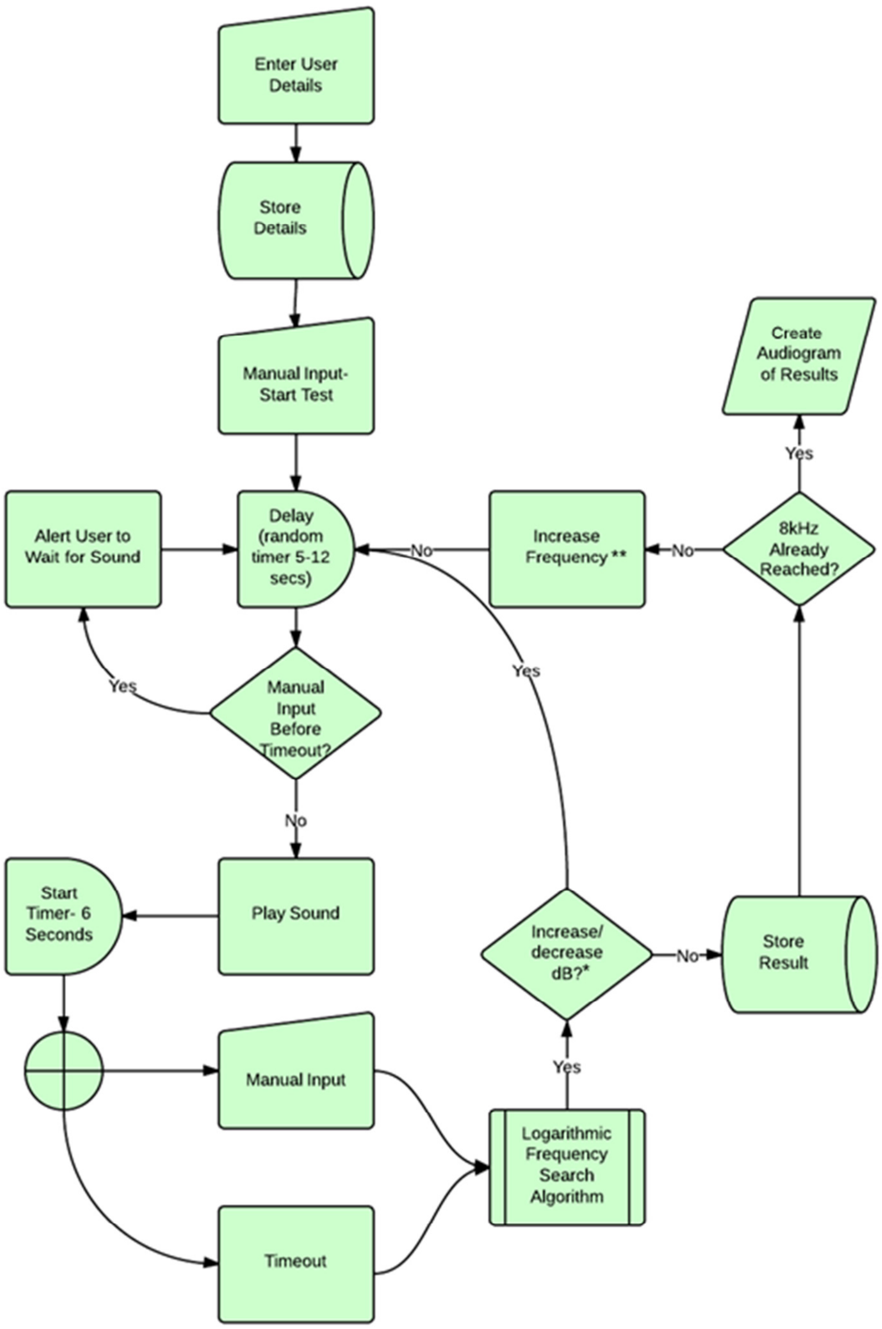

Figure 5: Application Structure Map

* dB sequence is -5, 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, and 80dB, commencing at 40.

** Frequency levels are 250Hz, 500Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz

4.2 Tones

With the use of non-standard tones in many of the applications previously mentioned, the sourcing and use of tones for use in the application for this research was of primary concern. Tones which adhere to international standards have been sourced from Dr Stephane Pigeon, PhD Engineer and professional sound engineer, who developed exclusive tones for use outside of a calibrated testing environment (Pigeon, 2013).

According to Dr Pigeon, he “wanted to find an independent reliable tool to test [his] hearing” and, as he was unable to find one, decided to develop his own. The test tones are based on the ISO 389-7:2005 international standard, which is recommended by the British Society of Audiology, and are classed as third octave band warble tones. These tones differ from pure-tone, static, pitch and speech discrimination tests as they minimise room and headphone resonance, and do not rely on specific headphones (Pigeon, 2013), which is ideal for the self-administered hearing test application, especially since the tones have not previously been approved for use outside of Dr Pigeon’s own testing.

4.3 Visual Style

The visual style of the application (Fig. 6) is aimed towards children, with bright colours, clear instructions and little use of text to reduce clutter and make the best use of screen real-estate. The simplistic visual elements of the application’s posting-box game provide the player with the means to quickly decipher the gameplay options and goals, accommodating those who may not be well accustomed to video games by overloading them with unfamiliar concepts. The gameplay methodology and design features are described in section 4.4. The application utilises images from the children’s story book *The Very Hungry Caterpillar* by Eric Carle.

Figure 6: Self-administered hearing test application main menu and user input screen

4.4 Gameplay Module Descriptors

The following table (table 2) outlines the gameplay module descriptors for the application that was designed and developed. Gameplay module descriptors are used to develop a structured representation of a game during the design phase, and to identify the technical requirements for core concepts, such as gameplay rules, scoring, interface, goals and user feedback, and are an essential component of any application design.

Module	Objective	Content/ Media	Interaction	Result
1. Rules	Define basic game play, where player must respond to sounds played by dropping tokens into a container within a specific time frame.	'Helper' avatar describes how to play, to the player, on commencement of the level (future implementation). A test run may also be required.	The player drags-and-drops token into container if sound is heard.	Player's response to sounds will provide an accurate measurement of hearing.
2. Scoring system	Gives feedback on player's actions, with animations (munching caterpillar). Results of test are collated and created in final audiogram.	Token will snap-back to point of origin if no sound has been played. Avatar will provide feedback (future implementation).	The dB (loudness) of the current frequency will increase/decrease according to the LFSA.	Player can see the result of their actions, encouraging listening.
3. Interface	Provide simplistic options and interface for player, no matter their comprehension of technology or games.	Colourful and animated imagery and interface. Animations for helper avatar, and during successful drop of token into container (future implementation)	Players touch and swipe their way around the interface.	Reduces chance of player becoming overwhelmed by an overly complex interface.
4. Goals/ Levels	Ensure player is aware of progress through visual indicators.	Structure of the game is in levels of audio frequency to define progress. Different tokens are used to denote level increase, and the caterpillar crunches on successful response.	The player selecting the token and dragging into the container, when hearing a sound.	The player is made aware of their progress through visual indictors. Completion of the test shows an audiogram.
5. Feedback	Guide players along the hearing test, giving them feedback through animations and snap-back to prevent using tokens when no sound is playing.	Animations provide feedback based on player's actions.	Player's actions trigger explicit feedback.	Player develops an understanding of game mechanics.

Table 3: Gameplay module descriptors

Chapter 5. Results

5.1 Pre-testing health professional feedback

Prior to conducting the testing, a meeting was held with experts from Telethon Speech and Hearing to demonstrate and discuss the self-administered hearing test application, and obtain preliminary feedback. The suggestions and general feedback from the meeting are summarised as follows.

The first of the suggestions was in regards to limitation of the number of frequencies played from six (250Hz, 500hz, 1khz, 2khz, 4kHz and 8kHz) to four frequencies (500Hz, 1kHz, 2kHz and 8kHz). This was due to existing testing procedures employed at TSH, and school-aged screening, which generally only focuses on four frequencies. This meant comparative results for the data analysis, obtained from a traditional audiogram, would provide data for those frequencies only. Additionally, for screening performed for school-aged children, tones tested at 1 kHz and 4 kHz are not played below 25dB, which is considered to be within the average hearing spectrum, and it was suggested to restrict tones for those frequencies to that minimum volume level.

The second suggestion included altering the application to support alternative testing regimes, by playing frequencies in random order. The structure of the application uses an adapted binary-search algorithm to work through several tones of differing volume level for each frequency. While the order of the tone volume varies depending on the participant response, the order of the tone frequencies is pre-set, working from lowest to highest.

The third suggestion provided, was in relation to the purpose of the study to obtain the quantitative data for validation of accuracy. As the application had been calibrated from the device, utilising software to measure the audio output against the original tones, a calibration had not been performed from the headphones. The reason for this was due to the third octave band warble tones used for the application, not requiring specific hardware, according to the ISO 389-7:2005 international standard. But, during the meeting, it was advised that the application could be verified for accuracy from the passive noise-cancelling headphones by utilising an artificial ear, and it was recommended that the testing procedure should perhaps focus on the qualitative data to gain feedback from parents, audiologists and gauge the children's engagement.

Finally, suggestions were made for the actual tool design, including more interesting animations for correct response feedback, and structure of the interactive story. As the story utilises a verbal narration, a suggestion was made to make the story non-verbal.

In addition to the suggestions for improvement, the staff expressed their interest in the application, stating that the applications for the screening tool were numerous, and could be utilised in a number of different environments, including third world countries and remote areas.

After the meeting, and subsequent discussion with the principal researcher and supervisor of the study, the following decisions were made, and actions implemented:

- The application tones were refined to include frequencies between 500 Hz – 4 kHz. The order of these frequencies was maintained, due to time constraints, as the application would require a significant programmatic restructure to randomise the order of tone frequency.
- An investigation was made into the use of an artificial ear to confirm device accuracy, and it was determined that this will be a suggestion for future research, as it was outside the scope and initial time frame for this pilot study, and would require significant funding.
- The study maintains focus on gathering both the qualitative and quantitative data, to answer the originally defined research questions, although less emphasis is being placed on the quantitative data to answer the primary research question.

- The application was revised to include more interesting feedback, in the form of auditory cheers and visual animations of colourful balloons and streamers when a correct response was given. Due to time constraints, the additional animations to make the story non-verbal was considered, but ultimately decided would be suggested for future studies.

5.2 Qualitative Data Results

Participant and audiologist surveys

Two audiologists were asked to complete a nine question, short answer survey, and four parents of the six participating children were asked to complete a ten question, short answer survey, regarding the use of a self-administered hearing test. One audiologist and two parents returned mostly completed surveys, while others did not return a survey. The surveys were provided upon completion of the test, once the parents and audiologists had witness the self-administered hearing test in use.

The survey questions were in relation to general impressions, use of the application, potential benefits, specific components including the design and presentation, and concerns and thoughts on the use of electronic transmission of test results. Questions for each survey were structured according to the participant, although questions were aimed at examining the same aspect, responses from the survey, were similar. The comparable benefits and concerns, together with the analysis are discussed in *Chapter 6: Discussion.* The responses to the surveys are as follows:

Audiologist Question 1: "How do you feel about parents/guardians using a self-administered hearing test for smart phones and tablet devices (such as iPhones and iPads)?"

Audiologist 1: "I think this can be a great idea for children who suffer with recurrent middle ear congestion. It would be a way for parents to 'self-check' if their child is hearing as well as used when congested"

Parent Question 1: "How comfortable are you with your child using a self-administered hearing test on a smart phone or tablet device?"

Parent 1: "very comfortable"

Parent 2: "very comfortable, I think it is a great concept"

Audiologist Question 2: "When would you like to see families using a verified self-administered hearing test for smart phones and tablet devices?"

No response was provided by the audiologist.

Parent Question 2: "When would you use a self-administered hearing test for smart phones and tablet devices, outside of regular testing?"

Parent 1: "in between hearing tests and if I though hearing was down"

Parent 2: "holidays if travelling [and] monitor ongoing"

Audiologist Question 3: "How do you think a self-administered hearing test for smart phones and tablet devices would impact health professionals?"

Audiologist 1: "I hope it doesn't lessen/reduce the community awareness of health professionals and the importance of complete diagnostic testing"

Parent Question 3: "Where do you feel a self-administered hearing test for smart phones and tablet devices would be most beneficial?"

Parent 1: "home"

Parent 2: "remote/rural areas"

Audiologist Question 4: "How do you think a self-administered hearing test for smart phones and tablet devices would benefit families?"

Audiologist 1: "quick and easy- save on cost and trips to clinic every time they feel their child is not responding well. Great for over-cautious families".

Parent Question 4: "How do you think a self-administered hearing test for smart phones and tablet devices would benefit your child and/or family?"

Parent 1: “could help determine if ears were blocked and if needed to see a doctor”

Parent 2: “I think it would make child’s participation easier. Fun device & games keep them interested longer”

Audiologist Question 5: Who do you feel would most benefit from a self-administered hearing test for smart phones and tablet devices?

Audiologist 1: “children already known to have hearing impairment. It is good as a screening tool rather than providing diagnosis e.g. site of lesion, amplification needs etc.”

Parent Question 5: “Who do you think would most benefit from a self-administered hearing test for smart phones and tablet devices?”

Parent 1: “parents – if in doubt could check yourself before seeking medical advice”.

Parent 2: “rural located children”.

Audiologist Question 6: What do you think about the current features of the self-administered hearing test?

Audiologist 1: “children obviously will love it. For hearing, again, it provides a good air-conduction”.

Parent Question 6: “What do you think about the interactive story/game testing process for the self-administered hearing test, compared to conventional?

Parent 1: “very good children love to use computers and this is something they can interact with”.

Parent 2: “- Fantastic concept”

Audiologist Question 7: What features would you like to see in a self-administered hearing test for smart phones and tablet devices?

No response was provided by the audiologist.

Parent Question 7: "What features would you like to see in a self-administered hearing test for smart phones and tablet devices?"

Parent 1: "- accurate result recording –something to keep child interested"

Parent 2: "Games to keep child interested"

Audiologist Question 8: How would you feel about patient's hearing test results being sent to you via electronic transmission?

Audiologist 1: "as a screening for already diagnosed hearing impaired children- it can inform 'us' of fluctuations due to congestion etc. Beyond that I'm not sure. It only provides minimal diagnostic information to demonstrate a hearing loss"

Parent Question 8: "How would you feel about your child's hearing test results being sent to your specialist via electronic transmission?

Parent 1: "really good"

Parent 2: "Fantastic- makes sense to use the technology available"

Audiologist Question 9: Is there anything else you would like to add?

No response was provided by the audiologist.

Parent Question 9: "Would you like to be notified about further developments or availability of a self-administered hearing test for smart phones and tablet devices?"

Parent 1: "yes"

Parent 2: "Definitely"

Parent Question 10: "Is there anything else you would like to add?"

Parent 1: "I think my child would have found it easier to just push a food item rather than push & drag"

Parent 2: no response provided.

5.3 Quantitative Data Results

To support the collection and data analysis of the quantitative research, qualitative observational notes were taken during each audiogram. Unfortunately, the testing procedure did not progress as planned, with the quantitative results from the testing tool difficult to obtain. The observation records have been analysed to aid in the identification of the issues encountered. These issues include:

- Selected headphones being too large for certain participants.
- Steep learning curve for participants under 4 years of age, requiring 3-4 attempts before grasping an understanding of the concept.
- Tool design
    - Becoming confused with the ‘how to’ screen, which demonstrates how to complete the touch-drag.
    - Frequently tapping the screen to circumvent the drag-and-drop process, resulting in erroneous data collection.
    - Quitting the application by pressing the devices ‘Home’ button mid-test, resulting in erroneous data collection.
- Children being more interested in the story component than the mini-games between each story.
- Children displaying signs of shyness or feeling uncomfortable, and ceasing to participate. One parent stating “It’s a fantastic concept, and at home she would be fine with it. She plays games like this at home with her grandma on the iPad”.
- Becoming excited, and talking to parents/audiologist/tester during the testing process, resulting in missing tones resulting in erroneous data collection.
- As the testing was conducted prior to a playgroup session, one child verbalised their desire to leave for the playgroup session.

The tests were conducted with six children, both male and female, including two children in a controlled environment, utilising a sound booth at Telethon

Speech and Hearing, and four children in an uncontrolled environment to perform additional analysis of children's engagement and response. 50 per cent of the participants were known to have an existing hearing loss, and were involved in existing programs for managing their hearing loss at Telethon Speech and Hearing or the Western Australian Institute for Deaf Education (WAIDE).

For the qualitative data analysis, only data extracted from the testing conducted in the controlled environment was utilised to verify the accuracy of the application. This is due to unknown contributing factors in an uncontrolled environment impacting on the results.

The children who were involved in the controlled environment testing were selected from children currently attending Telethon Speech and Hearing, restricting the age group to between 3-4 years of age. As a result, a portion of the data collected is unusable, and has been omitted from the study, due to the reasons previously described. Fortunately, some of the data from the tests has some comparable data.

One of the participants involved in the controlled environment testing participated in five attempts in total. The first two audiogram attempts were omitted from the data, due to the child's initial unwillingness to participate. The third audiogram (Fig. 8) shows a 10 dB reading for 500Hz and 1 kHz, which have been omitted from the results, as the child's parent was assisting in demonstrating the application. The 2 kHz result is also omitted, as the child was rapidly tapping the screen, which registered an invalid result.

For the fourth reading, at 4 kHz, the parent aided the child asking them to "listen". When the child heard the sound, they turned to the parent, smiling excitedly, and responded to the tone. The child then continued to respond to that frequency until the test ended, resulting in a registered heard tone of 55 dB for 4 kHz.

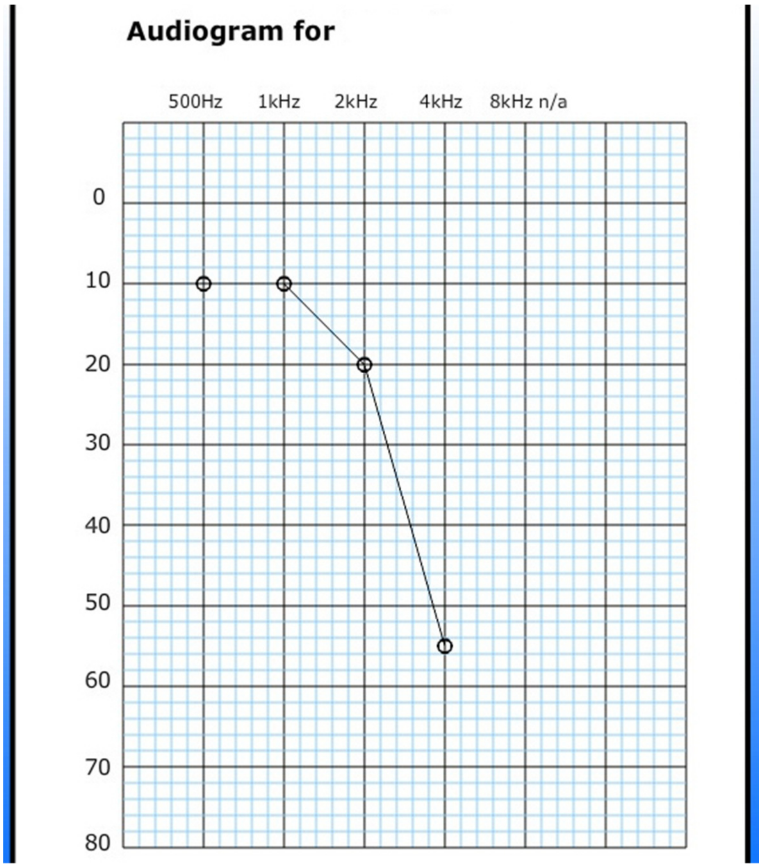

Figure 7: Participant third audiogram attempt

For the fourth attempt (Fig. 9), the parent, again, demonstrated the first frequency resulting in an invalid reading, which has been omitted from the collated results. The child then continued to participate for the remainder of the test resulting in three accurate readings of 55 dB for 1 kHz, 2 kHz and 4 kHz.

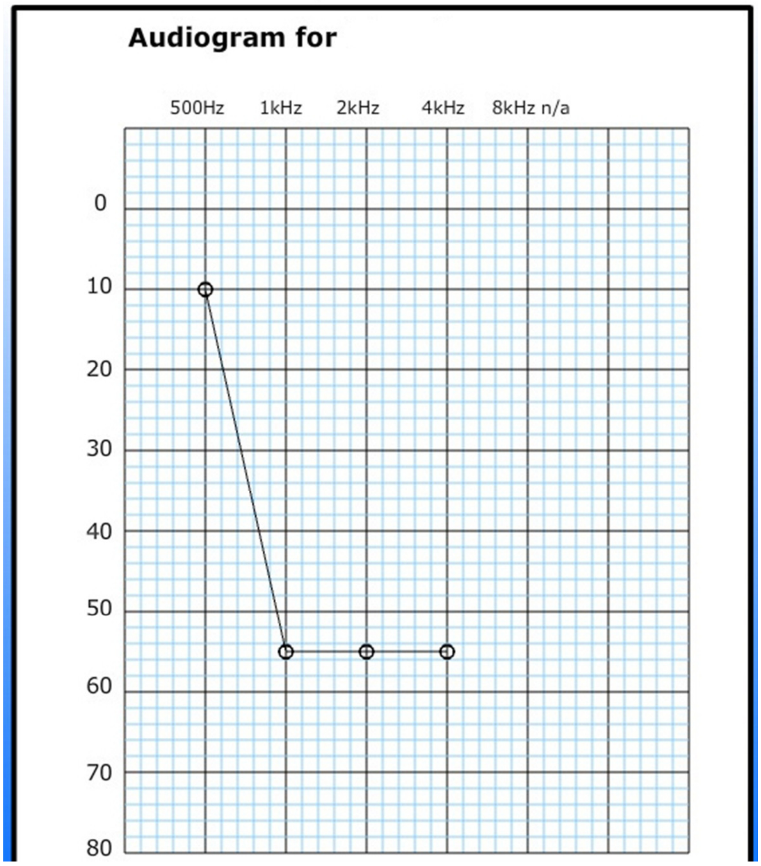

Figure 8: Participant fourth audiogram attempt

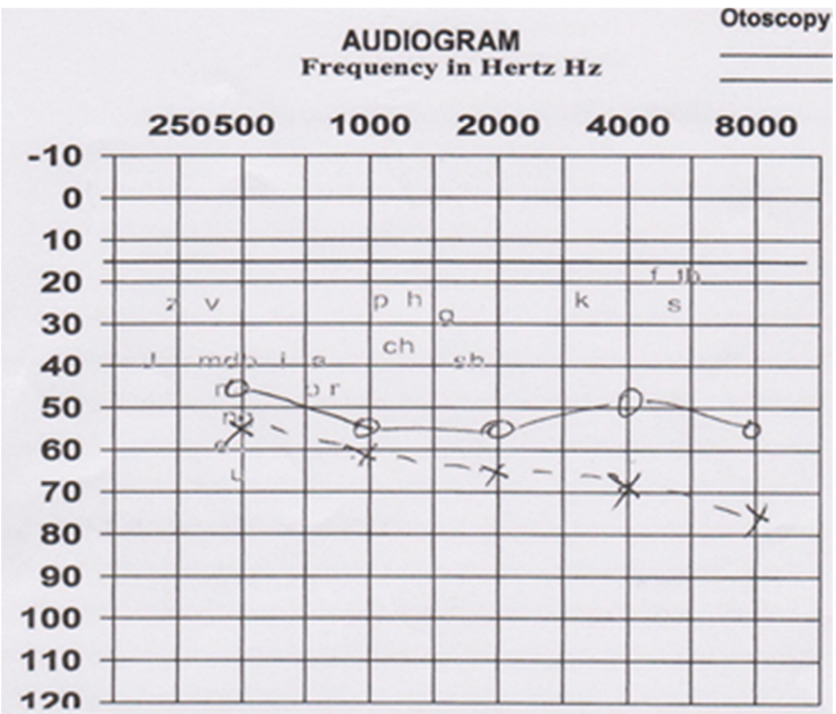

Figure 9 Participant's traditional audiogram

The audiogram provided by the audiologist (Fig. 10) is ear specific, noted by the use of 'O' and 'X' for each ear. To provide an analysis of the data, a median value can be derived for each frequency, but according to the audiologist who conducted the test, the probability of a child hearing the tones with the 'better' ear is highly likely in a bilateral hearing assessment. Based on the above audiogram, the results can be compared as follows:

Traditional Audiogram	Application Audiogram
500Hz- Lowest level heard 45dB	500Hz- Result omitted
1 kHz- Lowest level heard 55dB	1 kHz- Lowest level heard 55dB
2 kHz- Lowest level heard 55dB	2 kHz- Lowest level heard 55dB
4 kHz- Lowest level heard 50dB	4 kHz- Lowest level heard 55dB

Table 4 Comparison of traditional audiogram to application audiogram

Although only the single participant's results can be utilised for comparison, the results demonstrate a high level of accuracy, with a 5 dB disparity for the 4 kHz frequency, falling within the acceptable margin for error.

Chapter 6. Discussion

6.1 Expert perceptions

From the survey completed by the audiologist, and feedback received during the interview with experts from Telethon Speech and Hearing, the general consensus is that the preferred implementation for the self-administered hearing test application would be a companion screening tool for parents. Furthermore, the opinion of transmission of results electronically was positive, as a means of complementing existing services and for parents to monitor their child's hearing loss, saving on frequent trips to health specialists, rather than an instrument for providing a preliminary diagnosis.

This is due to the fact the application does not provide a complete diagnostic assessment of a child's ear health. A typical preliminary diagnostic assessment generally includes an audiogram, otoscopy and tympanometry, and the application currently addresses one of these. However, as noted previously, the application can be used with additional solutions, such as the Remotoscope, to work towards providing substantial data for a complete preliminary ear-health screening.

There was also some concern about the impact the application may have on health professionals, and the potential of reducing "community awareness of health professionals and the importance of complete diagnostic testing". It is important to reaffirm that the application is not designed to be a replacement for health professionals.

The results of the self-administered hearing test confirm the need for health professionals to monitor and review, perform additional testing, and provide a diagnosis and prescribe action or treatment. There is also a potential for increased community awareness with the use of the application, providing results for potential hearing loss, with referral to health professionals for children who may be otherwise unaware of a hearing loss or ear health problems.

Additionally, the initial concept for the application was for it to be utilised in certain remote areas of Australia, which are impacted by geographic, cultural and environmental limitations, restricting access to immediate health services. It is anticipated that with further testing, and collaboration with developers of additional solutions such as the Remotoscope, that a holistic approach to remote diagnosis could be achieved and implemented to address hearing loss in rural and remote areas, and may have potential to be used in the broader context of third world countries.

From the perspective of experts in the health industry, the self-administered hearing test application, in its current state, is an exciting new and feasible approach to remote screening of children's hearing.

6.2 Parent perceptions

Parents who completed the survey responded with primarily consistent answers, stating they would be comfortable utilising the application for their children, with one parent stating they thought it was a "fantastic concept" making "children's participation easier" by keeping children interested longer. Prolonged attention for children during testing, to be able to obtain consistent and accurate results, is vitally important.

The use of electronic transmission of results is looked upon favourably, with one parent stating the concept is "fantastic – makes sense to use the technology available". What is interesting is that no comments have been made in relation to issues such as records management, privacy or confidentiality, demonstrating either a general trust in the software application, or unfamiliarity of potential security issues. The sample size for this pilot study meant that no conclusions about the security concerns can be drawn. It may also be that the information letters provided to participants of the study clearly stated all information was coded and anonymous, eliminating any concerns about the study, and overshadowing issues that may arise with a commercially available application that is not ethically bound to maintain anonymity and appropriate management of records.

Few surveys noted any concerns about the use of the application itself, although one parent stated “I think my child would have found it easier to just push a food item rather than push and drag”, referring to tool design. This is discussed further (6.3 Observations), and supports the aforementioned issues that were experienced with collection of quantitative data, due to participants between the ages of 3-4 years having difficulty with the interface for the application. However, parent responses, for the features and design of the self-administered hearing test application, state that the best feature was the game component, dubbing it a “fun device”.

From the perspective of the parents of participants, the application would be suited as a companion application for use at home, or on holidays, for on-going monitoring, or for use in remote/rural areas, and is a feasible tool for use in screening children’s hearing ability and transmission of results to professionals for review. Additionally, while the application is looked upon favourably, serious consideration needs to be made into application interface, including input, to ensure that the developmental capabilities of children for specific age groups are met. It is also recommended, for future studies, that consideration is made to the investigation of electronic transmission of data, potential security issues for a commercially available application.

6.3 Observations

The analysis of the observational records revealed that the current application design is best suited for children five years of age or older, due to the interface design, as suggested by the feedback in the parent surveys. Children in this age bracket have demonstrated a much shorter learning curve (typically 1-2 turns to grasp the concept), as opposed to children aged between 3-4 years who typically had immense difficulty grasping the drag-and-drop concept.

During the testing process, one audiologist has suggested the use of physical tokens to aid with the posting process may be beneficial. For typical audiometric posting box play-testing, children will hold an object to their ear, such as a coloured token, shell or animal, and will place the object into a container when a sound is heard. The audiologist’s recommendation was to more closely emulate the process, by utilising a capacitive token, using similar technology to the stylus pens for tablet devices, so that the child can hold the object to their ear while listening and press it against the screen when a sound is heard. This suggestion will be considered for future versions, however it is recognised that merely replicating the current process may not be the best solution and may limit the usefulness of the application for self-administration.

The self-administered hearing test has also demonstrated that it encourages child participation, with both of the selected participants having experienced issues with completion of prior traditional testing. For the second participant, the audiologist had advised that regular hearing tests had not been performed, due to the stress caused for the child, and there were concerns that the child may not have wanted to participate in the study at all. When given the option to withdraw, the parent opted to participate, and the researcher advised the testing would be terminated if the child began showing signs of discomfort or stress. However, the child’s level of engagement came somewhat of a surprise to both the audiologist and the parent, with the child’s parent stating “this is great, I didn’t think he would do to well or sit”, as he became deeply immersed in the story component of the self-administered hearing test application. To terminate the test, the child’s parent asked the child to take a toilet break, so that the testing could conclude. This child’s increased attention interest was an unexpected but positive outcome of the study.

From an analysis of the observations, it has been determined that the interface and structure of the application needs to be amended to cater for the individual needs to children of diverse developmental needs. It is suggested, for future research, that consideration is made to identify the needs of children from different age groups, and amend the application to suit those needs.

Some examples of those amendments may include using a simple button press, use of physical tokens for interaction, and further integration of the game component into the story, for children aged between 3-4 years of age. Additionally, other factors need to be taken into consideration, such as size of headphones, and removal of complex instructions.

Chapter 7. Conclusion

When initially developing this pilot study, the focus was to determine, firstly, whether an application developed for self-administered hearing tests can be utilised for children; to reduce the strain on current telehealth services; and complement similar solutions be a feasible telehealth solution. To answer this question, a subsidiary question was developed, which was to determine the accuracy of the output from the device.

With the data that has been obtained and analysed, there is evidence to support the self-administered hearing test producing an accurate audiogram in comparison to a gold standard hearing assessment. However, due to a number of unforeseen circumstances, identified in the observational records, minimal quantitative data was obtained; and it may be argued that the sample size is not sufficient enough to base the answer to the question on those results alone. Ideally, the quantitative data gained from the testing procedure would have been substantial enough to derive a solid conclusion for the subsidiary research question.

The information obtained during the interview with experts from Telethon Speech and Hearing was invaluable in determining that further confirmation for the accuracy of the application would be possible, and can be verified using an artificial ear, which opens the door for future research.

Of crucial importance were the unexpected findings during testing that impact the testing procedures of the application, including the learning curve, individual child ability, age as well as the tool design. Despite this, data obtained from the surveys, interview and observations, clearly provides evidence to support the claim that a mobile application, developed for smart phone and tablet devices, can be used to supplement audiology testing for children and would be accepted by both parents and audiologists.

7.1 Future Research

As this pilot study has shown, the feasibility of this self-administered hearing test application, for children, may be utilised as a possible solution for the screening of hearing loss. But, before the application can be considered for commercial application, a number of issues have been identified in this thesis that need to first be addressed. This thesis concludes with some recommendations for future developments in this area, which are as follows:

Interface design

The interface should be suited for the diverse developmental needs of children. One suggestion may be to develop different versions of the application to cater for children of different age groups. For example, as identified in this study, too much text or complex instructional videos can overwhelm or confuse children under the age of 5, and alternative solutions should be investigated.

Additionally, integration of the story and game component should be explored to address issues with some children preferring story over segmented story followed by pure gameplay.

User input and feedback

It is suggested that an application, such as this, should utilise alternate input methods, suited for the diverse developmental needs and capabilities of children. Additional research needs to be conducted into this area to develop a better understanding of suitable input types, such as a button press for children aged 3-4 years, or drag-and-drop for children aged above 5 years.

The use of physical apparatus, such as a customised capacitive stylus, to aid in child input, warrants an investigation as traditional audiograms for children utilise physical tokens to place into posting boxes. This may prevent issues such as repetitive tapping of the screen creating erroneous data collection. For example, a child may be provided with several capacitive tokens in the shape of fruit, which could be used to feed the caterpillar. Furthermore, there is current technology available, which has been employed by Mattel's 'Apptivity', which utilises toys. Each toy is designed with unique contact points that are recognised by the iPad's multi-touch screen, to interact with the iPad software ("About Apptivity, 2013).

Hardware

For future research, hardware selection needs to be made with consideration for the children selected for the testing sample. Factors such as the size of headphones need to be taken into consideration; else the hardware may have an adverse impact on the testing results.

Test tones

The output tones for each frequency will need to be verified and the use of an artificial ear warrants additional information. Research needs to be conducted to identify the best course of action to gather sufficient data for the verification of accuracy.

Alternative testing regimes are suggested, including programmatically randomising the order or frequencies played, and investigation into the possibility of individual, or ear specific, testing.

Research method

With the application redeveloped according to the above suggestions, it is suggested that a longitudinal study be conducted, perhaps with the application made available for individual participants in their home, for non-diagnostic testing. Frequent meet-ups would be conducted to observe participants ability to complete the application testing process, and obtain feedback from the parents/guardians of the participants.

This form of research would potentially eliminate issues with children's behaviour, as a result of environment, time of day or other factors, hindering the data collection process as well as determine the feasibility of the application over time.

Final comment

This research has shown that a mobile application used for self-administered hearing tests can complement existing services and be a companion screening tool for parents. The new and innovative approach to remote screening of children's hearing can begin to address the issues in remote and rural areas where there are limited services and limited access to audiologists. It is intended that this research will continue, if possible, through a doctorate and will include extensive testing, revision and location based testing. The potential for improving earlier detection of hearing loss in children is a key factor in better health outcomes for children, their resultant learning, and ultimately their quality of life.

Reference list

About Apptivity. (2013). Retrieved May 20, 2013, from http://mattelapptivity.com/about.php

Bensink, M. E., Brown, C., Elliott, G., Perry, C., Scuffham, P., Smith, A. C., & Stewart, C. (2010). The feasibility of a community-based mobile telehealth screening service for Aboriginal and Torres Strait Islander children in Australia. *Telemedicine and e-Health, 16*, 950+.

Brennan, D. M., & Barker, L. M. (2004). *An interactive telemedicine system for remote speech-language pathology treatment.* Paper presented at the Engineering in Medicine and Biology Society, 2004. IEMBS '04. 26th Annual International Conference of the IEEE.

Burrow, S., & Thomson, N. (2006). Summary of Indigenous Health: Ear Disease and Hearing Loss. *Aboriginal and Islander Health Worker Journal, 30*(1), 2. http://search.informit.com.au.ezproxy.ecu.edu.au/documentSummary;dn=111778601791107;res=IELIND

Creswell, J. W. , & Plano-Clark, V. L. (2011). *Designing and Conducting Mixed Methods Research* (2nd ed.). Thousand Oaks, CA: Sage Publicaitons Inc. .

Fabry, D. (2010). Applications of telehealth for hearing care: telehealth has taken many years to become an "overnight" sensation. This article will address some of the obstacles, as well as opportunities, that suggest that a convergence of telecommunications and health care may finally become a reality. *Audiology Today, 22,* 18+.

Greene, J. C. . (2007). *Mixed Methods in Social inquiry*. San Francisco, CA: John WIley & Sons.

Hall, R. (2012). *Mixed Methods: In Search of a Paradigm.* Paper presented at the International Conference Innovative Research in a Changing and Challenging World, Phuket, Thailand.

He, A., Wei, D., & Zhang, Z. (2008). A mobile network-based multimedia teleconference system for homecare services. *Telemedicine and e-Health, 14*, 147+.

Healy, S. (2008, May 11). Computer a hearing aid, Newspaper, *The Sunday Mail,* p. 1. Retrieved from http://ezproxy.ecu.edu.au/login?url=http://search.proquest.com.ezproxy.ecu.edu.au/docview/353419325?accountid=10675

Hendley, J. O. (2002). Otitis Media. *The New England Journal of Medicine, 347*(15), 1169-1174. http://ezproxy.ecu.edu.au/login?url=http://search.proquest.com/docview/223938321?accountid=10675

Johnson, R. B. , & Onwuegbuzie, A. J. (2004). Mixed Methods Research: A Research Paradigm Whose Time Has Come. *Educational Researcher, 33*(7), 14-26.

Karunanithi, M. (2007). Monitoring technology for the elderly patient. *Expert Review of Medical Devices, 4*(2), 267-277.

Korschun, H. (2012). Diagnose ear infections at home with iPhone. http://news.emory.edu/stories/2012/09/remotoscope_for_ear_infections/campus.html

Masalski, M, & Kręcicki, T. (2013). Self-Test Web-Based Pure-Tone Audiometry: Validity Evaluation and Measurement Error Analysis. *Journal of Medical Internet Research (1439-4456), 15*(4), p. e71. doi:10.2196/jmir.2222

McCarthy, M., Muñoz, K., & White, K. R. (2010). Teleintervention for Infants and Young Children Who Are Deaf or Hard-of-Hearing. *Pediatrics, 126*(Supplement 1), S52-S58. doi: 10.1542/peds.2010-0354J

O'Keefe, S. (2012). A hearing loss problem has knock-on effects; In one remote community, more than 90 per cent of children have some form of hearing loss which could be rectified, and it has an impact in the classroom, *ABC Premium News*. Retrieved from http://ezproxy.ecu.edu.au/login?url=http://search.proquest.com/docview/1031098247?accountid=10675

Pigeon, I. S. (2013). Online Hearing Loss Test and Audiogram Printout. Retrieved April 5, 2013, from www.myhearingtest.net

Shargorodsky, J., & Fligor, B. J. (2011). Apps for Better Hearing. *Hearing Health, 27*(2), 38-39.

Stevens, C. (2013). *The Growing Child : Laying the foundations of active learning and physical health* Retrieved from http://ECU.eblib.com.au/patron/FullRecord.aspx?p=1170331

Tashakkori, A. , & Teddlie, C. . (2003). *The past and future of mixed methods research: From data triangulation to mixed model designs* Vol. B. A. Tashakkori & C. Teddlie (Eds.), *Handbook of Mixed Methods in Social and Behavioral Research*

Thompson, M. (2013, 12th March). [Telstra unveils roadmap to manage mobile broadband boom].

Timms, L., Grauaug, S., & Williams, C. (2012). Middle Ear Disease and Hearing Loss in School-Aged Indigenous Western Australian Children. *Asia Pacific Journal of Speech, Language and Hearing, 15*(4), 277-290. doi: 10.1179/136132812804731794

Weber, D. (2012). WA Indigenous children's hearing compared to third world. Retrieved Jun 22, 2012, from Australian Broadcasting Corporation http://ezproxy.ecu.edu.au/login?url=http://search.proquest.com.ezproxy.ecu.edu.au/docview/1021379773?accountid=10675

Yiengprugsawan, V., Hogan, A., & Strazdins, L. (2013). Longitudinal analysis of ear infection and hearing impairment: findings from 6-year prospective cohorts of Australian children. *BMC Pediatrics, 13*(1), 28.