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Mobile phone applications to screen for hearing loss in low-and middle-income countries: a state-of-the-art review

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DECLARATION

I, Humphrey Kwaku Abbey, hereby declare that the work on which this dissertation /or thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other University.

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ABSTRACT

Hearing impairment is a chronic condition for which limited screening and diagnostic services are available in low-and-middle income countries (LMICs). In addition to the conventional medical devices existing to screen for the condition, several smartphone- and tablet-based applications have been introduced as mobile health (mHealth) solutions. This study was aimed at reviewing the set of mobile health tools available for screening for hearing loss in both developed countries and LMICs. Furthermore, to consider the suitability of the screening tools identified in the first objective for use in developing countries. The research approach adopted for this study was that of a state-of-the-art review. Relevant literature on mobile technology solutions to assess hearing loss were identified in electronic databases and reviewed. The mHealth solutions were reviewed with a focus on: countries of origin and evaluation; devices, software platforms and hardware considerations; hearing loss characteristics of recruited populations; features of the tests conducted and of the testing environment; reference methods to which the mobile application was compared; application performance; feedback from users; and cost. Eighteen available smartphone- and tablet-based applications for hearing loss screening were reviewed. Studies on these applications included participants from a variety of ages and, with and without hearing loss. A variety of testing environments were used. Studies on the applications found 11 of them to have acceptable functionality for use in screening for hearing loss. These 11 applications are also potentially suitable for use in LMICs, although they have some limitations. While these applications are not able to replace the conventional audiometer, they have potential as a first point of access for referral to conventional audiometry, and to help increase access to hearing loss tests in resource-constrained health systems.

DEDICATION

I dedicate this master's thesis to my late mother Madam Joyce Enyonam Akua Addo-Abbey.

I also dedicate the thesis to my nuclear family Richmond Anertey Abbey (Father), Aretha Djargbley Adwoa Abbey (Sister), Cornelius Djartei Kwesi Abbey (Brother), and most especially to my hearing-impaired brother Ephraim Djarkwei Kwame Abbey.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABR	-	Auditory brainstem-evoked response
ANSI	-	American National Standards Institute
AMTAS	-	Automated Method for Testing Auditory Sensitivity
ASA	-	Acoustic Society of America
ASP	-	Academic Search Premier
AWI	-	Africa-Wide Information
CINAHL	-	Cumulative Index of Nursing and Allied Health Literature
dB	-	Decibels
dB HL	-	Decibels in Hearing Levels
dB SPL	-	Decibels of sound pressure levels
EEG	-	Electroencephalography
ENT	-	Ear, Nose and Throat
IEC	-	International Electrotechnical Commission
IEEE	-	Institute of Electrical and Electronics Engineers
GSI	-	Grason-Stadler Incorporation
HHIE-S	-	Hearing Handicap Inventory for the Elderly-Survey
HSNAE	-	Health Source: Nursing/Academic Edition
Hz	-	Hertz
iOS	-	iPhone Operating Software
ISO	-	International Organization for Standardization
kHertz	-	Kilohertz
LMIC	-	Low-to-middle income countries
mHealth	-	Mobile Health
NRCCDDII	-	National Research Council (US) Committee on Disability Determination for Individuals with Impairments
NSRT	-	National Technical Institute for the Deaf (NTID)- speech recognition test
NPV	-	Negative Predictive Value
OAEs	-	Otoacoustic Emissions
OSHA	-	Occupational Safety and Health Administration
OtoID	-	Ototoxicity Identification Device
PHC	-	Primary Health Care
PICO	-	Population, Intervention, Comparison and Outcome
PPV	-	Positive Predictive Value

PTA	-	Pure tone average
RETSPL	-	Reference Equivalent Threshold Sound Pressure Levels
SIN	-	Speech-in-noise
SRT	-	Speech Recognition Threshold
SSNHL	-	Sudden Sensorineural Hearing Loss
TIN	-	Tone-in-noise
UCT	-	University of Cape Town
USA	-	United States of America
USD	-	United States Dollars
UK	-	United Kingdom
URL	-	Uniform Resource Locator
WHO	-	World Health Organization
WoS	-	Web of Science
WVT	-	Whispered Voice Test

DEFINITION OF TERMS

Audibility threshold:	The faintest or lowest hearing level at which an induced response from a neuron is obtained in any case one half of a series of rising sound trials, with a minimum of two responses out of three required at a single level (American National Standards Institute, 2004 (Reaffirmed in 2009)).
Diagnosis:	**“**The process of identifying a disease, condition, or injury from its signs and symptoms” (National Cancer Institute, 2020).
Disabling hearing loss:	Hearing loss that is above 30 dB HL among children below the ages of 15 years, and a hearing loss above 40 dB HL among adults aged 15 years and more, in the better hearing ear (World Health Organization, 2018a).
Masking:	A procedure whereby noise or sound is rendered to the non-tested ear in order to keep it occupied while the test ear is being evaluated (Soer, 2014).
Screening:	**“**The presumptive identification of unrecognized disease in an apparently healthy, asymptomatic population by means of tests, examinations or other procedures that can be applied rapidly and easily to the target population” (World Health Organization, 2020).
Years lived with disability:	The degree of measure for the burden of a particular illness, and is calculated by “multiplying the prevalence of a disorder by the short- or long-term loss of health associated with that disability” (also known as the disability weight) (Murray et al., 2013; The National Institute of Mental Health, 2019).

CHAPTER 1

INTRODUCTION

Hearing loss or impairment is a chronic condition experienced when individuals can no longer hear from both ears or one either partially or completely. A hearing loss condition may be termed single sided- or unilateral hearing loss if only one of the ears is impaired (Moteki, 2019), and double sided- or bilateral hearing loss if it affects the two ears together (Howell et al., 2019). Hearing loss may result from the extreme use of audio devices, for example, listening to loud music with personal headsets (Vogel et al., 2010); prolonged exposure to damaging levels of sounds in noisy environments (Albera, 2019); ear infections such as chronic suppurative otitis media (Pichichero, 2018); age-related causes or natural ageing, also known as presbycusis (Bowl & Dawson, 2018).

Other major causes of hearing loss or impairment include genetics or childhood complications (Dessai, Ashraf & Michael, 2017); ototoxic reactions from all the medicines taken regularly by a patient in the form of antibiotics, chemotherapy and industrial chemicals (Rademaker-Lakhai et al., 2006); the unexpected onset of the condition and illness and or damage to the head from accidents (Micco, 2018).

In 2018, globally, 466 million individuals were suffering from “disabling hearing loss”, out of which 34 million were children (World Health Organization, 2018a). It was projected that the burden of the disease will affect above 900 million individuals by the year 2050 (World Health Organization, 2018b). The prevalence of hearing loss varies between developing and developed countries, with an increased prevalence in developing countries. Accessible data confirm that nearly ninety percent of individuals affected by hearing loss reside in countries in Asia Pacific, South-East Asia and sub-Saharan Africa regions, whereas the “high-income countries account for a small percentage of the reported cases” (Mulwafu, Kuper & Ensink, 2016; World Health Organization, 2018a).

The severity of hearing loss in developing regions is attributed largely to later diagnosis of the disease (Chari & Chan, 2017; Michels, Duffy & Rogers, 2019). The World Health Organization (2018a) attributes untreated hearing loss in developing countries to the dearth of diagnostic medical solutions, which costs the world an annual amount of United States dollars (USD) 750 billion.

Hearing loss has negative consequences, particularly if it is not screened and diagnosed beforehand. Typical examples are, missed opportunities for employment, child language retardation, inability to recognize speech especially in difficult environments, delayed social-emotional development, limited participation in daily lives, socio-economic problems as well as emotional problems, impaired academic performance and withdrawal from most activities are all causes for concern (Arlinger, 2003; Hawkins et al., 2012); Roush (2001:18).

Hearing disabilities contribute to social isolation, loss of autonomy, anxiety, depression, cognitive decline and dementia, all of which affect quality of life (Domagala-Zysk, 2019; Mehboob et al., 2019; Rutherford et al., 2018). The standard of good health, comfort, and happiness experienced by both children and adults with hearing disabilities are therefore compromised.

Early screening, diagnosis and treatment of the hearing loss condition can help reduce the annual global cost of unaddressed hearing disorders, and reduce the burden of the disorders on the lives of people affected by hearing loss (World Health Organization, 2018a).

Primary healthcare (PHC) providers for instance, family practice physicians, nurse practitioners, physician assistants and community healthcare workers (CHWs) are usually the first to evaluate individuals with hearing impairment or loss. Primary healthcare providers who are trained to perform primary otologic examinations (Mandavia et al., 2018) and conduct simple hearing test screening (Hussein et al., 2016) can perform examinations to identify hearing loss (Blazer, Domnitz & Liverman, 2016). Where PHC providers are able to identify that a patient is at risk, they must provide a referral for the patient to the appropriate specialists, that is, audiologists and or throat (ENT) specialists, who will perform a full diagnostic hearing assessment (Blazer, Domnitz & Liverman, 2016; Thoidis et al., 2019).

The prevalence of hearing loss in developing countries has led to demand for audiologists, screening and or diagnostic medical resources, and hearing care services all of which are limited in developing countries (Castillo & Steven, 2015; Nash et al., 2013). Even though people who are diagnosed in advanced stages of hearing disorder may benefit from the use of assistive devices, captioning, cochlear implants, some forms of education with social support, hearing aids and sign language (Scharp et al., 2018; World Health Organization, 2018a), these interventions are beyond the reach of many individuals in developing nations. It is therefore significant to support early screening of the hearing loss condition.

In South Africa, the increasing occurrence of hearing loss condition and the limited means for diagnosis are problematic at the national level (Stevens et al., 2013). The ratio of audiologists per 100,000 people in South Africa is 2.4 (Castillo & Steven, 2015) and as a whole 0.57 per 10,000 (Pillay et al., 2020). Comparatively, developed countries on average have 16.4 audiologists per 100,000 people (Chadha, 2014). The situation in South Africa renders hundreds of people with hearing loss unable to access screening and diagnostic services each year (Fagan & Jacobs, 2009). The prevalence of hearing disabilities in South Africa and the limited number of audiologists and audiological resources in the country, motivate for innovation (Samelli, Rabelo & Vespasiano, 2011).

Audiometers are medical devices used in screening for and in the diagnosis of hearing loss. They require low ambient noise during hearing loss testing and accurate calibration checks by a qualified health care worker (American Speech-Language-Hearing Association, 1997; Kapul et al., 2017).

Their limitations include high interobserver variability and low test-retest reliabilities (Maclennan-Smith, Swanepoel & Hall, 2013). In addition, audiometers are expensive to procure and difficult to calibrate (Mulwafu, Kuper & Ensink, 2016). In addition to the conventional medical devices available to screen for hearing loss, several smartphone - and tablet-based applications (apps) have been introduced as mobile health (mHealth) solutions.

A review of such mHealth solutions and their suitability for low-and middle-income country (LMIC) settings, would inform improvement of the mHealth tools, their adoption, and the development of new ones. This study reviewed such mHealth solutions and their suitability for LMIC settings. The research approach adopted for this study was that of a state-of-the-art review.

1.1 Problem statement

Despite improvements in medical devices developed to screen for hearing loss in the last two decades, there remains several challenges that limit the successful screening for hearing impairment among children, adults and the elderly population, especially in LMICs, such as South Africa. With hearing loss considered the "most frequent sensory deficit" in humans (Szudek et al., 2012), the number of audiologists in LMICs is low, resulting in limited services. This has led to people with hearing loss or impairments to experience little or no hearing care provisions at the early stages of the hearing disorder. The combined effect of high-priced hearing care services and the low numbers of skilled health professionals for hearing loss care give rise to complications of hearing disabilities (Dalton et al., 2003; Fagan & Jacobs, 2009). Mobile health solutions for hearing loss screening have been developed to address these limitations.

1.2 Aim of the study

The aim of the study was to review the mobile health applications that have been developed to screen for hearing loss in both developed countries and LMICs and identify those that may be suitable for use in LMICs.

1.3 Research objectives

In pursuit of the above aim, the specific objectives of the research study were:

i. To review the set of mobile health tools available for hearing loss screening in both developed countries and LMICs, with reference to: countries of origin; countries of evaluation; devices, software platforms and hardware considerations; hearing loss characteristics of recruited populations; features of the tests conducted and of the testing environment; reference methods to which the mobile application was compared; application performance; feedback from users; cost; and limitations.

ii. To consider the suitability for use of screening tools identified in LMICs.

1.4 Structure of the dissertation

The dissertation is structured into five chapters. Chapter 2 is a review of relevant literature on hearing loss screening and medical devices. The methodology of the research study is explained in Chapter 3. In Chapter 4, the results and outcomes of the review are presented. Chapter 5 discusses the findings of the review and concludes the study.

CHAPTER 2

REVIEW OF RELEVANT LITERATURE

This chapter will discuss the types of hearing loss, the various screening tests for hearing loss, the medical devices used in screening the condition, and the challenges presented by the latter.

2.1 Classification of hearing loss

Currently, the pure tone audiogram test is the "gold standard" for diagnostic testing (American Speech-Language-Hearing Association, 2015; Manganella et al., 2018; Prieve et al., 2013). The audibility of tones to a person is measured in decibels in hearing levels (dB HL) across a range of threshold frequencies (National Research Council (US) Committee on Disability Determination for Individuals with Impairments, 2004; Swanepoel & Laurent, 2014). Hearing loss can be classified based on the combined information of the severity of the hearing impairment (that is, the numerical ranks according to what range of sound tones should be heard), the configuration or the shape of the test results plotted on the audiogram (for instance, sloping, flat, rising, notch or U-shaped), and the type of hearing loss (Clark, 1981; Swanepoel & Laurent, 2014).

Conductive hearing loss, sensorineural hearing loss and mixed or combined hearing loss are classified based on where the hearing impairment is identified in the human ear (namely the outer ear, middle ear and the inner ear), which connected nerves to the ears are affected, and the sections of the brain that controls hearing. These three types of hearing loss are discussed below.

2.1.1 Conductive hearing loss

Normally, sound is conveyed in its mechanical form from the environment through the external ear canal of the middle ear to the stapes footplate (that is, the bone involved in the conduction of sound vibration), then to the inner ear. Intensity is one of the physical attributes of sound. Here, it helps the loudness of the sound to reach the inner ear to cause stimulus. When the natural flow of sound energy and its intensity or loudness is obstructed as a "result of a blockage in the external ear" otherwise "any disorder that unfavourably effects the middle ear" (Wroblewska-Seniuk et al., 2018), then conductive hearing loss is said to have occurred.

Some of its causes include otosclerosis; wax impaction; fluids in the middle ear; atresia of the ear canal; dislocation of the ossicular chain; perforation in the ear drum or the tympanic membrane; infection in the ear canal; and cholesteatoma (Alaqrabawi et al., 2016; Ebert, Zanation & Buchman, 2008). Among children below the ages of 15 years, conductive hearing loss is considered as the primary type of hearing loss that affects them, and it can be corrected easily (Al-Rowaily, Al-Fayez & Al-Jomiey, 2012).

2.1.2 Sensorineural hearing loss

Sensorineural hearing loss (that is, a reduction in the auditory threshold sensitivity) can result from inner fluid imbalances, cochlea damage or auditory nerve dysfunction. It is considered the most popular type of hearing impairment or loss (Acipayam, Koçak & Elbistanli, 2017). The causes of sensorineural hearing loss include illnesses, medication, presbycusis or natural aging, a blow to the head, hearing loss that runs in a family, a problem in the structure of the inner ear, and loud noises or explosions (Remenschneider et al., 2017).

2.1.3 Mixed or combined hearing loss

Mixed or combined hearing loss occurs when a reduction in the auditory threshold sensitivity or sensorineural hearing problem is compounded by conductive hearing problem (for example, otitis media plus effusion) It is caused by traumatic head injuries, noise-induced hearing problem with otitis media or advanced otosclerosis. Mixed or combined hearing loss can also occur when the air-filled central cavity of the ear, behind the eardrum and the cochlea (that is, portion of the inner ear that looks like a snail shell) develops abnormalities in the same ear (Gelfand, 2016:121; Lee et al., 2017).

The impact of mixed hearing loss is that of the combination of conductive hearing loss and sensorineural hearing loss (Whittemore et al., 2012). In some cases, the sensorineural condition as a component of mixed or combined hearing loss is mostly permanent, while the conductive condition could either be temporary or permanent and can be tested using advanced hearing test modalities by audiologists and procedures or traditional screening procedures which can be used by neurologists.

2.2 Bedside hearing tests

Traditional screening procedures and tools include the whispered voice, tuning forks, mechanical watch ticks, finger rubs, and the single or multiple-questions (Moyer, 2012). These are called ‘bedside hearing tests’ (Boatman et al., 2007) and are discussed below.

2.2.1 Whispered voice

The whispered voice test (WVT) is a common non-technological tool used in both developing and developed countries for the screening of hearing loss (Prescott et al., 1999). The WVT is one of the oldest and simplest ways of detecting hearing disorders (Nel et al., 2014). Before the hearing loss test begins, the patient is made to cover one ear. This is usually the ear that is not being tested. The audiologist then whispers a few words or numbers one at a time close to the patient being examined. The patient is given time to say the exact words that were mentioned. The strengths of the WVT are that it is a simple, and an effective way of screening for the hearing loss condition in settings where standard audiometric facilities are unavailable (Pirozzo, Papinczak & Glasziou, 2003). However, the screening results from the WVT can be challenged in terms of reliability and objectivity (Nel et al., 2014).

2.2.2 Tuning forks

The screening of hearing loss can also be done with the conventional Weber and Rinne tuning forks (Yueh et al., 2003). For the Weber tuning fork test, the audiologist places the vibrating fork on a midline osseous structure of the patient's forehead, while for the Rinne tuning fork test, the audiologist places the vibrating fork on the ear and the mastoid (that is, the portion of the temporal bone of the skull located behind the ear and containing open, air-filled spaces). A patient with a normal hearing will detect no inter-aural loudness differences and hear loud sounds at the ear for both the Weber and the Rinne tests. The commonly available tunings are 512 and 1024 hertz (Hz).

Tuning forks have been considered integral components of hearing examinations for clinical screening, assessment for surgical candidacy, and estimating the severity of hearing loss (Kelly, Elizabeth & Adam, 2018). Despite the strengths of tuning forks, they only evaluate hearing at a single low frequency, neglecting a wide spectrum of hearing frequencies during physical examinations (Bagai, Thavendiranathan & Detsky, 2006; Handzel et al., 2013).

2.2.3 Mechanical watch tick

The mechanical watch tick is another traditional way to screen for hearing loss (Bagai, Thavendiranathan & Detsky, 2006; Boatman et al., 2007). The identification of disabling hearing loss is determined by the ability of the patient to identify the ticks produced from the mechanical watch. The World Health Organization (2006) endorses the watch tick tool as an easy, standardized, and validated test. In addition, the watch tick is the most sensitive screening technology amongst all the 'bedside hearing tests' (Boatman et al., 2007). It has also been proven to be an effective way to screen for hearing loss in primary healthcare clinics (Walker et al., 2013). Yet, modern mechanical watches do not tick audibly due to high noise levels at screening centres, causing the test from the mechanical watch to yield unreliable results and high interobserver errors (Boatman et al., 2007; Moyer, 2012).

2.2.4 Single or multiple questions

Self-administered tests come in the form of a single question or multiple-question tests. For example, the Hearing Handicap Inventory for the Elderly-Screening (HHIE-S) which has been developed as a screening measure for the elderly (Moyer, 2012). With the single question self-assessment tool, the patient answers the following questions, "Do you have difficulty with your hearing?" or "Do you feel you have hearing impairment?". For the multiple-question version, more detailed questions are asked. For instance, "Can you hear most of the things people say (with a hearing aid if that's how you hear best)?", "Does a hearing problem cause you to have arguments with family members?" and "Do you feel that any difficulty with your hearing limits or hampers your personal or social life?". The HHIE-S is available online (Garrison & Bochner, 2015:828) nevertheless, the testing of hearing loss with self-reported measures do not offer objectivity in their results (Koopman et al., 2008; World Health Organization, 2015).

2.3 Hearing testing modalities currently used by audiologists

The poor case history and screening quality of the traditional testing devices (Boatman et al., 2007; Sindhusake et al., 2001) have resulted in the use of medical devices. According to the World Health Organization's Global Harmonization Task Force (2012), a medical device is any instrument, machine, or software developed specifically and medically for the purposes of screening and prevention of diseases.

2.3.1 Relevant procedures for hearing loss screening

Hearing assessments conducted for both adults and children can be categorized into five broad groups namely, auditory brainstem-evoked response test, pure-tone audiometry (that is, air conduction test), otoacoustic emissions test (OAEs), and the middle ear test (which comprises of tympanometry and otoscopy or visual inspection). The sections below describe these hearing tests modalities, focusing on how they are performed and how the screening results are obtained.

Pure tone audiometric testing

Pure tone audiometry is a recommended protocol for primary health screening (Huizing, 1951; Louw, Swanepoel & Eikelboom, 2018), and conventional pure tone audiometry is considered the "most common form of hearing measurement" and the "gold standard test" in determining the hearing loss condition of an individual (Al-Abri et al., 2016; Dewyer et al., 2019; Kam et al., 2012; Samelli et al., 2018). Audiometry derived from a pure-tone air conduction testing helps the audiologist to determine the hearing threshold of an individual at different frequencies and as well as assist him or her to identify the degree of hearing loss (Walker et al., 2013). The components used in pure tone audiometry include audio oscillator, amplifier, attenuator, and earphones. This testing quantifies the degree of hearing loss, but not whether the patient's hearing loss has a conductive component (Dewyer et al., 2019).

Middle ear testing: Tympanometry

Testing the structure and functioning of the middle ear is an assessment that is performed during hearing loss screening (Strain & Fernandes, 2015). The audiologist uses this kind of test to evaluate in detail how the involuntary muscle in the middle ear contracts in response to sound stimuli in the form of steady, pulsed or warble pure tone signals. The middle ear assessment is performed with a tympanometer, which is an objective technology for gathering information about the location of the hearing disorder. To perform tympanometry, an air pressure is pushed into the external ear canal of an individual to cause the eardrum to vibrate. A probe is then inserted through the external ear canal to allow the audiologist to listen to the different sounds caused by the air pressure released. The audiologist either increases or decreases the air pressure in the ear to make sure the ear drum is sensitive to the range of sounds caused by the changes in the air pressure for the tympanogram. Results from the tympanogram would either recommend conditions (for example, fluid in the middle ear, perforation of the eardrum, and a dysfunction of the eustachian tube) that may need medical attention or convey the status of the middle ear system (American Speech-Language-Hearing Association, 2022).

Middle ear testing: Otoscopy or visual inspection

If the tympanogram results suggest some irregularities, the audiologist then checks whether the ventilation tubes in the ear drums of the patient are affected or not (Stanton, 2009). In examining the structures of the tympanic membrane, external auditory canal, and the middle ear for the presence of hearing loss, otoscopy is also one of the clinical procedures that is used (Hawke, Keene & Alberti, 1990). This procedure is shown to be very adequate in assessing hearing loss (American Speech-Language-Hearing Association, 2022; Wormald, Browning & Robinson, 1995), using an otoscope. During hearing screening, the strength of the facial muscles are looked at, as these nerves travel through the middle ear and the head is gently immobilized. A speculum is inserted into an individual's external auditory canal of the ear to accommodate the otoscope. It is anticipated that, for the screening to be appropriate, the visual inspection of the ear or otoscopy examination must have seventy-five percent (75%) visualization of the tympanic membrane (Guldager, Melchiors & Andersen, 2020).

Otoacoustic emissions testing

The detection of hearing loss in new-born babies is crucial (Wood, Davis & Sutton, 2013), as it serves as a foundation for auditory stimulation for a child's language and speech development. The otoacoustic emissions (OAEs) is one of the recommended tools for neonatal hearing screening (Erenberg et al., 1999). It can estimate hearing sensitivity and test for functional hearing loss in infants (Yilmaz et al., 2006). This test can be applied and performed on adults as well (Hall, 2015). To perform an OAEs test, a small ear probe or earphone is put in the ears of the patient. The audiologist then presents sound stimuli through the probes or earphone to measure the sounds produced by the inner ear of the patient when the cochlea is stimulated (Stavroulaki et al., 2002; Yilmaz et al., 2006). Determining the status of the cochlea, the otoacoustic emissions test will shows if the hearing disorder is caused by blockages of and damages to the outer hair cells of the patient. The screening of hearing in babies are to identify permanent congenital or early-onset of hearing loss.

Auditory brainstem-evoked response testing

The auditory brainstem-evoked response (ABR) test is the second recommended hearing test also for neonatal hearing screening (Erenberg et al., 1999). The ABR test provides detailed data about the functioning of the cochlea and the necessary hearing pathways of the brain. The auditory brainstem-evoked test requires the measurement of the electrical activity of the brain, that is, electroencephalography (EEG), in response to a wide range of sound frequencies (Boo, Rohani & Asma, 2008; Stanton, 2009). During the automated auditory response test, soft-click stimuli is presented to the patient's ears through a disposable flexi-coupler earphone. The electrophysiological measure and function of the entire auditory pathway is recorded by the three surface jelly-like tab sensors (or scalp electrodes) positioned over the shoulder, vertex, nape and the cheek. A "pass" of the test is displayed if the automated auditory brainstem-evoked instrument's algorithm matches the ongoing brain waves from the patient.

2.3.2 Audiometric devices

The portability of an audiometer varies depending on its size, the corresponding tone frequencies the audiometer can perform, whether or not transducers are needed, the desired testing modalities (for example, pure-tone air or bone conduction, or word/speech recognition), operating preferences (that is, manual or automated), room noise monitoring, the capability of the audiometer to send the test results to an audiologist for further analysis, and guidelines for hearing testing methodology. Appendix A shows the minimum standard requirements for screening and diagnosing audiometers by institutions such as the American National Standards Institute (ANSI) or the American Society of Audiology (ASA) (American National Standards Institute, 2019), and the International Electrotechnical Commission (IEC) (Maling & Brenig, 1980).

Specifications for screening or diagnosing audiometers are provided by the ANSI/ASA and the IEC. Audiometers can therefore be categorized into three broad groupings; a) manual or conventional portable audiometers; b) computer-based, computer-assisted or computer-controlled audiometers; and c) smartphone- or tablet-based audiometers (Ho, Hildreth & Lindsey, 2009). These are discussed below.

Conventional portable audiometers

Conventional standalone audiometers are standard medical devices for audiological centres or ear, nose and throat (ENT) clinics. They are primarily used for screening (Brungart et al., 2018), and often include only pure-tone air conduction audiometric testing. They mostly have hardware components that are firmly fixed into the device and connected with a pair of headphones. Examples are the Amplivox audiometers (Amplivox Limited, Parkway, Birmingham-West Midlands); Madsen Itera audiometers by the Natus® Medical Incorporated, Pleasanton-California, United States of America (USA); Interacoustic Audiotest audiometers (Interacoustics AC Assens, Denmark); and the MAICO (MAICO Diagnostics GmbH, Berlin, Germany) audiometers.

Computer-based audiometers

Computer-based, computer-controlled or computer-assisted audiometers are also standalone devices that are controlled by a computer interface. Examples of such audiometers are the Grason-Stadler Incorporation (GSI) clinical audiometer, KUDUwave audiometer, Wireless Automated Hearing System, Telessaúde audiometer, Occupational Earcheck System, Auto-kit audiometer, Home Hearing Test™, Hearing Self Testing System, National Technical Institute for the Deaf (NTID)- speech recognition test (NSRT®) application system and the Home Audiometer Software.

. Appendix B shows the names, company or location, key features, test performed, and limitations of the computer-based audiometric devices.

Limitations of computer-based, computer-controlled or computer-assisted audiometers include:

- Low sound levels produced during hearing loss testing cannot be reproduced in practice (Eikelboom et al., 2013).
- Validations are done with small sample sizes and some have not been clinically validated (Ferrari et al., 2013; McPherson, Law & Wong, 2010).
- Screening results show higher referral rates (McPherson, Law & Wong, 2010).
- The use of expensive headphones increases their cost (Baer & Groth, 1998).
- The systems are highly dependent on commercial calibration (Soer, 2014).
- The categories of hearing loss they are suitable for are limited, as they lack external devices such as bone oscillators (Liao et al., 2011).

Mobile health applications

Mobile devices have emerged as support systems in providing hearing services (Barczik & Serpanos, 2018b; Sama et al., 2014). This phenomenon reflects trends in mobile health more generally. Mobile health (mHealth) involves the use of technologies for mobile communication in healthcare provision and has been defined by the World Health Organization's (WHO) Global Observatory for eHealth as the "medical and public health practice supported by mobile devices, such as mobile phones, patient monitoring devices, personal digital assistants (PDAs), and other wireless devices" (World Health Organization, 2011). Several smartphone- and tablet-based applications have been developed to evaluate mental health (Hamilton & Kramer, 2019; Radovic et al., 2016; Zhang, 2015), diabetes (Lithgow, Edwards & Rabi, 2016; Nørgaard et al., 2017) and eye care (Karthikeyan et al., 2019).

In the same way, a number of these smartphone- and tablet-based applications were developed in the field of hearing evaluation and assessment (Clark, J & Swanepoel, 2014; Coleman, 2011; Paglialonga, Tognola & Pinciroli, 2015). The increasing penetration of mobile phone devices in developing countries may provide the extensive access to the use of these smartphone- and tablet-based hearing test applications (Brungart et al., 2018).

The literature shows that there are several available mobile health applications that provide prospects for telehealth which are penetrating underserved communities (Bright & Pallawela, 2016; Mosa, Yoo & Sheets, 2012; Paglialonga, Tognola & Pinciroli, 2015; Swanepoel et al., 2019). Swanepoel & Hall (2010) conducted a systematic review of telehealth applications in audiology, with attention to audiological services, and clinicians or patient perception. Some of the audiological services that the researchers found to be promising for tele-audiology include hearing interventions, hearing screening and hearing diagnosis. The review found that limited information was gathered on patient perceptions of the tele-audiology applications.

Bright & Pallawela (2016) identified and compared available smartphone- and tablet-based applications for hearing and ear assessments in two popular application stores (that is, Apple's iPhone operating software (iOS) App and Google's Android Play Stores). The researchers found 30 applications of which only 11 were validated. The validated Apple-based hearing loss screening applications included CellScope, uHear™, AudCal, ShoeBOX audiometry, and EarTrumpet. The results of the review showed that many of the applications were developed to perform pure tone audiometry. The results highlighted opportunities provided by the applications such as self-administration, portability, low-cost, and accessibility in LMICs.

Paglialonga, Tognola & Pinciroli (2015) examined hearing-related mHealth applications in terms of availability, affordability and variety. A total of 203 applications were identified; seventeen percent (17%) were in the screening and assessment domain with services such as speech tests, apps for clinical equipment, questionnaires, pure-tone tests, speech-in-noise tests and smartphone/tablet-based audiometers; seven percent (7%) of applications were in the assistive tools domain with services such as alerts, and communication services; twenty-three percent (23%) of the applications were in the information and education domain with services like information and knowledge, educational tools and services, hearing aids and simulations of hearing loss; and fifty-three percent (53%) were in the intervention and rehabilitation domain with services like hearing aid services, tinnitus treatment, sound enhancement, auditory training, and speech and language rehabilitation tools.

A more recent study by Swanepoel et al. (2019) examined mobile applications that can detect hearing impairment, as well as their challenges and opportunities. The study classified the applications into two broad categories, namely the clinical applications (clinical hearing assessments) and consumer applications. Findings from the study revealed that, even though clinical applications typically determine hearing sensitivity across pure tones at different pitches, they were not suitable for "young infants" or any other "difficult-to-test" groups without assistance (Swanepoel et al., 2019:717). The consumer applications were grouped based on their ability to provide accurate tests using tones or speech stimuli to assess hearing and their availability on the Android and iOS operating system platforms. It emerged from the study that decision-support resources, affordability, integrated cloud-based quality control, accessibility, advanced sensors and hearing status tracking are among the advantages of both the consumer and clinical applications. Despite the advantages, data security issues and the lack of standardized guidelines or approaches to reporting on mobile health devices posed limitations.

Appendix C provides detailed information on the capabilities and limitations of available mHealth devices. Limitations of mHealth applications in screening for hearing loss include:

- Malfunctioning of the applications including freezing and restarting (Chan et al., 2019; Corry, Sanders & Searchfield, 2017).

- Limited self-testing capabilities (Foulad, Bui & Djalilian, 2013; van Zyl, Swanepoel & Myburgh, 2018).
- Inability to detect early-stage hearing loss and limitations with regard to the categories of hearing loss for which they are suitable (Chu et al., 2019).
- The need to purchase headphones increases cost (Manganella et al., 2018).
- The download and use of applications are geographically bound in some cases (Potgieter et al. 2016).
- Small sample sizes used in validating the accuracy of the applications (Kam et al., 2013; Yimtae et al., 2018).
- Data security (Swanepoel et al. (2019).
- Lack of standardized reporting guidelines (Swanepoel et al. (2019).

2.4 Summary

In developing countries, screening services for hearing loss are scarce, owing to shortage of specialist health professionals and resources such as technology, infrastructure, and finances (Boatman et al., 2007). Early screening of hearing loss can help reduce the prevalence of advanced hearing loss. In most cases, hearing disabilities are diagnosed in the advanced stages in developing countries, which require complex and expensive treatment measures that are not available in such regions (Chadha, 2014). Reflecting on the trends in mobile health more generally, mobile devices have emerged as tools for the assessment of hearing loss. The weaknesses of mHealth to screen for hearing loss in developing countries, include hardware and software compatibility issues, cost of the devices, limited testing capabilities, accuracy and limited scope of application for only adults or only children (Jayawardena et al., 2018; Mosa, Yoo & Sheets, 2012; Shojaeemend & Ayatollahi, 2018). Low-cost medical devices developed to assess hearing disorders in low resource settings, such as those relying on mHealth, have the potential to mitigate the impact of hearing loss on personal, economic, social and mental wellbeing.

CHAPTER 3
METHODOLOGY

This chapter gives an account of the research design including the literature search strategy, databases searched, data extraction and data analysis. The aim of the study was to review the mobile health applications that were developed to screen for hearing loss in both developed countries and LMICs and identify those that may be suitable for use in LMIC settings.

3.1 Research approach

The research approach adopted for this study was that of a state-of-the-art review. This type of review assesses the current state of knowledge on a topic and may offer new perspectives or identify priorities for future research (Grant & Booth, 2009). The focus here is on presenting the current state of knowledge on available mHealth tools for hearing loss screening and offering a perspective on the utility of such tools in LMICs. The literature search was framed using the population-intervention-comparison-outcome (PICO) model (Santos, Pimenta & Nobre, 2007; Stone, 2002).

3.2 Study setting

The study setting was not limited to developing countries. Available smartphone- and tablet-based device applications from developed countries that have been designed, developed and validated for use in developing countries were also considered. Developing countries include regions like sub-Saharan Africa, Latin America, South-eastern and Western Asia (United Nations Statistics Division, 2014). A second definition of developing countries from the World Bank (Fantom & Serajuddin, 2016) was also used. This classification includes upper middle-income countries, low-income countries and lower middle-income countries.

3.3 Literature sources

The following electronic databases were used to elicit relevant literature for this review: Academic Search Premier (ASP), Cumulative Index of Nursing and Allied Health Literature (CINAHL), Health Sources: Nursing/Academic Edition (HSNAE), Engineering Village (IE), PubMed, Web of Science (WoS), Institute of Electrical and Electronics Engineers (IEEE), Scopus and Africa-Wide Information (AWI). Apart from scholarly literature, grey literature and unpublished studies from media platforms were consulted to supplement the information extracted from the published literature. These media platforms included websites, OpenGrey, blogs, and handbooks and training manuals on the study topic. This multidimensional approach of accessing quite a few electronic databases and using diverse search strategies helps to ensure all-inclusive coverage (White & Schmidt, 2005).

3.4 Study eligibility criteria

The keywords in the search strategy for the study were chosen carefully to depict the PICO elements (Santos, Pimenta & Nobre, 2007; Stone, 2002): population (P) - hearing loss patients; intervention (I) – mobile devices; comparator (C) - audiometers; and outcome (O) - screening. Human subjects were assessed as the participating population in all the studies. Applications running on mobile phones, tablet computers, and handheld computers that addressed hearing loss screening were counted in the study. Studies published in languages other than English were excluded. Documents that were published from January 2000 to July 2019 were included. The start date was selected because, even though the first audiometer was invented in 1879 by Alexander Graham Bell (Shephard, 1977) and first used in a scientific paper by David E. Hughes (Stoney & Hawke, 1991), the relevant mobile technology-based medical devices were developed or designed after the year 2000.

3.5 Search methods

The relevant literature included in this study were selected using predefined search keywords. Appendix D shows the keywords and search terms used for the PubMed electronic database system. This search strategy was adapted for the other eight electronic databases used for the search. The keywords included the names of all the medical devices identified in the preliminary literature review and presented in Appendix D. The keywords included hearing disorders, hearing tests, hearing screening, mobile applications, audiometers, and mobile health technologies. The keywords comprised both free text and medical subject headings (MeSH). The search strategy was designed, tested and revised in consultation with two University of Cape Town (UCT) Health Sciences librarians.

Data searches were done between 21 July 2019 and 26 July 2019. For validity of the literature needed for the study, relevant research studies were considered within the period of 1 January 2000 to 23 July 2019. After the search strategy had been developed and applied, the extracted documents were examined against the inclusion criteria.

3.6 Study selection and consensus

After the author had screened the extracted articles against the inclusion criteria, two additional researchers reviewed search outputs before reaching consensus on the full text articles to be included in the study. The first screening of the records was done considering search outputs' titles and abstracts. After consensus were reached on the abstracts and titles, the full text articles for all the search outputs were examined to determine their eligibility, first by the author, after which the second and third researchers were consulted, and consensus reached. Selected studies were exported to the Endnote referencing and citation manager (EndNote X9 - Clarivate Analytics, Philadelphia, USA) and duplicates were removed.

3.7 Data extraction

A data extraction form was created and used to extract relevant information from the selected articles. The information extracted from the articles included names of the authors of the relevant studies, the year in which the study was conducted, and the location of the study which included the setting of the study and country where the application had originated. Other information included the methodology used such as the mobile technology applications, the reference tests used, external audio devices or headphones employed, test frequencies and calibration methods. The definition of hearing impairment or hearing loss and as well as the types of hearing loss or condition, the name of the medical device(s) used, and participants or study population were also extracted. The outcomes and results from the eligible studies were also extracted. Appendix E shows the data extraction template.

3.8 Data analysis

The procedure for analysing data as described by Bowen (2009) was used for this study. The data analysis process began with, drawing data from the selected documents eligible for the study. This involved initially skimming through the documents, series of thorough examination of the documents through reading and finally interpretation of the information. This is the first step in using thematic analysis approach. This step enabled the familiarization with the data before separation of words and sentences. “Careful and strategic separation of words and sentences after a focused re-reading and review of the data allowed for manual coding”.

Words and sentences after a focused re-reading and review of the data led to a careful separation and strategical separation that allowed for manual coding. This was done by the researcher and was discussed with supervisors before making a final decision. The codes and themes were generated from the analysis of the data merged from the skim reading and interpretation of the data. They provided objectivity and sensitivity in the selection and analysis of the data from the eligible articles. Codes that frequently emerged were grouped and organised to generate themes. The analysis was theoretically driven by thoughts that guided the nature of documents selected and the overall concepts guided the study, hence it was both deductive and inductive.

The study also adopted an interactive process which combined elements of content analysis (that is, to categorically organize data in relation to the research questions) and thematic analysis (which is, to form a recognized pattern within data) to analyse data extracted from the documents. This is because the approaches are used for generating unanticipated insights and it is flexible to use (Bowen, 2009; Braun & Clarke, 2014) The openness and flexibility of the inductive approach allows for patterns and the themes to emerge from the data (Braun & Clarke, 2014). Drawing from the works of Bowen (2009) and Braun & Clarke (2014), the researcher combined the codes that were put together to establish themes to show relationships and maintain a coherent analysis.

To address the first objective of the study, mHealth solutions were reviewed according to the following themes: countries of origin and evaluation; devices, software platforms and hardware considerations; hearing loss characteristics of recruited populations; features of the tests conducted and of the testing environment; reference methods to which the mobile application was compared; application performance; feedback from users; cost; and limitations. To address the second objective of the study, attention was paid to the suitability of the mHealth tools for use in LMICs, based on the characteristic identified in the first objective.

CHAPTER 4

RESULTS

This chapter presents the results from the review of smartphone- and tablet-based health applications to screen for hearing loss.

The first objective of the study was to review the set of mobile health tools available for hearing loss screening in both developed countries and LMICs. To this end, smartphone- and tablet-based applications are discussed with regard to their countries of origin and evaluation; devices, software platforms and hardware considerations; hearing loss characteristics of recruited populations; features of the tests conducted and of the testing environment; reference methods to which the mobile application was compared; application performance; feedback from users; and the cost of the applications.

The second objective was to consider the suitability of these screening tools in developing countries. To this end, attention was paid to the suitability and prospects of the mHealth tools for use in LMICs, according to the following themes: features suitable for LMICs, functionality, cost and limitations.

4.1 Selection of studies for review

The database searches produced 797 records, out of which 156 duplicates were removed automatically using the EndNote reference manager. Table 4. 1 shows the distribution of the extracted records from the nine electronic databases. Due to inconsistencies with indexing from the nine electronic databases mentioned earlier (Chapter 3.3), an additional 88 records had to be removed manually as additional duplicates. The titles and abstract of the remaining 553 records were screened for eligibility. Forty articles were excluded for reasons including articles being published in the form of reviews, surveys, editors' comments, and research notes. Five hundred and thirteen full text articles were screened for eligibility.

Table 4. 1: Distribution of retrieved articles from all nine electronic databases.

	Database name	**Number of records**
1.	Academic Search Premier	85
2.	African-Wide Information	11
3.	CINAHL	15
4.	Engineering Village	24
5.	Health Source: Nursing/Academic Edition	44
6..	Institute of Electrical and Electronics Engineers	42
7.	PubMed	72
8.	Scopus	357
9.	Web of Science	136
Total		**786**

Four hundred and fifty-one full text articles were excluded as non-related records leaving a total of 62 articles which were relevant to the scope of the review. Thirteen articles were excluded because the full text could not be obtained, despite authors being contacted. Five articles were excluded because their indexing could not be traced from the electronic database that provided them. Forty-four articles overall met the inclusion criterion for the study. Five additional articles were identified as important to the study from the list of references of the eligible articles, thus they were counted in the review. A total of 49 studies were eligible for the review.

The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) flow diagram, adapted from Moher et al. (2009), for the study is shown in Figure 4. 1.

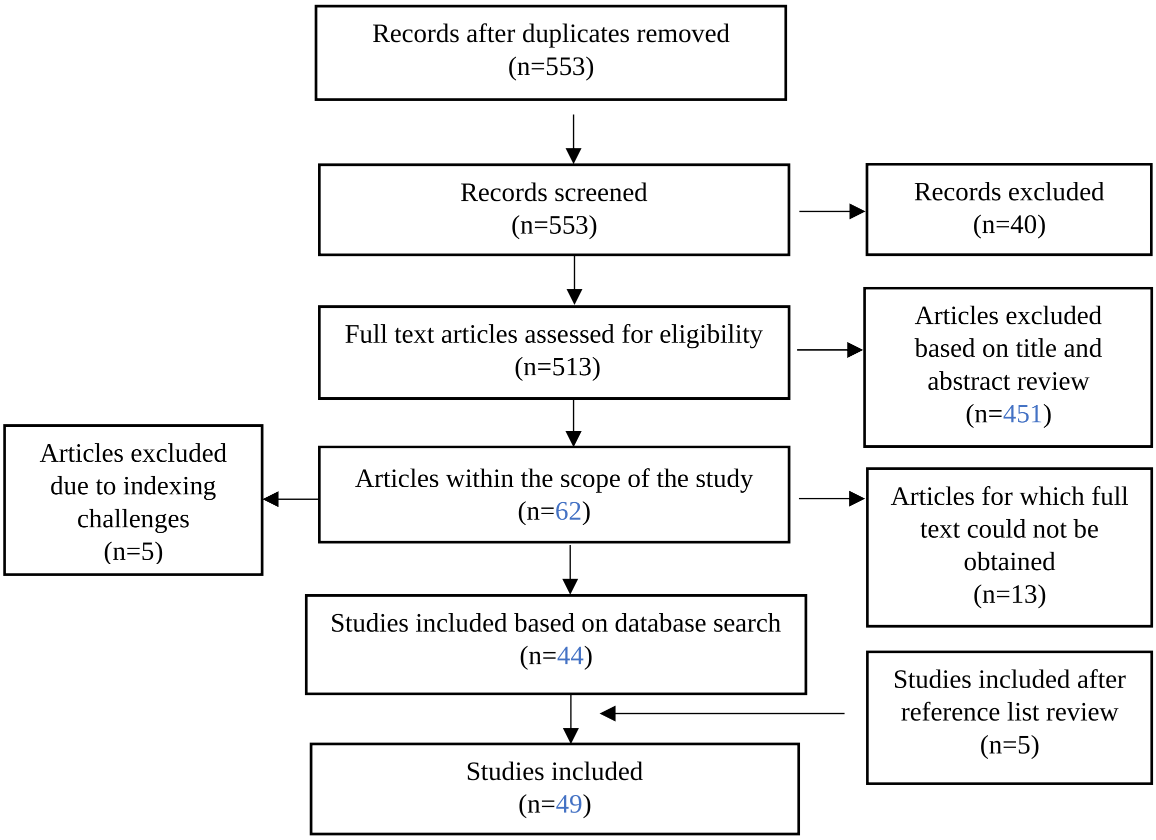

Figure 4. 1: Adapted PRISMA diagram showing the process of selecting studies for the study.

The characteristics of the 49 studies eligible for the review is presented in Appendix F. They addressed a variety of smartphone- and tablet-based applications for hearing screening in both developed and developing countries. The smartphone- and tablet-based applications amounted to 18 in total.

4.2 Summary of mHealth tools

A description of the 18 identified smartphone- and tablet-based applications, their essential information, or characteristics such as, name or description of device, company and /or location of development, tests performed by the device application, operating software platforms, download location for applications, and limitations identified is presented in Appendix C.

Table 4. 2: Distribution of mHealth applications reported by the 49 eligible studies.

	Name of application	**Frequency**
1.	Agilis Health Mobile Audiogram (Agilis Audiogram)	1
2.	GSI Automated Method for Testing Auditory Sensitivity (AMTAS)	2
3.	AudCal	1
4.	Audiogram Mobile	1
5.	Ear Scale	1
6.	EarTrumpet	2
7.	hearScreen™	8
8.	Hearing Test™	5
9.	Hearing-Test application	1
10.	Hearing Test System	3
11.	Hearing Test with Audiogram	1
12.	Ototoxicity Identification Device (OtoID)-Tablet	1
13.	ShoeBOX Audiometry	8
14.	Sound Scouts	1
15.	Tablet-based Hearing Screening Test (THST)	1
16.	uHear™	10
17.	uHearing Test	1
18.	Virtual Audiologist (ViA)	1
Total		**49**

Table 4. 2 above shows the distribution of the smartphone- and tablet-based applications identified in the 49 eligible studies. The uHear™ application screening tool was reported on, most frequently (10 times), followed by the ShoeBOX, hearScreen™ and the Hearing Test™ software (8, 8 and 5 times respectively).

4.3 Countries of origin and of evaluation

In terms of the country of origin or where the smartphone- and tablet-based applications were designed and developed, thirteen (13) different countries were found. From Table 4. 3, the two dominant countries of origin, development and design for the smartphone- and tablet-based applications were the United States of America (USA) and Canada (5 and 2 times respectively). The other 11 countries had a smartphone- or tablet-based application each developed there as shown in Table 4. 3.

Table 4. 3: Countries where the mHealth applications were developed.

	Country of origin	Frequency
1.	Australia	1
2.	Brazil	1
3.	Canada	2
4.	Hong Kong	1
5.	Italy	1
6.	The Netherlands	1
7.	Poland	1
8.	Singapore	1
9.	South Africa	1
10.	South Korea	1
11.	Spain	1
12.	Taiwan	1
13.	United States of America	5
Total		**18**

The mHealth applications were evaluated in 21 different countries; these settings are presented in Table 4. 4. The top three countries for evaluation were South Africa, the USA and Canada (9, 9 and 6 times respectively), followed by Australia and Israel with validation of three mHealth application each.

Table 4. 4: Countries in which the identified mHealth applications were validated.

	Country of evaluation	Number of studies
1.	Australia	3
2.	Belgium	1
3.	Brazil	1
4.	Canada	6
5.	China	2
6.	Dominican Republic	1
7.	India	1
8.	Israel	3
9.	New Zealand	1
10.	Nigeria	1
11.	Oman	1
12.	Philippines and United States of America (joint)	1
13.	Poland	2
14.	South Africa	9
15.	South Korea	1
16.	Spain	1
17.	Taiwan	1
19.	The Netherlands	2
20.	Turkey	2
21.	United States of America	9
Total		**49**

4.4 Devices and software platforms

The device types used for evaluating the auditory functioning of the recruited participants in the 49 studies were examined. Smartphones were the most common mHealth devices (40 out of 49), while tablets were used in 9 of the 49 studies. The operating software platforms of the 18 smartphone- and tablet-based applications are presented in Figure 4. 2. Nine applications were developed for the iPhone operating software (iOS) from Apple, three were developed for Android from Google, four applications were developed for both Apple and Google, software platform for two applications was not indicated.

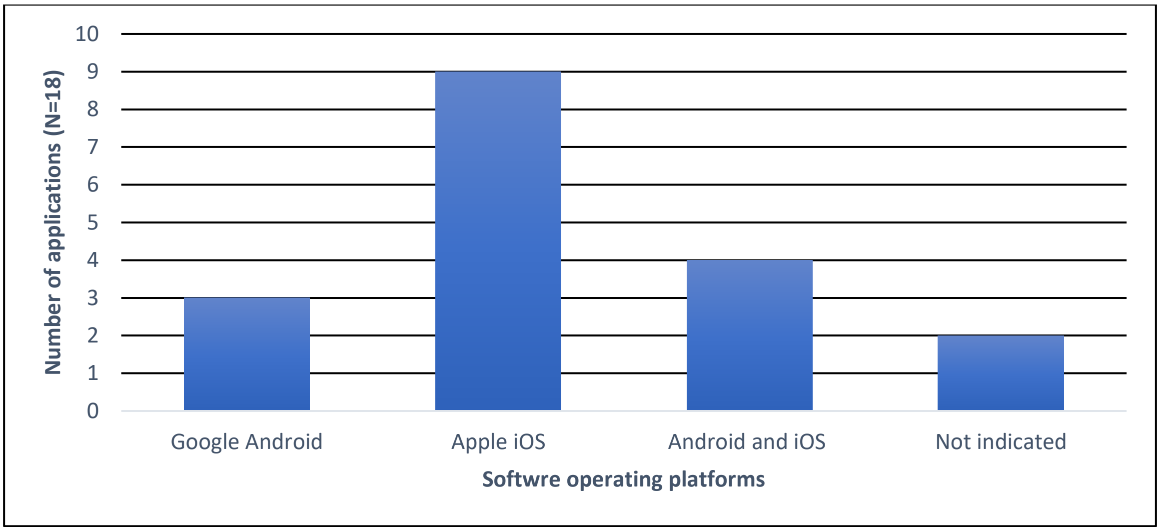

Figure 4. 2: Distribution of mHealth applications designed for different operating system platforms.

The Apple iOS was the dominant platform, followed by Android. Appendix C provides the software platforms and download locations of the 18 smartphone- and tablet-based applications.

4.5 Hardware considerations: transducers and calibration

The transducers or external devices used, as well as the calibration of the audiological screening tools were considered. The identified studies in some cases allowed for patients (if the testing was self-administered) or clinicians (that is, professionals) to plug in either personal headphones or a required set of headphones (for example, supra-aural or circumaural) and bone conductors, while in other cases hearing aids were used. The transducers reported in the reviewed studies include the following: a combination of headphones and earbuds, supra-aural TDH models, bone oscillator, Sennheiser HDA models, hearing aids, Phillips's headset, headphones or headsets, Apple EarPods, Bose Noise cancelling, Etymotic earphones and bundled earphones.

In Table 4. 5, the distribution of audiometric headphones or non-audiometric headphones reported for applications across the studies are presented. The most frequently reported transducers were Apple EarPods, headphones, bundled earphones, Sennheiser HAD models and the (9, 7, 7 and 7 times respectively).

Table 4. 5: Types of transducers reported in the identified studies.

	Transducers	Number of studies
1.	Apple EarPods	9
2.	Bose QuietComfort Noise cancelling®	2
3.	Both headphones and earphones	2
4.	Bundled earphones	7
5.	Creative EP 210	2
6.	Etymotic earphones	1
7.	Hearing aids	2
8.	Headphones or headsets	7
9.	Phillips's headset	1
10.	Sennheiser HAD models	7
11.	Supra-aural TDH models	5
12.	Not indicated	4
Total		**49**

Significant occlusion effects were reported to have occurred when the transducers were inserted deeply into the ear canal of the participants during audiometric testing. The TDH 39 and HDA 200 headphones were the only kinds of transducers used during hearing loss testing that were calibrated audiometrically.

These were done against the reference equivalent threshold sound pressure levels (RETSPLs) according to the guidelines of ANSI/ASA S3.6 of 2010, the ISO 389-8 of 2004, and the ISO 389-1 of 2006 (International Standardization Organization (ISO), 2004; International Standardization Organization (ISO), 2006).

4.6 Hearing loss characteristics of recruited populations

Appendix G presents the hearing loss status and characteristics of sample populations used in the 49 studies addressing the smartphone- and tablet-based mHealth applications. Age ranges and hearing loss status are described below.

4.6.1 Age ranges

Participants in the 49 studies identified came from a range of age groups. The participants with hearing loss and normal hearing or both were in three broad age categories namely, children (below 18 years), adults (above 18 years), and the elderly (above 65 years). These categories are represented in **Error! Reference source not found.** while Appendix G shows the distribution. Most screened population sample for hearing loss using the 18 identified smartphone- and tablet-based applications was composed of children, followed by adults and the elderly (that is, 12, 8 and 3 respectively).

There were mHealth applications that could screen only a particular group of age group population, and there were others that could screen two groups of ages (for example, children and adults, or adults and the elderly in the 49 identified studies.

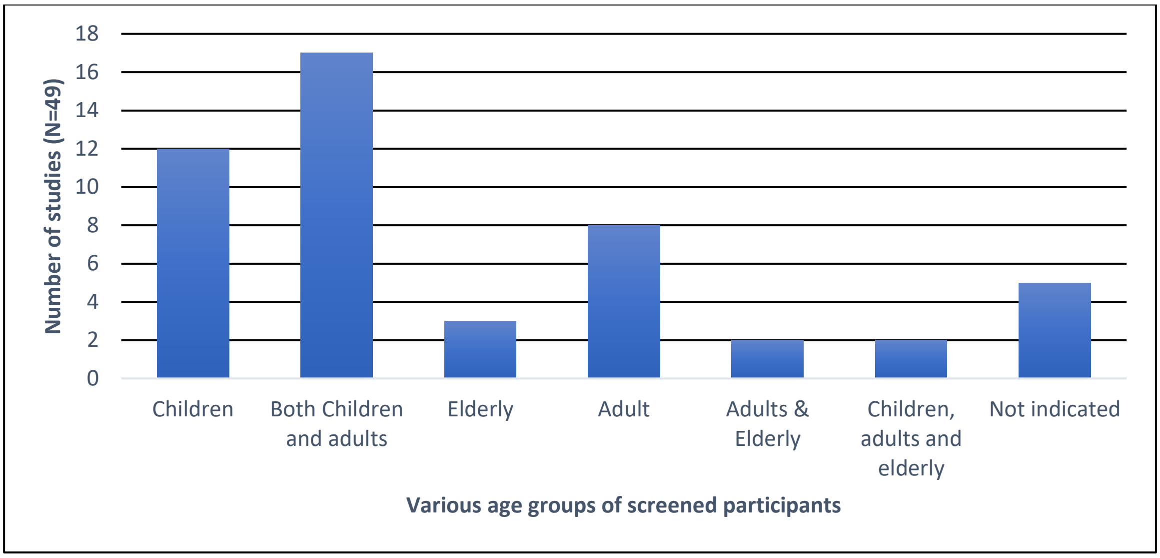

Figure 4. 3: Age groups distribution of research participants in 49 studies.

Error! Reference source not found. above shows that, 17 studies used smartphone- and tablet-based application to screen both children and adults, two studies used the applications to screen only adults and the elderly. Also, two other applications were used to screen both adults, children and the elderly.

4.6.2 Hearing status of recruited sample population

On the other hand, twenty out of the 49 studies included patients with otologic symptoms, for instance, hearing loss or hearing impairment, vertigo, cochlear implant in addition to Meniere disease. Figure 4. 4 shows the distribution of hearing loss status of the sample population in the eligible studies.

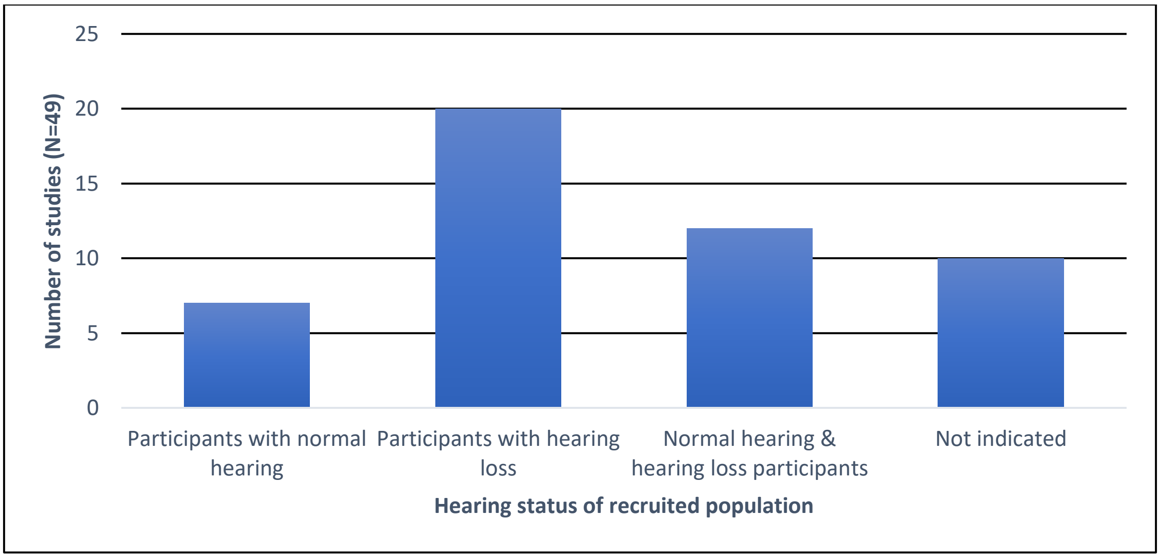

Figure 4. 4: Distribution of hearing status of sample populations in the 49 eligible studies.

In Figure 4. 4 above, seven (7) of the 49 studies included participants with normal hearing, while 12 of the studies included subjects with and without hearing loss. Ten of the studies did not indicate the hearing status of the recruited population before the hearing testing was performed.

4.7 Testing environments

Recruited participants underwent screening for hearing loss either in audiological testing rooms or in open spaces such as, homes of the participants, clinic, or hospital spaces, outside of sound booth environments and rooms close to hallways with ambient moderate traffic. As shown in Table 4. 6, fifteen out of the 49 studies reported on the use of the mHealth applications in sound-treated test environments, while 30 of the studies reported on non-audiological rooms. Twenty-two studies conducted hearing loss testing in quiet spaces such as, libraries, single clinic rooms, classrooms, quiet office space, quiet hospital room and physician's office. Nine of the smartphone- and tablet-based applications were tested in soundproof booths.

Table 4. 6: Distribution of the test environments of mHealth apps in the eligible studies.

	Kinds of testing Environments	**Number of studies**
1.	Clinic waiting areas	5
2.	Double walled chamber	2
3.	Examination rooms	1
4.	Homes of recruited participants	1
5.	Noisy environment and quiet room	2
6.	Soundproof booth	9
7.	Soundproof booth and examination room or quiet room	3
8.	Quiet rooms	22
9.	Quiet room, waiting room and soundproof room	1
10.	Not indicated	3
Total		**49**

One study used an application to screen for hearing loss in three test environments (that is, the quiet room, waiting room, soundproof room). Three of the 49 studies did not indicate the test environments. The most frequently used testing rooms were quiet rooms and soundproof booths (22 and 9 times respectively). Details of the test environments of the applications are presented in Appendix K.

Ambient noise has an effect on hearing test results. As presented in Appendix J, out of the 18 smartphone- and tablet-based applications, 8 were able to measure the ambient noise levels in the testing rooms before and during the hearing screening, while studies conducted on 10 of the mHealth applications did not mention if the application was able to measure the ambient noise levels during hearing loss testing. The ambient noise levels captured during the testing periods in all 49 studies are presented in Appendix J.

If the ambient noise levels measured in the 49 studies were too high, or the recruited participants failed the initial screening, or the recruited participants could not hear one sound due to an interference, retesting or rescreening was done. Among the 49 studies reviewed, 9 reported that the corresponding applications allowed for rescreen, one study mentioned that its application did not perform a retest but that participants were given referrals. The remaining 40 studies did not mention rescreening.

4.8 Features of the tests available on the mHealth applications

This section addresses the tests available on the mHealth apps with regard to their administration of test, testing modalities and sound stimuli, language, screening frequencies, definition of hearing loss and duration of the tests.

4.8.1 Administration/operators of tests on mHealth devices

All identified applications were designed either to be self-administered, that is, a screening test that is performed by a non-audiologist personnel or the recruited participant, and others were for the health providers or audiologist to administer. Figure 4. 5 below shows the distribution of mHealth devices that were operated by the individuals and those that were administered solely by a profession while further information on who performs the screening is provided in Appendix I.

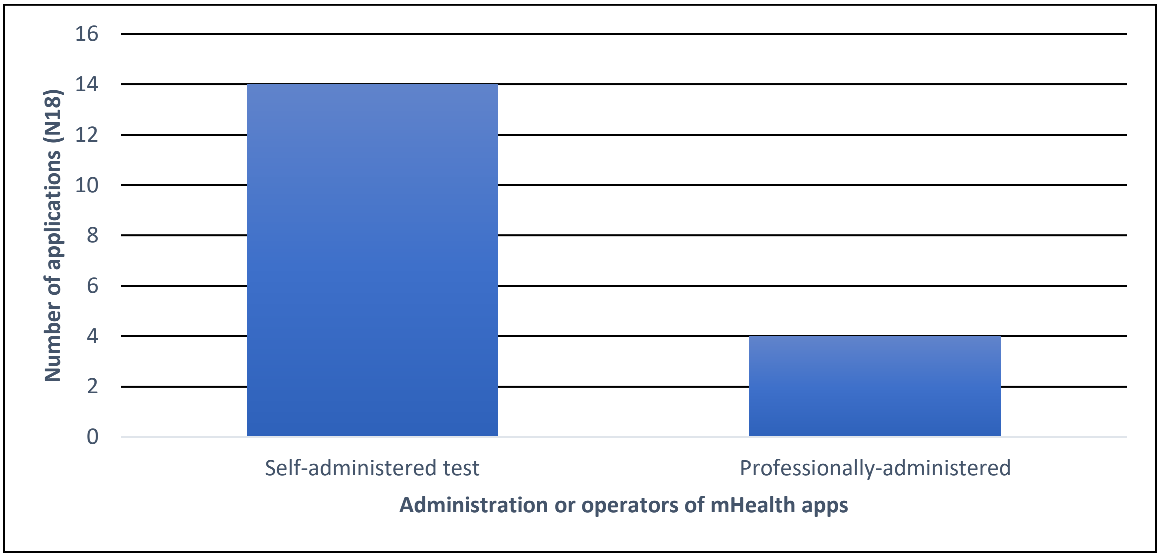

Figure 4. 5: Distribution of administration or operators of 18 mHealth apps.

From Figure 4. 5 above, fourteen of the 18 mHealth applications had self-administration capabilities, while the remaining four had to be administered by a health professional.

4.8.2 Testing modalities and sound stimuli

From the 49 studies reviewed, 19 reported that the test signals presented were by pure-tone air conduction only, twelve by both pure tone air- or and bone-conduction and nineteen by both pure tone air- or and speech. Of the 18 mHealth applications, 4 were used to conduct pure-tone audiometric testing (that is, both air-conduction or and bone-conduction). The testing modality for each of the 18 applications is presented in Appendix H. The most frequently used auditory sound stimulus presented during screening was pure tone from either headphones or earphones.

4.8.3 Screening frequencies

Stimuli were presented within a range of pitches and loudness levels. A number of threshold frequency protocols and guidelines (American Academy of Audiology, 1997a; American Academy of Audiology, 1997b; American Academy of Audiology, 2011a; American Speech-Language-Hearing Association, 1992; American Speech-Language-Hearing Association, 1997) have been developed for screening in infants, young children and adults. It is recommended that pure tone signals during hearing tests be conducted at 1, 2 and 4 kHz for screening purposes (Skarzynski & Piotrowska, 2012). From the review, the most frequently tested frequency range was between 0.25 kHz and 8000 Hz. From the study, out of the 18 mHealth applications, 16 were able to conduct tests at the recommend frequencies for screening. Appendix I provides details on the test frequencies used by the mHealth applications.

4.8.4 Screening intensity levels

The World Health Organization (2018a) defines disabling hearing loss in children at a threshold of 30 dB HL and for adults at 40 dB HL, in both cases in the better hearing ear. Figure 4. 6 shows the distribution of the screening intensities used in the eligible studies. Screening intensity levels were adjusted to the nature of test environment for all studies.

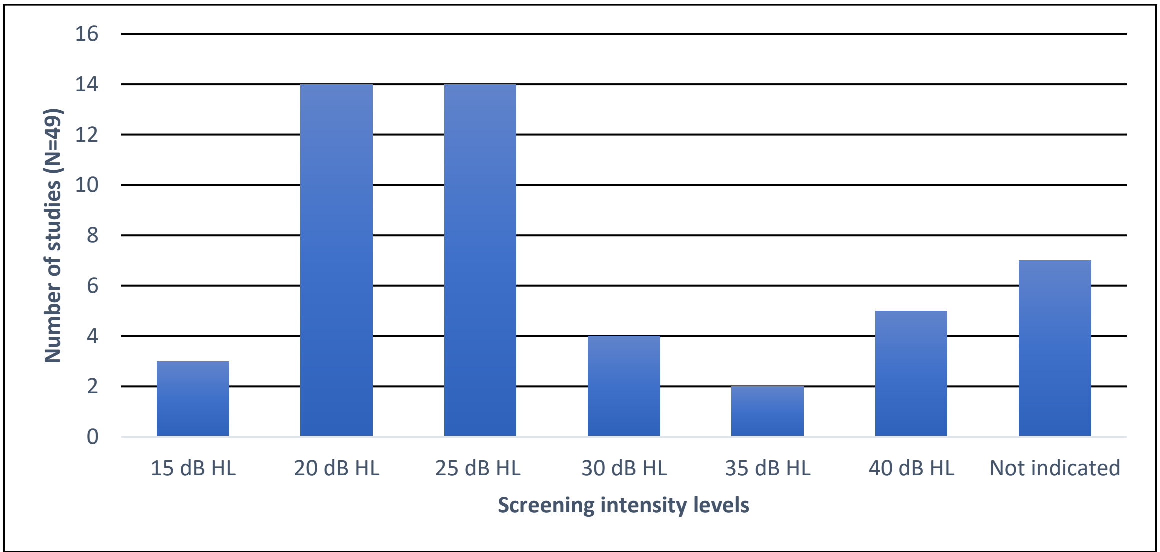

Figure 4. 6: Distribution of screening intensity thresholds used in defining hearing loss in the 49 eligible studies.

The most frequently used thresholds for hearing loss in either ear of the participants and for referral were 20 dB HL (14 studies) and 25 dB HL (14 studies). These were considered appropriate for the test environments used.

4.8.5 Duration of hearing test

Table 4. 7 shows a summary of the time to complete hearing tests in the included studies, while Appendix L provides further information. Most of the studies reported screening time from 0.01 minutes to 3.00 minutes followed by 3.01 minutes to 6.00 minutes.

Table 4. 7: Hearing test durations (in minutes) reported in the 49 eligible studies.

	Test times	Number of studies
1.	0.01 sec – 3.00 mins	8
2.	3.01 mins – 6.00 mins	6
3.	6.01 mins – 9.00 mins	4
4.	9.01 mins – 12.00 mins	1
5.	12.01 – 15.00	2
6.	15.01 – 18.00	2
7.	Not indicated	26
Total		**49**

The fastest screening time of an applications recorded was 46.2 seconds which is for hearScreen™ smartphone-based application in a normal hearing group of participants, while the slowest screening time was 16.1 minutes recorded using the GSI AMTAS application for automated audiometry in a group of 44 participants.

4.8.6 Language of the mHealth applications

The countries in which the mHealth applications were developed influenced the language options available for their operation and the screening instructions provided. The screening language options of the applications are presented in Appendix M and summarized in Table 4. 8. Eleven different languages were identified.

Table 4. 8: Language capabilities of the 18 mHealth applications.

	Languages	Number of applications in studies
1.	Dutch	1
2.	English	17
3.	Spanish	4
4.	French	3
5.	German	4
6.	Italian	2
7.	Japanese	1
8.	Korean	1
9.	Polish	1
10.	Portuguese	1
11.	Russian	1
12.	Language independent applications	1

As shown in Table 4. 8 English was the most common device language used in providing instructions on the display screens of the applications.

4.9 Reference methods to which the mHealth applications were compared

The applications were compared to several reference methods. The detailed distribution of the reference methods used in the eligible studies are presented in Appendix K. Pure tone audiometry was most frequently used as the reference method.

4.10 Application performance

The performance of the 18 mHealth applications is discussed below with reference to calculated sensitivity values, specificity values, and functionality. Further information is presented in Appendix L and Appendix P.

4.10.1 Sensitivity

Out of the 49 studies reviewed, 21 reported on sensitivity while the remaining 39 did not report on the subject as presented in Appendix L. The distribution of sensitivity levels found in these studies is shown in Figure 4. 7. The lowest sensitivity level of the identified applications recorded was 33 percent and the maximum level recorded was 100 percent in those studies that reported these parameters. For 11 smartphone- and tablet-based applications that recorded the sensitivity levels, 7 recorded sensitivity levels of greater than 90 percent.

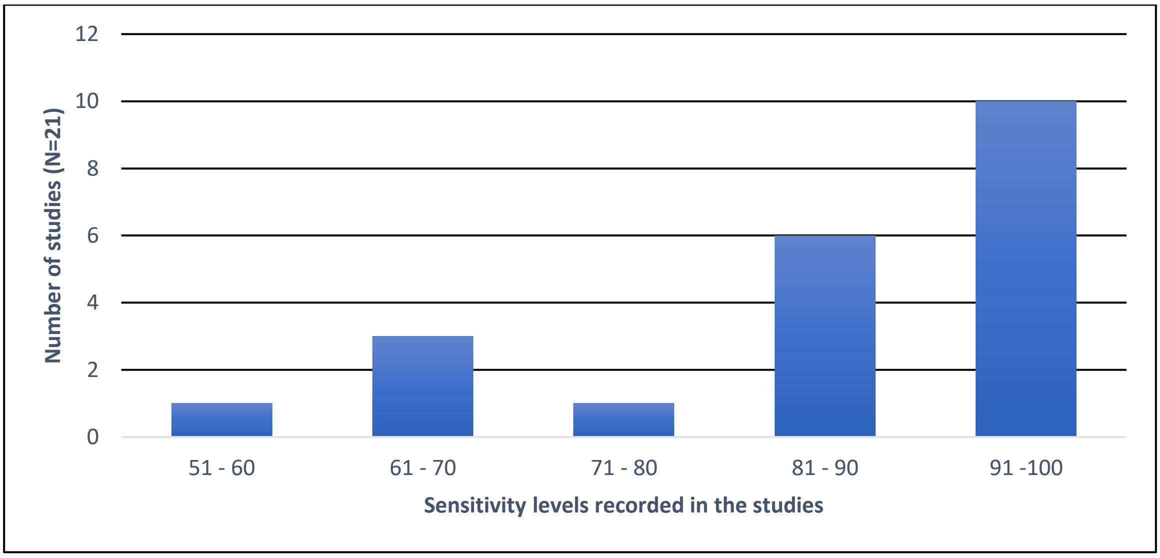

Figure 4. 7: Sensitivity levels (%) as reported in 21 studies.

From the study, the mHealth applications with these high sensitivity levels are the Ear Scale, Hearing Test™, Hearing Test system, ShoeBOX, uHear™, uHearingTest and the THST application. One of the reasons for the high sensitivity of the mHealth applications reviewed, is the control of ambient noise in the various testing environments.

4.10.2 Specificity

Twenty Studies out of the 49 studies reviewed, reported on the specificity of the mHealth applications. Details of the specificity values of the smartphone- and tablet-based applications in the identified studies are presented in Appendix L, while the summary is shown by Figure 4. 8. The lowest specificity level recorded was 15 percent while the highest was 100 percent. The most frequently reported specificity was between 91 percent and 100 percent (8 studies); the applications with high specificity levels are the Ear Scale, Hearing Test™, Hearing Test System, ShoeBOX, Sound Scouts, uHear™, THST, uHearingTest and the hearScreen™ smartphone-based application.

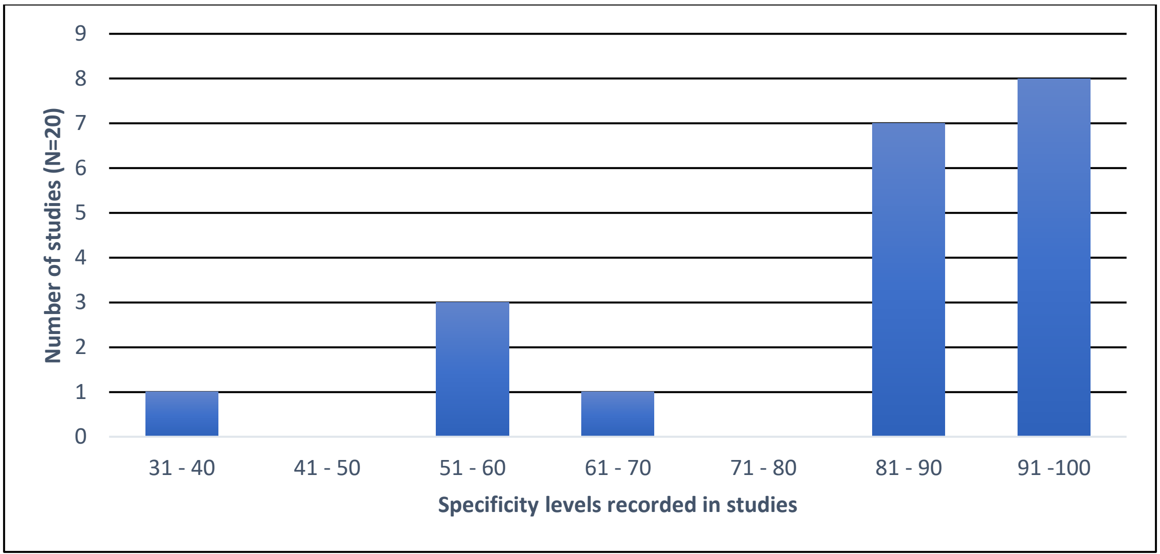

Figure 4. 8: Specificity levels (%) as reported in 20 studies.

From Figure 4. 8, seven studies showed specificity of 81 percent to 90 percent, while three studies had specificity of 51 percent to 60 percent. One study showed specificity of 36.4 percent, while another reported a range of values.

4.10.3 Functionality

Functional evaluation of the 18 mHealth applications in the 49 studies is presented in Appendix O while Table 4. 9 presents a summary. Eleven applications were identified as having acceptable functionality (that is, results were acceptably accurate or higher values were found for the smartphone- and tablet-based applications, according to the evaluations done) while the remaining 7 smartphone- and tablet-base applications were identified with non-acceptable functionalities.

Table 4. 9: The mHealth applications with acceptable functionality.

	Acceptable applications	**Non-acceptable applications**
1.	AudCal	Agilis Mobile
2.	Ear Scale	GSI AMTAS
3.	EarTrumpet	Audiogram Mobile
4.	Hearing Test with Audiogram	Hearing-Test application
5.	Hearing Test™ software (e-audiologia.pl)	OtoID-tablet
6.	Hearing Test System	uHearingTest
7.	hearScreen™	Sound Scouts
8.	ShoeBOX	
9.	THST	
10.	uHear™	
11.	ViA	

4.11 Feedback from users

Post-test feedback data were recorded for 6 out of the 18 mHealth applications. The remaining 12 applications did not report on the experiences of recruited participants. In the areas of user experience, satisfaction, use of the device and the presence of a tester, patients generally preferred mHealth hearing tests to conventional methods. The ability to test outside specialised facilities was considered favourable for the mHealth tools. Appendix N provides information on post-test feedback, including tools used to solicit subjective assessments, patient satisfaction and user experiences.

4.12 Cost

The costs of downloading and purchasing the 18 smartphone- and tablet-based applications are provided in Table 4. 10. Nine applications (AudCal, Ear Scale, hearScreen™, Hearing Test™, ShoeBOX, Sound Scouts, uHear™ and the uHearingTest) can be downloaded at no cost. The mHealth applications without requirements for external materials to be attached (such as ear stimulators, acoustic couplers, transducers, sound-level meter, bone oscillators and audiometers) have lower costs.

Table 4. 10: Cost of identified mHealth applications by December 2020.

	Name of the platform	Price of software (USD)	Price of hardware (USD) – excludes smartphone/tablet	References/ Uniform Resource Locator (URLs)
1.	Agilis Health Mobile Audiogram	Claimed to be low cost, no cost provided	No additional hardware is required	Manganella et al. (2018)
2.	GSI-AMTAS™	Commercially available, no cost provided.	No additional hardware is required.	Margolis & Moore (2011) and Eikelboom et al. (2013)
3.	AudCal	Free	No additional hardware is required.	https://apps.apple.com/us/app/audcal /id647212278
4.	Audiogram Mobile	$38.99	No additional hardware required	https://apps.apple.com/us/app/audiogram-mobile/id643041369
5.	Ear Scale	Free	No additional hardware required.	Chu et al. (2019)
6.	EarTrumpet	$3.99	No additional hardware required.	https://apps.apple.com/us/app/eartrumpet/id385494796
7.	hearScreen™	Free (however, requires a subscription fee to use)	$860 (Samsung J5 Prime + Sennheiser HD280 Pro headphone) and $990 (Samsung A3 + Sennheiser HD280 Pro headphones)	https://www.hearxgroup.com/shop/hardware
8.	Hearing Test™	Free for the standard version and approximately $4 for Pro version.	No additional hardware required	https://play.google.com/store/apps/details?id=mobile.eaudiologia&hl=en
9.	Hearing-Test App	Not commercially available	No additional hardware required	Renda et al. (2016)
10.	Hearing test system	Not accessible	No additional hardware is required.	Kam et al. (2012)
11.	HT with Audiogram	Not accessible	No additional hardware is required.	Kelly et al. (2018)
12.	OtoID-Tablet	Relatively low-cost claimed, but no cost provided.	No additional hardware is required	Brungart et al., (2018)
13.	ShoeBOX	Free (however, requires subscription fee to use).	$2000 (Humanitarian), $3100 (Standard version), $4100 (Professional version) and $400 for annual calibration	https://apps.apple.com/us/app/shoebox-audiometry-standard/id8732 72921
14.	Sound Scouts	Free; in-app purchases free in Australia	No additional hardware required.	https://apps.apple.com/au/app/sound-scouts/id911637845
15.	THST	Not commercially available	No additional hardware is required.	Samelli et al. (2017)
16.	uHear™	Free	No additional hardware is required.	https://apps.apple.com/us/app/uhear/id309811822
17.	uHearingTest	Free	No additional hardware is required.	Barczik & Serpanos (2018b)
18.	ViA	Not commercially available	No additional hardware is required.	Kocian et al. (2017)

The cost of applications is further increased if the accessories must be calibrated, for example, the headphone cost about USD 40. Total cost for android-based applications and products were observed to be less expensive compared to Apple-based products. Further analysis of the results on cost of the applications revealed that, some of the smartphone- and tablet-based applications (for example, hearScreen™ and ShoeBOX) identified in the literature were packaged for sale. Although these headphones are readily available, they are expensive and often unaffordable for underserved communities.

4.13 Limitations of the 18 mHealth applications

Figure 4. 9 summarises the limitations of the mHealth apps as discussed in the eligible studies. Seven broad categories of limitations have been identified. They are the hardware components, audiometric assessment, regulation and calibration, software malfunctioning, geographical space, screening environment and usability of the application. Further information is provided in Appendix C.

Four applications were found to have limitations relating to the hardware components of the application, that is, the type of transducer used, or high sensitivity and specificity values can only be obtained using an iOS device. The applications include Agilis Audiogram (Manganella et al., 2018), Hearing Test System (Kam et al., 2012), ShoeBOX (Yeung et al., 2013), and the Sound Scouts app (Dillon et al., 2018).

In terms of audiometric measurement issues, for example, inappropriate tool for the detection of hearing loss or inability of an application to perform more than one screening modality test, 5 applications were found with such limitations. They include Ear Scale (Chu et al., 2019), hearScreen™ (Louw et al., 2018), Hearing Test™ (Renda et al., 2016), Hearing Test with Audiogram (Kelly et al., 2018) and the OtoID-Tablet application (Brungart et al., 2018).

Regarding software malfunctioning, such as, freezing or quitting of hearing tests during assessments, three applications were identified. The GSI AMTAS app (Eikelboom et al., 2013), Audiogram Mobile (Corry, Sanders & Searchfield, 2017) and Hearing-Test app (Youngmin et al., 2014). The ViA application (Kocian et al., 2017) and the THST application (Samelli et al., 2017) were identified to have limitations in how the applications were used by the patients during hearing screening in testing environments. Examination of the AudCal app (Larrosa et al., 2015) revealed that standard calibration was not possible.

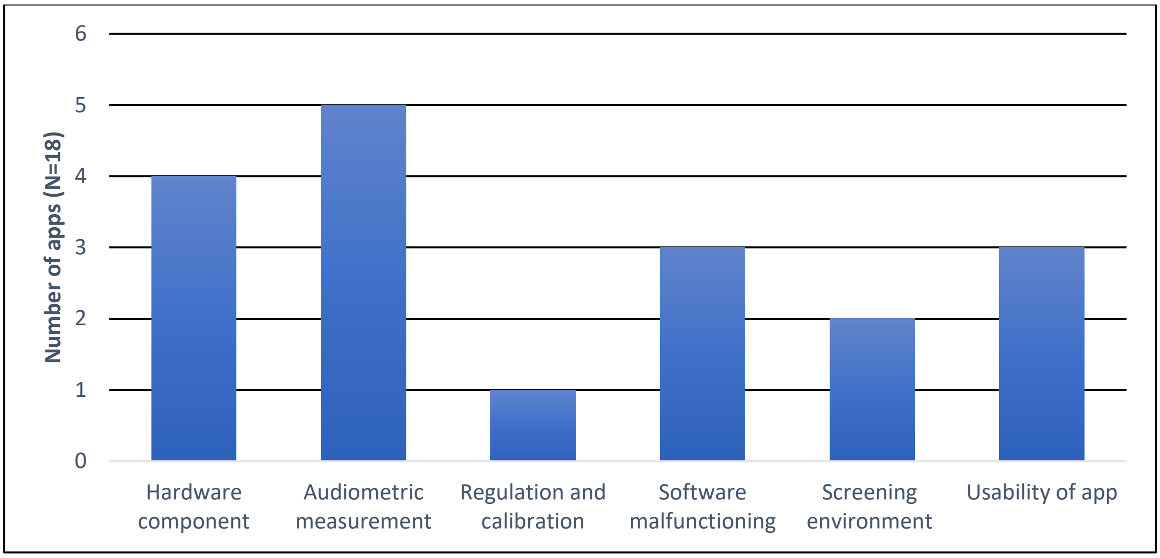

Figure 4. 9: Plot shows distribution of various limitations of mHealth applications.

The usability of the apps during hearing testing affected the functionality of the EarTrumpet (Foulad, Bui & Djalilian, 2013), the uHear™ (Peer & Fagan, 2015) and the uHearing Test application (Barczik & Serpanos, 2018a).

4.14 Considerations for LMICs

The previous sections addressed the first objective of this study, namely, to review the set of mobile health tools available for hearing loss screening in both developed countries and LMICs. This section addresses the second objective, namely, to consider the suitability of these screening tools identified for use in developing countries.

4.14.1 mHealth applications developed and evaluated in LMICs

This section presents the applications that are developed and evaluated for use in low- and middle-income countries (LMICs). LMICs in this context is based on the World Bank (Fantom & Serajuddin, 2016) and the United Nations Statistics Division (2014) definitions. Countries of origin and evaluation of the mHealth applications were presented earlier in Table 4. 3 and Table 4. 4, respectively.

Out of the 13 different countries where mHealth applications were developed as presented earlier (Table 4. 3), eight are high-income countries and 6 are LMICs. Thirteen of the 18 applications were developed in the eight high-income countries (namely Australia, Canada, Italy, Netherlands, Spain, USA, Poland and Singapore). Five of the mHealth applications (hearScreen™, Ear Scale, Hearing Test System, THST and the Hearing-Test application) were developed in five LMICs (Brazil, South Africa, Taiwan, Hong Kong and South Korea.). 0

With regards to the countries where the 18 mHealth applications were evaluated (Table 4. 4), out of the 21 different countries identified, 10 were high-income countries while the other 11 were LMICs. In terms of the 49 studies reviewed, 25 of the studies evaluated the respective mHealth applications in high-income countries, while the remaining 24 studies evaluated the mHealth applications in LMICs.

From the 18 smartphone- and tablet-based applications examined in the study, nine of the applications - the uHear™, hearScreen™, Ear Scale, EarTrumpet, Hearing Test™, Hearing-Test app, Hearing Test system, ShoeBOX and the THST application - were evaluated in LMICs. The remaining 9 applications were evaluated against manual audiometry in high-income countries.

4.14.2 mHealth applications suitable for LMICs

Eleven mHealth applications were considered potentially suitable for LMICs by the authors of the studies, regardless of country of origin or evaluation. These were: AudCal, Ear Scale, EarTrumpet, Hearing Test with Audiogram, hearScreen™, Hearing Test™, Hearing Test System, ShoeBOX, THST, uHear™ and ViA. These applications are discussed below. All these smartphone- and tablet-based applications showed acceptable functionality on evaluation in various studies.

AudCal audiology app

AudCal is an audiology application developed and validated in Spain. It was developed for iPhone or iPad mobile devices. It requires the user to enter at most 8 data points from an already generated pure-tone audiometry in order for the application to generate hearing impairment (that is, monaural and binaural) results. The hearing loss threshold defined by the AudCal audiology app is a pure tone average above 20 dB HL. The application does not include bone conduction. The AudCal application is an inexpensive tool compared to audiometers (Larrosa et al., 2015). The AudCal can be used for example, as a screening test in a remote population in which pure-tone air conduction threshold tests are not possible and is therefore suitable for LMICs (Larrosa et al., 2015:1126). However, dependence on Apple-based devices could be a limitation in LMICs.

Ear Scale iOS-based smartphone hearing test app

The Ear Scale smartphone hearing test application, which runs on iOS-based smartphones, was both developed and validated in Taiwan. The application was reported as having no cost (Chu et al., 2019). The application was developed to perform a pure-tone air conduction hearing test. The application has been found to be unsuitable for the detection of hearing impairments at the early stages (Chu et al., 2019). Possible hearing impairment was estimated at hearing threshold greater than 25 dB HL. While the suitability of the Ear Scale application has not been discussed for use in LMICs in the studies reviewed, the application may be suitable for such settings, because it could be used in situations where a hearing test is needed but access to an audiologist is limited. In addition, the no-cost nature of the application would be beneficial for LMICs. However, reliance on iOS could be a limitation in LMICs.

EarTrumpet iOS-based application

The EarTrumpet application was developed in the United States of America. It was evaluated in Turkey and the USA. The app performs the pure-tone air conduction hearing test in an automated fashion (Foulad, Bui & Djalilian, 2013). The application cannot be used on Android operating devices and cannot perform pure-tone bone conduction and speech audiometry (Derin et al., 2016). The application cost was USD 3.99 at the time of review. The presence of hearing loss was determined at a hearing threshold greater than 20 dB HL. According to the authors (Foulad, Bui & Djalilian, 2013), the application is capable of a more comprehensive audiologic evaluation than conventional audiometry. The application also enables testing for hearing loss in remote areas and medically underprivileged regions due to the portability of the device (Foulad, Bui & Djalilian, 2013:705). Low cost is another advantage. However, reliance on iOS could be a limitation in LMICs.

Hearing test with Audiogram application

The Hearing test with Audiogram application is a tablet-based tool for hearing loss screening (Stoddard, 2015). It was developed in Singapore. The application was evaluated in the USA. The application when installed on a smartphone- or tablet-based device allows the user to perform pure-tone audiometry repeatedly. The application can be downloaded from the iTunes App and Google Play Stores. The application does not perform pure-tone bone conduction testing (Kelly et al., 2018). Hearing loss was categorized with a "pass" if the pure-tone average was below 20 dB HL. During the time of the review, the cost of the application was not available. Compared to an audiologist, a facilitator with no or minimal training can monitor the screening test by the application. In addition, the application is "appropriate and in settings without access to audiometric equipment" (Kelly et al., 2018:410), thus making the app feasible for use in LMICs.

Hearing Test System application

A research team in China developed the Hearing Test system. It is a computerized self-administered hearing test for smartphone and tablet-based iOS devices. The application can perform unmasked pure-tone air conduction hearing tests. It was evaluated in China and Hong Kong. The cost of the application was not available at the time of the review. A referral is considered if a participant has a hearing threshold higher than 25 and/or 30 dB HL. One of its limitations, is that large threshold variabilities were identified with the use of the application because the insert headphones or earphones were loosely plugged into the mobile devices during hearing screening (Kam et al., 2012). It is considered as a suitable screening tool for LMICs, as the application was evaluated among first and second grade school children in China, an LMIC country (Kam et al., 2013). However, reliance on iOS could be a limitation in LMICs.

Hearing Test™ software

The Hearing Test™ software (e-audiologia.pl) is an Android-based system (Chauhan & Shah, 2018; Masalski et al., 2016). The app was developed in Poland. The application was designed to screen for pure-tone air conduction hearing impairments with evaluation conducted in Nigeria, Poland, Turkey and India. Hearing loss thresholds used by the app are 20 dB HL and 25 dB HL. The Hearing Test™ software application is a free application (Renda et al., 2016). Quiet rooms are a recommended test environment (Kam et al., 2012). The application was demonstrated to be an alternative hearing loss screening method in underserved areas making it a suitable screening tool in LMICs (Renda et al., 2016). The no-cost nature of the application is an advantage for LMICs.

The hearScreen™ smartphone-based application

The hearScreen™ smartphone-based application was developed in South Africa; it has recently been licensed by the University of Pretoria to a private company (hearScreen Pty) as a low-cost application (Swanepoel et al., 2014). The application can be used on both Apple-based and Android-based mobile devices. The application was validated in South Africa, the USA and in the Philippines. The application is currently restricted to pure-tone air conduction. The hearing loss threshold was between 15 dB HL and 35 dB HL. The application cannot perform pure-tone bone conduction threshold testing and speech audiometry. The hearScreen™ app is suitable for use in LMICs and providing access to hearing care service to underserved communities, as it is a simple, time efficient screening tool "with adequate sensitivity and specificity for children and adults" (Louw et al., 2017). Its low cost is an advantage for LMICs.

ShoeBOX tablet-based application

The ShoeBOX iPad based audiometer is an interactive testing method (Rourke, Kong & Bromwich, 2016) to assess hearing. The application was evaluated in Canada, the USA and the Dominican Republic. The application can perform conditioned play audiometry or play audiometry (that is, to train a child to listen carefully for sound stimuli in the form of warble tones and make responses within the framework of the designed game). The hearing loss thresholds used by the app were 25 dB HL and 30 dB HL. The application has a free component and a priced component with additional functionality and hardware. The application could be useful in areas where internet connectivity is a challenge, making the ShoeBOX application an acceptable tool for use in LMICs (Yeung et al., 2015; Yeung et al., 2013). Reliance on an iPad could be a limitation in LMICs.

Tablet-based hearing screening test (THST) app

The THST application was designed as an interactive game that can apply pure tones during hearing screening. It is an Apple-based application for iPads and iPhone. Brazil is the country of origin. It was evaluated against manual audiometry in the same country. At the time of the review, the application was not commercially available. A hearing loss threshold of 20 dB HL was used at screening frequencies of 1, 2 and 4 kHz. Although the THST application was developed for children, it was evaluated among the adult population and shown to be reliable compared to conventional audiometry (Samelli et al., 2018). The THST application "can be used in places with no internet access and where local audiologists are not available", making it suitable for use in LMICs (Samelli et al., 2018:5). However, reliance on Apple-based devices may be a limitation in LMICs.

The uHear™ iPod-based hearing loss screening test app

The uHear™ application was developed in Canada as a self-administered screening tool for hearing loss. The uHear™ iPod-based hearing loss screening application is capable of performing pure-tone air conduction hearing sensitivity test and speech-in-noise (SIN) test. Countries where evaluation of the tool were conducted include Belgium, USA, Israel, Oman and South Africa. The uHear™ application has some disadvantages; it has been shown to be inaccurate for low frequencies, testing must be performed in a quiet room and instructions are mainly in English (Peer & Fagan, 2015). The hearing loss thresholds for the uHear™ app included 15, 25, 35 and 40 dB HL. The app is free of charge. The uHear™ application can mostly be used in areas where screening resources are limited and is therefore suitable for LMICs (Sethi et al., 2018:e4). Its no-cost nature is an advantage for LMICs. However, reliance on an iPod may be a limitation.

Virtual Audiologist (ViA) application

The virtual audiologist is an Android-based application developed by the Medical Centre at the University of Utrecht (Netherlands). The ViA application can perform both pure-tone air conduction and bone conduction hearing tests. It was evaluated as an intelligent smartphone audiometry system in the Netherlands. The hearing loss threshold for the ViA app was not indicated, however both the air-conduction and bone-conduction thresholds could be determined. A limitation of the application is that, the ViA app is targeted at only people with early stages of the hearing loss (Kocian et al., 2017). Even though the ViA was developed in a high-income country, according to the authors (Kocian et al., 2017), the target users for the ViA application are patients with correctable hearing loss who live in medically underserved areas, to relieve the load on healthcare providers. This suggests that it is suitable for use in LMICs.

Table 4. 11: Summary of mHealth apps' suitability for use in LMICs and areas with limited access to audiologists, based on authors' claims.

mHealth app	Hearing tests available on app	Affordability for purchase	Evaluation LMIC setting	Testing in uncontrolled environment	Hearing loss threshold	Limitations
AudCal	Air conduction audiometry	Low cost solution	Spain	Yes	20 dB HL	Reliance on iPhone. Also, the app does not allow for the assessment of bone conduction and speech audiometry.
Ear Scale	Air conduction audiometry	Free application	Taiwan	Yes	25 dB HL	In detecting hearing impairment, the app is unsuitable. Dependence on Apple-based devices.
EarTrumpet	Pure tone audiometry	Low cost solution	USA and Turkey	Yes	20 dB HL	The app cannot be used on Android-based mobile devices. Reliance on iOS-based devices.
HT with Audiogram	Pure tone audiometry	Commercially not available	USA	Yes	20 dB HL	The app does not perform pure-tone bone conduction testing.
Hearing Test system	Air conduction audiometry	Not commercially available	China and Hong Kong	Yes	25 and 30 dB HL.	Dependence on Apple devices; due to loose insert of earphones during testing, large threshold variability was recorded by the app.
Hearing Test™	Pure-tone air conduction	Free	Nigeria, Poland, Turkey and India	Yes	20 and 25 dB HL	The app's testing results cannot help to distinguish between sensorineural- and conductive hearing loss.
hearScreen™	Air conduction audiometry	Free software; cost for additional hardware	South Africa, USA and Philippines	Yes	15, 20, 25, 30 and 35 dB HL.	The app cannot perform pure-tone bone conduction and speech audiometry.
ShoeBOX	Automated pure-tone air testing, with masking.	Free software; cost for additional hardware	Canada, USA and Dominican Republic	Yes	25 and 30 dB HL	When non-standard transducers are used and low frequency noise is not managed, the app is likely to have limitations. Reliance on iPad and iPod devices.
THST	Pure-tone air conduction	Not commercially available	Brazil	Yes	20 dB HL	The app requires its software to run on only iPhone mobile devices.
uHear™	Pure-tone air conduction	Free	Belgium, USA, Israel, Oman and South Africa	Yes	15, 25, 35 and 40 dB HL	Dependence on iPod devices and the hearing test of the app must be performed in a quiet environment.
ViA	Pure tone air- and bone conduction	Not commercially available	Netherlands	Yes	Not indicated	The app only targets people with early stages of hearing loss diseases.

4.15 Summary of findings

Eighteen available smartphone- and tablet-based applications for hearing loss screening were reviewed. Studies on these applications included participants from a variety of ages and both with and without hearing loss. The majority of the mHealth applications have self-administration capabilities, with four needing to be administered by a health professional. A variety of testing environments were used. Studies on the applications found 11 of them to have acceptable functionality for hearing loss screening.

Feedback from users with regard to user experience, satisfaction, use of the device and the presence of a tester, indicated that patients generally preferred the mHealth hearing tests to conventional methods. Several apps were free to download, while hardware purchases would increase costs in some cases.

Additional findings from the study include the following:

i. The majority of the applications were smartphone-based.
ii. Apple iOS was the most frequently used platform.
iii. The most common transducers used were headphones.
iv. The most common types of test environment were quiet rooms or spaces.
v. The most frequently used testing modality was air conduction and the most frequently used sound stimuli were pure tones.
vi. The most common language for testing was English.
vii. The most common threshold for defining hearing loss was at 20 dB HL.
viii. The most common reference method was pure-tone audiometry.

Finally, the review has identified several smartphone- and tablet-based applications that may be suitable for use in LMICs, based on claims by study authors. A summary is provided in Table 4. 11.

CHAPTER 5
DISCUSSION AND CONCLUSION

A number of smartphone- and tablet-based audiometry tools have been developed to screen for hearing loss in both developed and developing countries, since the introduction of automated audiometry. This study has reviewed smartphone- and tablet-based apps available for hearing loss screening based on studies published between January 2000 and July 2019. Eleven applications were indicated by studies as having acceptable functionality for hearing loss screening. These 11 applications are also potentially suitable for use in LMICs, based on claims by study authors, although they have some limitations. This chapter discusses key study findings, considers the limitations of the review and finally draws conclusions.

5.1 Screening intensity levels

The World Health Organization (2012) defines hearing loss in children against a threshold of 30 dB HL and for adults at 40 dB HL. According to the American Academy of Audiology (2011b), the use of sound intensity levels between 25 dB HL and 40 dB HL is advised. Several studies conducted in India, China and African countries have shown the utilization of screening threshold levels between 25 dB HL and 40 dB HL (Al-Rowaily, Al-Fayez & Al-Jomiey, 2012; Kam et al., 2013; Lo & McPherson, 2013). For the reviewed studies, the hearing loss threshold mostly were between 15 and 40 dB HL. Hearing thresholds of 15 dB HL or less were due to testing in a sound treated environment (Sandström et al., 2016), no abnormalities in tested ear (Sethi et al., 2018), hearing testing in better ears (Khoza-Shangase & Kassner, 2013) and study samples which consisted of normal-hearing participants (Potgieter et al. 2016).

5.2 Software platforms

The most common platform and avenue used for automated audiometry by the smartphone- or tablet-based applications in the review was iOS. Among the 18 mHealth applications reviewed, the uHear™ iOS-based smartphone application was published on most frequently since 2000, a finding in agreement with that of Bright & Pallawela (2016). The hearScreen™ smartphone application on the other hand was the first application to be developed on the Android platform.

5.3 Operators of the mobile applications

Hearing test applications can either be operated by a hearing health professional or they can be self-administered by a person who is not trained clinically. Self-administration of hearing test reduces the cost of paying for a test in a clinical setting (Corry, Sanders & Searchfield, 2017), removes travelling time to see a professional (Abu-Ghanem et al., 2016), improves access to hearing care (Clark & Swanepoel, 2014), ensures short time to test (Sohn et al., 2011) and provides an efficient option to combat the lack of skilled health professionals in resource-constrained settings (van Tonder et al., 2017). Of the 18 mHealth applications reviewed, 14 allowed patients to perform a hearing test on their own.

One function of the test-operator is to determine actively the hearing thresholds to avoid difficulty that patients may experience when operating the smartphone- and tablet-based devices. As an example, for the hearScreen™ smartphone-based application, this would include community health workers, school health nurses, and audiology students as well as experts in audiology (van Tonder et al., 2017).

5.4 mHealth vs reference methods

Screening is usually supervised by a qualified audiologist, in various settings (American Academy of Audiology, 1997a; American Academy of Audiology, 1997b; American Speech-Language-Hearing Association, 1997; Mauk & Behrens, 1993). This is considered as the "conventional screening principle" or the "gold standard" for hearing loss screening (Smith & Makenzie, 1999).

For clinical testing, manual audiometry which includes pure-tone air conduction audiometry and bone conduction audiometry determined in a certified sound booth with a conventional audiometer is required (American Speech-Language-Hearing Association, 2015). Automated audiometry must include a number of testing modalities for the hearing test to be valid and at the same time a reliable tool for assessing hearing impairment (Ho, Hildreth & Lindsey, 2009; Margolis & Morgan, 2008; Margolis & Moore, 2011). Conventional pure-tone audiometry is considered the gold standard for hearing loss testing (Smith & Makenzie, 1999). Nevertheless, it is not available universally due to limited access to equipment for proper testing, the cost of purchasing conventional screening devices, the need for a certified hearing expert to conduct the hearing assessment and availability of test centres.

Hearing testing by the mHealth applications were evaluated in various ways. Few of the studies reviewed reported further on the evaluation of the mHealth apps by comparison with a reference. The most frequently used reference test in the 49 studies reviewed was pure-tone audiometry, the gold standard for hearing loss testing.

Some mHealth tools reviewed in this study cannot replace conventional audiological screening measures. Reasons for this are: most of the mHealth applications cannot distinguish between sensorineural and conductive hearing loss; self-test applications can allow the users to drive the result of the hearing test; and variables such as, ambient noise levels during testing, the characteristics of the headphones used as transducers and the lack of standardization of devices used can affect the quality of the results (Honeth et al., 2010; Kam et al., 2012; Manganella et al., 2018; McPherson, Law & Wong, 2010).

Rather, the 18 mHealth applications identified in this study could serve as alternatives to overcome the deficits in health systems where comprehensive hearing screening and assessments are lacking. As screening tools, these apps can indicate whether referral is required to conventional measures where available.

5.5 Cost

Depending on the pricing of the hearing-related apps, some perform basic hearing tests and others perform specialized hearing tests (Coleman, 2011). The review found that several applications were free to download or low cost, while hardware purchases would increase costs in some cases. Applications considered suitable for LMICs, either had low or free download costs, or were not yet commercially available. The cost implications on LMIC use for yet to be commercialized app are therefore not yet known.

5.6 Testing environment

Ambient noise has an effect on hearing test results (Foulad, Bui & Djalilian, 2013; Peer & Fagan, 2015; Szudek et al., 2012). Out of the 18 mHealth applications reviewed, 11 were able to measure the ambient noise levels in the testing rooms before and during the hearing screening. Testing for hearing loss in an environment that is not soundproof may pose a challenge to the accuracy of the test results and the operation of the mobile applications. Soundproofing may be difficult to achieve in under-resourced communities. However, the audiometric threshold may be adapted when a sound-treated booth or room is not used.

All 14 of the mHealth applications considered potentially to be suitable for LMICs, were able to screen for hearing loss in an uncontrolled environment. The hearScreen™ smartphone application for example has an active noise reduction algorithm that addresses environmental noise and makes the device suitable for use in a variety of settings (Swanepoel et al., 2014).

At low ambient noise levels, audiometers and mHealth applications implemented in various environments, can be as accurate as results that are obtained in a sound treated booth. The control of ambient noise was considered a factor contributing to high sensitivity of mHealth apps. For the 11 smartphone- and tablet-based applications that recorded the sensitivity levels, 7 recorded sensitivity levels of greater than 90 percent. However, with regard to the 14 mHealth applications found potentially suitable for use in LMIC settings, only two applications (ShoeBOX and the Hearing Test system) met low ambient noise requirements. A study conducted by Kam et al. (2014) using the Hearing Test system recorded an ambient noise level between 40 and 51 dBA/SPL.

In a similar study, the ambient noise level recorded by the hearScreen™ smartphone-based application ranged between 45 and 65 dBA/SPL. These values are in accordance with three standards on the maximum permissible background noise levels namely the Occupational Safety and Health Administration (OSHA) Table D-2 (1981), Occupational Safety and Health

Administration (OSHA) Table D-1 (1983) and the ANSI S3.1-1991 standard as reported by Franks (1995). One of the challenges with the implementation of mHealth hearing screening apps is the presence of the health personnel (that is, testers). In a study by Corry, Sanders & Searchfield (2017), participants were distracted by the presence of the testers which affected the hearing results of the patients and the participants.

5.7 Language

One key issue with mHealth application development and use is language (Kruse et al., 2019). Studies conducted in LMICs have shown the language of the mHealth applications to be a barrier (Bigna et al., 2013; Ginsburg et al., 2015; Mohan et al., 2017; Nhavoto, Grönlund & Klein, 2017). The mHealth applications identified in this study were predominantly in English. The applications that had more than one language for instruction during hearing testing to suit the language background and preference of the user (patient or tester) include AudCal, Audiogram Mobile, EarTrumpet, Hearing Test™, ShoeBOX and the uHear™ application.

5.8 Prospects of the mHealth applications

Given the decreasing costs and increased use of internet-enabled smartphones in Africa (Malila, Mutsvangwa & Douglas, 2019) and other developing regions, the mobile solutions reviewed offer an opportunity for more users to be reached compared to conventional audiometers or computer-controlled audiometers. Despite the inability of the mHealth tools reviewed in this study to replace conventional measures (Honeth et al., 2010; Kam et al., 2012; McPherson, Law & Wong, 2010), they provide alternatives for resource-constrained health systems lacking in conventional tools.

The mHealth applications also provide initial screening services that may be followed up by conventional measures where the latter do exist. Hearing testing with smartphone- and tablet-based applications presents several challenges including calibration (Corry, Sanders & Searchfield, 2017; Louw et al., 2017; Na et al., 2014) and evaluation (Bright & Pallawela, 2016). Further development of the applications and advances in technology are likely to address these challenges, increasing the utility of the applications.

5.9 Study limitations

The study was limited to smartphone- or tablet-based applications that were found in peer reviewed scientific literature; thus, mHealth tools for which publications were not available, may have been missed. Also, the study focussed on smartphone- and tablet-based applications only for screening purposes. This inclusion criterion left out hearing loss diagnostic applications, a study of which would provide additional understanding of the landscape, trends and prospects of mHealth applications in the area of hearing loss assessment in LMICs.

5.10 Conclusion

Hearing loss is a disabling condition. Several smartphone- or tablet-based applications were developed and evaluated as hearing loss screening tools in settings such as homes and offices, and for mass screenings at schools. These were reviewed under the first objective of this study. Under the second objective, the study revealed mHealth tools for hearing loss screening, that may be suitable for LMIC settings. While these are not able to replace the conventional audiometer, they have potential as a first point of access for referral to conventional audiometry, and to help increase access to hearing loss tests in resource-constrained health systems. The findings of the review may inform improvement of the mHealth tools, their adoption, and the development of new ones.

5.10.1 Recommendations for future research

The widespread deployment of mHealth applications in multiple LMICs requires attention to the language of users so further studies should focus on how different languages; especially vernacular ones can be incorporated in smartphone or tablet based applications meant to screen for hearing loss. In addition, studies on usability, feasibility of incorporation of mHealth solutions into health systems, and availability of referral systems, would be of interest for all the applications considered potentially suitable for LMICs.

REFERENCES

Abu-Ghanem, S., Handzel, O., Ness, L., Ben-Artzi-Blima, M., Fait-Ghelbendorf, K. & Himmelfarb, M. 2016. Smartphone-based audiometric test for screening hearing loss in the elderly. *Eur Arch Otorhinolaryngol.* 273(2):333-339. DOI:10.1007/s00405-015-3533-9.

Acipayam, H., Koçak, H. & Elbistanli, M. 2017. Sudden Sensorineural Hearing Loss. In *An Excursus into Hearing Loss*. S. Hatzopoulos and A. Ciorba, Eds. London, United Kingdom: IntechOpen. 71-91. Available:https://www.intechopen.com/books/an-excursus-into-hearing-loss/sudden-sensorineural-hearing-loss [2019, August 12].

Al-Abri, R., Al-Balushi, M., Kolethekkat, A., Bhargava, D., Al-Alwi, A., Al-Bahlani, H. & Al-Garadi, M. 2016. The Accuracy of IOS Device-based uHear as a Screening Tool for Hearing Loss: A Preliminary Study From the Middle East. *Oman Med J.* 31(2):142-145. DOI:10.5001/omj.2016.27.

Al-Rowaily, M., Al-Fayez, A. & Al-Jomiey, M. 2012. Hearing Impairments Among Saudi Preschool Children. *Int J Pediatr Otorhinolaryngol.* 76:1674-1677[2020, February 28].

Alaqrabawi, W.S., Alshawabka, A.Z., Al-Addasi, Z.M. & Alaraifi, J.A. 2016. What are the Predictive Causes of Conductive Hearing Loss in School-Age Children in Jordan? *J Med J.* 50(4):187-194. DOI:10.12816/0035054.

Albera, A. 2019. Environmental noise and hearing loss. *Otorinolaringologia.* 69(2):113-118. DOI:10.23736/s0392-6621.18.02201-4.

American Academy of Audiology. 1997a. Position Statement: Identification of hearing loss and middle-ear dysfunction in preschool and school-age children. *Audiology Today*. 9(3):21 - 23[2020, October 13].

American Academy of Audiology. 1997b. Position Statement: Identification of hearing loss and middle-ear dysfunction in children. *Audiology Today*. 9(3):18-20[2020, October 13].

American Academy of Audiology. 2011a. *Practice Guidelines: Childhood Hearing Screening*. American Academy of Audiology (AAA). Available: http://www.audiology.org/resources/documentlibrary/Documents/ChildhoodScreening-Guidelines.pdf [2020, October 13].

American Academy of Audiology. 2011b. *Childhood Hearing Screening Guidelines*. United States of America: American Academy of Audiology. Available: http://www.audiology.org [2020, March 04].

American National Standards Institute. 2004 (Reaffirmed in 2009). *Methods for Manual Pure-Tone Threshold Audiometry*. New York, United States of America: American National Standards Institute (ANSI) Available: https://webstore.ansi.org/standards/asa/ansiasas3212004r2009 [2019, October 12].

American National Standards Institute. 2019. *Specification for Audiometers (ANSI/ASA S3.6-2018)*. New York, United States of America: American National Standards Institute (ANSI). Available: https://webstore.ansi.org/standards/asa/ansiasas32018 [2019, September 27].

American Speech-Language-Hearing Association. 1992. Considerations in screening adults/older persons for handicapping hearing impairments. *Asha.* 34(8):81 - 87[2020, October 13].

American Speech-Language-Hearing Association. 1997. *Guidelines for Audiologic Screening*. Florida, United States of America: ASHA. Available: https://www.asha.org/policy/ [2018, May 05].

American Speech-Language-Hearing Association. 2015. *Type, Degree, and Configuration of Hearing Loss*. Florida, United States of America: ASHA. Available: https://www.asha.org/public/hearing/Configuration-of-Hearing-Loss/ [2019, August 20].

American Speech-Language-Hearing Association. 2022. *Childhood Hearing Screening*. Florida, United States of America: ASHA. Available: https://www.asha.org/practice-portal/professional-issues/childhood-hearing-screening/#collapse_1 [2022, January 17].

Arlinger, S. 2003. Negative consequences of uncorrected hearing loss - a review. *Int J Audiol.* 42:2S17-12S20. DOI:10.3109/14992020309074639.

Baer, J.E. & Groth, J. 1998. The Madsen Aurical. *Trends Amplif.* 3(4):152-161. DOI:10.1177/108471389800300404.

Bagai, A., Thavendiranathan, P. & Detsky, A.S. 2006. Does This Patient Have Hearing Impairment? *JAMA.* 295(4):416-428. DOI:10.1001/jama.295.4.416.

Barczik, J. & Serpanos, Y.C. 2018a. Accuracy of Smartphone Self-Hearing Test Applications Across Frequencies and Earphone Styles in Adults. *Am J Audiol.* 27(4):570-580. DOI:10.1044/2018_AJA-17-0070.

Barczik, J. & Serpanos, Y.C. 2018b. Accuracy of Smartphone Self-Hearing Test Applications Across Frequencies and Earphone Styles in Adults. *American Journal of Audiology.* 27(4):570-580. DOI:10.1044/2018_AJA-17-0070.

Bigna, J.J.R., Kouanfack, C., Noubiap, J.J.N., Plottel, C.S. & Koulla-Shiro, S. 2013. A randomized blinded controlled trial of mobile phone reminders on the follow-up medical care of HIV-exposed and HIV-infected children in Cameroon: study protocol (MORE CARE). *Trials.* 14(313). DOI:10.1186/1745-6215-14-313.

Blazer, D.G., Domnitz, S. & Liverman, C.T. 2016. Hearing Health Care for Adults: Priorities for Improving Access and Affordability. In *Hearing Health Care for Adults: Priorities for Improving Access and Affordability.* D.G. Blazer, S. Domnitz and C.T. Liverman, Eds. Washington (DC): The National Academies Press. 324. DOI:10.17226/23446.

Boatman, D.F., Miglioretti, D.L., Eberwein, C., Alidoost, M. & Reich, S.G. 2007. How accurate are bedside hearing tests? *Neurology.* 68(16):1311-1314. DOI:10.1212/01.wnl.0000259524.08148.16.

Boo, N.Y., Rohani, A.J. & Asma, A. 2008. Detection of sensorineural hearing loss using automated auditory brainstem-evoked response and transient-evoked otoacoustic emission in term neonates with severe hyperbilirubinaemia. *Singapore Med J.* 49(3):209-214.

Bowen, G. 2009. Document Analysis as a Qualitative Research Method. *Qualitative Research Journal.* 9:27-40. DOI:10.3316/QRJ0902027.

Bowl, M. & Dawson, S.J. 2018. Age-Related Hearing Loss. *Cold Spring Harb Perspect Med.* 9(8):1-14. DOI:10.1101/cshperspect.a033217.

Braun, V. & Clarke, V. 2014. What can "thematic analysis" offer health and wellbeing researchers? *International journal of qualitative studies on health and well-being.* 9:26152-26152. DOI:10.3402/qhw.v9.26152.

Brennan-Jones, C.G., Eikelboom, R.H., Swanepoel de, W., Friedland, P.L. & Atlas, M.D. 2016. Clinical validation of automated audiometry with continuous noise-monitoring in a clinically heterogeneous population outside a sound-treated environment. *Int J Audiol.* 55(9):507-513. DOI:10.1080/14992027.2016.1178858.

Bright, T. & Pallawela, D. 2016. Validated Smartphone-Based Apps for Ear and Hearing Assessments: A Review. *JMIR Rehabil Assist Technol.* 3(2):1-11. DOI:10.2196/rehab.6074.

Brungart, D., Schurman, J., Konrad-Martin, D., Watts, K., Buckey, J., Clavier, O., Jacobs, P.G., Gordon, S. et al. 2018. Using tablet-based technology to deliver time-efficient ototoxicity monitoring. *International Journal of Audiology.* 57(sup4):S25-S33. DOI:10.1080/14992027.2017.1370138.

Castillo, N.M. & Steven, V. 2015. *hearScreen™: A case study by UNESCO-Pearson Initiative for Literacy*. Paris, France: S.a.C.O. The United Nations Educational. Available: https://unesdoc.unesco.org/ark:/48223/pf0000258877 [2018, June 06].

Chadha, S. 2014. Community Ear and Hearing Care. In *Open Access Guide to Audiology and Hearing Aids for Otolaryngologists*. d.W. Swanepoel, C. Laurent and J. Fagan, Eds. Cape Town, South Africa: University of Cape Town. 1-14. Available:https://vula.uct.ac.za/access/content/group/27b5cb1b-1b65-4280-9437-a9898ddd4c40/Community%20ear%20and%20hearing%20care.pdf%20 [2018, July 23].

Chan, K.H., Dreith, S., Uhler, K.M., Tallo, V., Lucero, M., De Jesus, J. & Simoes, E.A. 2019. Large-scale otoscopic and audiometric population assessment: A pilot study. *Int J Pediatr Otorhinolaryngol.* 117:148-152. DOI:10.1016/j.ijporl.2018.11.033.

Chari, D.A. & Chan, D.K. 2017. Diagnosis and Treatment of Congenital Sensorineural Hearing Loss. *Curr Otorhinolaryngol Rep.* 5(4):251-258. DOI:10.1007/s40136-017-0163-3.

Chauhan, N. & Shah, J. 2018. Smart Phone Based Audiometry in City Traffic Police. *Indian J Otolaryngol Head Neck Surg.* 70(3):342-345. DOI:10.1007/s12070-018-1327-2.

Chu, Y.C., Cheng, Y.F., Lai, Y.H., Tsao, Y., Tu, T.Y., Young, S.T., Chen, T.S., Chung, Y.F. et al. 2019. A Mobile Phone-Based Approach for Hearing Screening of School-Age Children: Cross-Sectional Validation Study. *JMIR Mhealth Uhealth.* 7(4):e12033 (p.12031-p.12013). DOI:10.2196/12033.

Clark, J. & Swanepoel, d.W. 2014. Technology for hearing loss--as We Know it, and as We Dream it. *Disabil Rehabil Assist Technol.* 9(5):408-413. DOI:10.3109/17483107.2014.905642.

Clark, J.G. 1981. Uses and abuses of hearing loss classification. *ASHA.* 23(7):493-500. Available: https://www.ncbi.nlm.nih.gov/pubmed/7052898 [2019, August 13].

Coleman, M. 2011. There's a hearing app for that. *The Hearing Journal.* 64(11):12-16. DOI:10.1097/01.HJ.0000407398.79717.4f.

Corry, M., Sanders, M. & Searchfield, G.D. 2017. The accuracy and reliability of an app-based audiometer using consumer headphones: pure tone audiometry in a normal hearing group. *Int J Audiol.* 56(9):706-710. DOI:10.1080/14992027.2017.1321791.

Dalton, D.S., Cruickshanks, K.J., Klein, B.E., Klein, R., Wiley, T.L. & Nondahl, D.M. 2003. The impact of hearing loss on quality of life in older adults. *The gerontologist.* 43(5):661-668.

Derin, S., Cam, O.H., Beydilli, H., Acar, E., Elicora, S.S. & Sahan, M. 2016. Initial assessment of hearing loss using a mobile application for audiological evaluation. *J Laryngol Otol.* 130(3):248-251. DOI:10.1017/S0022215116000062.

Dessai, T., Ashraf, H. & Michael, C. 2017. Seasonality sway birth and hearing loss? *Egypt J Otolaryngol.* 33(1):84-88. DOI:10.4103/1012-5574.199418.

Dewyer, N.A., Jiradejvong, P., Lee, D.S., Kemmer, J.D., Henderson Sabes, J. & Limb, C.J. 2019. Automated Smartphone Audiometry: A Preliminary Validation of a Bone-Conduction Threshold Test App. *Ann Otol Rhinol Laryngol.* 128(6):508-515. DOI:10.1177/0003489419828770.

Dillon, H., Mee, C., Moreno, J.C. & Seymour, J. 2018. Hearing tests are just child's play: the sound scouts game for children entering school. *Int J Audiol.* 57(7):529-537. DOI:10.1080/14992027.2018.1463464.

Domagala-Zysk, E. 2019. Older Persons With Subjectively Assessed Hearing Problems in Poland: Quality of Life and Coping Strategies. *Am Ann Deaf.* 164(3):381-394. DOI:10.1353/aad.2019.0020.

Ebert, C.S., Zanation, A.M. & Buchman, C.A. 2008. Another Cause for Conductive Hearing Loss With Present Acoustic Reflexes. *Laryngoscope.* 118(11):2059-2061. DOI:10.1097/MLG.0b013e3181806414.

Eikelboom, R.H., Swanepoel, d.W., Motakef, S. & Upson, G.S. 2013. Clinical validation of the AMTAS automated audiometer. *Int J Audiol.* 52(5):342-349. DOI:10.3109/14992027.2013.769065.

Erenberg, A., Lemons, J., Sia, C., Trunkel, D. & Ziring, P. 1999. Newborn and infant hearing loss: detection and intervention.American Academy of Pediatrics. Task Force on Newborn and Infant Hearing, 1998- 1999. *Pediatrics.* 103(2):527-530. DOI:10.1542/peds.103.2.527.

Fagan, J. & Jacobs, M. 2009. Survey of ENT services in Africa: need for a comprehensive intervention. *Glob Health Action.* 2(1):1-7. DOI:10.3402/gha.v2i0.1932.

Fantom, N.J. & Serajuddin, U. 2016. *The World Bank's Classification of Countries by Income*. (Polivy Research Working Paper 7528). Washington, D.C., United States W.B. Group. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2741183 [2019, August 19].

Ferrari, D.V., Lopez, E.A., Lopes, A.C., Aiello, C.P. & Jokura, P.R. 2013. Results obtained with a low cost software-based audiometer for hearing screening. *Int Arch Otorhinolaryngol.* 17(3):257-264. DOI:10.7162/S1809-97772013000300005.

Foulad, A., Bui, P. & Djalilian, H. 2013. Automated audiometry using apple iOS-based application technology. *Otolaryngol Head Neck Surg.* 149(5):700-706. DOI:10.1177/0194599813501461.

Franks, J.R. 1995. Hearing Measurement. In *Occupational Exposure to Noise: Evaluation, Prevention and Control*. Berenice Goelzer, C.H. Hansen and G.A. Sehrndt, Eds. Netherlands: Published on behalf of the World Health Organization. 183 - 232. Available:https://www.who.int/occupational_health/publications/occupnoise/en/ [2019, December 01].

Gan, K.B., Azeez, D., Umat, C., Ali, M.A.M., Wahab, N.A.A. & Mukari, S.Z.M.-S. 2012. Development of a computer-based automated pure tone hearing screening device: A preliminary clinical trial. *Biomedizinische Technik/Biomedical Engineering.* 57(5):323-332. DOI:10.1515/bmt-2011-0086.

Garrison, W.M. & Bochner, J.H. 2015. Applications of the NTID speech recognition test (NSRT®). *Int J Audiol.* 54(11):828-837. DOI:10.3109/14992027.2015.1055837.

Gelfand, A.S. 2016. *Essentials of Audiology*. Fourth. New York, United States of America: Thieme Medical Publishers, Inc.[2020, November 15].

Ginsburg, A.S., Delarosa, J., Brunette, W., Levari, S., Sundt, M. & Larson, C. 2015. mPneumonia: development of an innovative mHealth application for diagnosing and treating childhood pneumonia and other childhood illnesses in low-resource settings. *PLoS One*. 10(10):e0139625. DOI:10.1371/journal.pone.0139625].

Grant, M.J. & Booth, A. 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*. 26:91 - 108. DOI:10.1111/j.1471-1842.2009.00848.x.

Guldager, M.J., Melchiors, J. & Andersen, S.A.W. 2020. Development and Validation of an Assessment Tool for Technical Skills in Handheld Otoscopy. *Ann Otol Rhinol Laryngol*. 129(7):715-721. DOI:10.1177/0003489420904734.

Hall, J.W. 2015. *Evidence-Based Clinical Applications of OAEs in Children and Adults*. Houston-Texas, United States of America: Audiologyonline. Available: https://www.audiologyonline.com/articles/evidence-based-clinical-applications-oaes-15471 [2019, August 12].

Hamilton, M. & Kramer, M. 2019. Applications of Mental Health Statistics. *J Royal Stat Soc*. 133(2):261. DOI:10.2307/2343697.

Handzel, O., Ben-Ari, O., Damian, D., Priel, M.M., Cohen, J. & Himmelfarb, M. 2013. Smartphone-Based Hearing Test as an Aid in the Initial Evaluation of Unilateral Sudden Sensorineural Hearing Loss. *Audiol Neurotol*. 18(4):201-207. DOI:10.1159/000349913.

Hawke, M., Keene, M. & Alberti, P.W. 1990. *Clinical otoscopy : an introduction to ear diseases*. 2nd ed. New York: Churchill Livingstone[2022, January 16].

Hawkins, K., Bottone, F.G., Jr., Ozminkowski, R.J., Musich, S., Bai, M., Migliori, R.J. & Yeh, C.S. 2012. The prevalence of hearing impairment and its burden on the quality of life among adults with Medicare Supplement Insurance. *Qual Life Res*. 21(7):1135-1147. DOI:10.1007/s11136-011-0028-z.

Ho, A.T.P., Hildreth, A.J. & Lindsey, L. 2009. Computer-assisted audiometry versus manual audiometry. *Otol Neurotol*. 30(7):876-883. DOI:10.1097/MAO.0b013e3181b120d0.

Honeth, L., Bexelius, C., Eriksson, M., Sandin, S., Litton, J.E., Rosenhall, U., Nyren, O. & Bagger-Sjoback, D. 2010. An internet-based hearing test for simple audiometry in nonclinical settings: preliminary validation and proof of principle. *Otol Neurotol*. 31(5):708-714. DOI:10.1097/MAO.0b013e3181de467a.

Howell, J.B., Appelbaum, E.N., Armstrong, M.F., Chapman, D. & Dodson, K.M. 2019. An Analysis of Risk Factors in Unilateral Versus Bilateral Hearing Loss. *Ear Nose Throat J*. 98(6):330-333. DOI:10.1177/0145561319840578.

Huizing, H. 1951. Pure tone audiometry. *Acta Otolaryngol*. 40(1-2):51-61. DOI:10.3109/00016485109138907.

Hussein, S.Y., Swanepoel, D., de Jager, L.B., Myburgh, H.C., Eikelboom, R.H. & Hugo, J. 2016. Smartphone hearing screening in mHealth assisted community-based primary care. *Journal of Telemedicine and Telecare*. 22(7):405-412. DOI:10.1177/1357633x15610721.

Jayawardena, A., Waller, B., Edwards, B., Larsen-Reindorf, R., Esinam Anomah, J., Frimpong, B., Gina, A., Netterville, J. et al. 2018. Portable audiometric screening platforms used in low-resource settings: A review. *J Laryngol Otol*. 133(2):74-79. DOI:10.1017/S0022215118001925.

Kam, A., Sung, J.K., Lee, T., Wong, T.K. & van Hasselt, A. 2012. Clinical evaluation of a computerized self-administered hearing test. *Int J Audiol*. 51(8):606-610. DOI:10.3109/14992027.2012.688144.

Kam, A., Gao, H., Li, L.K.C., Zhao, H., Qiu, S. & Tong, M.C.F. 2013. Automated hearing screening for children: A pilot study in China. *Int J Audiol.* 52(12):855-860. DOI:10.3109/14992027.2013.832419.

Kam, A., Li, L.K.C., Yeung, K.N.K., Wu, W., Huang, Z., Wu, H. & Tong, M.C.F. 2014. Automated hearing screening for preschool children. *J Med Screen.* 21(2):71-75. DOI:10.1177/0969141314528322.

Kapul, A.A., Zubova, E.I., Torgaev, S.N. & Drobchik, V.V. 2017. Pure-tone Audiometer. *J Phys.: Conf Ser.* 881(1):012010. DOI:10.1088/1742-6596/881/1/012010.

Karthikeyan, S., Thangarajan, R., T.N, N. & Srinivasan, K. 2019. Android mobile applications in eye care. *Oman J Ophthalmol.* 12(2):73-77. DOI:10.4103/ojo.OJO_226_2018.

Kelly, E.A., Stadler, M.E., Nelson, S., Runge, C.L. & Friedland, D.R. 2018. Tablet-based Screening for Hearing Loss: Feasibility of Testing in Nonspecialty Locations. *Otol Neurotol.* 39(4):410-416. DOI:10.1097/MAO.0000000000001752.

Khoza-Shangase, K. & Kassner, L. 2013. Automated screening audiometry in the digital age: Exploring Uhear™ and its use in a resource-stricken developing country. *International Journal of Technology Assessment in Health Care.* 29(1):42-47. DOI:10.1017/S0266462312000761.

Kocian, A., Ienco, C., Chessa, S. & Grolman, W. 2017. Intelligent Smartphone Audiometry. *8th International Symposium on Ambient Intelligence, ISAmI 2017*. Porto, Portugal, 2017, June 21 to 23 2017. 112-120. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85021684392&doi=10.1007%2ff978-3-319-61118-1_15&partnerID=40&md5=cc3319da33a72b473079c1c6792ebceb [2019, July 16].

Koopman, J., Davey, E., Thomas, N., Wittkop, T. & Verschuure, H. 2008. How should hearing screening tests be offered? *Int J Audiol.* 47(5):230-237. DOI:10.1080/14992020801908236.

Kruse, C., Jose, B., Stephanie, O., Susana, M.V.L., Inderdeep, K.B. & Narce, S. 2019. Barriers to the Use of Mobile Health in Improving Health Outcomes in Developing Countries: Systematic Review. *J Med Internet Res.* 21(10):e13263. DOI:10.2196/13263.

Larrosa, F., Rama-Lopez, J., Benitez, J., Morales, J.M., Martinez, A., Alañon, M.A., Arancibia-Tagle, D., Batuecas-Caletrio, A. et al. 2015. Development and evaluation of an audiology app for iPhone/iPad mobile devices. *Acta Oto-Laryngologica.* 135(11):1119-1127. DOI:10.3109/00016489.2015.1063786.

Lee, J.M., Jung, J., Moon, I.S., Kim, S.H. & Choi, J.Y. 2017. Benefits of active middle ear implants in mixed hearing loss: Stapes versus round window. *Laryngoscope.* 127(6):1435-1441. DOI:10.1002/lary.26244.

Leensen, M.C.J. & Dreschler, W.A. 2013. The applicability of a speech-in-noise screening test in occupational hearing conservation. *Int J Audiol.* 52(7):455-465. DOI:10.3109/14992027.2013.790565.

Liao, W.-H., Young, S.-T., Lien, C.-F. & Wang, S.-J. 2011. An audiometer to moniter pregressive hearing change in school-aged children. *J Med Screen.* 18(1):8-11. DOI:10.1258/jms.2011.010120.

Lithgow, K., Edwards, A. & Rabi, D. 2016. Smartphone Application Use for Diabetes Management. *Can J Diabetes.* 40(5):S30. DOI:10.1016/j.jcjd.2016.08.088.

Lo, A. & McPherson, B. 2013. Hearing screening for school children: Utility of noise-cancelling headphones. *BMC Ear Nose Throat Disord.* 13(6):1-10. DOI:10.1186/1472-6815-13-6.

Louw, C., Swanepoel, D.W. & Eikelboom, R.H. 2018. Self-Reported Hearing Loss and Pure Tone Audiometry for Screening in Primary Health Care Clinics. *J Prim Care Community Health.* 9:1-8. DOI:10.1177/2150132718803156.

Louw, C., Swanepoel, W., Eikelboom, R.H. & Myburgh, H.C. 2017. Smartphone-Based Hearing Screening at Primary Health Care Clinics. *Ear Hear.* 38(2):e93-e100. DOI:10.1097/aud.0000000000000378.

Louw, C., Swanepoel, D.W., Eikelboom, R.H. & Hugo, J. 2018. Prevalence of hearing loss at primary health care clinics in South Africa. *African Health Sciences.* 18(2):313-320. DOI:10.4314/ahs.v18i2.16.

Maclennan-Smith, F., Swanepoel, D.W. & Hall, J.W., 3rd. 2013. Validity of diagnostic pure-tone audiometry without a sound-treated environment in older adults. *Int J Audiol.* 52(2):66-73. DOI:10.3109/14992027.2012.736692.

Malila, B., Mutsvangwa, T.E.M. & Douglas, T.S. 2019. Mobile Health for Africa. In *Biomedical Engineering for Africa.* T.S. Douglas, Ed. Cape Town, South Africa: University of Cape Town Libraries. 204-217. DOI:10.15641/0-7992-2544-0.

Maling, G.J. & Brenig, A. 1980. IEC issues new audiometer standard. *J Acoust Soc Am.* 67(1):357. DOI:10.1121/1.383770.

Mandavia, R., Bhutta, M.F., Lapa, T. & Smith, M. 2018. A cross-sectional evaluation of the validity of a smartphone otoscopy device in screening for ear disease in Nepal. *Clin Otolaryngol.* 43(1):31-38. DOI:10.1111/coa.12898.

Manganella, J.L., Stiles, D.J., Kawai, K., Barrett, D.L., O'Brien, L.B. & Kenna, M.A. 2018. Validation of a portable hearing assessment tool: Agilis Health Mobile Audiogram. *Int J Pediatr Otorhinolaryngol.* 113:94-98. DOI:10.1016/j.ijporl.2018.04.010.

Margolis, R. & Morgan, D.E. 2008. Automated Pure-Tone Audiometry: An Analysis of Capacity, Need, and Benefit. *Am J Audiol.* 17(2):109-113. DOI:10.1044/1059-0889(2008/07-0047).

Margolis, R. & Moore, B.C.J. 2011. AMTAS®: Automated method for testing auditory sensitivity: III. Sensorineural hearing loss and air-bone gaps. *Int J Audiol.* 50(7):440-447. DOI:10.3109/14992027.2011.575085.

Masalski, M., Kipinski, L., Grysinski, T. & Krecicki, T. 2016. Hearing Tests on Mobile Devices: Evaluation of the Reference Sound Level by Means of Biological Calibration. *J Med Internet Res.* 18(5):e130. DOI:10.2196/jmir.4987.

Mauk, G.W. & Behrens, T.R. 1993. Historical, political and technological context associated with early identification of hearing loss. *Semin Hear.* 14:1-17[2021, January 21].

McPherson, B., Law, M. & Wong, M. 2010. Hearing screening for school children: comparison of low-cost, computer-based and conventional audiometry. *Child Care Health & Dev.* 36(3):323-331. DOI:10.1111/j.1365-2214.2010.01079.x.

Mehboob, S., Rafi, S.T., Ahmed, N. & Mehjabeen. 2019. Association of hearing loss with depression, anxiety and stress in patients suffering from Chronic Suppurative Otitis Media. *Pak J Med Sci.* 35(2):510-514. DOI:10.12669/pjms.35.2.152.

Micco, A.G. 2018. The Unrecognized Dangers of Sudden Hearing Loss. *JAMA Otolaryngol Head Neck Surg.* 144(7):621-622. DOI:10.1001/jamaoto.2018.0992.

Michels, T., Duffy, M. & Rogers, D. 2019. Hearing Loss in Adults: Differential Diagnosis and Treatment. *Am Fam Physician.* 100(2):98-108. Available: https://www.ncbi.nlm.nih.gov/pubmed/31305044 [2020, February 04].

Mohan, B., Sharma, S., Sharma, S., Kausha, D., Singh, B. & Takkar, S. 2017. Assessment of knowledge about healthy heart habits in urban and rural population of Punjab after SMS campaign- a cross-sectional study. *Indian Heart J.* 69(4):480 - 484. DOI:10.1016/j.ihj.2017.05.007.

Moher, D., Alessandro, L., Tetzziaff, J., Altman, D. & Group, T.P. 2009. Preferred Reporting Items for Systematic Reviews and

Meta-Analyses: The PRISMA Statement. *PLoS medicine.* 6(7):e1000097. DOI:10.1371/journal.pmed.1000097.

Mosa, A.S.M., Yoo, I. & Sheets, L. 2012. A Systematic Review of Healthcare Applications for Smartphones. *BMC Med Inform Decis Mak.* 12(1):67-97. DOI:10.1186/1472-6947-12-67.

Mosley, C.L., Langley, L.M., Davis, A., McMahon, C.M. & Tremblay, K.L. 2019. Reliability of the Home Hearing Test: Implications for Public Health. *J Am Acad Audiol.* 30(3):208-216. DOI:10.3766/jaaa.17092.

Moteki, H. 2019. Epidemiology of unilateral hearing loss. *Otolaryngol Head Neck Surg.* 91:198-201. Available: https://www.researchgate.net/publication/333261701_Epidemiology_of_unilateral_hearing_loss [2019, September 08].

Moyer, V.A. 2012. Screening for hearing loss in older adults: U.S. Preventive Services Task Force recommendation statement. *Ann Intern Med.* 157(9):655-661. DOI:10.7326/0003-4819-157-9-201211060-00526.

Mulwafu, W., Kuper, H. & Ensink, R.J. 2016. Prevalence and causes of hearing impairment in Africa. *Trop Med Int Health.* 21(2):158-165. DOI:10.1111/tmi.12640.

Murray, C.J., Atkinson, C., Bhalla, K., Birbeck, G., Burstein, R., Chou, D., Dellavalle, R., Danaei, G. et al. 2013. The state of US health, 1990-2010: burden of diseases, injuries, and risk factors. *JAMA.* 310(6):591-608. DOI:10.1001/jama.2013.13805.

Na, Y., Joo, H.S., Yang, H., Kang, S., Hong, S.H. & Woo, J. 2014. Smartphone-based hearing screening in noisy environments. *Sensors (Basel).* 14(6):10346-10360. DOI:10.3390/s140610346.

Nagaraja, M.N. 2009. *Specifications for Audiometers*. India: Indian Institute of Technology Bombay. Available: www.ee.iitb.ac.in›prjaudio›specs_audiometer_nagaraja_july09 [2019, September 30].

Nash, S.D., Cruickshanks, K.J., Huang, G.-H., Klein, B.E.K., Klein, R., Nieto, F.J. & Tweed, T.S. 2013. Unmet hearing health care needs: the Beaver Dam offspring study. *Am J Public Health.* 103(6):1134-1139. DOI:10.2105/AJPH.2012.301031.

National Cancer Institute. 2020. *Diagnosis*. Maryland, United States of America: National Cancer Institute. Available: https://www.cancer.gov/publications/dictionaries/cancer-terms/def/diagnosis [2020, July 23].

National Research Council (US) Committee on Disability Determination for Individuals with Impairments. 2004. *Hearing Loss: Determining Eligibility for Social Security Benefits.* Washington (D. C), United States of America: National Academies Press (US)DOI:10.17226/11099.

Nel, N., Gous-Kemp, C.S., Muller, H., Motitswe, J., Tlale, L. & Mahlo, F.D. 2014. Using the 'Whisper Test' to Identify Hearing Loss in Young Children. *Mediterr J Soc Sci.* 5(14):511-520. DOI:10.5901/mjss.2014.v5n14p511.

Nhavoto, J.A., Grönlund, Å. & Klein, G.O. 2017. Mobile health treatment support intervention for HIV and tuberculosis in Mozambique. *PLoS One.* 12(4):e0176051. DOI:10.1371/journal.pone.0176051.

Nørgaard, S., Nichum, V., Barfred, C., Juul, H., Secher, A., Ringholm, L., Damm, P. & Mathiesen, E. 2017. Use of the smartphone application "Pregnant with Diabetes". *Dan Med J.* 64(11):pii:A5417[2019, November 07].

Occupational Safety and Health Administration (OSHA). 1981. *Occupational Noise Exposure: Hearing Conversation Amendment*. Available: https://www.osha.gov/ [2020, March 04]United States of America: Federal Registry.

Occupational Safety and Health Administration (OSHA). 1983. *Occupational Noise Exposure: Hearing Conversation Amendment*. Available: https://www.osha.gov/ [2020, March 06]United States of America: Federal Registry.

Paglialonga, A., Tognola, G. & Pinciroli, F. 2015. Apps for Hearing Science and Care. *Am J Audiol.* 24(3):293-298. DOI:10.1044/2015_AJA-14-0093.

Peer, S. & Fagan, J. 2015. Hearing loss in the developing world: evaluating the iPhone mobile device as a screening tool. *S Afr Med J.* 105(1):35-39. DOI:10.7196/samj.8338.

Pichichero, M.E. 2018. Helping children with hearing loss from otitis media with effusion. *Lancet.* 392(10147):533-534. DOI:10.1016/s0140-6736(18)31862-2.

Pillay, M., Tiwari, R., Kathard, H. & Chikte, U. 2020. Sustainable workforce: South African Audiologists and Speech Therapists. *Hum Resour Health.* 18(1):47. DOI:10.1186/s12960-020-00488-6.

Pirozzo, S., Papinczak, T. & Glasziou, P. 2003. Whispered voice test for screening for hearing impairment in adults and children: systematic review. *British Medical Journal.* 327(7421):967. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC259166/pdf/bmj32700967.pdf.

Prescott, C.A.J., Omoding, S.S., Fermor, J. & Ogilvy, D. 1999. An evaluation of the 'voice test' as a method for assessing hearing in children with particular reference to the situation in developing countries. *Int J Pediatr Otorhinolaryngol.* 51(3):165-170. DOI:10.1016/S0165-5876(99)00263-3.

Prieve, B., Beauchaine, K.L., Sabo, D., Schooling, T., Culpepper, B. & Tharpe, A.M. 2013. *Evidence-Based Systematic Review of Newborn Hearing Screening Using Behavioral Audiometric Threshold as a Gold Standard*. Washington (D.C), United States of America: American Speech-Language-Hearing Association (ASHA). Available: https://www.asha.org/articlesummary.aspx?id=8589954225 [2019, December 17].

Rademaker-Lakhai, J.M., Crul, M., Zuur, L., Baas, P., Beijnen, J.H., Simis, Y.J., van Zandwijk, N. & Schellens, J.H. 2006. Relationship between cisplatin administration and the development of ototoxicity. *J Clin Oncol.* 24(6):918-924. DOI:10.1200/jco.2006.10.077.

Radovic, A., Vona, P., Santostefano, A., Ciaravino, S., Miller, E. & Stein, B. 2016. Smartphone Applications for Mental Health. *Cyberpsychol Behav Soc Netw.* 19(7):465-470. DOI:10.1089/cyber.2015.0619.

Remenschneider, A.K., Gaudin, R., Kozin, E.D., Ishai, R., Quatela, O., Hadlock, T.A. & McKenna, M.J. 2017. Is the cause of sensorineural hearing loss in patients with facial schwannomas multifactorial? *Laryngoscope.* 127(7):1676-1676. DOI:10.1002/lary.26327.

Renda, L., Selcuk, O.T., Eyigor, H., Osma, U. & Yilmaz, M.D. 2016. Smartphone Based Audiometric Test for Confirming the Level of Hearing; Is It Useable in Underserved Areas? *J Int Adv Otol.* 12(1):61-66. DOI:10.5152/iao.2016.1421.

Roush, J. 2001. *Screening for hearing loss and otitis media in children.* 1. Australia: Singular/Thomson Learning. Available: https://www.amazon.com/Screening-Hearing-Otitis-Media-Children/dp/0769300006 [2018, May 02].

Rutherford, B.R., Brewster, K., Golub, J.S., Kim, A.H. & Roose, S.P. 2018. Sensation and Psychiatry: Linking Age-Related Hearing Loss to Late-Life Depression and Cognitive Decline. *Am J Psychiatry.* 175(3):215-224. DOI:10.1176/appi.ajp.2017.17040423.

Salisu, A.D. 2016. Extending otology services to the rural community: Use of smartphone for hearing screening. *Niger J Basic Clin Sci.* 13(2):72-77. DOI:10.4103/0331-8540.187359.

Sama, P., Eapen, Z., Weinfurt, K., Shah, B. & Schulman, K. 2014. An evaluation of mobile health application tools. *JMIR Mhealth Uhealth.* 2(2):e19. DOI:10.2196/mhealth.3088.

Samelli, A.G., Rabelo, C.M. & Vespasiano, A.P. 2011. Development and analysis of a low-cost screening tool to identify and classify hearing loss in children: a proposal for developing countries. *Clinics (Sao Paulo).* 66(11):1943-1948. Available: https://www.ncbi.nlm.nih.gov/pubmed/22086526 [2018, November 01].

Samelli, A.G., Rabelo, C.M., Sanches, S.G.G., Aquino, C.P. & Gonzaga, D. 2017. Tablet-Based Hearing Screening Test. *Telemed J E Health.* 23(9):747-752. DOI:10.1089/tmj.2016.0253.

Samelli, A.G., Rabelo, C.M., Sanches, S.G.G., Martinho, A.C. & Matas, C.G. 2018. Tablet-based tele-audiometry: Automated hearing screening for schoolchildren. *J Telemed Telecare.* 10.1177/1357633X18800856. DOI:10.1177/1357633X18800856.

Sandström, J., Swanepoel, D.W., Carel Myburgh, H. & Laurent, C. 2016. Smartphone threshold audiometry in underserved primary health-care contexts. *International Journal of Audiology.* 55(4):232-238. DOI:10.3109/14992027.2015.1124294.

Santos, C.M.d.C., Pimenta, C.A.d.M. & Nobre, M.R.C. 2007. The PICO strategy for the research question construction and evidence search. *Rev Lat Am Enfermagem.* 15(3):508-511. DOI:10.1590/S0104-11692007000300023.

Scharp, K.M., Barker, B.A., Rucker, S.N. & Jones, H.D. 2018. Exploring the Identities of Hearing Parents who Chose Cochlear Implantation for their Children with Hearing Loss. *J Deaf Stud Deaf Educ.* 23(2):131-139. DOI:10.1093/deafed/enx060.

Sethi, R.K.V., Ghanad, I., Kanumuri, V., Herrmann, B., Kozin, E.D. & Remenschneider, A.K. 2018. Mobile Hearing Testing Applications and the Diagnosis of Sudden Sensorineural Hearing Loss: A Cautionary Tale. *Otol Neurotol.* 39(1):e1-e4. DOI:10.1097/mao.0000000000001621.

Shephard, D.A. 1977. The contributions of Alexander Graham Bell and Thomas Alva Edison to medicine. *Bull Hist Med.* 51(4):610-616. Available: https://www.ncbi.nlm.nih.gov/pubmed/343848 [2019, May 30].

Shojaeemend, H. & Ayatollahi, H. 2018. Automated audiometry: A review of the implementation and evaluation methods. *Healthc Inform Res.* 24(4):263-275. DOI:10.4258/hir.2018.24.4.263.

Sindhusake, D., Mitchell, P., Smith, W., Golding, M., Newall, P., Hartley, D. & Rubin, G. 2001. Validation of self-reported hearing loss. The Blue Mountains Hearing Study. *Int J Epidemiol.* 30(6):1371-1378. DOI:10.1093/ije/30.6.1371.

Skarzynski, H. & Piotrowska, A. 2012. Screening for pre-school and school-age hearing problems:Eauropean consensus statement *Int J Pediatr Otorhinolaryngol.* 76:120-121[2020, December 17].

Smith, A.W. & Makenzie, I.J. 1999. *WHO EAR AND HEARING DISORDERS SURVEY* Geneva, Switzerland: World Health Organization. Available: https://apps.who.int/iris/handle/10665/67892 [2019, December 19].

Soer, M. 2014. Pure Tone Audiometry. In *Open Access Guide to Audiology and Hearing Aids for Otolaryngologists*. d.W. Swanepoel, C. Laurent and J. Fagan, Eds. Cape Town, South Africa: University of Cape Town. 1-14. Available:https://vula.uct.ac.za/access/content/group/27b5cb1b-1b65-4280-9437-a9898ddd4c40/Theory%20and%20practice%20of%20pure%20tone%20audiometry%20_PTA_.pdf [2018, July 23].

Sohn, J., Kim, D., Ku, Y., Lee, K. & Lee, J. 2011. Study on self hearing assessment using speech sounds. *Conf Proc IEEE Eng Med Biol Soc.* 2011:2384-2387. DOI:10.1109/iembs.2011.6090665.

Stanton, J. 2009. Pediatric Hearing Assessment. In *Pediatr Otolaryngol Clin*. R.B. Mitchell and K.D. Pereira, Eds. Dordrecht; New York: Humana Press. 251. Available:http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=285714 [2019, November 18].

Stavroulaki, P., Vossinakis, I., Dinopoulou, D., Doudounakis, S., Adamopoulos, G. & Apostolopoulos, N. 2002. Otoacoustic Emissions for Monitoring Aminoglycoside-Induced Ototoxicity in Children With Cystic Fibrosis. *Arch Otolaryngol Head Neck Surg.* 128(2):150-155. DOI:10.1001/archotol.128.2.150.

Stevens, G., Flaxman, S., Brunskill, E., Mascarenhas, M., Mathers, C.D., Finucane, M. & Global Burden of Disease Hearing Loss Expert, G. 2013. Turning up the volume on hearing loss in South Africa. *Eur J Public Health Editorial.* 23(1):2. DOI:10.1093/eurpub/ckr176.

Stoddard, J. 2015. *The Top 5 cell phone Hearing Test Apps*. Lakewood-New Jersey, United States of America: Century Hearing Aids. Available: https://centuryhearingaids.com/blog/tthe-top-5-cell-phone-hearing-test-apps/ [2019, November 04].

Stone, P.W. 2002. Popping the (PICO) question in research and evidence-based practice. *Applied Nursing Research.* 15(3):197-198. Available: https://www.ncbi.nlm.nih.gov/pubmed/12173172 [2018, February 02].

Stoney, P. & Hawke, M. 1991. The first audiometer: a Welsh connection. *J Otolaryngol.* 20(2):144. Available: http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=19749635 [2020, January 28].

Strain, G.M. & Fernandes, A.J. 2015. Handheld tympanometer measurements in conscious dogs for the evaluation of the middle ear and auditory tube. *Vet Dermatol.* 26(3):193-197, e139-e140. DOI:10.1111/vde.12195.

Swanepoel, d.W. & Hall, J.W., 3rd. 2010. A systematic review of telehealth applications in audiology. *Telemed J E Health.* 16(2):181-200. DOI:10.1089/tmj.2009.0111.

Swanepoel, d.W. & Laurent, C. 2014. Classification of Hearing Loss. In *Open Access Guide to Audiology and Hearing Aids for Otolaryngologists*. J. Fagan, Ed. Cape Town, South Africa: University of Cape Town. 1-4. Available:https://vula.uct.ac.za/access/content/group/27b5cb1b-1b65-4280-9437-a9898ddd4c40/Classification%20of%20hearing%20loss.pdf [2019, August 20].

Swanepoel, d.W., de Sousa, K., Smits, C. & Moore, D. 2019. Mobile applications to detect hearing impairment: opportunities and challenges. *Bulletin of the World Health Organization.* 97(10):717-718. DOI:10.2471/BLT.18.227728.

Swanepoel, d.W., Myburgh, H.C., Howe, D.M., Mahomed, F. & Eikelboom, R.H. 2014. Smartphone hearing screening with integrated quality control and data management. *Int J Audiol.* 53(12):841-849. DOI:10.3109/14992027.2014.920965.

Szudek, J., Ostevik, A., Dziegielewski, P., Robinson-Anagor, J., Gomaa, N., Hodgetts, B. & Ho, A. 2012. Can Uhear me now? Validation of an iPod-based hearing loss screening test. *J Otolaryngol Head Neck Surg.* 41 Suppl 1:S78-84. Available: https://www.ncbi.nlm.nih.gov/pubmed/22569055 [2019, April 17].

The National Institute of Mental Health. 2019. *What are YLDs ?* Boulevard, United States of America: The National Institute of Mental Health Information Resource Center. Available: https://www.nimh.nih.gov/health/statistics/disability/what-are-ylds.shtml [2019, September 26].

Thoidis, I., Vrysis, L., Markou, K. & Papanikolaou, G. 2019. Development and evaluation of a tablet-based diagnostic audiometer. *Int J Audiol.* 58(8):1-8. DOI:10.1080/14992027.2019.1600204.

United Nations Statistics Division. 2014. *Millennium Development Indicators: World and regional groupings*. New York, United States of America: United Nation Available: https://unstats.un.org/unsd/mdg/Host.aspx?Content=Data/RegionalGroupings.htm [2019, June 03].

van Tonder, J., Swanepoel, W., Mahomed-Asmail, F., Myburgh, H. & Eikelboom, R.H. 2017. Automated Smartphone Threshold Audiometry: Validity and Time Efficiency. *J Am Acad Audiol.* 28(3):200-208. DOI:10.3766/jaaa.16002.

van Zyl, M., Swanepoel, D.W. & Myburgh, H.C. 2018. Modernising speech audiometry: using a smartphone application to test word recognition. *Int J Audiol.* 57(8):561-569. DOI:10.1080/14992027.2018.1463465.

Vogel, I., Brug, J., van der Ploeg, C. & Raat, H. 2010. Discotheques and the risk of hearing loss among youth: Risky listening behavior and its psychosocial correlates. *Health Educ Res.* 25(5):737-747. DOI:10.1093/her/cyq018.

Walker, J.J., Cleveland, L.M., Davis, J.L. & Seales, J.S. 2013. Audiometry screening and interpretation. *Am Fam Physician.* 87(1):41-47. Available: https://www.aafp.org/afp/2013/0101/p41.html [2018, July 18].

White, A. & Schmidt, K. 2005. Systematic literature reviews. *Complement Ther Med.* 13(1):54-60. DOI:10.1016/j.ctim.2004.12.003.

Whittemore, K.R., Dornan, B.K., Lally, T. & Dargie, J.M. 2012. Persistent conductive or mixed hearing loss after the placement of tympanostomy tubes. *Int J Pediatr Otorhinolaryngol.* 76(10):1465-1470. DOI:10.1016/j.ijporl.2012.06.022.

Wood, S.A., Davis, A.C. & Sutton, G.J. 2013. Effectiveness of targeted surveillance to identify moderate to profound permanent childhood hearing impairment in babies with risk factors who pass newborn screening. *Int J Audiol.* 52(6):394-399. DOI:10.3109/14992027.2013.769067.

World Health Organization's Global Harmonization Task Force. 2012. *Definition of the Terms 'Medical Device' and 'In Vitro Diagnostic (IVD) Medical Device'*. Geneva, Switzerland: World Health Organization. Available: http://www.imdrf.org/docs/ghtf/final/sg1/technical-docs/ghtf-sg1-n071-2012-definition-of-terms-120516.pdf#search= [2018, August 08].

World Health Organization. 2006. *Primary Ear and Hearing Care Training Resource*. Geneva, Switzerland: World Health Organization Press. Available: http://www.who.int/pbd/deafness/activities/hearing_care/trainer.pdf [2018, June 22].

World Health Organization. 2011. *mHealth: New horizons for health through mobile technologies*. Geneva, Switzerland: W.H. Organization. Available: https://www.who.int/ehealth/mhealth_summit.pdf [2019, November 13].

World Health Organization. 2012. WHO Global estimates on prevalence of hearing loss.

World Health Organization. 2015. *Systematic review of needs for medical devices for ageing populations: commissioned to the Australian Safety and Efficacy Register of New Interventional Procedures – Surgical (ASERNIP-S)*. (978 92 4 150922 0). Geneva, Switzerland: World Health Organization. Available: http://apps.who.int/medicinedocs/documents/s22064en/s22064en.pdf [2018, June 22].

World Health Organization. 2018a. *Deafness and hearing loss- a media centre fact sheet*. Geneva, Switzerland: World Health Organization. Available: http://www.who.int/mediacentre/factsheets/fs300/en/ [2018, July 16].

World Health Organization. 2018b. *Addressing the rising prevalence of hearing loss*. Geneva, Switzerland: World Health Organization. Available: https://apps.who.int/iris/bitstream/handle/10665/260336/9789241550260-eng.pdf [2020, July 29].

World Health Organization. 2020. *Screening*. Geneva, Switzerland: World Health Organization. Available: https://www.who.int/cancer/prevention/diagnosis-screening/screening/en/ [2020, July 23].

Wormald, P.J., Browning, G.G. & Robinson, K. 1995. Is otoscopy reliable? A structured teaching method to improve otoscopic accuracy in trainees. *Clin Otolaryngol.* 20(1):63-67. DOI:10.1111/j.1365-2273.1995.tb00014.x.

Wroblewska-Seniuk, K., Dabrowski, P., Greczka, G., Szabatowska, K., Glowacka, A., Szyfter, W. & Mazela, J. 2018. Sensorineural and conductive hearing loss in infants diagnosed in the program of universal newborn hearing screening. *Int J Pediatr Otorhinolaryngol.* 105:181-186. DOI:10.1016/j.ijporl.2017.12.007.

Yeung, J., Heley, S., Beauregard, Y., Champagne, S. & Bromwich, M.A. 2015. Self-administered hearing loss screening using an interactive, tablet play audiometer with ear bud headphones. *Int J Pediatr Otorhinolaryngol.* 79(8):1248-1252. DOI:10.1016/j.ijporl.2015.05.021.

Yeung, J., Javidnia, H., Heley, S., Beauregard, Y., Champagne, S. & Bromwich, M. 2013. The new age of play audiometry: prospective validation testing of an iPad-based play audiometer. *J Otolaryngol Head Neck Surg.* 42(MAR):21. DOI:10.1186/1916-0216-42-21.

Yilmaz, S., Karasalihoglu, A.R., Tas, A., Yagiz, R. & Tas, M. 2006. Otoacoustic emissions in young adults with a history of otitis media. *The Journal of Laryngology & Otology.* 120(2):103-107. DOI:10.1017/S0022215105004871.

Yimtae, K., Israsena, P., Thanawirattananit, P., Seesutas, S., Saibua, S., Kasemsiri, P., Noymai, A. & Soonrach, T. 2018. A Tablet-Based Mobile Hearing Screening System for Preschoolers: Design and Validation Study. *JMIR Mhealth Uhealth.* 6(10):1-26: e186. DOI:10.2196/mhealth.9560.

Youngmin, N., Hyo Sung, J., Hyejin, Y., Soojin, K., Sung Hwa, H. & Jihwan, W. 2014. Smartphone-Based Hearing Screening in Noisy Environments. *Sensors.* 14(6):10346-10360. DOI:10.3390/s140610346.

Yousuf Hussein, S., Swanepoel, W., Mahomed, F. & Biagio de Jager, L. 2018. Community-based hearing screening for young children using an mHealth service-delivery model. *Glob Health Action.* 11(1):1-7. DOI:10.1080/16549716.2018.1467077.

Yousuf Hussein, S., Wet Swanepoel, D., Biagio de Jager, L., Myburgh, H.C., Eikelboom, R.H. & Hugo, J. 2016. Smartphone hearing screening in mHealth assisted community-based primary care. *J Telemed Telecare*. 22(7):405-412. DOI:10.1177/1357633X15610721.

Yu, J., Ostevik, A., Hodgetts, B. & Ho, A. 2011. Automated Hearing Tests: Applying the Otogram to Patients Who Are Difficult to Test. *J Otolaryngol Head Neck Surg.* 40(5):376-383. DOI:10.2310/7070.2011.100095.

Zhang, M. 2015. Mental Health Smartphone Application - A New Initiative for Mental Health Care Providers. *Asia Pac Psychiatry.* [2019, November 06].

APPENDICES

Appendix A: Required features for acceptable pure-tone and speech audiometers. (Adopted from: Nagaraja (2009)

Requirements		**Pure-tone**					**Speech**			
		T1	T2	T3	T4	T5	HF	A	B	C
Transducers	Two earphones	Y	Y	Y	Y	N	Y	Y	Y	Y
	Insert earphones	Y	N	N	N	N	N	N	N	N
	Electrical output	Y	Y	N	N	N	N	Y	Y	N
	Bone vibrator	Y	Y	Y	N	N	N	Y	N	N
Hearing levels	Test frequencies	Y	Y	Y	Y	Y	N	Y	N	N
Test Signals Switching	Presentation	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Pulsed tone	Y	Y	N	Y	N	Y	N	N	N
	Frequency Modulation	Y	Y	N	N	N	N	N	N	N
Reference Tone	Alternate presentation	Y	Y	N	N	N	N	N	N	N
	Simultaneous presentation	Y	N	N	N	N	N	N	N	N
Speech Input	Replay device	N	N	N	N	N	N	N	N	N
	Electrical Input for recorded material	Y	Y	N	N	N	N	Y	Y	Y
	Microphone	N	N	N	N	N	N	Y	Y	N
Masking	Narrow band noise	Y	Y	Y	N	N	Y	N	N	N
	White noise	Y	Y	N	N	N	N	N	N	N
	Speech spectrum noise	N	N	N	N	N	N	Y	Y	Y
Routing of Masking	Contralateral earphone	Y	Y	Y	N	N	Y	Y	Y	Y
	Ipsilateral earphone	Y	N	N	N	N	N	Y	N	N
	Loudspeaker	Y	Y	N	N	N	N	Y	Y	N
	Bone conductor	Y	N	N	N	N	N	N	N	N
	Subject response system	Y	Y	Y	Y	N	Y	Y	N	N
	Signal indicated	Y	Y	N	N	N	Y	Y	Y	Y
	Audible Monitoring	Y	N	N	N	N	N	Y	Y	N
	Operator to subject speech	Y	N	N	N	N	N	Y	N	N
	Talk back system	N	N	N	N	N	N	Y	Y	N

Y, Yes; N, No; T1, Type 1 audiometer; HF, High frequency.

Appendix B: Computer-based audiometers and their features and limitations.

	Name or description of device	Company and /or location	Features	Tests performed	Limitations identified
1.	GSI clinical audiometer	Eden Prairie (USA)	• Channel specific store buttons • Centering Visual Reinforcement Audiometry • Simultaneous processes	Pure-tone air conduction, bone conduction with masking, speech recognition threshold, and word recognition score.	The audiometer only assesses the effectiveness of sound amplification, and the sound cards used with the audiometer are not able to reproduce the desired low sound levels (Eikelboom et al., 2013).
2.	KUDUwave™ audiometer	GeoAxon (South Africa)	• Active Noise Monitoring • Patient Management Built-in • Assistive interpretation • Pre-recorded speech word lists • Tele-audiology enabled	Pure-tone audiometry (that is, air conduction and bone conduction).	Results from the testing of the audiometer is preferred by most patients to be interpreted by a specialist and not by the device (Brennan-Jones et al., 2016).
3.	Telessaúde (TS) audiometer	(Brazil)	• Affordable • Written in clear and simple instructions	Pure-tone threshold audiometry, speech audiometry, and otologic inspections.	Evaluation of the TS audiometric device was found to have been done using a small number of people (Ferrari et al., 2013).
4.	Occupational Earcheck (OEC) System	The National Hearing Foundation and the Leiden University Medical Centre (Netherlands)	• Optimized version of the test • Five alternative masking noise condition	High frequency hearing loss test and speech intelligibility.	Performing a test with the OEC system at homes of users can affect the results of the test due to the presence of environmental noise, the variety of external devices used, the quality of frequency responses by the users and the parameters set individually by the user (Leensen & Dreschler, 2013).
5.	Auto-kit audiometer	Gan et al. (2012) (Malaysia)	• Simple and cheap computer-controlled audiometer to screen for hearing loss in developing countries. • The test menu shows a two-way screening level at 25 dB HL for	Pure-tone hearing loss test	The auto-kit audiometer has still not been evaluated after its preliminary clinical trial (Gan et al., 2012).

			impairments that are slight and 40 dB HL for impairments that are moderate. •		
6.	Etymotic 'Home Hearing Test™' (HHT)	Robert H. Margolis (Etymotic Research, Elk Grove Village, IL, USA)	• Simple and clear instructions • Accuracy of the testing results are based on quantitative measures • Calibration meets standards for audiometers • Results of the test is communicated in clear and understandable language •	Pure-tone air conduction threshold	Even though the HHT can identify and classify hearing loss, on its own, the HHT cannot fully address the need for improving the uptake of hearing health services (Mosley et al., 2019).
7.	Home Audiometer Software	McPherson, Law & Wong (2010) (China)	• Measuring hearing sensitivity at 11 frequency threshold points. • Application software automatically determines hearing threshold between 0.5 kHz and 4.0 kHz.	Pure-tone air conduction	The computer-based audiometer had referral rates of 56 percent among eight participants and the study subject sample size was too small for system validation (McPherson, Law & Wong, 2010).
8.	Octogram™	Ototronix Tympany, Houston-Taxas, USA)	• Accessory equipment such as the Otovest which allows the connection of an ear inserts. • Otobow which is a bow-like headband allows for a placement of a bone oscillator. •	Pure-tone air and bone conduction with or without masking	While the accuracy of the air conduction threshold was high, the accuracy of bone conduction had lower accuracy results (Ho, Hildreth & Lindsey, 2009; Yu et al., 2011).
9.	The Madsen Aurical™	Natus® Medical Incorporated (California, USA)	• A built-in HI-PRO box for programming • Performance of Traditional audiometry • Rehabilitative audiometry • Automated loudness scaling • A real ear measurement system • A hearing instrument test box	Air and one conduction audiometry, speech audiometry, and central auditory testing.	The audiometer is able to perform SPL audiometry, however, the use of additional headsets makes the device more expensive to purchase (Baer & Groth, 1998).

Appendix C: Key features of the 18 mHealth applications and their limitations.

	Name or description of device	Company and /or location	Tests performed	Platform	Download location	Limitations identified
1.	Agilis Health Mobile Audiogram	Agilis Health Incorporation (Cambridge Massachusetts, USA)	Pure-tone air conduction	iOS	https://apps.apple.com/us/app/agilis/id830476395	Even though the application was designed for mobile use, the headphones (that is, Etymotic HF5 ear bud) used during its validation were not those provided with the Apple iPad mini device (Manganella et al., 2018).
2.	GSI AMTAS refers to both Flex™ and AMTAS Pro™	Grason-Stadler Incorporation (Eden Prairie, Minnesota, USA)	Pure-tone audiometry (that is, air and bone conductions)	Not indicated	Not indicated	During pure-tone audiometric testing in a lower frequency, the AMTAS is likely to record a higher value, while in a higher frequency, there is a tendency for the application to record lower values (Eikelboom et al., 2013).
3.	AudCal	Jorge A. R. Martinez (Spain)	Pure-tone air conduction	iOS	https://apps.apple.com/us/app/audcal/id-647212278	Future regulations of the application cannot be done as no detailed description of the application was provided by the developers, which in turn will discourage researchers in the field (Larrosa et al., 2015).
4.	Audiogram Mobile	Vincenzo Cocciolo (Italy)	Air conduction at three levels (that is, audiologist level, high level, and entry level. While the pure-tone bone conduction is through the entry level with a Panasonic HGS10.	iOS	https://apps.apple.com/gb/app/audiogram-mobile/id643041369	During testing with the application, a few malfunctions were identified by the testers which includes the application freezing which required a restart of the app, and the quitting of the application while testing is ongoing (Corry, Sanders & Searchfield, 2017).
5.	Ear Scale	Wen-Hui Liao (Taiwan)	Hearing scale test (HST)	iOS	Application has been validated, download link is yet to be registered and distributed.	The Ear Scale application in a study was an unsuitable tool for the detection or prevention of hearing impairments at the early stages (Chu et al., 2019).

6.	EarTrumpet	Praxis Biosciences (Irvine-California, USA)	Pure-tone air conduction hearing test	iOS	https://apps.apple.com/us/app/eartrumpet/id385494796	The EarTrumpet application cannot be used on Android operating devices and cannot perform other testing modalities such as pure-tone bone conduction and speech audiometry (Foulad, Bui & Djalilian, 2013).
7.	hearScreen™		Pure-tone air conduction hearing test	Android and iOS		The application cannot perform pure-tone bone conduction threshold testing and speech audiometry even though tests have been developed and validated on other mobile devices (Louw et al., 2018).
8.	Hearing-Test Application	Youngmin Na and Hyo Sung Joo (Korea)	Pure-tone air conduction audiometry	Android	Application has been validated, download link is yet to be registered and distributed.	The Hearing-Test application explains the selection of a noise type during the testing, however the application forcing the user to select an environmental noise type, caused them to choose wrong noise type options (Youngmin et al., 2014).
9.	Hearing Test™	Marcin Masalski (Poland)	Screens for pure-tone air conduction hearing impairments	Android	https://play.google.com/store/apps/details?id=mobile.eaudiologia&hl=en_ZA	The results obtained after performing a hearing test with the application does not distinguish between conductive and sensorineural hearing loss especially in underserved communities considering where the study was done (Renda et al., 2016).
10.	Hearing Test System	Anna Chi Shan Kam (China)	Pure-tone air conduction	iOS and Android	Application has been validated, download link is yet to be registered and distributed.	Large threshold variabilities were identified with the use of the application, because the insert headphones or earphones were loosely plugged into the smartphone- and tablet-based devices (Kam et al., 2012).
11.	Hearing Test with Audiogram	Pieezo Hearsay Pte Limited (Singapore)	Pure-tone air conduction	iOS and Android	The iOS version of the application is no longer available on the Apple Store, however, according to the authors of the study (Kelly et al., 2018), the Android version is	The tablet-based application does not perform pure-tone bone conduction testing (Kelly et al., 2018).

					available but could not be traced. The following link was found for the app (https://www.148apps.com/app/512571089/).	
12.	OtoID-tablet	Department of Veterans Affairs (Portland Oregon, USA	distortion-product otoacoustic emissions (DPOAEs) testing and Fixed-frequency threshold testing.	Not indicated	Not indicated	The introduction of the tablet-based OtoID application is unable to augment “traditional audiogram-based protocols” for Ototoxicity Monitoring Programmes with potential tests such as Békésy Tracking Audiometric testing and comprehensive OAE testing (Brungart et al., 2018).
13.	ShoeBOX	Clearwater Clinical Group (Ottawa, Canada)	Conditioned play audiometry	iOS	Application has been validated, download link is yet to be registered and distributed.	Even though the ShoeBOX application performs objective hearing test, in the analysis of patient data, identified patient with difficulty in hearing assessments were excluded to ensure the performance of the hardware of the application (Yeung et al., 2013).
14.	Sound Scouts	Sound Scouts Limited (Australia)	Tone-in-noise (TIN)	iOS & Android	https://apps.apple.com/au/app/sound-scouts/id911637845	Hearing test results showing the high sensitivity (100 percent) and specificity (98 percent) of the application was only obtained using iPad devices (Dillon et al., 2018).
15.	Tablet-based hearing screening test (THST) application	Samelli et al. (2017) (Brazil)	Sweep audiometric air conduction	iOS	Application has been validated, download link is yet to be registered and distributed.	The THST application was developed for children, however, the test and validation of the application was done among the adult population (Samelli et al., 2017).
16.	uHear™	Don Hayes and Unitron (Canada)	Pure-tone air conduction and speech-in-noise.	iOS	https://itunes.com/apps/uHear	The uHear™ was inaccurate for low frequency thresholds, test must be performed in a quiet room, and instructions are mainly in English (Peer & Fagan, 2015).

17.	uHearingTest	WooFu Tech, LLC (Canada)	Pure-tone air conduction	iOS	https://uhearingtest-ios.soft112.com/	The uHearing Test application showed inaccurate results when it was compared to the uHear™ application (Barczik & Serpanos, 2018b).
18.	Virtual audiologist (ViA)	Medical Centre at the University of Utrecht (Netherlands)	Pure-tone air conduction and bone conduction.	Android	Application has been validated, download link is yet to be registered and distributed.	The use of the ViA application is targeted at only people with early stages of the hearing loss disease (Kocian et al., 2017).

iOS- iPhone operation software

Appendix D: Keyword and search terms for electronic databases.

Searched terms or keywords		Results
Population: Hearing loss patients		
#1	Hearing disorders [MeSH]	84653
#2	Hearing Loss [MeSH]	67135
#3	Persons with hearing impairment [MeSH]	46605
S1	(#1 OR #2 OR #3)	**84653**
Intervention: Mobile devices		
#4	Cell phone [MeSH]	9859
#5	Computers, Handheld [MeSH]	6794
#6	Mobile application [MeSH]	4708
#7	Telemedicine [MeSH]	26190
#8	Android OR automated OR digital health OR iPad OR iPhone OR mobile devices OR mobile phone OR mobile technology OR portable electronic application OR smartphone OR tablet OR tele-health	258766
S2	(#4 OR #5 OR #6 OR #7 OR #8)	**280846**
Comparator: Audiometers		
#9	Audiometry [MeSH]	33349
#10	Audiometer OR Audiogram	53870
#11	Amplivox OR AMTAS OR KUDUwave OR MAICO	56
S3	(#9 OR #10 OR #11)	**53897**
Outcome: Screening or diagnosing		
#12	Diagnosis [MeSH]	8300370
#13	Hearing tests [MeSH]	45727
#14	Screening [MeSH]	141261
S4	(#12 OR #13 OR #14)	**8307077**
S5	S1 AND S2 AND S3 AND S4	420
S6*	hearScreen OR hearZA OR uHear OR EarTrumpet	12
S7	S5 OR S6	**424**
Filter by humans		**422**
Filter by date limits (January 2000- July 2019)		**358**
Filter by full text		**326**
Filter by language (English)		**77**
*This term was added to ensure that any studies on the mobile technology-based devices identified in the preliminary literature review, would be included. Any additional mobile technology-based devices identified, were subjected to specific searches.		

Appendix E: Data extraction form

Information extracted	Study 1	Study 2	Study 3	Study 4
Background of the journal articles				
Names of the author(s) and year study was conducted				
Name of journal of published article				
Title of the study				
Aim of the study				
Country in which study was conducted				
Type of study				
Concept of the study				
Methods employed by researchers				
Population background				
Study population or group				
Study participants				
Total number of participants sampled				
Age groups				
Measure of tendencies				
Hearing characteristics				
Hearing loss status of recruited population				
Hardware components of the mobile application				
Name of mobile device application				
Type of mobile device application				
Types of transducers used by the mobile solution				
Vender-provided or user provided				
Sound level meters (SLMs)				
External devices used with mobile application				
Software components of the mobile application				
Validated year of test modalities				
How the medical device works				
Applications marketing store				
Mobile application functionality				
Data collection				
Data management of medical devices				
Screening with mobile device applications				
Ambient noise levels				
Test time				
Test-retest				
Masking functionalities of mobile application				
Testing modalities of the mobile application				
Gold reference comparator to mobile application				
Test threshold determination used				
Test threshold measurement systems				
What is used as sound stimuli				
Pure-tone averages & definition of hearing loss				
Pure tone audiometry score				
Sensitivity				
Specificity				
Positive predictive value (PPV)				
Negative predictive value (NPV)				
Findings of the study				
Functional effectiveness of mobile application				
Cost of mobile application				
Clinical testing				
User satisfaction				
User experiences				
Limitations of the study and mobile application				
Potential of application in developing countries				
Recommendations				
Future directions of the study				

Appendix F: Characteristics of the 49 studies that were reviewed.

Authors and year	Country	Application	Aim or objective of the study	Focus of study	Findings
Manganella et al. (2018)	USA	Agilis Health Mobile Audiogram	"To examine if the tablet-based Agilis Health Mobile Audiogram (Agilis Audiogram) is an effective and valid measure of hearing thresholds".	Evaluation	The Agilis audiogram as a tablet-based application "is a valid measure of hearing" and the hearing thresholds of the patients obtained with the application "were in agreement with the thresholds found when using traditional audiometric testing".
Margolis & Moore (2011)	United Kingdom (UK)	GSI AMTAS	"To measure the occlusion effect produced by three earphones – circumaural, supra-aural, and insert – and to compare air-and bone conduction thresholds obtained with manual and automated methods for subjects with sensorineural hearing loss".	Evaluation and comparison.	For objective 1 of the study, "supra-aural produced the largest occlusion effects, followed by the insert and circumaural earphones". While findings with objective 2 of the study showed that, "air conduction thresholds were systematically higher for the AMTAS circumaural measurements than for the manual/supra-aural measurements audiometry by about 7 dB over the range 0.25-2.0 kHz, but thresholds did not differ markedly for higher frequencies".
Eikelboom et al. (2013)	Western Australia		"To validate the air- and bone-conduction AMTAS automated audiometry system".	Evaluation	In a quiet room, the AMTAS tablet-based application when compared to the manual thresholds showed tolerable pure tone average (PTA) air conduction values between 5.88 and 6.87 dB, while PTA bone conduction values ranged between 6.16 and 8.76 dB. All these values were within the acceptable threshold variation of 10 dB advised by Occupational regulators.
Larrosa et al. (2015)	Spain	AudCal audiology app	"To develop and evaluate a newly developed professional, computer-based hearing handicap calculator and a manual hearing sensitivity assessment test for the iPhone and iPad".	Development and evaluation	The smartphone-based application appears to be accurate as a hearing loss screening tool with a mean difference 6.38 dB HL which is within the acceptable mean threshold variation.

Corry, Sanders & Searchfield (2017)	New Zealand	Audiogram Mobile	"To undertake a preliminary evaluation of the test-retest reliability, and accuracy of an iPad audiometer app using commercial earphones as a low alternative to a clinical audiometer in a restricted sample of normal hearing participants".	Evaluation	The Audiogram Mobile iPad audiometer experienced series of malfunctioning during testing for almost one third of the hearing tests performed in the study. However, it was considered cheaper compared to standard audiometers on the market.
Chu at al. (2019)	Taiwan	Ear Scale	"To demonstrate a new approach to rapidly screen hearing status and provide stratified test values, using a smartphone-based hearing screening app, for each screened ear of school-age children".	Evaluation	The study claimed that "this is the first report proposing a method for stratifying hearing test results on a smartphone and then using it for hearing screening in school children".
Foulad, Bui & Djalilian (2013)	USA	EarTrumpet	"To determine the feasibility of an Apple iOS-based automated hearing testing application".	Development and evaluation	The automated threshold method for pure-tone air conduction audiometry was found to give easy access to patients during hearing testing. Also, the accuracy of the tablet-based application (EarTrumpet) was obtained from its use in a non-sound treated environment or testing was completed without a sound booth.
Derin et al. (2016)	Turkey		"To compare an Apple iOS mobile operating system application for audiological evaluation with conventional audiometry".	Evaluation	The EarTrumpet iOS-based application was found to be "useful for initial hearing loss evaluation".
Na et al. (2014)	Korea	Hearing-Test application	To develop a "smartphone-based hearing screening methods that can ubiquitously test hearing".	Development	The HTS of the Hearing-Test application was developed, and in addition was able to improve hearing screening at threshold points (that is, 1.0 kHz and 2.0 kHz) due to the built-in microphone of the smartphone application.
Kelly et al. (2018)	USA	Hearing Test with Audiogram	"To determine the feasibility of audiometric screening with tablet-based applications in typical clinic locations: examination room and clinic waiting area".	Feasibility	The tablet-audiometric application from the study showed that it represents a feasible screening tool to improve hearing loss assessment accessibility.

Barczik & Serpanos (2018)	USA	uHearingTest	"To evaluate smartphone-based self-hearing test applications (apps) for accuracy in threshold assessment and validity in screening for hearing loss across frequencies and earphone transducer styles".	Evaluation	Findings from the study confirm that "self-hearing test apps can be accurate for hearing threshold assessment or screening hearing loss using appropriate transducers".
Samelli et al. (2017)	Brazil	Tablet-based hearing screening test (THST)	To "describe and validate a tablet-based hearing screening test developed for interactive remote hearing screening and compare the performance of an audiometry screening tablet application with conventional audiometry".	Development and evaluation	The application development was described. Evaluation results showed that the application could enable identification of individuals at high risk of having hearing loss.
Dillon et al. (2018)	Australia	Sound Scouts	"To create a hearing test useable without the involvement of a clinician or calibrated equipment, suitable for children aged 5 or older".	Development	The Sound Scouts application was developed, and at 30 dB HL in either ear of the participants, the application was able to identify that 98% of the children passed the hearing test with normal hearing. Also, 85% of the children that participated in the study failed the hearing test with some degrees of hearing loss conditions.
Kocian et al. (2017)	Netherlands	ViA	"Design and implement a virtual audiologist dubbed ViA, performing air-conduction and bone-conduction hearing loss tests based on a standard in contrast to existing solutions".	Development and evaluation	The ViA application in the study was found to potentially identify correctable hearing loss among subjects in office areas and any other setting.
Salisu (2016)	Nigeria	Hearing Test™	"To assess the reliability of using the smartphone for hearing screening by comparing results obtained with those of a standard calibrated audiometer".	Evaluation	Application is quite accurate in detecting especially high-frequency hearing impairment with a specificity value of 100% and a sensitivity value of 96%.
Renda et al. (2016)	Antalya, Turkey		"To determine the hearing levels of participants of a randomized group using a smartphone hearing application".	Usability	The hearing test from the smartphone-based application may be an alternative method in underserved areas to screen the hearing levels of patients as its mean threshold difference was within the 10 dB.

Masalski et al. (2016)	Wroclaw, Poland		"To determine the reference sound level for sets composed of a mobile device and bundled headphones".	Evaluation	The application presented in the study can be applied in hearing screening examinations on a large scale.
Masalski et al. (2018)	Wroclaw, Poland		"To determine the accuracy of automated audiometry conducted on Android-based mobile sets".	Evaluation	Results from the study showed that, "the mean SD of the reference sound levels were determined on a subject's mobile device using the Bekesy audiometry", consistent with results of previous studies.
Chauhan & Shah (2018)	India		"To study hearing threshold in traffic police".	Assessment	Using the Hearing Test application in the study confirmed that there were "a significant number of traffic persons found to have hearing problems".
Kam et al. (2012)	Hong Kong	Hearing Test system	"To establish the reliability and validity of a computerized self-administered hearing test".	Evaluation	The Hearing Teat System application can be used by people of different ages and education levels as "a reliable and valid measure of unasked air-conduction hearing thresholds".
Kam et al. (2013)	China		"To establish the reliability and validity of an automated hearing test system for children".	Evaluation	Results from the study on the Hearing Test system suggested that improvements of the application could progress the specificity values of 82% and the sensitivity value of 63%.
Kam et al. (2014)	China		"To establish the reliability and validity of an automated hearing screening test system for preschoolers and to investigate the risk factors for hearing loss".	Evaluation	The Hearing Test system application was validated with its unique noise-cancelling headphone. As a result, referral rates of the hearing test performed decreased from 51.69% to 19.38%.
Rourke, Kong & Browwich (2016)	Canada	ShoeBOX	"To determine the prevalence of hearing loss in children aged 4 to 11 years in Iqaluit, Nunavut". "To test and demonstrate the use of our tablet audiometer as a portable hearing-testing device in a remote location".	Usability	Even though the language of the application was English, the participants were able to use the application, as such it was considered as "time efficient".

Yeung et al. (2015)	Canada		"To evaluate the screening capability of a tablet audiometer outside the setting of a supervised audiology clinic". "To determine if a layperson, in an uncontrolled setting, could use a tablet computer and standard consumer headphones to screen for hearing loss and facilitate earlier recognition and diagnosis of hearing loss in children".	Evaluation	Out of the 80 patients included in the study, the ShoeBOX application showed a strong sensitivity (91.2%) and negative predictive values (89.7%) for the testing of hearing loss. Findings from the study showed that, in an unsupervised setting, the application is valid and sensitive in children.
Tse, Ramsay & Lelli (2018)	Canada		"To assess feasibility of using iPad-based audiometry daily to capture hearing fluctuations in a small".	Feasibility	All five participants (1 man and 4 women) were able to test their hearing quickly and without problem at home with the ShoeBOX tablet-based application.
Pereira et al. (2018)	USA		"To evaluate the validity and efficiency of tablet-based automated audiometry in school-aged children, 6-12 years old, for diagnostic purposes".	Evaluation	The ShoeBOX application was found to be a valid screening tool as findings from the study "exhibited that the majority (67%) of threshold differences between automated and standard were within the clinically accepted range (10 dB). Also, the testing times recorded for standard audiometry (12.3 mins) and automated audiometry (11.9 mins) were similar for the two age groups.
Levy et al. (2018)	Dominican Republic		"To examine the feasibility of hearing screening using tablet audiometry among a cohort of school-aged children in rural Dominican Republic".	Feasibility	Since the tablet-based application's monitoring system for noise has not been validated independently, several false-positives results were noticed among the 423 subjects recruited in the study, and 10.4% failed the screening protocol with the tablet-based application.
Saliba et al. (2017)	Canada		"To compare the accuracy of 2 previously validated mobile-based hearing tests in determining pure tone threshold and screening for hearing loss". "To determine the accuracy of mobile audiometry in noisy	Evaluation	Both applications (that is, the consumer app and the professional app) correctly estimated PTA thresholds. The consumer app recorded a high specificity (95.9%) and sensitivity (87.5%) while the professional app obtained a strong sensitivity (100%) and

			environments through noise reduction strategies”.		specificity (95.9%) to screen for moderate hearing loss. The two applications provided noise reduction strategies during testing in noisy environments and a as result, they were again found to be very effective in such setting.
Thompson et al. (2015)	USA		“To examine the validity of a tablet-computer-based audiometer for measuring hearing thresholds in a moderately noisy environment”.	Evaluation	Even though not all participants completed the conventional testing, the threshold percentage obtained was 97 with the tablet-based application and was within 10 dB.
Yeung et al. (2013)	Canada		“To validate an iPad-based play audiometer that addresses the shortcomings of existing audiometry”.	Evaluation	From the study, the poor placement of headphones used with the application during the testing, and the rushing the recruited child through the testing period affected the accuracy of the results, thereby causing the overlooking of children with different types of hearing-impaired cases.
Lycke et al (2017)	Belgium	uHear™	“To prospectively validate the modified uHear™ scoring system”.	Evaluation	The uHear™ smartphone application in this study was found to be a credible screening tool which identified 26.7% of the ninety ears (forty-five participants) tested as experiencing some degree of hearing loss.
Sethi et al. (2017)	USA		“Present a case in which a widely used hearing testing app was employed after hours in a patient with a complaint of unilateral sudden hearing loss”.	Evaluation	The uHear™ smartphone-based application in the study showed low prospects and poor accuracy in the assessment of sudden sensorineural hearing loss.
Livshitz et al. (2017)	Israel		“To examine the accuracy of application-based screening audiometry in comparison to a standard audiogram in the evaluation of hearing thresholds in a nonselected elderly population and the acceptability of the application-based hearing screening test in this population”.	Evaluation	The uHear™ smartphone application in this study was found to be “inaccurate in assessing hearing thresholds for screening purposes in the elderly”.

Al-Abri et al. (2016)	Oman		“To determine and explore the potential use of uHear as a screening test for determining hearing disability by evaluating its accuracy in a clinical setting and a soundproof booth when compared to the gold standard conventional audiometry".	Evaluation	In this study, “the mean difference between conventional audiometer and uHear in the side room was greater than 10 dB at all frequencies”.
Abu-Ghanem et al. (2014)	Israel		“To investigate the role of a smartphone-based test as a screening tool for hearing loss among the elderly”.	Evaluation	Results from the study showed that the uHear application used among 30 retired patients in measuring hearing thresholds were consistent with previous studies with a specificity value of 0.60 and sensitivity value of 1.00 compared to manual audiometry.
Lycke et al. (2016)	Belgium		“Validation of uHear™ as a screening tool to detect hearing loss in older patients with cancer without a known diagnosis of presbycusis, as part of a Comprehensive Geriatric Assessment (CGA).”	Evaluation	From the study, the uHear™ smartphone-based application showed a perfect sensitivity (100%) and negative predictive value (100.0%), and 36.4% as its specificity value.
Peer & Fagan (2015)	South Africa		“To evaluate the uHear app using an Apple iPhone as a possible hearing screening tool in the developing world”. “To determine the accuracy of certain hearing thresholds that could prove useful in early detection of hearing loss for high-risk populations in resource-poor communities”.	Evaluation	The uHear™ application from the study was found to obtain a sensitivity value of 1.0 and with specificity ranging between 0.68 to 0.88 in all the three environments within which the application was used in. Results from the study show that the iPhone uHear application is “adequate to screen for disabling hearing loss and has good accuracy to high-frequency hearing loss in SRs and QRs”.
Khoza-Shangase & Kassner (2013)	South Africa		“To determine the accuracy of UHear™, a downloadable audiometer on to an iPod Touch©, when compared with conventional audiometry”.	Evaluation	The uHear™ smartphone application was found not accurate compared to conventional audiometry as, the mean difference between the two methods was from 9.2 to 23.4, instead of a permissible limit of 10 dB.

Handzel et al. (2013)	Israel		To evaluate and estimate the "accuracy of the application-based hearing test in the evaluation of SSNHL".	Evaluation	The uHear™ application reflected hearing threshold more accurately in mid and high tones compared to low tones with specificity of 91% and sensitivity of 76%.
Szudek et al. (2012)	USA		"To evaluate the uHear iPod-based application as a test for hearing loss".	Evaluation	The uHear™ was found to be a valid screening hearing test with sensitivity of 98%, specificity of 82%.
Louw et al. (2017)	South Africa	hearScreen™	"To evaluate the performance of smartphone-based hearing screening with the hearScreen™ application in terms of sensitivity, specificity. Referral rates, and time efficiency at two primary health care clinics".	Evaluation	From the study involving the use of the hearScreen™ smartphone application on a total of 1236 participants, accuracy measures recorded are highlighted as follows. Specificity (83.1%) Sensitivity (81.7%) Negative predictive values (75.6%) Positive predictive value (87.6%) Referral rates (17.5%) Average initial screening time (61.35 secs).
Hussein et al. (2018)	South Africa		"This study investigated the feasibility of a smartphone-based hearing screening program for preschool children operated by community healthcare workers (CHWs) in community-based early childhood development (ECD) centers".	Feasibility	Out of the 6424 children screened in the study using the hearScreen™ smartphone-based application, the application was seen to detect unidentified hearing loss with a referral rate of 24.9% making the app a feasible tool to screen for hearing loss among children between the ages of 3 and 6 years.
Swanepoel et al. (2014)	South Africa		"Determine the validity of smartphone acoustic calibration using non-audiometric headphones". "Determine the validity of smartphone-based environmental noise monitoring". "Conduct a preliminary clinical validation in a sample of school children".	Evaluation	The study provided "first evidence of smartphone-based audiometry on devices other than iOS products and is the only application to date that allows for unique calibration of phone and headphone pairs according to prescribed standards". Screening outcomes from the hearScreen™ and the conventional hearing methods were 97.8% in agreement with each other (no significant difference).

Sandström et al. (2016)	South Africa		"To validate a calibrated smartphone-based hearing test in a sound booth environment and in primary health-care clinics".	Evaluation	The findings of the study indicate that, the hearing threshold obtained from the hearScreen™ and conventional method in a sound booth was 63.4% for normal hearing (that is hearing below or equal to 15 dB HL).
Mahomed-Asmail et al. (2016)	South Africa		"To determine the validity of a smartphone hearing screening technology (hearScreen™) compared with conventional screening audiometry in terms of (1) sensitivity and specificity, (2) referral rate, and (3) test time".	Evaluation	Sensitivity was equivalent with a value of 0.75, while specificity was higher (0.98) than conventional audiometry (0.97). Recorded referral rates were lower for the hearScreen™ with 3.2% compared to referral rates by the conventional method of 4.6%. The hearScreen™ smartphone-based application was considered faster screening tool than the conventional method.
Swanepoel et al. (2015)	South Africa		"Investigated a tele-assisted community-based programme for identification of hearing loss using smartphone-based hearing screening operated by generalist health care workers (i.e. CHWs)".	Evaluation	Positive attitudes from community health workers in using the hearScreen™ application was shown, and the use of the medical device showed easy to-administer characteristics.
van Tonder et al. (2017)	South Africa		"To validate the threshold version (hearTest) of the validated hearScreen™ smartphone-based application using inexpensive smartphones (Android operating software) and calibrated supra-aural headphone".	Evaluation	The hearTest application obtained 94.4% of the hearing screening threshold among the 30 adults recruited.
Chan et al. (2019)	Philippines and USA		"Large-scale otoscopic and audiometric assessment of populations is difficult due to logistic impracticalities, particularly in low- and middle-income countries (LMIC). We report a novel assessment methodology based on training local field workers, advances in audiometric testing equipment and cloud-based technology".	Pilot, Evaluation	Five Pilipino nurses were trained on the key activities from the robustness and key components of the audiometric population assessment methodology.

Appendix G: Characteristics of the study participants in all 49 identified studies.

	Name of application(s)	Name of Author(s)	Study population	Age ranges	Central tendency	Total Participants
1	Agilis Health Mobile Audiogram	Manganella et al. (2018)	Patients	21 - 28	Average 24.2	54
2	GSI AMTAS	Margolis & Moore (2011)	Clinic patients	21 - 65	N/A	25
		Eilkelboom et al. (2013)	Public & patients	N/A	N/A	54
3	AudCal	Larrosa et al. (2015)	Patients	18 - 91	Mean age 43.9	110
4	Audiogram Mobile	Corry, Sanders & Searchfield (2017)	Public	21 - 26	Median age 23	20
5	Ear Scale	Chu et al. (2019)	Public	11 - 12	Mean age 11	85
6	EarTrumpet	Foulad, Bui & Djalilian (2013)	Patients & NH	20 – 85	Mean age 58	42
		Derin et al. (2016)	N/A	19 - 85	Mean age 53.59	32
7	Hearing Test™	Salisu (2019)	Staff and patients	16 - 68	Mean age 33.4	60
		Masalski et al. (2016)	N/A	18 – 35	N/A	8620
		Masalski et al. (2018)	Public	18 – 71	Mean age 36	70
		Renda et al. (2016)	Outpatient clinic	18 – 66	Mean age 34.6	100
		Chauhan & Shah (2018)	Traffic police	N/A	N/A	88
8	Hearing-Test app	Na et al. (2014)	NH and patients	20 - 66	N/A	36
9	Hearing Test system	Kam et al. (2012)	Adults patients	18 – 73	Mean age 47	100
		Kam et al. (2013)	Primary students	6 - 10	Mean age 7.03	325
		Kam et al. (2014)	Pre-schoolers	3 - 7	N/A	6231
10	Hearing Test with Audiogram	Kelly et al. (2018)	Adult patients	18 - 85	Mean age 61	107
11	OtoID-Tablet	Brungart et al. (2017)	N/A	N/A	N/A	N/A
12	ShoeBOX	Tse, Ramsay & Lelli (2018)	Patients	45 - 55	Average age 49.8	5
		Pereira et al. (2018)	Public children	6 - 12	N/A	32
		Yeung et al. (2013)	Patients	3 - 13	Mean age 5.2	85
		Saliba et al. (2017)	Patients and NH	18 - 65	Mean age 49.7	33
		Levy et al. (2018)	Public children	5 - 17	Median age 10.5	423
		Thompson et al. (2015)	Patients	4 - 88	Mean age 51	49
		Yeung et al. (2015)	Patients	5 - 17	Mean age 9.5	80
		Rourke, Kong & Browwich (2016)	Public children	4 - 11	N/A	218
13	Sound Scouts	Dillon et al. (2018)	NH public	5 - 14	N/A	541
14	THST	Samelli et al. (2017)	Public adults	18 - 34	Mean age 22.3	30
15	uHear™	Szudek et al. (2012)	Adults patients	20 – 91	Mean age 46	100
		Khoza-Shangase and Lisa (2013)	Primary schoolers	8 – 10	Mean age 9	86
		Sethi et al. (2017)	Single patient	31	N/A	1

		Handzel et al. (2013) Abu-Ghanem et al. (2015) Lycke et al. (2016) Al-Abri et al. (2016) Peer & Fagan (2015) Livshitz et al. (2016) Lycke et al. (2017)	Adults patients Public retired Adults Patients University students Clinic patients Patients	20 – 82 65 – 94 70 – 85 > 17 15 – 86 > 65 70 - 91	Average age 51.4 Mean age 84.4 Average age 76.5 N/A Mean age 43 Mean age 74.6 Mean age 76.4	32 26 33 70 25 60 45
16	uHearing Test	Barczik & Serpanos (2018)	Adults patients	18 – 84	Mean age 48.7	22
17	ViA	Kocian et al. (2017)	N/A	N/A	N/A	N/A
18	hearScreen™	Swanepoel et al. (2014)	Public	5.6 – 7.7	Mean age 6.5	162
		Sandström et al. (2016)	Public and Patients	18 - 88	Mean age 41	94
		van Tonder et al. (2017)	Patients and public	24 - 92	Mean 59	95
		Mahomed-Asmail et al. (2016)	Public	5 - 12	Average 8	1070
		Yousuf Hussein et al. (2015)	Public	2 - 85	N/A	706
		Louw et al. (2017)	Public	3 - 97	Mean 37.8	1236
		Chan et al. (2019)	Patients	N/A	Mean 14.6	47
		Yousuf Hussein et al. (2018)	Public	3 - 6	N/A	6424

NH, Normal hearing; N/A, Not indicated

Appendix H: Names and test modalities of the audiometric platforms reviewed.

	Names of applications	Test modalities	No. of studies
1	GSI AMTAS	Pure-tone audiometry	2
2	ViA	Pure-tone audiometry	1
3	THST	Pure-tone audiometry	1
4	ShoeBOX	Pure-tone audiometry	8
5	hearScreen™	Pure-tone air conduction and speech audiometry	8
6	uHear™	Pure-tone air conduction and speech audiometry	10
7	AudCal	Pure-tone air conduction (only)	1
8	Audiogram Mobile	Pure-tone air conduction (only)	1
9	Ear Scale	Pure-tone air conduction (only)	1
10	EarTrumpet	Pure-tone air conduction (only)	2
11	Agilis Audiogram	Pure-tone air conduction (only)	1
12	uHearingTest	Pure-tone air conduction (only)	1
13	Hearing Test™	Pure-tone air conduction (only)	5
14	Hearing-Test App	Pure-tone air conduction (only)	1
15	Hearing Test system	Pure-tone air conduction (only)	3
16	HT with Audiogram	Pure-tone air conduction (only)	1
17	OtoID-Tablet	Pure-tone air conduction (only)	1
18	Sound Scouts	Pure-tone air conduction and speech audiometry	1
	Total	**18**	**49**

Appendix I: Test frequencies and people who performed them.

Mobile applications	**Tested frequencies (kHz)**	**PTAs**	**Manual audiometry by**	**Mobile/tablet audiometry by**
Agilis Audiogram (Manganella et al., 2018)	0.5, 1, 2, 4, 8	4-PTA	Paediatric audiologist	Self-administered
GSI AMTAS (Eilkelboom et al., 2013)	0.25, 0.5, 1, 2, 4, 8 for Air conduction 0.5, 1, 2, 4 for Bone conduction	4-PTA	Research audiologist	Research audiologist
AudCal (Larrosa et al., 2015)	0.5, 1, 2, 3, 4, 8	4-PTA	N/A	Professional
Audiogram Mobile (Kelly et al., 2018)	0.25, 0.5, 1, 2, 4, 8	Not measured	An audiology intern	An audiology intern
Ear Scale (Chu et al., 2019)	0.25, 0.5, 1, 2, 4	4-PTA	Audiologist	Self-administered
EarTrumpet (Derin et al., 2016)	0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6, 8	Was measured but not indicated.	Audiologist	Self-administered
hearScreen™ (Yousuf Hussein et al 2015)	1, 2, 4	3-PTA	Registered audiologist and	Professional
Hearing Test™ (Masalski et al., 2016)	0.25, 0.5, 1, 2, 4, 6, 8	4-PTA	Audiology assistant/ Audiologist	Self-administered
Hearing-Test App (Na et al., 2014)	0.5, 1, 2, 4, 8	3-PTA	N/A	Self-administered
Hearing Test System (Kam et al., 2012)	0.25, 5.0, 1, 2, 4, 8	3-PTA	Audiologist and School Nurse	Self-administered
HT with Audiogram (Kelly et al., 2018)	0.25, 0.5, 1, 2, 4, 8	3 / 4-PTA	Audiologist	Self-administered
OtoID-Tablet (Brungart et al., 2018)	0.5 – 2	N/A	N/A	Self-administered
ShoeBOX (Thompson et al., (2015)	0.25, 0.5, 1, 2, 4, 6, 8	3/4/5-PTA	Audiologist	Self-administered
Sound Scouts (Dillon et al., 2018)	0.5, 1, 2, 4	4-PTA	N/A	Self-administered
THST (Thoidis et al., 2019)	0.125, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6, 8	3-PTA	Audiologist	Self-administered
uHear™ (Abu-Ghanem et al., 2015)	0.25, 0.5, 1, 2, 4, 6	3 / 4/ 6-PTA	Audiologist	Self-administered
uHearingTest (Barczik & Serpanos, 2018b)	0.25, 0.5, 1, 2, 4, 8	3-PTA	Audiologist	Self-administered
ViA (Kocian et al., 2017)	0.25, 0.5, 1, 2, 4, 8	4-PTA	Audiologist	Self-administered

kHz, kiloHertz; N/A, Not indicated; HW, Hughson-Westlake; MHW, modified Hughson-Westlake; PTA, pure-tone audiometry; SRT, speech recognition threshold; 1-PTAv, 0.5; 3-PTAv, 0.5, 1, 2; 3i-PTA, 1, 2, 4; 4-PTA, 0.5, 1, 2, 4; 5-PTA, 0.5, 1, 2, 4, 8; 6-PTA, 0.25, 0.5, 1, 2, 4, 6 (All PTA units are in kHz).

Appendix J: Stimulus, ambient noise and sound levels of the 18 mHealth applications.

Name of the platform	**Stimuli type**	**Ambient noise (dBA/SPL)**	**Sound level intensity (dB SPL)**	**Threshold intensity (dB/SPL)**
Agilis Audiogram	Pure tones	N/A	N/A	N/A
GSI AMTAS™	Pure tones	38.5	35	35 - 70
AudCal	Pure tones	N/A	75	0 - 75
Audiogram Mobile	Pure tones	60	N/A	10 - 100
Ear Scale	Pure tones	50	20	0 - 100
EarTrumpet	Pure tones	N/A	35	0 - 80
Hearing Test™	Pure tones	N/A	N/A	40 - 60
Hearing-Test App	Pure tones	40	N/A	30 - 80
Hearing Test System	Pure tones	40 - 51	N/A	-10 - 70
HT with Audiogram	Pure tones	N/A	N/A	N/A
hearScreen™	Pure tones	45 - 65	50	30 - 50
OtoID-Tablet	Pure tones	N/A	N/A	N/A
ShoeBOX	Warble tones	39.5	15	-10 - 90
Sound Scouts	Pure tones and Speech.	N/A	35	N/A
THST	Continuous, pulsed, and warble.	N/A	30	-10 to max.
uHear™	Pure tones	50	N/A	41 - 42
uHearingTest	Pure tones	N/A	N/A	N/A
ViA	Pure tones	N/A	N/A	N/A

N/A, Not indicated; dB SPL, Decibels of sound pressure levels;

Appendix K: Conventional audiometers, protocols, and test environments for the 49 studies.

Reference	Reference test	Where	Device/App calibration	Test environment	Type of transducers used
Swanepoel et al. (2014)	Interacoustics Impedance Audiometer AT 235 and GSI Auto Tymp	Local school	Calibration of the phone and headphones was done using these prescribed standards (that is, ANSI/ASA S3.6, 2010; and ISO 389-1,1998	Quiet room	Telephonics TDH 39P headphones
Yousuf Hussein et al. (2016)	Not indicated	Homes of patients	Not indicated	Quite rooms	Not indicated
Sandström et al. (2016)	Clinical audiometer GSI 61 and KUDUwave diagnostic audiometer	Department of Speech-Language Pathology and Audiology	Calibration was done using the app’s calibration function as prescribed by ISO 389-1,1998	Sound booth and examination rooms at designated primary healthcare clinics	Supra-aural earphones (TDH 49) and insert earphones covered by circumaural earcups
Mahomed-Asmail et al. (2016)	GSI Auto Tymp or an Interacoustics Impedance Audiometer AT 235 and KUDUwave Type 2 Clinical audiometer	Five stations in a school	Calibration was done using the app’s calibration function as prescribed by standards (ISO 389-1,1998; ANSI/ASA S3.6-2010)	Quiet room	Telephonics TDH 39P headphone and insert earphones covered by circumaural earcups
van Tonder et al. (2017)	GSI 61 two-channel audiometer and Otometrics Otosuite	Clinic centres	The hearScreen™ calibration function was used to calibrate the headphones (ISO 389-9, 2009)	Soundproof booth	TDH 39 audiometric headphones and insert earphones
Louw et al. (2017)	KUDUwave Type 2 Clinical Audiometer	Clinic centre	The hearScreen™ calibration function was used to calibrate the headphones (ANSI/ASA S3.6-2010; ISO 389-1, 1998)	Examination room	Circumaural ear cups
Yousuf Hussein et al. (2018)	Not indicated	Early childhood development (ECD) centres or creches.	Calibration was done using the application’s calibration function as prescribed by ISO 389-1,1998.	Room with the least noise possible.	Not indicated
Chan et al. (2019)	Handheld audiometer	Schools	Not indicated	Quiet classrooms rooms	Sennheiser HD 280 Pro for audiometry

Manganella et al. (2018)	Audiogram	Soundproof audio booth meeting ANSI requirements for ambient noise levels.	Standardized calibration protocols were followed for the hardware, software and the headset.	Sound audio booth chamber meeting ANSI requirements for ambient noise levels.	Etymotic HF5 earphones
Margolis & Moore (2011)	Interacoustics AC 40 or GSI 61	Two-room, double-wall sound attenuating chamber	The air conduction stimuli of the application were calibrated to the International (ISO 389-8, 2004) and the American (ANSI S3.6-2010) specifications.	Two-room, double-wall sound attenuating chamber	Telephonics TDH50 supra-aural earphone (Type 51 cushion), Sennheiser HDA 200 circumaural earphones and the Etymonic Research ER3A insert earphone.
Eilkelboom et al. (2013)	GSI 61 Clinical audiometer	Certified sound booth	The air conduction stimuli of the application were calibrated to the International (ISO 389-8, 2004) and the American (ANSI S3.6-2010) specifications.	Quiet room	Sennheiser HDA 200 circumaural earphones
Larrosa et al. (2015)	Audiotest 256 b clinical audiometers	Sound-treated booths.	The pure-tone air conduction tests were performed using calibrated ISO standard headphones in a sound booth.	Sound-treated booths	Apple EarPods
Corry, Sanders & Searchfield (2017)	GSI-61 Type 1 audiometer	Soundproof booth	Calibration was performed using a Type 2250 Brǜel & Kjær sound level meter.	Soundproof booth	Apple EarPods
Chu et al. (2019)	GSI 18 screening audiometer	Quiet room	The reference equivalent threshold sound pressure level (RETSPL) method was used with calibrated bundled headphones when calibrating the audiometric equipment.	Sound-treated booth	Apple EarPods
Foulad, Bui & Djalilian (2013)	GSI 16 audiometer	Double-walled sound booth	Not indicated	Sound booth and a quiet room	Apple EarPods

Derin et al. (2016)	AC 40 clinical audiometer	Soundproof booth	Not indicated	Quiet room	Philips SHP 1900 headset
Salisu (2019)	Welch/Alyn TM 262 Auto Tympanometer or Audiometer	Quiet consulting room	Not indicated	Quiet consulting room	Bundled earphone from phone
Masalski et al. (2016)	Interacoustics AD 229e clinical audiometer	Sound booth	The calibration of the application was done in a sound booth with a calibrated headphone (TDH-39) according to ISO 389-1:1998.	Home of participants	Bundled earphone from phone
Masalski et al. (2018)	Interacoustic AC 229e clinical audiometer	Sound booth	The calibration of the application was done in a sound booth with a calibrated headphone (TDH-39) according to ISO 389-1:1998.	Sound booth	Bundled earphone from phone
Renda et al. (2016	Interacoustics AC 229e clinical audiometer	Sound booth	The headphones were calibrated according to the American National Standards Institute Standards (S3.6-2004.2204). The application generates pure-tone signals with calibration function to the required reference equivalent threshold sound pressure level (RETSPL).	Sound booth	Bundled earphone from phone
Chauhan & Shah (2018)	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated
Na et al. (2014)	Orbiter 922 clinical audiometer	Not indicated	The smartphone microphone, earphone and the hearing threshold shift (HTS) were calibrated to provide a sound level in standard units.	Noisy and quiet environments.	Bundled earphone from phone
Kam et al. (2012)	GSI 61 Clinical audiometer	Soundproof booth	Not indicated	Quiet room	Apple iPod

Kam et al. (2013)	Madsen Itera clinical audiometer	Sound booth in a coach	Not indicated	Quiet classroom	Bose QuietComfort®15 Acoustic Noise Cancelling®
Kam et al. (2014)	Madsen Itera clinical audiometer	Sound booth in a coach	Not indicated	Quiet rooms in the kindergartens	Bose QuietComfort®15 Acoustic Noise Cancelling®
Kelly et al. (2018)	Calibrated audiometer	Soundproof room	Not indicated	Quiet examination room and in the clinic's waiting area.	Bose QuietComfort®15 Acoustic Noise Cancelling®
Brungart et al. (2018)	Not indicated	Not indicated	Not indicated	Not indicated	Circumaural earphones
Rourke, Kong & Browwich (2016)	Not indicated	School library	The tablet device's microphone was calibrated against the American National Standards Institute on maximum permissible ambient noise levels and attenuation characteristics.	School libraries	Headphone
Yeung et al. (2015)	Clinical audiometer	Double-walled sound booth	Not indicated	Single clinic room without sound insulation.	TDH 39
Tse, Ramsay & Lelli (2018)	Not indicated	Not indicated	Calibration of devices and headphones conformed with ANSI S3.6, CSA Z107.6-16 and IEC 60645-1 and 60645-3 standards.	Quiet an environment as possible.	TDH 39 and TDH 50
Pereira et al. (2018)	Equinox Interacoustics audiometer	Soundproof audio booth	Not indicated	Soundproof booth	HDA-280
Levy et al. (2018)	Not indicated	Not indicated	Not indicated	Outside of a sound-treated environment.	TDH 50
Saliba et al. (2017)	GSI AudioStar Pro audiometer	Double-walled sound booth	Not indicated	Sound booth	3A E-A-Rtone headphone

Thompson et al. (2015)	Madsen Astera clinical audiometer	Consulting room off a hallway with moderate traffic.	Not indicated	Consulting room off a hallway with moderate traffic.	TDH 39
Yeung et al. (2013)	Tablet play audiometer	Double-walled sound booth	Not indicated	Double-walled sound booth	Headphones
Dillon et al. (2018)	Speech recognition threshold	Not indicated	Not indicated	Quietest room	Sennheiser HD215
Samelli et al. (2017)	GSI 61 Type 1 clinical audiometer	Acoustic booth	Not indicated	Nonsound proof booth, but screening in quiet room.	TDH 39
Lycke et al. (2017)	Interacoustics AC3 audiometer	Sound booth	Not indicated	Quiet hospital room or physician office	Apple earbuds
Barczik & Serpanos (2018)	Beltone 10D audiometer	Quiet room	Not indicated	Quiet room	Earbuds and Sennheiser Model XP 100
Sethi et al. (2017)	Physical examination using a 512 Hz tuning fork	Quiet room	Not indicated	Quiet room	Earbuds
Livshitz et al. (2016)	Pure-tone audiometry	Non- soundproof quiet room	Not indicated	Non- soundproof quiet room	AKG K512 MK II
Al-Abri et al. (2016)	Normal hearing threshold	Soundproof both	Not indicated	Side room and soundproof booth	Headphones
Abu-Ghanem et al. (2015)	Interacoustics Clinical audiometer AC33	Quiet room (non-soundproof)	Not indicated	Quiet room (non-soundproof)	Sennheiser CX300 earbuds
Lycke et al. (2016)	Interacoustics Clinical audiometer AC3	Sound booth	Not indicated	Quiet hospital room or physician office	iPod touch earbuds
Peer & Fagan (2015)	Not indicated	Not indicated	Not indicated	Waiting room, quiet room, soundproof room	Earbud
Khoza-Shangase and Lisa (2013)	Typical audiometer AD299e	Quiet room	Not indicated	Quiet room	Headphone
Handzel et al. (2013)	Standard audiograms	Quiet office space (not soundproof)	Not indicated	Quiet office space (not-soundproof)	Creative EP 630

Szudek et al. (2012)	Clinical audiometers	Sound- treated booth	Not indicated	Sound-treated booth and waiting room.	Earbuds
Kocian et al. (2017)	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated

Appendix L: Performance of 18 applications in 49 identified studies.

Mobile application	Reference(s)	HL Definition (dB HL)	Test time	Retest	Masking intensity	Se (%)	Sp (%)	PPV (%)	NPV (%)
Agilis Mobile	Manganella et al. (2018)	PTAv >20	10 mins	Yes	N/A	N/A	N/A	N/A	N/A
GSI AMTAS	Margolis & Moore (2011)	N/A	N/A	Yes	N/A	N/A	N/A	N/A	N/A
	Eilkelboom et al. (2013)	PTAv >20	16.1 mins	Yes	N/A	N/A	N/A	N/A	N/A
AudCal	Larrosa et al. (2015)	PTAv >20	N/A	No	N/A	N/A	N/A	N/A	N/A
Audiogram Mobile	Corry, Sanders & Searchfield (2017) in a study by Kelly et al. (2018)	PTAv >20	4.01 mins	Yes	Yes,	QR - 85 WA - 87	N/A	N/A	N/A
Ear Scale	Chu et al. (2019)	PTAv >25	N/A	N/A	N/A	100	100	0	0
EarTrumpet	Foulad, Bui & Djalilian (2013)	PTAv >20	N/A	Yes	Yes, 35 dB	N/A	N/A	N/A	N/A
	Derin et al. (2016)	PTAv >20	N/A	Yes	Yes, 35 dB	N/A	N/A	N/A	N/A
Hearing Test™	Salisu (2019)	PTAv >25	N/A	Yes	Yes, 45 dB	96	100	N/A	N/A
	Masalski et al. (2016)	PTAv >20	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Masalski et al. (2018)	PTAv >20	N/A	Yes	Yes, 40 dB	N/A	N/A	N/A	N/A
	Renda et al. (2016)	PTAv >20	<8 mins	N/A	Yes, 40 – 60	N/A	N/A	N/A	N/A
	Chauhan & Shah (2018)	N/A	5 mins	N/A	N/A	N/A	N/A	N/A	N/A
Hearing-Test	Na et al. (2014)	N/A	15 mins[1]	N/A	N/A	N/A	N/A	N/A	N/A
Hearing Test System	Kam et al. (2012)	PTAv >25	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Kam et al. (2013)	PTAv >25	N/A	Yes	N/A	50[2] / 63[3]	82[4]	13	97
	Kam et al. (2014)	PTAv >30	2.49 mins	N/A	N/A	33 - 95	15 -100	N/A	N/A
Hearing Test with Audiogram	Kelly et al. (2018)	PTAv >20	6 mins	N/A	N/A	QR - 87.8 WA - 89	WR 69.4 WA 68.2	N/A	N/A
OtoID-tablet	Brungart et al. (2018)	N/A	15 mins	Yes	N/A	N/A	N/A	N/A	N/A
ShoeBOX	Rourke, Kong & Browwich (2016)	PTAv >30	193 secs	N/A	N/A	N/A	N/A	N/A	N/A
	Yeung et al. (2013)	PTAv >25	N/A	N/A	N/A	91.2	57.8	62.0	89.7
	Tse, Ramsay & Lelli (2018)	N/A	4.2 mins	N/A	N/A	N/A	N/A	N/A	N/A
	Pereira et al. (2018)	N/A	12.3 mins	N/A	N/A	N/A	N/A	N/A	N/A
	Saliba et al. (2017)	PTAv >25	350.9 secs	N/A	N/A	100	95.9	N/A	N/A
	Thompson et al. (2015)	PTAv >25	N/A	N/A	N/A	90	88.9	N/A	N/A
	Levy et al. (2018)	PTAv >30	530.42 secs	N/A	N/A	N/A	N/A	N/A	N/A
	Yeung et al. (2015)	PTAv >25	2.5 mins	N/A	N/A	93.3	94.5	82.3	98.1
Sound Scouts	Dillon et al. (2018)	PTAv >20	N/A	N/A	N/A	85	98	N/A	N/A
THST	Thoidis et al. (2019)	PTAv >20	N/A	N/A	Yes, 35 dB	100	100	N/A	N/A

[1] Time was mentioned as practice time before the hearing assessment starts.
[2] Sensitivity of the Hearing Test System at a PTAv >25.
[3] Sensitivity of the Hearing Test System at a PTAv > 30.
[4] Specificity of Hearing Test System at a PTAv >25 and >30 was the same.

uHear™	Lycke et al. (2017)	PTAv >40	N/A	N/A	N/A	68.2	86.8	62.5	89.4
	Sethi et al. (2017)	PTAv >15	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Livshitz et al. (2016)	PTAv >35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Al-Abri et al. (2016)	PTAv >25	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Abu-Ghanem et al. (2015)	PTAv >40	371.50 secs	N/A	N/A	100	60	N/A	N/A
	Lycke et al. (2016)	PTAv >40	N/A	N/A	N/A	100	36.4	22.2	100
	Peer & Fagan (2015)	PTAv >40	N/A	N/A	N/A	100	88	Least	High
	Khoza-Shangase and Lisa (2013)	PTAv >15	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Handzel et al. (2013)	PTAv >25	N/A	N/A	N/A	76 – 94	86 – 91	N/A	N/A
	Szudek et al. (2012)	PTAv >40	N/A	N/A	N/A	98	82	N/A	N/A
uHearingTest	Barczik & Serpanos (2018)	PTAv >25	N/A	N/A	N/A	85.7 – 90.5	87 – 96.7	85.7 – 92.3	90.9 – 93.6
ViA	Kocian et al. (2017)	N/A	N/A	Yes	N/A	N/A	N/A	N/A	N/A
hearScreen™	Swanepoel et al. (2014)	PTAv >20	1.015 mins	N/A	N/A	N/A	N/A	N/A	N/A
	Mahomed-Asmail et al. (2016)	PTAv >25	54.3 secs	N/A	N/A	75	98.5	N/A	N/A
	Yousuf Hussein et al. (2015)	PTAv >25	46.2 – 50.0 secs	N/A	N/A	N/A	N/A	N/A	N/A
	Yousuf Hussein et al. (2018)	PTAv >25	1.133 mins	N/A	N/A	N/A	N/A	N/A	N/A
	Louw et al. (2017)	PTAv >30	1.232 mins	N/A	N/A	81.7	83.1	87.6	75.6
	Chan et al. (2019)	PTAv >35	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Sandström et al. (2016)	PTAv >15	4.933 – 5.917mins	N/A	N/A	N/A	N/A	N/A	N/A
	van Tonder et al. (2017)	PTAv >20	6.75 mins	N/A	N/A	N/A	N/A	N/A	N/A

* hearZA/DIN SRT compared to the best ear 4FPTA; **hearZA/DIN SRT compared to maximum SRS dB; NM, normal hearing.
QR, quiet examination room; WA – waiting area; N/A, not indicated.

Appendix M: Language screening options of the 18 mHealth applications.

	Application names	English	German	Spanish	French	Polish	Italian	Japanese	Korean	Portuguese	Russian	Dutch
1.	Agilis Audiogram	Y	-	-	-	-	-	-	-	-	-	-
2.	GSI AMTAS	Y	-	-	-	-	-	-	-	-	-	-
3.	AudCal	Y	-	Y	-	-	-	-	-	-	-	-
4.	Audiogram Mobile	Y	Y	Y	Y	-	Y	-	-	-	-	-
5.	Ear Scale	Y	-	-	-	-	-	-	-	-	-	-
6.	EarTrumpet	Y	Y	-	-	-	-	-	-	-	-	-
7.	hearScreen™	Y	-	-	-	-	-	-	-	-	-	-
8.	Hearing Test™	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-
9.	Hearing-Test App	Y	-	-	-	-	-	-	-	-	-	-
10.	Hearing Test System	Y	-	-	-	-	-	-	-	-	-	-
11.	HT with Audiogram	Y	-	-	-	-	-	-	-	-	-	-
12.	OtoID-Tablet	Y	-	-	-	-	-	-	-	-	-	-
13.	ShoeBOX	The ShoeBOX tablet-based application is largely language dependent.										
14.	Sound Scouts	Y	-	-	-	-	-	-	-	-	-	-
15.	THST	Y	-	-	-	-	-	-	-	-	-	-
16.	uHear™	Y	Y	Y	Y	-	-	-	-	-	-	Y
17.	uHearingTest	Y	-	-	-	-	-	-	-	-	-	-
18.	ViA	Y	-	-	-	-	-	-	-	-	-	-

Y, Yes

Appendix N: Results on post-test feedback from participants on the 18 applications.

Names of mobile device application	Number of participants	Tool used in assessing satisfaction	Experience	Satisfaction	Device/hardware feedback	Testing modalities	Instructor feedback
Agilis Health Mobile Audiogram	27	N/A	All participants were able to self-administer the Agilis Audiogram.	Direction from the instructions from the app was clear and straightforward.	6 participants preferred a supra-aural headphone instead of the clinical ear buds during examination.	N/A	2 people wanted the audiologist with them in the sound booth during testing. This would reduce anxiety and enable them to seek clarity.
GSI AMTAS	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AudCal	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Audiogram Mobile	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ear Scale	N/A	N/A	N/A	N/A	N/A	N/A	N/A
EarTrumpet	42	N/A	Participants were more comfortable, and found the application less intimidating, more convenient, and more comfortable.	Mobile application was simple to use.	All patients preferred the tablet-based audiometry if they were not going to be required or asked to visit the clinic.	If clinic visit was a requirement, 90% preferred the tablet-based to the conventional method.	N/A
Hearing Test™	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hearing-Test App	16	A questionnaire-based study to people.	N/A	N/A	81% of the users thought the application was easy to use.	N/A	All users wanted practice time less than 15 minutes.
Hearing Test System	N/A	N/A	N/A	N/A	N/A	N/A	N/A

HT with Audiogram	107 for all groups (but 35 were tested with the HT with audiogram application)	5-Question patient survey	Patients preferred conventional audiogram (70%) if they could schedule a tablet-based hearing test at their primary care doctor's office rather than a separate audiology clinic appointment, to the tablet-based audiogram (27%).	97% of the 107 patients indicated that they would be willing to have further definitive testing performed if they had performed the tablet-based hearing and hearing loss was found. 49% of patients would prefer tablet-audiometry to conventional audiogram, if they were required to schedule an outpatient audiology clinic appointment to test their hearing.	Patient preferences were 39%, 45% and 16% for conventional audiometry, mobile application audiometry and no preference, respectively.	99% of patients found the mobile application hearing test was easy to use.	N/A
OtoID-Tablet	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ShoeBOX	32	N/A	56% percent of the participants in a study preferred automated audiometry.	N/A	N/A	No technical difficulties were experienced.	N/A
Sound Scouts	N/A	N/A	N/A	N/A	N/A	N/A	N/A
THST	N/A	N/A	N/A	N/A	N/A	N/A	N/A
uHear™	30	uHear questionnaire	N/A	N/A	N/A	N/A	N/A
uHearingTest	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ViA	N/A	N/A	N/A	N/A	N/A	N/A	N/A

NA, Not indicated.

Appendix O: The functionality of the 18 smartphone – and tablet-based applications.

	Name of app	Functionality of the applications
1	Agilis Mobile	The app "overestimated the severity of hearing loss", however, was within the 95% confidence interval range (Manganella et al., 2018).
2	GSI AMTAS	Acceptable threshold variations were found in both AC (5.88 dB and 6.87 dB) and BC (6.16 dB and 8.76 dB) (Eilkelboom et al., 2013).
3	AudCal	Excellent reliability was found by intra-class correlation coefficient of 0.93 and a Cronbach's alpha index of 0.96 (Larrosa et al., 2015).
4	Audiogram Mobile	Test and test-retest reliability was similar between the conventional audiometry and smartphone-based app (Corry, Sanders & Searchfield, 2017).
5	Ear Scale	The application was reasonably accurate for the screening of hearing loss with high sensitivity and specificity (100%) (Chu et al., 2019).
6	EarTrumpet	Ninety-six percent of threshold values obtained during screening were within 10 dB of the corresponding threshold using the conventional method (Foulad, Bui & Djalilian, 2013).
7	HT with Audiogram	Seventy-one percent of the pure-tone thresholds were measured by the application within ± 10 dB of audiometry (Kelly et al., 2018).
8	Hearing-Test app	The application was able to properly estimate the hearing threshold in a quiet and even a noisy environment (Na et al., 2014).
9	Hearing Test™	The agreement between the audiograms was excellent with values ranging between 87.8% to 93.3% (Renda et al., 2016).
10	Hearing Test system	A high test-retest reliability was observed with an intraclass correlation coefficient (97%) between the audiograms (Kam et al., 2012).
11	OtoID-Tablet	The app functions effectively when used with hard-wired headphones complying fully with standard specification (Brungart et al., 2018).
12	ShoeBOX	Data showed no statistically significant difference between thresholds obtained by both audiometry methods (Yeung et al., 2013).
13	Sound Scouts	The application was able to correctly identify hearing loss in only two-thirds of the cases it found (Dillon et al., 2018).
14	THST	From the results, a perfect concordance was indicated between the two methods with 100% for all measures (Samelli et al., 2018).
15	uHear™	The uHear™ app overestimated PTA among participants with hearing loss between 4 dB and 6 dB (Szudek et al., 2012).
16	uHearingTest	The application was accurate in the assessment of hearing threshold for mild hearing loss (Barczik & Serpanos, 2018).
17	ViA	ViA can potentially identify individuals with correctable hearing loss (Kocian et al., 2017).
18	hearScreen™	"No statistically significant difference in performance between the techniques was noted" (Mahomed-Asmail et al., 2016).

Appendix P: The World Bank's Low- and Middle-Income Countries or economies.

Afghanistan	Albania	Algeria	American Samoa	Angola	Argentina	Armenia	Azerbaija	Bangladesh	Belarus
Belize	Benin	Bhutan	Bolivia	Bosnia and Herzegovina	Botswana	Brazil	Bulgaria	Burkina Faso	Burundi
Cabo Verde	Cambodia	Cameroon	Central African Republic	Chad	China	Colombia	Comoros	Congo, Democratic Republic	Congo, Republic
Costa Rica	Cote d'Ivoire	Cuba	Djibouti	Dominica	Dominican Republic	Ecuador	Egypt, Arab Republic	El Salvador	Equatorial Guinea
Eritrea	Eswatini	Ethiopia	Fiji	Gabon	The Gambia	Georgia	Ghana	Grenada	Guatemala
Guinea	Guinea-Bissau	Guyana	Haiti	Honduras	India	Indonesia	Iran, Islamic Republic	Iraq	Jamaica
Jordan	Kazakhstan	Kenya	Kiribati	Korea, Democratic People's Republic	Kosovo	Kyrgyz Republic	Lao PDR	Lebanon	Lesotho
Liberia	Libya	Madagascar	Malawi	Malaysia	Maldives	Mali	Marshall Islands	Mauritania	Mauritius
Mexico	Micronesia, Federal States	Moldova	Mongolia	Montenegro	Morocco	Mozambique	Myanmar	Namibia	Nepal
Nicaragua	Niger	Nigeria	North Macedonia	Pakistan	Panama	Papua New Guinea	Paraguay	Peru	Philippines
Russian Federation	Rwanda	Samoa	Sao Tome and Principe	Senegal	Serbia	Sierra Leone	Solomon Islands	Somalia	South Africa
South Sudan	Sri Lanka	St. Lucia	St. Vincent and the Grenadines	Sudan	Suriname	Syrian Arab Republic	Tajikistan	Tanzania	Thailand
Timor-Leste	Togo	Tonga	Tunisia	Turkey	Turkmenistan	Tuvalu	Uganda	Ukraine	Uzbekistan
Vanuatu	Vietnam	West Bank and Gaza	Yemen, Republic	Zambia	Zimbabwe				